Atomic Energy of Canada Limited

VOID COEFFICIENT MEASUREMENTS IN ZEEP

CRRP-942

by

R.E. GREEN, G.A. BEER and D.W. HONE

Chalk River, Ontario

June, 1960

AECL No. 1053

ATOMIC ENERGY OF CANADA LIMITED
Chalk River Project

VOID COEFFICIENT MEASUREMENTS IN ZEEP

by

R.E. Green, G.A. Beer, D.W. Hone

CRRP-942

Chalk River, Ontario June, 1960

CONTENTS

INTRODUCTION

An important factor in the control and safety of liquid-cooled and boiling water power reactors is the reactivity effect associated with a change in the coolant density or the presence of voids in the coolant, i.e. the so-called void coefficient. There are three situations where the coolant density can be decreased and even reduced to zero (coolant completely expelled). These are as follows:

(1) a coolant pump failure with subsequent boiling and evaporation of all the coolant,

(2) a break in the coolant circuit which permits the escape of coolant and results in boiling in the core channels, and

(3) a power surge which might ultimately expel all the coolant. The initial surge raises the coolant temperature, hence lowers its density and if the void coefficient is positive and large enough to overcome the fuel temperature coefficient (which is usually negative), the reactor will become unstable and the reactivity will increase until all the coolant has boiled off.

Since the reactor control system must be able to cope with the reactivity changes associated with coolant density changes as well as with a complete loss of coolant, the void coefficient is an important factor in the design of any power reactor. This report describes recent experiments done in ZEEP to determine the reactivity effect of a loss of coolant for a lattice of 7-element UO_2

clusters. Previous experiments in 19-element UO_2 cluster lattices which were described in RPI-51 have been reanalyzed using the methods of the present report and those results are also presented here.

EXPERIMENTAL

1. Description of Fuel and Lattice

A cross-sectional view of the 7-element UO_2 fuel clusters used in these experiments is shown in Fig. 1. The UO_2 was in the form of pellets 2.40 cm in diameter and 2.54 cm long having a density of 10.2 gm/cm^3. The fuel was arranged in bundles 47.3 cm long with five such bundles forming a complete fuel assembly. The thin-walled Al coolant tube (see Fig. 1) served to hold the fuel bundles as well as define the coolant volume. The coolant area was 17.65 cm^2. Fig. 2 shows the geometrical details of these fuel bundles while Fig. 3 is a sketch of a complete fuel assembly. 55 such assemblies were placed in ZEEP to form a hexagonal lattice with a pitch of 24.56 cm. The lattice arrangement is shown in Fig. 4. The numbering system used to identify the fuel assemblies is also shown on this diagram. (Note that the central rod is designated CR.)

2. Coolant Exclusion Technique

Fig. 5 illustrates the method used to expel the coolant from the fuel assemblies. The coolant tubes were made airtight at the top and each was fitted with Poly-flo plastic 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 a cylinder of helium. When the He pressure was applied the coolant was expelled into the moderator region of the lattice through the holes in the bottom plugs of the coolant tubes. By varying the He pressure, the D_2O in the coolant tubes could be made to assume any desired level.

It was also possible to expel the coolant from any one fuel assembly or group of assemblies in the lattice by interchanging couplings and manipulating the appropriate valves on the manifolds.

It was, of course, necessary to know the relationship between He pressure and the D_2O level in the coolant tubes. This was determined in the following way. An oil manometer (see Fig. 5) was connected to the manifold at the He cylinder and the pressure required to completely expel the coolant from the central assembly was observed for various moderator levels. The point of complete exclusion was determined by observing the onset of bubbling in the moderator. (An oscillation of the oil level in the oil manometer also marked this point.) The relationship between oil manometer reading and moderator level as read from the D_2O manometer is shown in Fig. 6. The relationship is, as expected, quite linear and from the slope of this curve the He pressure required to alter the coolant level by 1 cm was found in terms of oil manometer divisions. In a given experiment then, knowledge of the critical moderator level and the oil manometer reading defines the coolant level $h_{coolant}$ since;

$$h_{coolant} = h_{MOD.} - mh_{OM} \tag{1}$$

where $h_{MOD.}$ is the critical moderator height above the zero plane,

h_{OM} is the oil manometer reading, and

m is the reciprocal of the slope of Fig. 6.

3. Determination of the Reactivity Change

The experimental procedure was as follows. The change in height required to keep the reactor critical when the coolant was expelled from a given region of the lattice was measured. This height change Δh can be expressed as a change in buckling ΔB^2 using the relation,

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

where h is the extrapolated height of the unperturbed lattice. In using (2) we have assumed that the radial and axial extrapolation lengths in ZEEP are independent of D_2O level so that ΔB^2 is a function only of the change in critical height Δh. If we also make use of the two-group relation between k_∞ and B^2, viz.,

$$k_\infty = (1 + L^2B^2)(1 + L_s^2B^2) \qquad (3)$$

then the measured critical height changes can be expressed as reactivity changes using

$$\begin{aligned} \delta k_\infty &= (L^2 + L_s^2 + 2L^2L_s^2B^2)\ \Delta B^2 \\ &= \pi^2(L^2 + L_s^2 + 2L^2L_s^2B^2) \left[\frac{1}{(h+\Delta h)^2} - \frac{1}{h^2}\right] \qquad (4) \end{aligned}$$

where δk_∞ is the uniform change in k_∞ throughout the lattice which is equivalent to the actual changes made, and L^2, L_s^2 and B^2 have their usual meanings.

The critical height changes were measured with a selsyn-driven height probe with which it is possible to measure changes in height to ±0.007 cm. Although short-lived delayed neutron effects were always outwaited the height probe readings still had to be corrected for

(a) the fact that the reactor was not critical at the exact moment that the height was measured, and

(b) the long term variation of pile reactivity due to temperature drift and long-lived photoneutron effects.

Correction (a) was kept small by taking measurements only when the period was greater than 1 hour. The size of the correction was obtained by measuring the change in period produced by a measured change in height. Correction (b) was obtained by measuring the critical height for some standard condition (in this case with the coolant in all assemblies) before and after the other measurements were made and assuming a linear variation of reactivity with time. If a long sequence of measurements was made the standard measurement was repeated after every 5 or 6 measurements and a curve of reactivity vs. time was determined from which corrections could be obtained. The corrections were of the order of 0.02 cm, i.e. about three times the quoted error in the measurements.

RESULTS AND DISCUSSION

Two series of measurements were made in this lattice, one in which ZED-2 D_2O (99.75 atom %) filled the reactor and the other in which ZEEP D_2O (99.52 atom %) filled the reactor. Using ZED-2 D_2O, the effects of coolant loss from single clusters, from groups of clusters and from all 55 clusters in the pile were measured. The reactivity effect as a function of coolant level was also measured. The same experiments were done for ZEEP D_2O except that only one single cluster experiment was done, that being the central one.

1. ZED-2 D_2O Results

The reactivity effects associated with a complete loss of coolant from single rods at various positions in the pile are listed in Table 1 for ZED-2 D_2O. The Δh values in column 4 are the differences in critical height between the cases where the coolant is expelled and the standard pile with coolant in all clusters. The values of δk_∞ given in column 5 are obtained using Eqn. (4) with the following values of L^2, L_s^2 and B^2;

$L^2 = 161.3$ cm^2

$L_s^2 = 130.2$ cm^2, and

$B^2 = 5.69$ m^{-2}.

Table 2 gives the results for exclusion from groups of rods comprising various radial regions in the pile. These regions can be determined from the cluster numbers given in the first column of the table by referring to Fig. 4. For the results listed in

Tables 1 and 2, the He pressure was adjusted so that the coolant level was always near the bottom of the coolant tube. Although the level was not exactly the same each time it was always within ~ 3 cm of the bottom of the tube. Since, as will be seen below, the reactivity effect is rather insensitive to coolant level in this region no corrections have been made for this.

Table 3 gives the results for the reactivity effect as a function of coolant level. In this experiment the coolant was expelled from all 55 clusters simultaneously. Critical heights were measured for a range of He pressures for which the coolant levels were obtained using Eqn. (1).

2. ZEEP D_2O Results

The reactivity effects for complete coolant exclusion from various groups of rods in the lattice having ZEEP D_2O (99.52 atom %) as coolant and moderator are given in Table 4 while the results for the reactivity effect as a function of coolant level are shown in Table 5. The values of L^2, L_s^2 and B^2 used for this case were;

$$L^2 = 159.8 \text{ cm}^2,$$

$$L_s^2 = 129.6 \text{ cm}^2 \quad \text{and}$$

$$B^2 = 5.56 \text{ m}^{-2}.$$

Table 1: Reactivity Effect of Coolant Loss From Single Clusters: ZED-2 D_2O

Cluster No.	Radius cm	h cm	Δh cm		δk_∞ mk
CR	0	208.16	$-0.196_4 \pm 0.007_0$		+0.1358
		208.22	-0.195_2		+0.1348
		208.22	-0.199_3		+0.1376
		208.22	-0.190_7		+0.1317
				MEAN	+0.1350 ±0.0023
2	24.56	208.87	$-0.154_5 \pm 0.007_0$		+0.1068
3			-0.160_2		+0.1107
4			-0.158_3		+0.1094
5			-0.150_9		+0.1043
				MEAN	+0.1078 ±0.0023
8	42.54	208.87	$-0.110_4 \pm 0.007_0$		+0.0755
10			-0.108_0		+0.0738
12			-0.115_6		+0.0790
14			-0.107_3		+0.0734
16			-0.108_0		+0.0738
18			-0.104_5		+0.0714
				MEAN	+0.0745 ±0.0019
7	49.12	208.87	$-0.089_1 \pm 0.007_0$		+0.0609
9			-0.096_9		+0.0683
11			-0.083_5		+0.0571
13			-0.087_0		+0.0595
15			-0.082_4		+0.0563
17			-0.089_2		+0.0611
				MEAN	+0.0605 ±0.0019
20	64.98	208.87	$-0.033_3 \pm 0.007_0$		+0.0227
23			-0.038_0		+0.0260
26			-0.041_1		+0.0281
29			-0.036_7		+0.0251
32			-0.038_3		+0.0262
35			-0.037_0		+0.0253
				MEAN	+0.0256 ±0.0019
19	73.68	208.87	$-0.020_2 \pm 0.007_0$		+0.0138
22			-0.025_4		+0.0173
25			-0.020_8		+0.0142
28			-0.024_8		+0.0169
31			-0.018_3		+0.0125
34			-0.023_7		+0.0162
				MEAN	+0.0152 ±0.0019
38	85.08	208.22	$-0.005_7 \pm 0.007_0$		+0.0039
41			-0.008_7		+0.0060
44			-0.014_1		+0.0097
47			-0.011_3		+0.0078
50			-0.003_2		+0.0022
53			-0.003_3		+0.0023
				MEAN	+0.0053 ±0.0019
37	88.54	208.87	$-0.014_5 \pm 0.007_0$		+0.0099
40			-0.014_5		+0.0099
43			-0.020_5		+0.0140
46			-0.023_8		+0.0163
49			-0.009_2		+0.0063
52			-0.018_4		+0.0126
				MEAN	+0.0115 ±0.0019

Table 2: Reactivity Effect of Total Coolant Loss From Various Radial Regions: ZED-2 D_2O

Clusters Excluded	h cm	Δh cm		δk_∞ mk
CR[*]				+0.1350 ±0.0023
CR+(1-6)	208.22	-1.055 ±0.007		+0.733
		-1.057		+0.735
			MEAN	+0.734 ±0.010
CR+(1-18)	208.22	-2.039 ±0.007		+1.427
		-2.034		+1.423
			MEAN	+1.425 ±0.020
CR+(1-36)	208.22	-2.445 ±0.007		+1.717
		-2.436		+1.711
			MEAN	+1.714 ±0.024
CR+(1-54)	208.51	-2.558 ±0.007		+1.789
	208.51	-2.613		+1.828
	208.44	-2.702		+1.894
	208.22	-2.609		+1.833
	208.22	-2.636		+1.853
	208.26	-2.649		+1.861
			MEAN	+1.843 ±0.015
(1-6)	208.22	-0.889 ±0.007		+0.617 ±0.012
(7-18)	208.22	-1.102 ±0.007		+0.766 ±0.015
(19-36)	208.22	-0.502 ±0.007		+0.348 ±0.007
(1-54)	208.22	-2.502 ±0.007		+1.757
	208.26	-2.498		+1.753
			MEAN	+1.755 ±0.025
(7-54)	208.22	-1.732 ±0.007		+1.209
	208.26	-1.729		+1.207
			MEAN	+1.208 ±0.017
(19-54)	208.26	-0.726 ±0.007		+0.503 ±0.010
(37-54)	208.22	-0.238 ±0.007		+0.164
	208.26	-0.255		+0.176
			MEAN	+0.170 ±0.006

---

[*] Average of four values - see Table 1.

Table 3: Reactivity Effect vs. Coolant Level: ZED-2 D_2O

Oil Manometer in.	Coolant Level[a] cm	Δh cm.	δk_{∞} mk
0.00 ±0.02	179.2 ±0.2	0.000	0.000
1.11	172.0	+0.239 ±0.007	-0.164 ±0.005
2.10	165.5	+0.478	-0.328 ±0.007
3.01	159.5	+0.672	-0.460 ±0.009
4.00	153.0	+0.834	-0.570 ±0.011
5.00	146.3	+0.965	-0.659 ±0.013
6.00	139.7	+1.074	-0.733 ±0.015
6.00	139.7	+1.070	-0.730 ±0.015
6.99	132.9	+1.051	-0.718 ±0.014
7.92	126.5	+0.976	-0.666 ±0.013
8.93	119.6	+0.834	-0.570 ±0.011
9.92	112.6	+0.619	-0.424 ±0.008
10.91	105.6	+0.351	-0.241 ±0.005
11.93	98.5	+0.113	-0.077 ±0.005
12.88	91.8	-0.089	+0.061 ±0.005
12.92	91.6	-0.111	+0.076 ±0.005
13.92	84.3	-0.510	+0.352 ±0.007
14.93	77.1	-0.902	+0.624 ±0.012
15.92	70.0	-1.276	+0.885 ±0.018
16.92	62.9	-1.639	+1.140 ±0.023
17.92	55.8	-1.985	+1.386 ±0.028
18.92	48.9	-2.059	+1.436 ±0.029
19.92	41.9	-2.297	+1.605 ±0.032
19.92	41.9	-2.301	+1.608 ±0.032
20.92	34.9	-2.485	+1.739 ±0.035
21.92	28.0	-2.591	+1.814 ±0.036
23.92	14.4	-2.667	+1.869 ±0.037
25.62	2.8	-2.702	+1.894 ±0.038

$h = 208.44$ cm.

(a) As measured from zero plane of pile, which is 4.4 cm below the bottom of the fuel.

Table 4: Reactivity Effect of Total Coolant Loss From Various Radial Regions: ZEEP D_2O

Clusters Excluded	h cm	Δh cm		δk_∞ mk
CR	219.52	$-0.294_6 \pm 0.007_0$		+0.1720
		-0.290_8		+0.1698
		-0.295_8		+0.1727
		-0.293_6		+0.1715
		-0.290_6		+0.1697
			MEAN	+0.1711 ±0.0018
CR+(1-6)	219.52	-1.602 ±0.007		+0.944
		-1.622		+0.956
		-1.618		+0.954
			MEAN	+0.951 ±0.008
CR+(1-18)	219.52	-3.238 ±0.007		+1.930
		-3.279		+1.954
		-3.291		+1.961
			MEAN	+1.948 ±0.017
CR+(1-36)	219.52	-4.056 ±0.007		+2.431
		-4.102		+2.459
		-4.107		+2.463
			MEAN	+2.451 ±0.021
CR+(1-54)	219.52	-4.412 ±0.007		+2.651
	219.52	-4.463		+2.683
	219.52	-4.498		+2.704
	219.71	-4.540		+2.723
	219.71	-4.538		+2.721
			MEAN	+2.696 ±0.014
(1-54)	219.52	-4.190 ±0.007		+2.515 ±0.037
(7-54)	219.52	-3.024 ±0.007		+1.800 ±0.027
(19-54)	219.52	-1.383 ±0.007		+0.814 ±0.012
(37-54)	219.52	-0.459 ±0.007		+0.268 ±0.004
CR+(7-18)	219.52	-2.050 ±0.007		+1.212 ±0.018

Table 5: Reactivity Effect vs. Coolant Level: ZEEP D_2O

Oil Manometer in.	Coolant Level[(a)] cm.	Δh cm	δk_∞ mk.
0.00 ±0.02	190.5 ±0.2	0.000	0.000
1.99	177.5	+0.466 ±0.007	-0.270 ±0.004
3.96	164.5	+0.837	-0.484 ±0.007
5.97	151.0	+0.964	-0.557 ±0.008
7.97	137.5	+0.949	-0.548 ±0.008
10.00	123.2	+0.489	-0.283 ±0.004
9.99	123.3	+0.485	-0.281 ±0.004
12.00	108.9	-0.254	+0.148 ±0.004
13.98	94.8	-0.916	+0.536 ±0.008
15.99	80.1	-1.967	+1.159 ±0.017
18.00	65.6	-2.923	+1.733 ±0.026
19.97	51.5	-3.702	+2.206 ±0.033
19.98	51.4	-3.716	+2.216 ±0.033
21.99	37.3	-4.164	+2.491 ±0.037
23.97	23.6	-4.428	+2.654 ±0.040
26.00	9.8	-4.519	+2.710 ±0.041
26.93	3.4	-4.540	+2.723 ±0.041
26.93	3.4	-4.538	+2.722 ±0.041

h = 219.71 cm.

(a) As measured from zero plane of pile, which is 4.4 cm below the bottom of the fuel.

3. Errors

In determining values of δk_∞ using Eqn. (4) the main source of error was thought to be due to the uncertainty in the measurement of Δh. Although we feel that Δh is good to ± 0.007 cm, the experimental spread in δk_∞ for large Δh suggests that the uncertainty is several times this. As a result, the errors in the δk_∞ values shown in the tables have been determined as follows. The standard deviation in the experimental results of δk_∞ for the largest value of Δh was found. This value, or the error due to the uncertainty in Δh, whichever was greater, was taken as the error in a measurement. Of course, for the mean of n measurements, $1/\sqrt{n}$ times the appropriate error is quoted. The result of this treatment means that for the ZED-2 D_2O results the error in a single measurement was taken as the larger of $\pm 2\%$ or the % error due to the Δh uncertainty, while for the ZEEP D_2O experiments the error in a single measurement was taken as the larger of $\pm 1\frac{1}{2}\%$ or the % error due to uncertainty in Δh. (For one measurement consisting of two determinations the spread was greater than that given by either of the above errors and for this case one-half the spread was taken as the error.)

One systematic error in these measurements should be mentioned. When the coolant is expelled from a cluster, some D_2O remains behind on the walls of the assembly and on the (horizontal) end plates of the fuel bundles. This effect will reduce the magnitude of the reactivity effect. However, since we believe this D_2O "holdup" to be $\leq 1\%$ (and the fluctuations in this quantity correspondingly smaller) no corrections have been made for it.

4. Treatment of Results

A proper analysis of the results given in Tables 1 - 5 would involve two-group perturbation theory for a reflected pile and would mean fitting the results to equations having many variable parameters. Since the results probably do not warrant such a treatment we have chosen to use the bare pile approximation and to fit the data to this in the region of the pile sufficiently removed from the boundaries where this theory holds.

We therefore assume that the reactivity effect of a loss of coolant from a region of the lattice with volume V can be expressed as follows;

$$\delta k_\infty = \frac{\beta\int_V \phi^2(r,z)dV + \gamma\int_V \overline{\text{grad}_r\phi(r,z)}^2 dV + \theta\int_V \overline{\text{grad}_z\phi(r,z)}^2 dV}{\int_{\text{pile}} \phi^2(r,z)dV} \qquad (5)$$

where δk_∞ is as defined above (p. 5), and

β, γ and θ are parameters proportional to the changes which occur in the pile constants f, ϵ, p, Σ and D.

We further assume that ϕ is given by the fundamental solution of the reactor equation, viz.,

$$\nabla^2\phi(r,z) + B^2\phi(r,z) = 0 \qquad (6)$$

For ZEEP then, we have,

$$\phi(r,z) = J_o(\lambda r)\cos(\alpha z) \qquad (7)$$

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

The gradient squared term in (5) has been separated into radial and axial components to allow for the fact that the changes in diffusion constant upon loss of coolant are not expected to be the same along and perpendicular to the coolant channel.

Inserting (7) into (5) and evaluating δk_∞ for the special cases which we have studied we get the following results:

(a) For a complete loss of coolant from a radial region defined by radii R_1 and R_2. Here the axial dependence can be integrated out and δk_∞ becomes,

$$\delta k_\infty(R_1,R_2) = \frac{(K_{zc}\beta + K_{zs}\alpha^2\theta)\int_{R_1}^{R_2} J_o^2(\lambda r)rdr + K_{zc}\lambda^2\gamma\int_{R_1}^{R_2} J_1^2(\lambda r)rdr}{\int_0^{R_p} J_o^2(\lambda r)rdr} \qquad (8)$$

where $R_p = 2.405/\lambda$ is the radius of the equivalent bare pile.

The constants K_{zc}, K_{zs} are given by,

$$K_{zc} = \int_{-(h/2-E_L)}^{(h/2-E_U)} \cos^2\alpha z dz \Big/ \int_{-h/2}^{h/2} \cos^2\alpha z dz \qquad (9)$$

$$K_{zs} = \int_{-(h/2-E_L)}^{(h/2-E_U)} \sin^2\alpha z dz \Big/ \int_{-h/2}^{h/2} \cos^2\alpha z dz \qquad (10)$$

where E_U and E_L are the upper and lower axial extrapolation lengths respectively.

For exclusion from a core of rods, $R_1 = 0$, $R_2 = R$, and Eqn. (8) reduces to

$$\delta k_\infty(0,R) = \frac{(K_{zc}\beta + K_{zs}\alpha^2\theta)\left[J_o^2(\lambda R) + J_1^2(\lambda R)\right] + K_{zc}\lambda^2\gamma\left[J_1^2(\lambda R) - J_o(\lambda R)J_2(\lambda R)\right]}{\left(\frac{R_p}{R}\right)^2 J_1^2(2.405)} \tag{11}$$

(b) Total coolant exclusion from a single assembly at radius R. In this case we assume that $J_o(\lambda r)$ and $J_1(\lambda r)$ are constant over the cell at R so that δk_∞ reduces to

$$\delta k_\infty(R) = \frac{(K_{zc}\beta + K_{zs}\alpha^2\theta)\ J_o^2(\lambda R) + K_{zc}\lambda^2\gamma\ J_1^2(\lambda R)}{\left(\frac{R_p}{R_{cell}}\right)^2 J_1^2(2.405)} \tag{12}$$

For the special case of the central rod $R = 0$ and (12) further reduces to

$$\delta k_\infty(0) = \frac{(K_{zc}\beta + K_{zs}\alpha^2\theta)}{\left(\frac{R_p}{R_{cell}}\right)^2 J_1^2(2.405)} \tag{13}$$

(c) For the case when the coolant is expelled partially from all 55 assemblies in the pile simultaneously so that the coolant level is at z the radial dependence is integrated out and δk_∞ becomes

$$\delta k_\infty(z) = \frac{(K_{RO}\beta + K_{R1}\lambda^2\gamma)\int_z^{h/2-E_U}\cos^2\alpha z dz + K_{RO}\alpha^2\theta\int_z^{h/2-E_U}\sin^2\alpha z dz}{\int_{-h/2}^{h/2}\cos^2\alpha z dz} \tag{14}$$

where the constants K_{RO}, K_{R1} are defined as,

$$K_{RO} = \int_0^{R_c} J_0^2(\lambda r)rdr \Big/ \int_0^{R_p} J_0^2(\lambda r)rdr \qquad (15)$$

$$K_{R1} = \int_0^{R_c} J_1^2(\lambda r)rdr \Big/ \int_0^{R_p} J_0^2(\lambda r)rdr \qquad (16)$$

R_c is the radius of the reacting core of the pile and is given by

$$R_c = 0.525\ d\sqrt{N} \qquad (17)$$

where d is the lattice pitch and

N is the number of fuel assemblies in the pile, 55 in these experiments.

The results shown in Tables 1 - 5 were fitted to the appropriate expression for δk_∞ using the method of least squares and values of β, γ and θ were obtained. In making these fits only data obtained in regions of the pile farther from the boundaries than 2 migration lengths were used.

Fig. 7 is a plot of the reactivity effect for a loss of coolant from a single rod at various radii in the pile, i.e., the results given in Table 1. It can be seen that the reactivity effect decreases steadily with increasing radius until we approach the core-reflector interface, where the effect begins to increase again. This behaviour is reasonable since the presence of the D_2O and graphite reflector surrounding the UO_2 core will tend to make the effect more positive. This effect is predicted by the more exact two-group theory. A similar radial variation of void coefficient was observed by Andersen et al(1) in experiments in JEEP.

The solid curve shown is the least squares fit to Eqn. (12). The fit is good except in the region of the core-reflector boundary where, as mentioned above, the simple theory used here breaks down.

Fig. 8 is a plot of the reactivity effect as a function of coolant level for ZED-2 D_2O (see Table 3). It is seen that as the level falls the reactivity effect first becomes negative, goes through a minimum at $\sim h/5$ below the moderator level, then begins to go positive, passing through zero when the coolant level is $\sim 2h/5$ below the moderator level and finally asymptotically approaches the value of +1.84 mk for total coolant exclusion. This behaviour is readily explained if we assume that the reactivity effect is given by Eqn. (5), since when the coolant level is near the top of the pile the contribution to the positive flux squared term is very small and so the gradient squared terms, which are negative, are dominant. Then as more coolant is removed the flux squared term which is larger predominates and the reactivity effect becomes positive. The solid line is the least squares fit to Eqn. (14). Here also the fit is good except in the region of the bottom D_2O-graphite reflector.

Fig. 9 shows the results of the same experiment using ZEEP D_2O. The behaviour is the same except that the value for complete coolant exclusion is +2.70 mk. Here also the solid line is the fit.

5. Discussion of 7-element Results

Table 6 is a summary of the results of the least squares fitting and contains the values obtained for β, γ and θ as well as values of various pile parameters. The errors shown for β, γ and θ are those determined from the "goodness of fit" only and do not include experimental or systematic errors. The table lists two sets of values for γ, one obtained from a fit to the single rod exclusion results and the other from a fit to the results for groups of rods. For the latter case the fit was not very good as evidenced by the large error in the fitted values and so the values from the single rod fits have been used. (A probable reason for the poor radial region fit will be discussed more fully below.) For the ZEEP D_2O case the single rod fit involves only the central rod result since single rod effects were not measured for various radii as was done for ZED-2 D_2O. As can be seen from Eqn. (13), the central rod fit gives a value of $(K_{zc}\beta + K_{zs}\alpha^2\theta)$. Putting in the value of θ obtained from the axial fit yields a value of β which can then be substituted back into the expression $(K_{R0}\beta + K_{R1}\lambda^2\gamma)$, also obtained from the axial fit, to give γ. For the ZED-2 D_2O case two complete radial and axial fits were possible and since each fit yields values for two constants one of the parameters β, γ or θ can be doubly determined. This was done for β and the value listed in the table is the average from the two fits. The 11th line of the table contains a predicted value of δk_∞ for the reactivity effect of full pile coolant exclusion using the fitted parameters in the expression,

$$\delta k_\infty \text{(full pile)} = K_{zc}K_{R0}\beta + K_{zc}K_{R1}\lambda^2\gamma + K_{zs}K_{R0}\alpha^2\theta \qquad (18)$$

Table 6: Results for 7-element UO_2 Clusters

		ZED-2 D_2O (99.75 atom %)	ZEEP D_2O (99.52 atom %)
α^2 m^{-2}		2.272	2.045
λ^2 m^{-2}		3.419	3.519
K_{zc}		0.9838	0.9868
K_{zs}		0.6984	0.7083
K_{RO}		0.9342	0.9415
K_{R1}		0.4619	0.4818
θ (Axial fit) mk/m^{-2}		-1.361 ± 0.005	-1.449 ± 0.006
γ (Single rod fit) mk/m^{-2}		-1.138 ± 0.083	-1.066 ± 0.082 (a)
γ (Radial region fit) mk/m^{-2}		-1.12 ± 0.19	-0.87 ± 0.21
β mk		$+5.89 \pm 0.07$ (b)	$+6.75 \pm 0.14$ (a)
δk_∞ (Full Pile Predicted) =			
$(K_{zc}K_{RO}\beta+K_{zc}K_{R1}\lambda^2\gamma+K_{zs}K_{RO}\alpha^2\theta)$	mk	+1.629	+2.515
δk_∞ (Full Pile Experimental)	mk	$+1.843 \pm 0.015$	$+2.696 \pm 0.014$
θ/γ		1.20 ± 0.09	1.36 ± 0.10

(a) Central rod fit only - see text.

(b) Average of two values - see text.

The experimental results for full pile exclusion are shown on the 12th line. The disagreement, while not large ($\sim 10\%$), is partly due to the failure of the simple model at the core-reflector boundaries. Also the use of values of L^2, L_s^2 and B^2 for the unperturbed lattice in Eqn. (4) is not strictly correct when the coolant is excluded from a large fraction of the lattice.

One interesting result of these experiments is the fact that θ is 28% greater than γ which is possibly indicative of the anisotropy in the diffusion constant when the coolant is removed, and should be a rough measure of the streaming effect in voided coolant channels. The errors are such that we attach no significance to the fact that θ/γ is different for the two D_2O purities.

Another interesting result is the fact that the full pile effect for ZEEP D_2O is 0.85 mk greater than for ZED-2 D_2O. This would appear to be because the ZEEP D_2O contains more H_2O contaminant than ZED-2 D_2O whence removal of the same amount of this more absorptive coolant produces a more positive reactivity effect. This is verified by the fact that β, the flux squared coefficient in the reactivity expression is 0.86 mk larger for ZEEP D_2O than for ZED-2 D_2O.

Perhaps worth mentioning is the fact that there is some evidence for an interaction effect between excluded and nonexcluded regions of the lattice. This effect was noticed when it was found that the sum of the reactivity effects for exclusion from several small radial regions was always larger than the actual measured effect for the composite region (see Tables 2, 4). This discrepancy is $\sim 10\%$ in going from single rod effects to the whole pile effect. This can be explained if one assumes an interaction which only affects either the flux squared term or the gradient squared term since the net full pile reactivity effect is the algebraic sum of these fairly large terms which are of opposite sign. Hence a small interaction effect in either of these will produce an effect (percentagewise) several times larger in the net result. Another explanation for this effect is the use of unperturbed lattice parameters in the expression for δk_∞, Eqn. (4), as mentioned above.

6. 19-element UO_2 Cluster Experiments

Fig. 10 shows in cross section the cluster assembly we have used to study coolant loss effects in 19-element UO_2 cluster lattices as reported in RPI-51(2). For this assembly the coolant area was 26.47 cm^2. In these experiments only one assembly like that shown in Fig. 10 was used; the remaining clusters in the lattice had no pressure or calandria tubes. The D_2O purity used varied slightly (a few parts per 10,000) for the various lattices but an average value is 99.60 atom %. Also, the coolant was replaced by air rather than helium. The reactivity effect of a loss of coolant was measured for three lattice spacings with the assembly at the center of the pile and also with it at an off-centre position. With only these two measurements it was not possible to determine θ and in RPI-51 it was taken equal to γ. Furthermore, the model used in RPI-51 was slightly different so it was decided to reanalyze the results using the treatment outlined above (pp.15 - 18) making some allowance for the fact that $\theta \neq \gamma$.

From the two measurements taken, values of $(K_{zc}\beta + K_{zs}\alpha^2\theta)$ and $K_{zc}\lambda^2\gamma$ (hence γ) can be obtained using Eqns. (12) and (13). In order to obtain β some assumption about θ must be made. θ has been taken as 1.28 γ, the value found for the 7-element experiments. This was done because, although the 19-element coolant area is larger than that for the 7-element cluster which tends to make θ larger, the average void size is smaller which tends to reduce θ. Thus, since θ is a rather complicated function of void shape it was decided to use the value obtained in the 7-element experiments. Using $\theta = 1.28\ \gamma$ then, β can be deduced knowing K_{zc}, K_{zs} and α^2. The values of γ obtained for the three lattices where this parameter was measured are shown in Fig. 11. It can be seen that γ is not a strong function of lattice pitch. Fig. 12 shows the values of β obtained for these lattices as well as for some other lattices where central rod experiments only were done. In these cases β was obtained by extrapolating the curve shown in Fig. 11 to obtain γ and using $\theta = 1.28\ \gamma$ as outlined above. These results are summarized in Table 7. The point shown for Coolant Tube I in Fig. 12 was obtained from an experiment with an assembly having a different coolant area (22.67 cm^2 - see Fig. 13). The value plotted here has been corrected to the same coolant area as Coolant Tube II (which was used for all the other experiments in these lattices), assuming that δk_∞ is proportional to coolant area. The 7-element ZEEP D_2O result for β, corrected for coolant area is also shown on Fig. 12. The large errors in some of these 19-element cluster results are due to the presence of the driving regions which were used to make these lattices critical$^{(2)}$.

Table 7: Results for 19-element UO_2 Clusters

Pitch cm	19.05	21.59[a]	24.13	26.67[b]	26.67[c]	30.48
$V_{MOD.}/V_{UO_2}$	8.10	11.52	15.38	19.61	19.61	26.86
α^2 m^{-2}	2.890	1.866	1.596	2.326	2.585	2.101
λ^2 m^{-2}	1.229	3.081	3.216	1.910	1.801	1.539
K_{zc}	0.9803	0.9910	0.9925	0.9861	0.9840	0.9870
K_{zs}	0.6348	0.7468	0.7682	0.6927	0.6745	0.7093
$K_{zc}\lambda^2\gamma$ mk	n.m.	n.m.	-6.79 ± 1.3	-5.96 ± 5.2	n.m.	-4.69 ± 4.3
γ mk/m^{-2}	-1.42 ± 2.8[d]	-1.83 ± 2.8[d]	-2.13 ± 0.40	-3.17 ± 2.7	-3.17 ± 2.8[e]	-3.09 ± 2.8
$\theta = 1.28\gamma$ mk/m^{-2}	-1.82	-2.34	-2.72	-4.05	-4.05	-3.95
$K_{zc}\beta+K_{zs}\alpha^2\theta$ mk	-7.47 ± 1.00	-0.62 ± 0.18[f]	$+7.00 \pm 0.13$	$+8.20 \pm 0.36$	$+6.96 \pm 0.44$	$+13.47 \pm 0.34$
β mk	-4.16 ± 8.8	$+2.66 \pm 5.0$	$+10.42 \pm 0.65$	$+14.94 \pm 6.3$	$+14.25 \pm 7.0$	$+19.61 \pm 5.9$

n.m. = not measured

a - For this lattice, coolant tube I, with a different coolant area, was used.

b - This lattice contained 31 UO_2 clusters - see RPI-51.

c - " " " 55 " " " "

d - These values obtained from graph of γ vs. lattice pitch - Fig. 11.

e - This value assumed equal to value obtained in 31 cluster lattice with same pitch.

f - This value has been corrected to same coolant area as coolant tube II, assuming $\delta k_\infty(0) \propto$ Area.

These produced large extrapolated radii so that the gradient squared was not sufficiently large to allow γ to be well determined. Although the errors are large, the trend is definite - an increasing void coefficient with increasing moderator-to-fuel volume ratio.

CONCLUSIONS

Experiments to determine the void coefficient for 7- and 19-element UO_2 cluster lattices have been described. In the 7-element UO_2 lattices the effect was measured as a function of both radius and coolant level for one lattice pitch only, using two D_2O purities; for the 19-element UO_2 lattices it was measured as a function of radius only for several lattices but only one D_2O purity. It was found that the measured effects can be fairly well fitted using a bare pile perturbation theory which takes into account the anisotropy in the diffusion constant when the coolant is removed. The main conclusions to be drawn from this work appear to be the following.

(a) An anisotropy in the diffusion constant upon coolant removal which suggests that $\Delta D_z/\Delta D_r \sim 1.28$.

(b) The flux squared term in the void coefficient for the 19-element lattices appears to be a monotonically increasing function of the lattice pitch or $V_{MOD.}/V_{UO_2}$. It is zero at a $V_{MOD.}/V_{UO_2}$ of ~ 9.8 and increases to $\sim +20$ mk at $V_{MOD.}/V_{UO_2} = 27$, the largest pitch studied.

(c) The gradient squared terms appear to be fairly independent of pitch and are negative, their contribution to the net void coefficient being determined by the size of the reactor, since they are weighted by shape dependent buckling factors.

(d) There appears to be some evidence in the 7-element experimental results for the presence of an interaction effect between the "coolant-excluded" and unperturbed regions of the lattice. However, this point has not definitely been proven and may be explained by the fact that parameters for the unperturbed lattice are used throughout, even when the regions excluded are large fractions of the pile volume.

(e) A change in D_2O purity of a few tenths of a per cent makes quite a noticeable change in the reactivity effect and seems to affect mainly the flux squared term.

In conclusion, it might be mentioned that we feel that the most important parameter in the void coefficient from the point of view of power reactor safety is β, the coefficient of the flux squared term. This is because in large power reactors the buckling will be small and so the gradient squared terms will not be important. Hence, the flux squared term β will make the predominant contribution to the reactivity effect.

ACKNOWLEDGEMENTS

The authors would like to thank all who contributed in any way throughout the course of this work, and in particular W. Dickerson, P.D.J. Ferrigan, K.J. Hohban and D.J. Roberts who helped in the preparation and performance of the experiments. They would like to thank J.T.R. Young for preparing the drawings and Miss E. Gehlert for typing the manuscript. Helpful discussions with E. Critoph and A.G. Ward are also acknowledged.

REFERENCES

1. E. Andersen, V.O. Eriksen, K. Hubers, P. Schmid; 1958 Geneva Conference Paper P/572.
2. R.E. Green, D.W. Hone, A. Okazaki; Chalk River Report RPI-51 (1959).

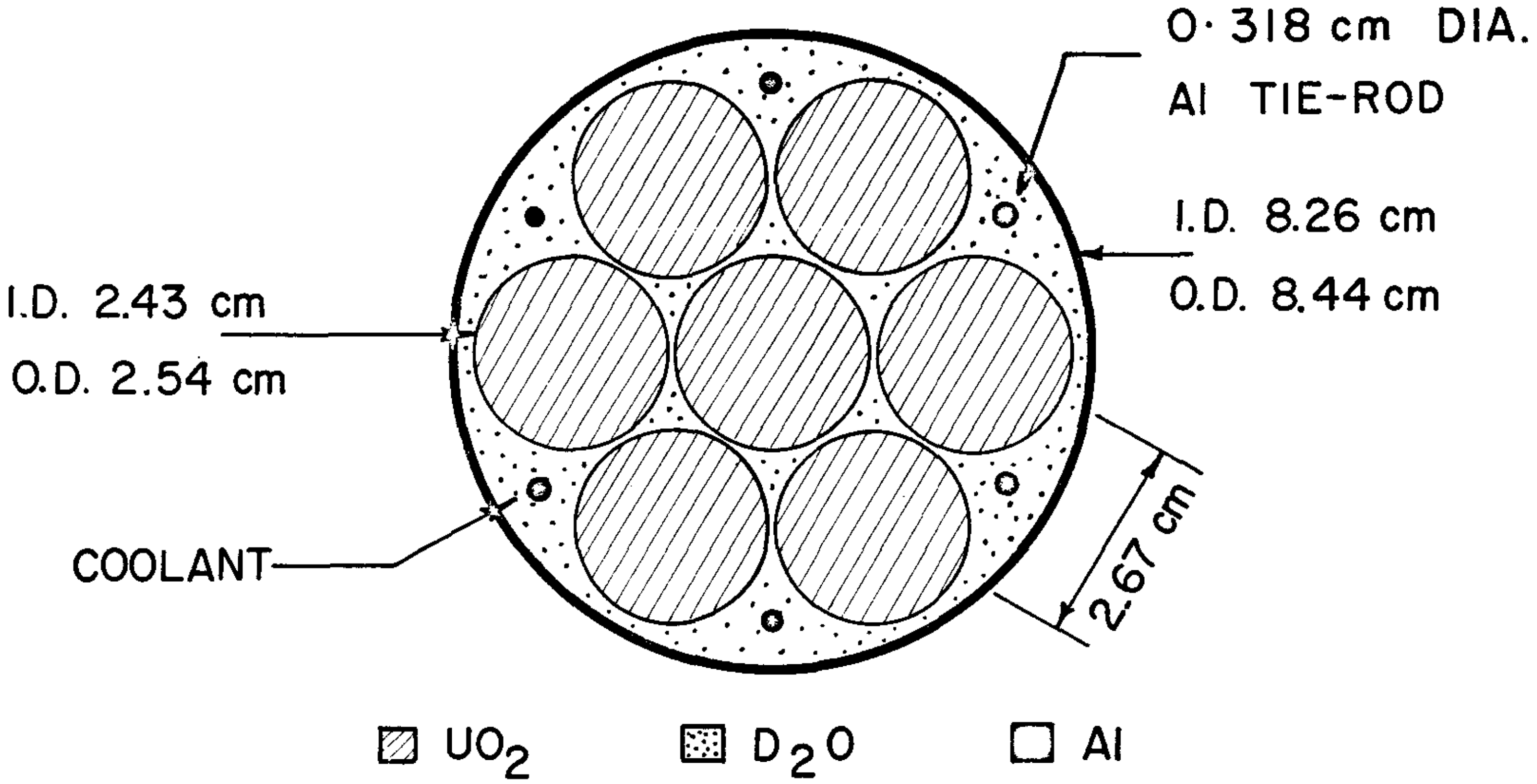

FIG. 1: 7-ELEMENT 2.40 cm UO_2 FUEL CLUSTER

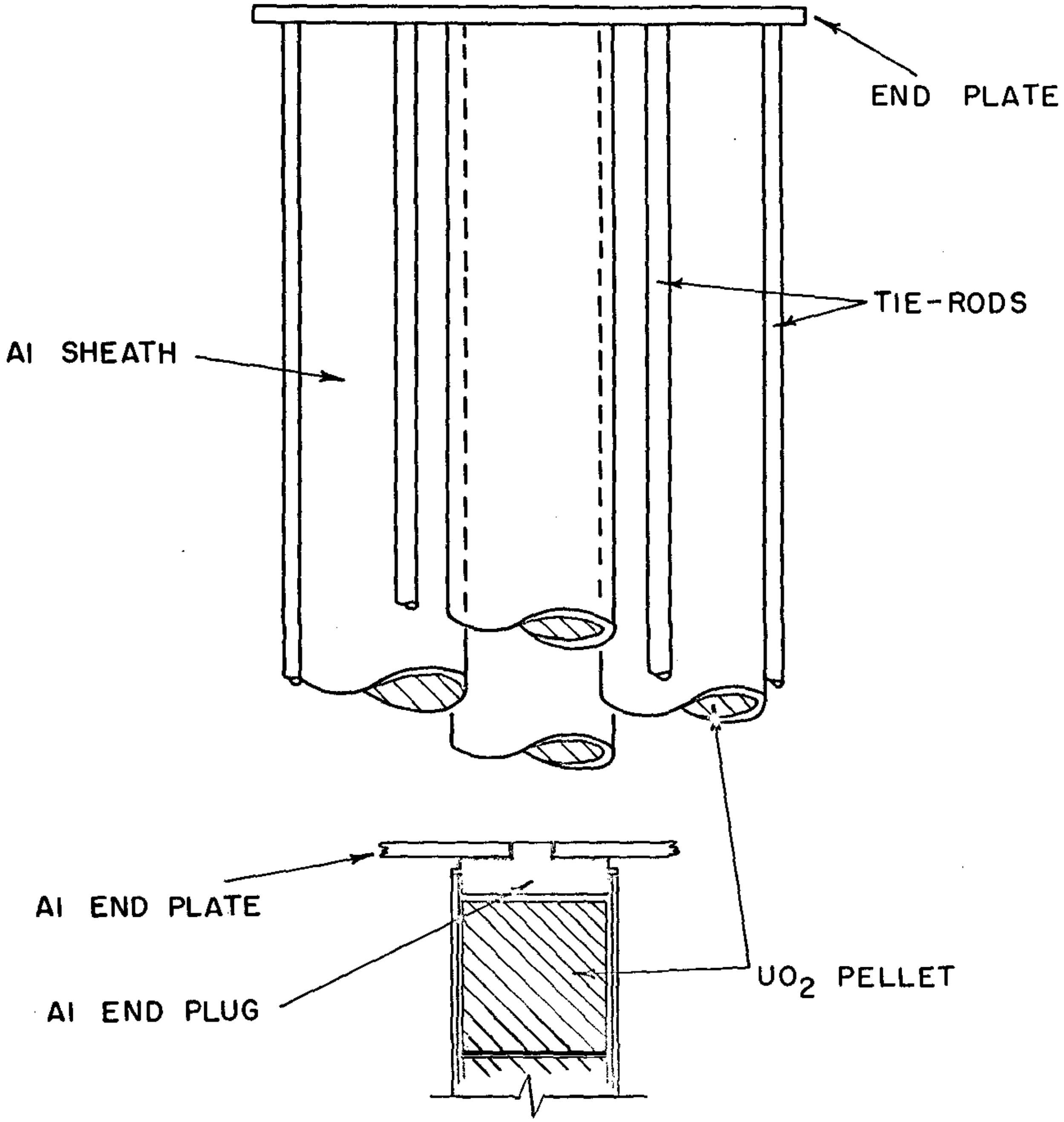

FIG. 2: DETAILS OF FUEL BUNDLE

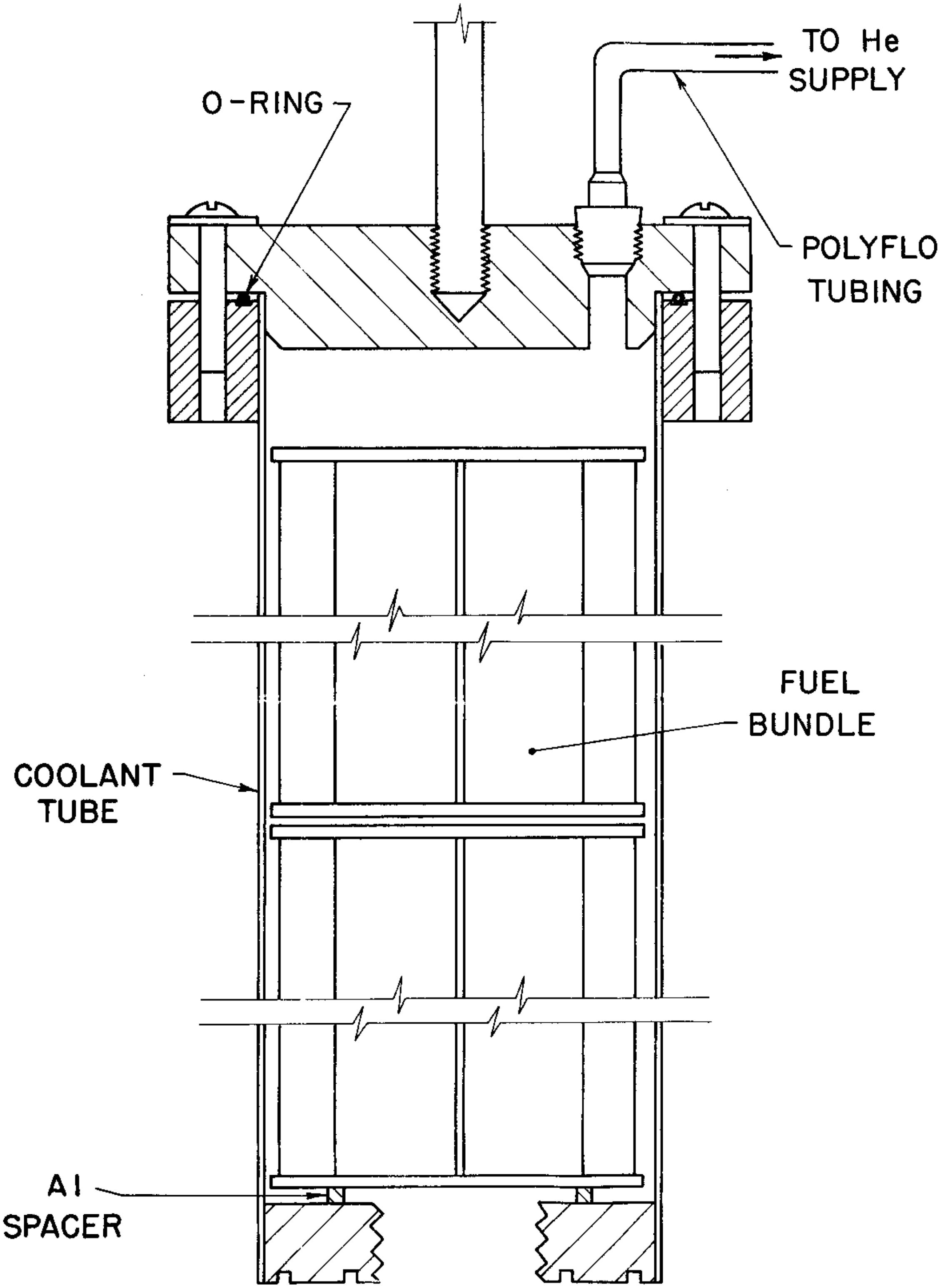

FIG. 3: 7-ELEMENT UO_2 FUEL ASSEMBLY

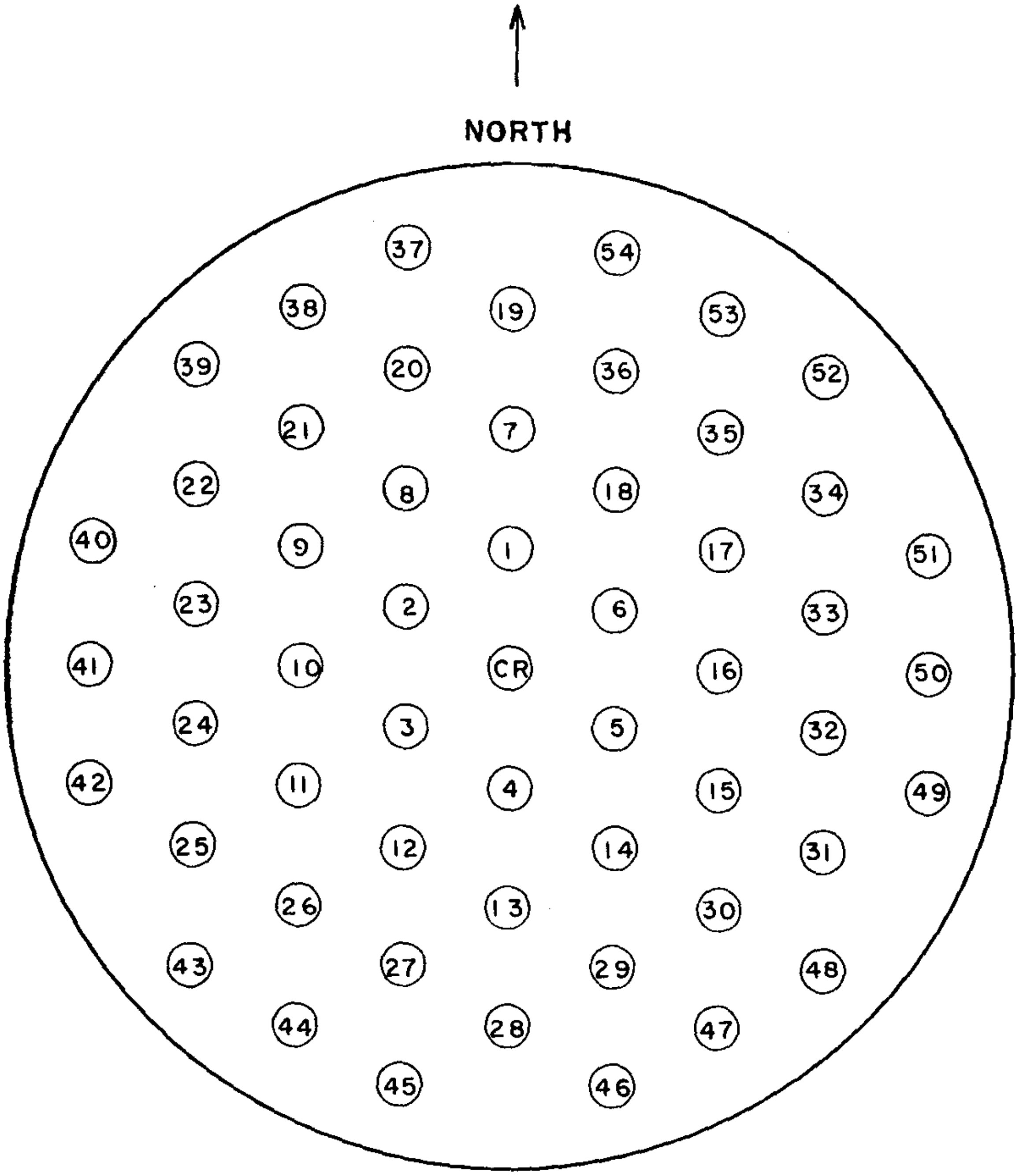

FIG. 4: 7- ELEMENT UO_2 LATTICE ARRANGEMENT

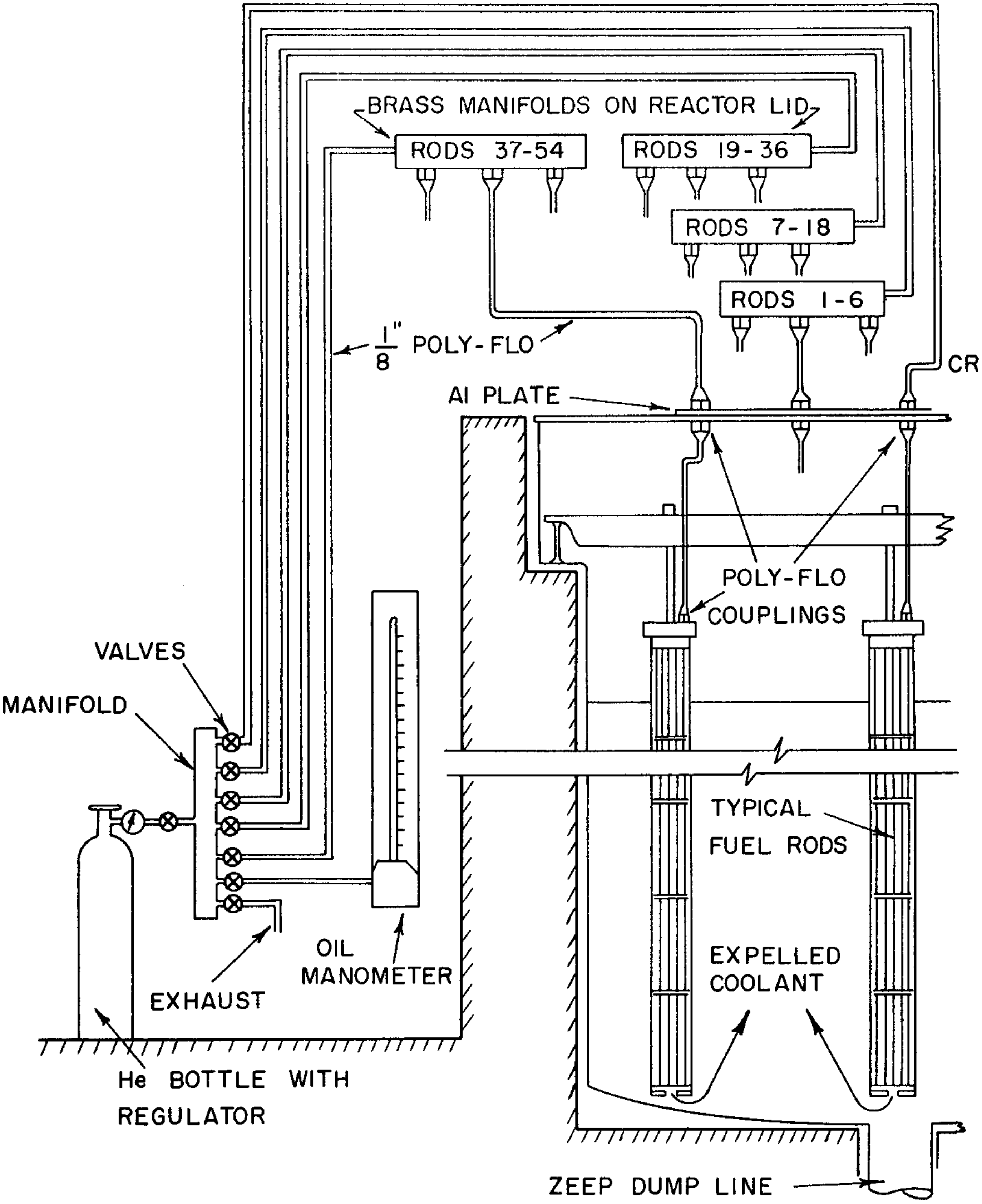

FIG. 5: COOLANT EXCLUSION CIRCUIT

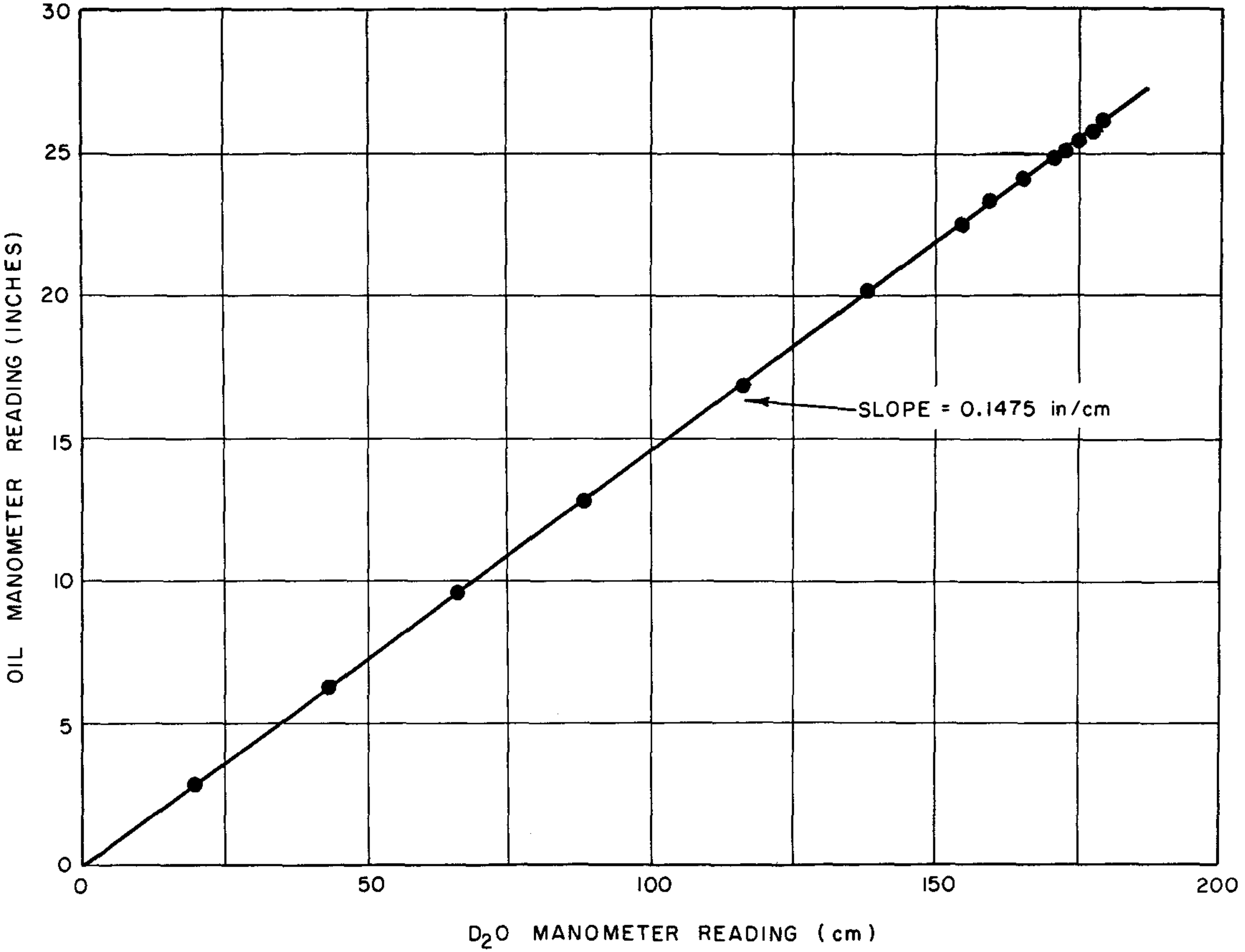

FIG. 6: HELIUM PRESSURE FOR COMPLETE EXCLUSION vs MODERATOR LEVEL

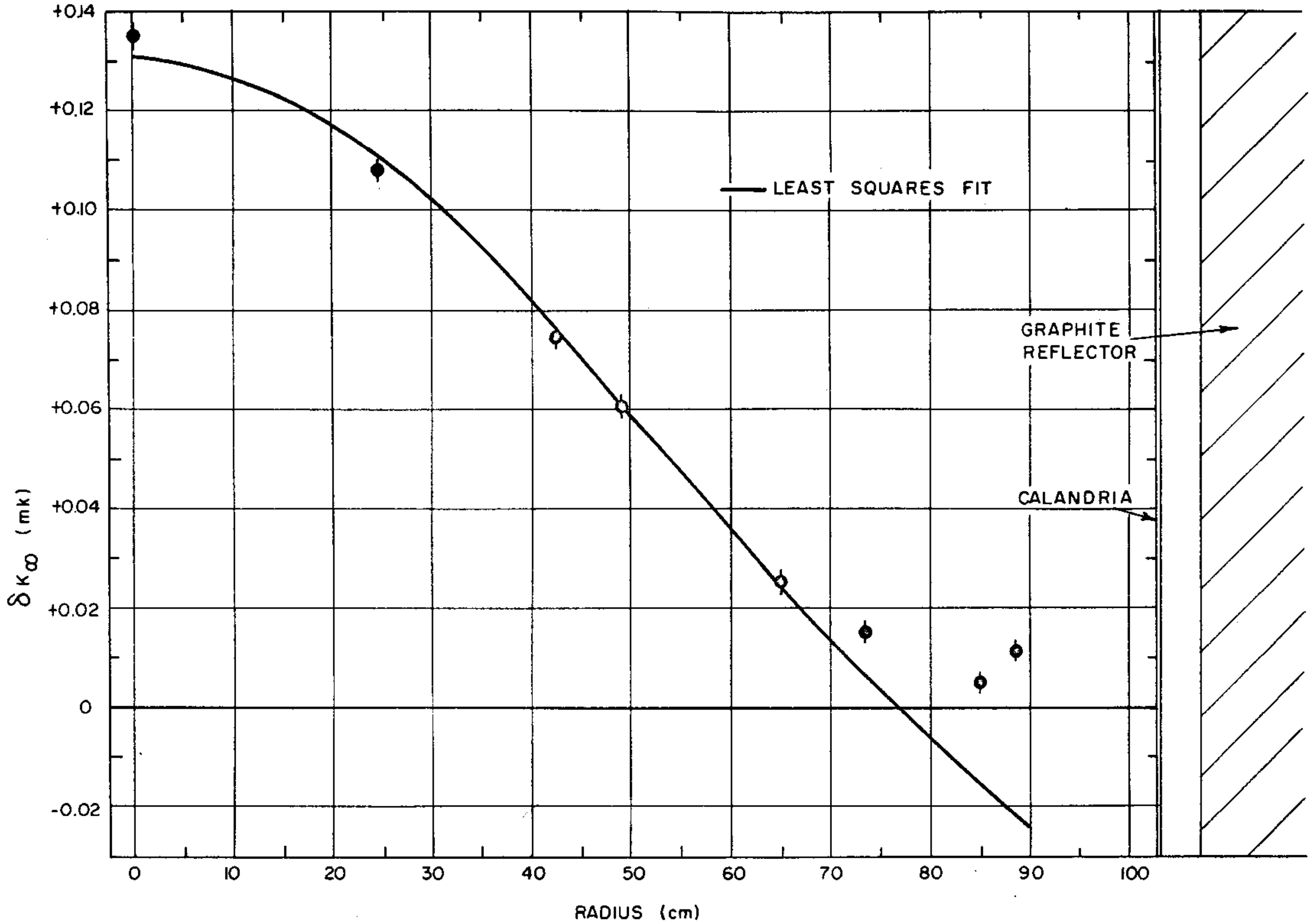

FIG. 7: SINGLE CLUSTER REACTIVITY EFFECT vs RADIUS - ZED - 2 D_2O

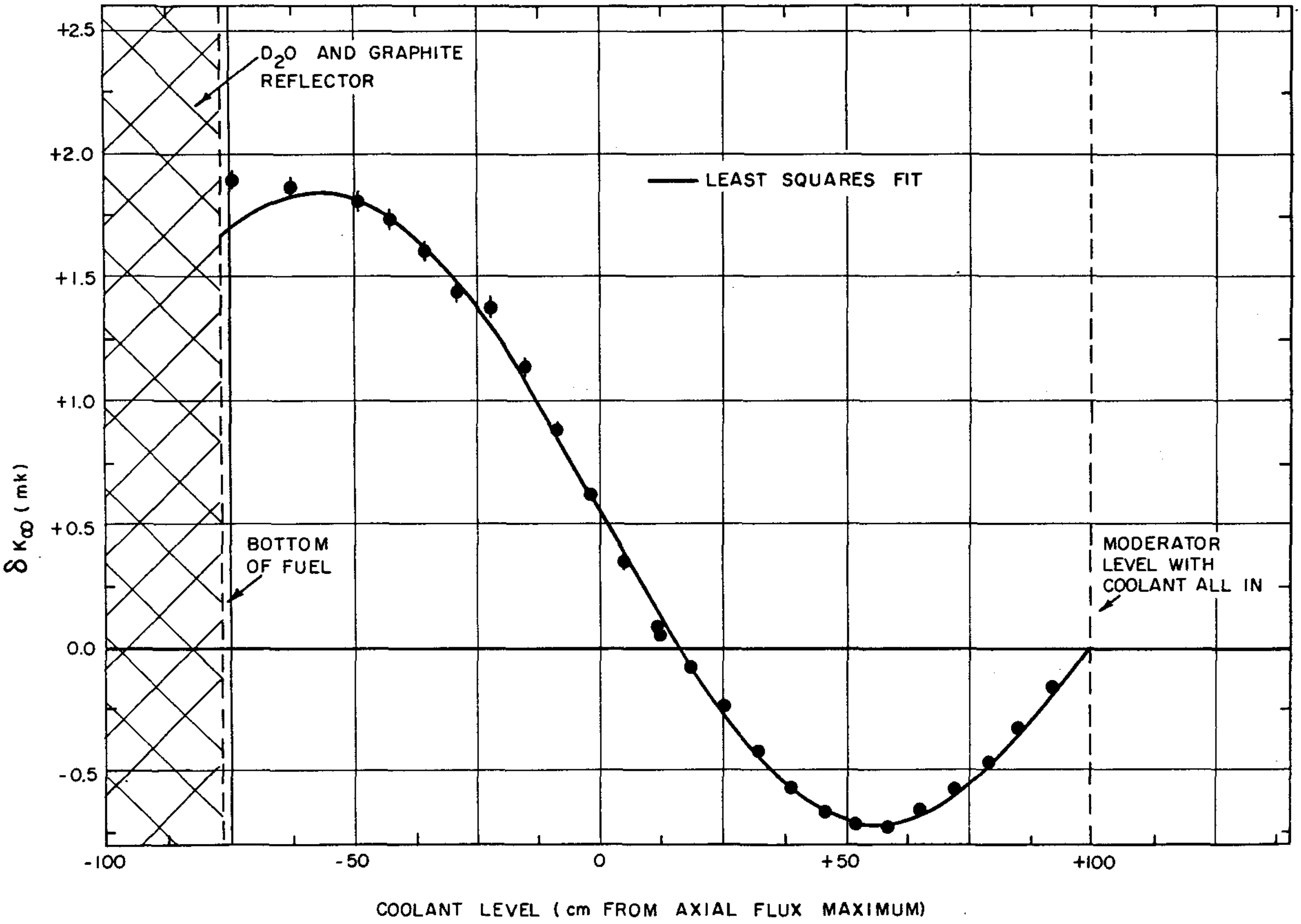

FIG. 8: REACTIVITY EFFECT vs COOLANT LEVEL—ZED-2 D_2O

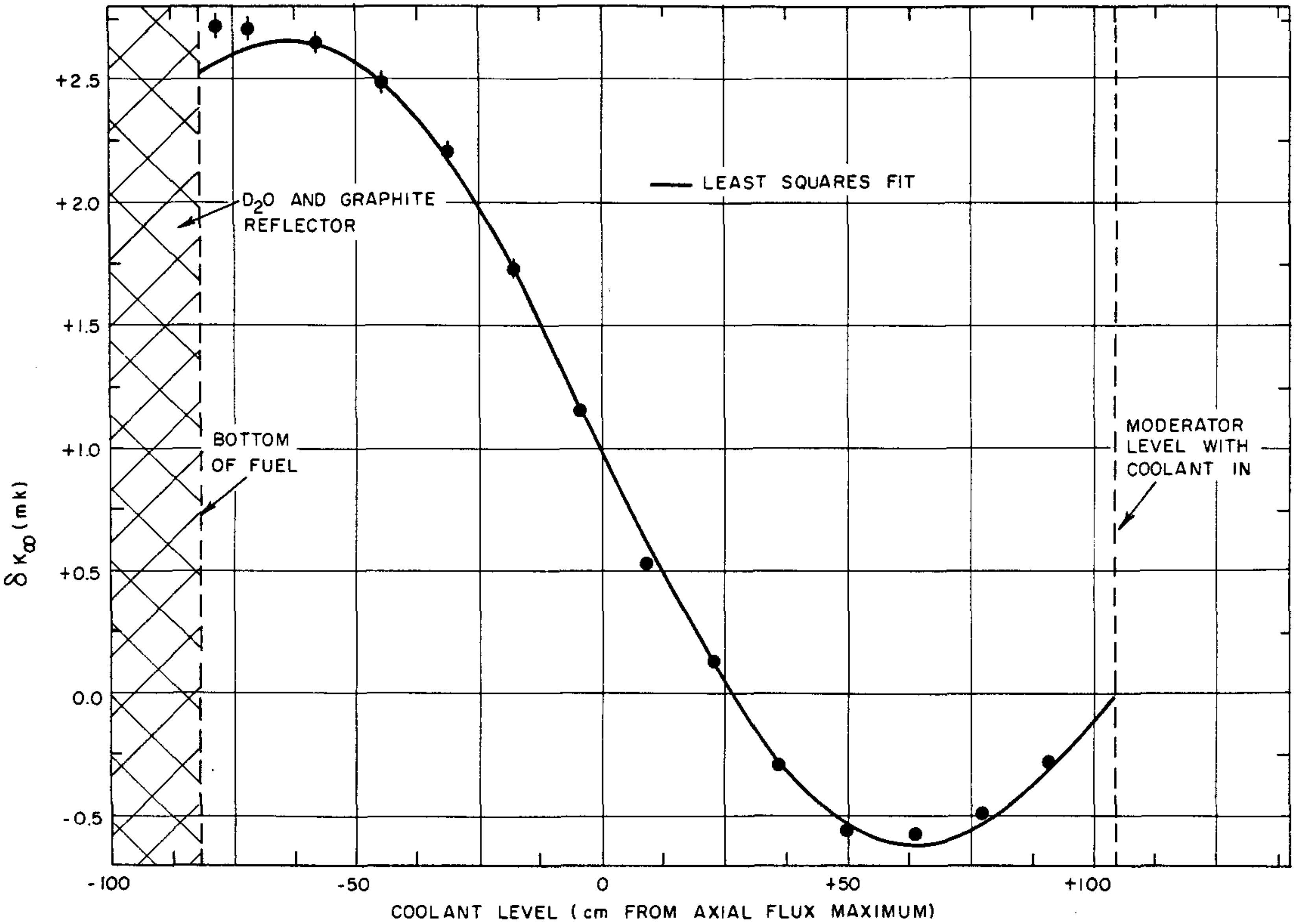

FIG. 9: REACTIVITY EFFECT vs COOLANT LEVEL– ZEEP D_2O

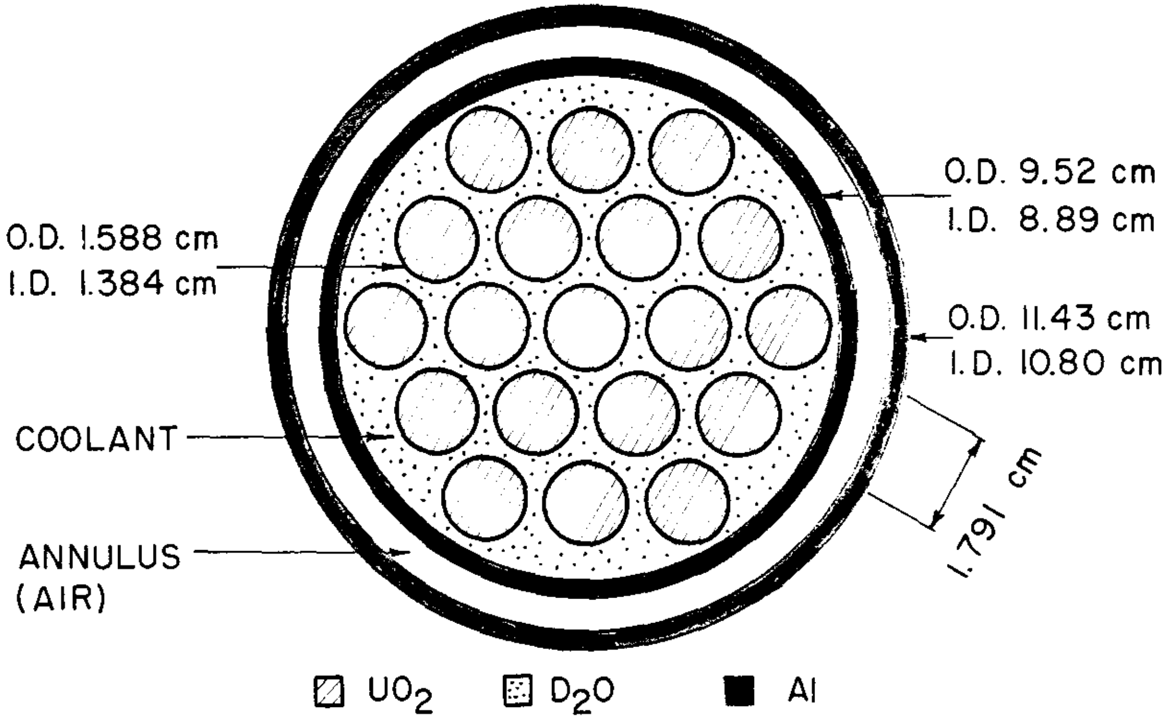

FIG. 10: 19-ELEMENT 1.32 cm UO_2 FUEL CLUSTER

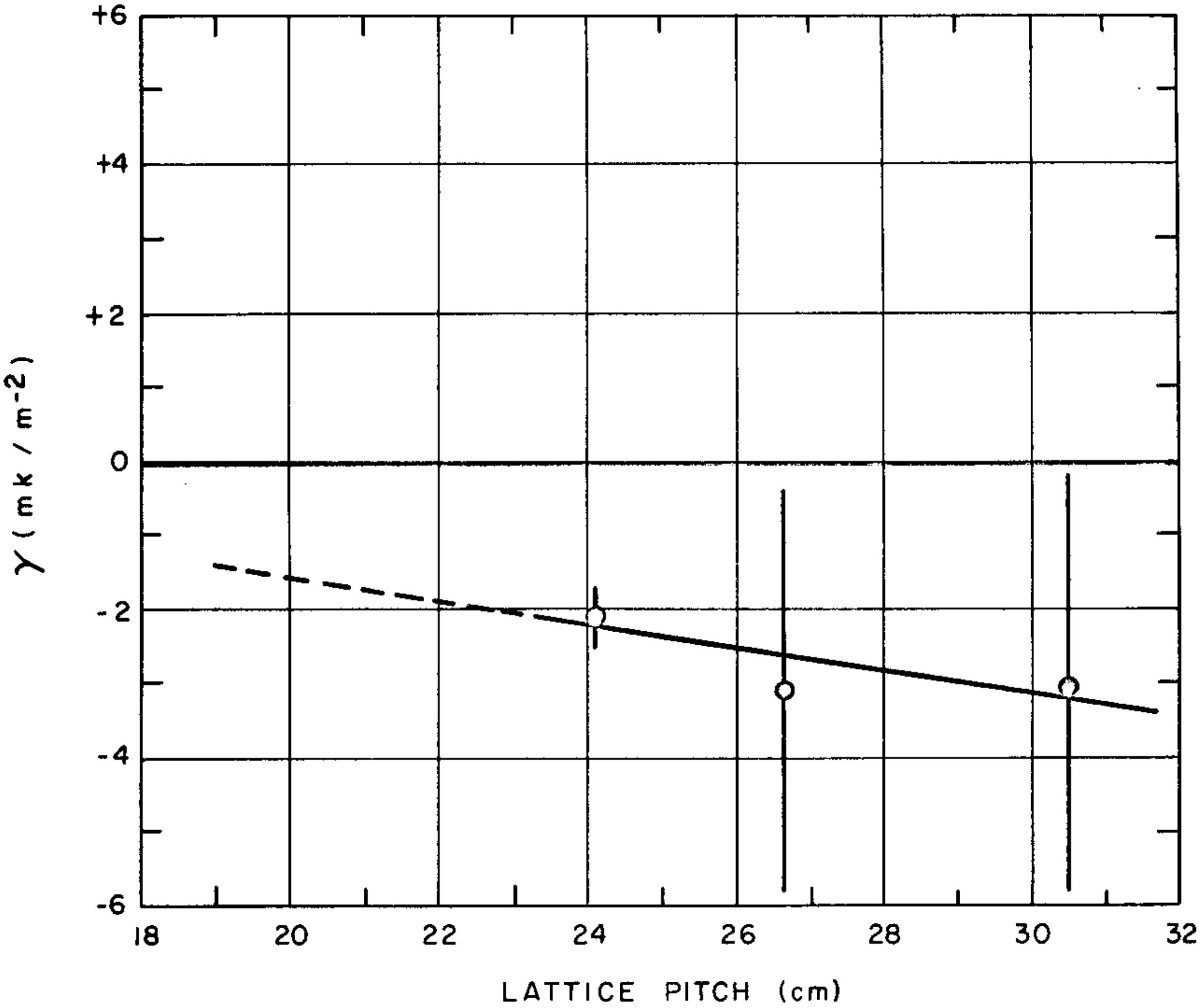

FIG. 11: γ vs PITCH FOR 19-ELEMENT UO_2 CLUSTER LATTICES

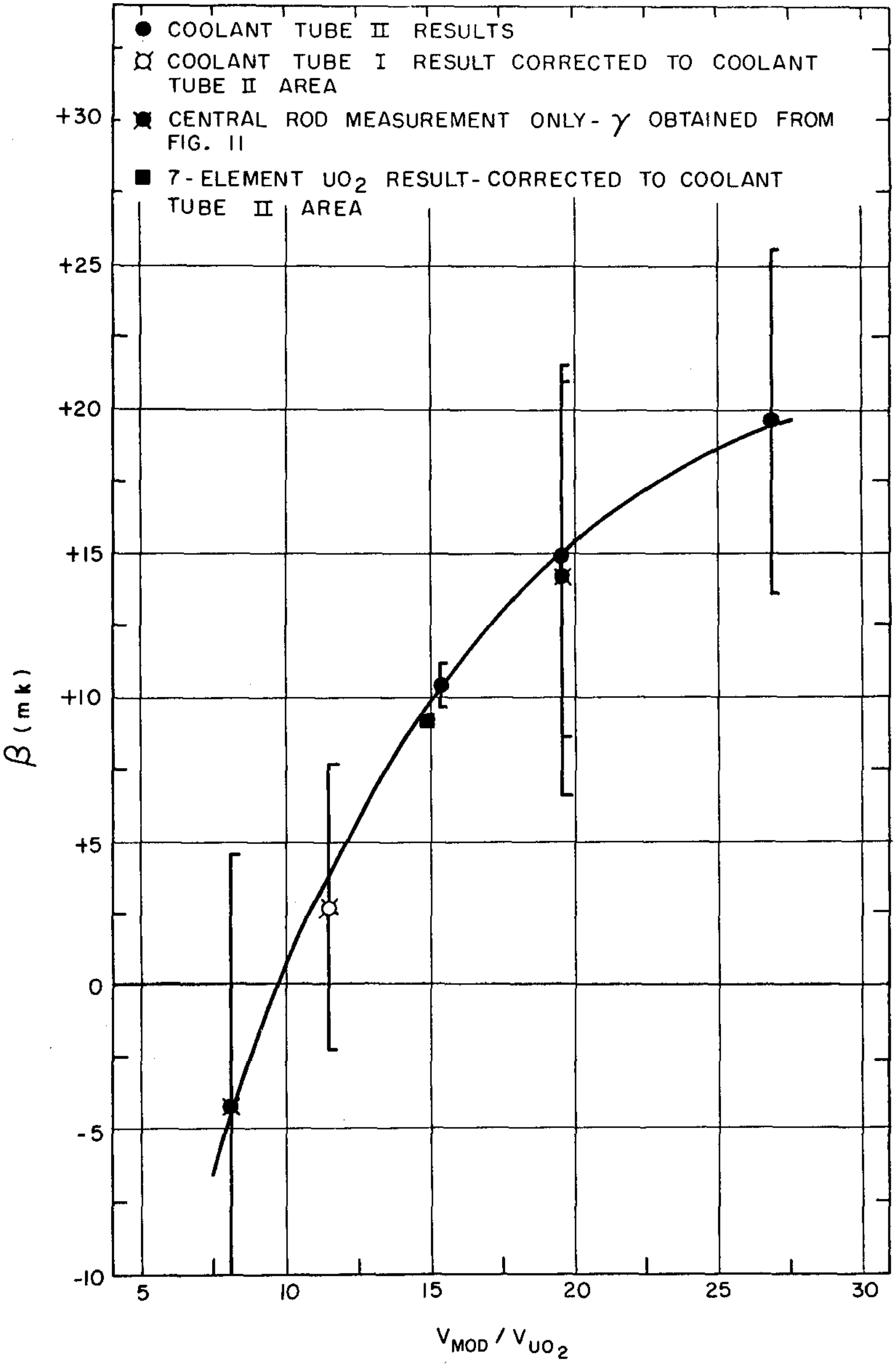

FIG. 12: β vs V_{MOD}/V_{UO_2} FOR 19-ELEMENT UO_2 CLUSTER LATTICES

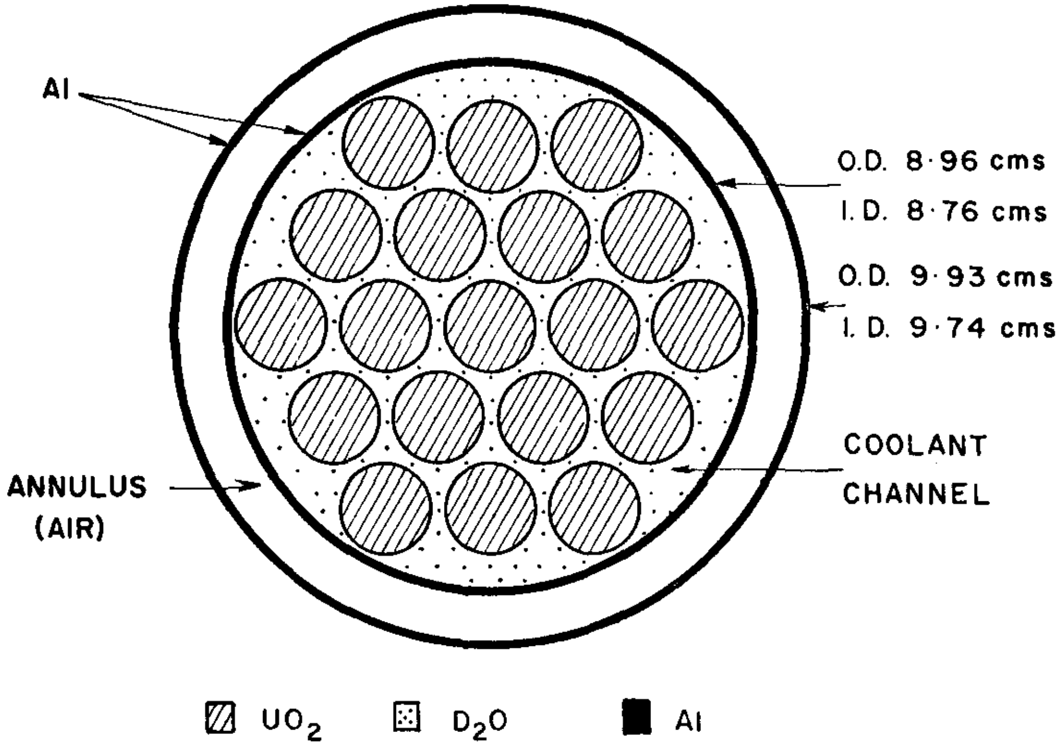

FIG. 13: COOLANT TUBE I ASSEMBLY