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Abstract: The distribution of thermal neutrons has been measured in typical lattice cells in multiplying assemblies of 1.027% enriched uranium rods in ordinary water. Relative fluxes were found with small foils of dysprosium oxide dispersed in lucite and polyethelene. The measured flux distributions are given, and the implied thermal utilizations are calculated.

Experimental Methods: The experimental methods have been discussed to some extent in a previous memorandum (BNL Log No. C-7568) on measurements of intracell flux distributions for 1.3% enriched uranium rods in light water. We repeat them here, however, because some procedures have changed.

All thermal neutron fluxes were measured with dysprosium. The utility of this detector comes from its small resonance absorption, which makes the measurement of cadmium differences unnecessary. Since dysprosium is currently available only as the oxide powder, a carrier for it is necessary. Before the set measurements reported here, we used lucite as the carrier. A mixture of dysprosium oxide and lucite molding powder was compressed to a ten mil thick wafer in a metallurgical hot press, and 1/16" diameter foils were punched from it. These foils were the detectors which, when placed in the moderater and the uranium rod, served to measure the local thermal neutron flux.

These foils are quite brittle, and despite careful handling, they consistently chipped. The result was that the intercalibration factors of the foils frequently changed. Although intercalibrations were made before and after each

intracell flux distribution measurement, it was often difficult to decide on what calibration factor was to be applied in a given case.

As a result, we have switched to using polyethelene instead of lucite. In a way, polyethelene is more inconvenient, because it is not available as a fine molding powder. To make the foils, we have found it necessary to begin the mixing process using small pieces of the plastic. These are placed on thin aluminum foil which in turn is placed in a glass plate heated by an ordinary hot plate. When the polyethelene reaches a good consistency, dysprosium oxide is added, and the mixture is kneaded until as much powder as possible is taken up and is distributed throughout. Another layer of aluminum foil is then placed on top of the mixture, and this sandwich is pressed between glass plates until it has the proper thickness. During pressing, the polyethelene cools and solidifies. The aluminum foil adheres strongly to the wafer of plastic; even when foils are punched out, they retain a thin protective aluminum coating.

The foils made in this manner have shown excellent resistence to abuse. Occasionally a section of the aluminum foil comes free, but this does not seem to change calibration factors. The only calibration factor changes which have occurred can apparently be attributed to the loss of dysprosium which has been imperfectly assimilated with the polyethelene. Care taken in the kneading process reduces these changes to a negligible factor.

We have continued the procedure of intercalibrating all foils before and after an intracell flux distribution measurement. This practice now provides increasingly accurate calibration factors over a period of time, and also serves

to indicate when a calibration factor has changed because the foil has lost dysprosium.

The neutron flux in a typical lattice cell is determined by placing dysprosium foils simultaneously in milled depressions in one end of a split uranium rod and in the water moderater adjacent to it. A typical foil array is shown in figure 1. A cross of thirteen foils in the rod gives the flux distribution there. Foils are placed in an aluminum holder in the water, along two lines. One line of foils in the water measures the flux variation between neighboring rods. The second line gives the flux along the median line of the triangle formed by three adjacent rods. This measurement then does not give the flux everywhere throughout a triangular lattice cell, but Cleska and Mozer have shown in BNL Log No. C-6983 that the information obtained is sufficient to permit calculating by relaxation methods a contour diagram of the flux everywhere.

Because of the exponential attenuation of the neutron flux in the vertical direction, considerable care must be exercised to assure that foils in the rod and in the water are at the same height. The final calculation of the intercell flux distributions reported in BNL Log No. 7568 (measurements with 1.3% enriched rods) was not done until after the uranium rods were shipped to WAPD. As a result, we have found since that at least two of the measurements reported (those for the 4:1 and 3:1 clean lattices) are wrong, almost certainly because of height positioning errors. Probably the fluctuations observed in flux averages in the water as the boron poisoning was changed can be attributed to such errors, too. We took two precautions to prevent this happening with the measurements reported here. First, the method of adjusting the height of water and rod foils to be the same was simplified and made almost foolproof. Second, we did not release the uranium until the analysis was

complete. As a result, we are moderately sure that incorrect adjustment of foil heights does not cause any appreciable error in the flux traverses given in this report.

Intercalibrations of the foils is accomplished by subjecting them simultaneously to the same neutron flux, and measuring their relative activities. The exposure is done in a lucite wheel which is placed horizontally in the bottom of the exponential experiments water tank. The foils are placed on the periphery of the wheel; the latter is rotated at a constant rate by means of a stream of air played on vanes attached to the long shaft passing through the wheel. A small warp of the shaft relative to the wheel causes the foils to receive a slightly uneven exposure history. This effect has been measured; because of it a correction of at most 1.8% must be applied to the final intercalibration factors.

In accordance with our usual practices, we counted all foils in every case in several counters (usually six - at least four). The total counts from a run were used to intercalibrate the counters for that run, and the tabulated count rates for all counters after application of the counter calibration factors were used to determine errors in reducing data and in the count-taking. The amount of analysis involved is considerable, but we feel that this system has been invaluable in reducing computational errors to a minimum. Furthermore we are not forced to rely on the integrity of any one counter and scaling circuit.

All foil counts are carried out to at most ± 1% statistical error. Foils were counted on both sides (although occasionally this may not have happened - it is impossible to tell one side of a 1/16" diameter plastic foil from the other).

Results: The measured neutron fluxes for water-to-metal volume ratios 1:1, 1.5:1, 2:1, 3:1, and 4:1 are listed in tables I-V. The flux plots are shown in figures 2 - 6. The curves in the figures are drawn by eye so as to provide a reasonable fit to the flux values. In addition, the following criteria derived from cell symmetry were used:

1. Because of the cylindrical symmetry of the rod, corresponding points on the crossed pattern of foils were lumped together and their fluxes were averaged. The result is that the points at .067", .184", and .250" from the rod center represent four times as many measurements as does the center point. Thus their statistical weight in fitting to the curve shape in the rod is approximately twice as great as that for the center. The curve in the rod is so drawn as to fit the outer points better than it does the center point.
2. The flux curve along the line joining neighboring rods is made to peak at the half-way point.
3. Examination of the cell geometry in figure 1 shows that the two lines of foils in the water have one corresponding point where the measured fluxes should be the same. On the short line, called the center-to-center line in the tables, this is the midpoint. On the long line, called the diagonal in the tables, the point occurs where the line is passing midway between two rods. In figure 1, this point is approximately at the outermost foil position on the line of the diagonal. The curves are so drawn as to make the flux equal at these corresponding points.

The flux values are all normalized in such a way as to make the plotted curves

have the value 1.00 at the center of the rod. Of course, proper selection of this normalization factor depends on the correctness with with the curves were drawn, and some error must enter into the choice.

The points of intersection of the water and rod curves with the aluminum rod cladding were also selected by eye, the criteria being simply that the over-all curve represent the measured points as well as possible, and that the absorption in the aluminum is very small. Some error must of course occur, but repetitions of the curve drawing indicate that selection of this point is wrong by at most $\sim$1%. The effect would be an error of about .5% in the rod disadvantage factor, and a much smaller error in the deduced thermal utilization.

Thermal Utilization: Using the experimental flux curves, one may calculate the average flux in the uranium and in the moderater. Calculation of the thermal utilization makes use of these flux averages and the assumed capture cross-sections for the media.

The flux averages in the metal have been performed by numerical evaluation of

$$\frac{2}{R^2} \int_0^R r \, dr \, \phi(r) = \bar{\phi}_m \qquad (1)$$

where R is the rod diameter, $\phi(r)$ is the measured flux, and $\bar{\phi}_m$ is the average.

The hexagonal symmetry of the water region of a unit lattice cell can be idealized to an equivalent cylinder of the same volume. Mozer has shown that integration of an averaged radial distribution over this equivalent cylinder gives for all practical purposes the same flux averages as does a more sophisticated net-point calculation over the exact lattice cell. We have used this equi-

valent cylinder calculation to obtain the average flux in the water, evaluating numerically

$$\frac{2}{R_2^2 - R_1^2} \int_{R_1}^{R_2} r \, d \, r \, \phi \, (r) = \bar{\phi}_w \qquad (2)$$

R_2 and R_1 are the outer and inner radii of the equivalent water anulus, and ϕ (r) is here the average of the flux distributions measured along the two lines.

The values of the averaged fluxes obtained this way are given in table VI, and are plotted in figure 7. The deviations of experimentally determined points from the smooth curves appear to be $\sim 2\%$ at most for $\bar{\phi}_w$, and $\sim 1\%$ at most for $\bar{\phi}_m$.

Thermal utilizations are calculated from the expression

$$f = \frac{\bar{\phi}_m \ \Sigma_m}{\bar{\phi}_m \ \Sigma_m + \bar{\phi}_w \ \Sigma_w \ V_w + \bar{\phi}_a \ \Sigma_a \ V_a} \qquad (3)$$

Here $\bar{\phi}_a$ is the flux in the aluminum cladding, and Σ_m, Σ_w, Σ_a are respectively the absorption cross-sections of metal, water, and aluminum. V_w and V_a are respectively water-to-uranium and aluminum-to-uranium volume ratios. The cross-sections used are given in table VII. These were calculated by Oleska, and were reported in BNL Log No. C-7174. All cross-sections were averaged over a Maxwell distribution at room temperature.

The final values of thermal utilization are listed in table VIII, and are plotted against the water-to-uranium volume ratio in figure 8.

It is apparent that the measured values of f fit a smooth curve much better

than might have been expected from the appearance of the average fluxes in figure 7. The reason for this is probably two-fold. First, the value of f for all these lattices is so near to 1 that relatively large errors must occur before the change in f is apparent. At the 4:1 volume ratio, an error of 2% in $\bar{\phi}_w$ causes f to be wrong by only about .3%. At the 1:1 volume ratio a 2% error in $\bar{\phi}_w$ causes an error in f of only about .1%.

The second reason is that some errors in the analysis are self-compensating. For instance, if too low a value is taken for the flux in the aluminum, this has the associated effect of reducing the flux averages in the uranium and in the water. Similarly, a small error in setting the heights of foils in the water might cause the flux average in the water to be wrong, but the necessity for matching the flux in the water and in the uranium at the aluminum boundary will change the other average fluxes in the same direction.

Table I

Intracell Flux Distribution, .600" Diameter Rods of 1.027% Enriched Uranium in Light Water. Water-to-Metal Volume Radio = 1:1.

Distance from rod center (inches)	Measured relative flux	Remarks
.000	.985	Flux
.084	1.009	in
.167	1.034	Uranium
.250	1.111	
.378	1.276	Flux in
.478	1.314	Water
.578	1.328	(Diagonal)
.677	1.292	
.779	1.315	
.379	1.193	Flux in
.479	1.347	Water
		(Center-to-center)

Table II

Intracell Flux Distribution, .600" Diameter Rods of 1.027% Enriched Uranium in Light Water. Water-to-Metal Volume Ratio = 1.5:1.

Distance from rod center (inches)	Measured relative flux	Remarks
.000	.993	Flux
.084	1.020	in
.167	1.055	Uranium
.250	1.144	
.378	1.327	Flux in
.442	1.429	Water
.507	1.454	(Diagonal)
.573	1.426	
.639	1.461	
.704	1.377	
.770	1.410	
.370	1.337	Flux in
		Water
.498	1.465	(Center-to-center)
.564	1.337	

Table III

Intracell Flux Distribution, .600" Diameter Rods of 1.027% Enriched Uranium in Light Water. Water-to-Metal Volume Ratio = 2:1.

Distance from rod center (inches)	Measured relative flux	Remarks
.000	.993	Flux
.083	1.015	in
.167	1.072	Uranium
.250	1.166	
.376	1.365	Flux in
.445	1.458	Water
.518	1.495	(Diagonal)
.590	1.517	
.659	1.492	
.730	1.503	
.798	1.493	
.868	1.524	
.375	1.386	Flux in
.445	1.461	Water
.514	1.508	(Center-to-center)
.583	1.454	
.655	1.379	

Table IV

Intracell Flux Distribution, .600" Diameter Rods of 1.027% Enriched Uranium in Light Water. Water-to-Metal Volume Ratio = 3:1.

Distance from rod center (inches)	Measured relative flux	Remarks
.000	1.000	Flux
.084	1.019	in
.167	1.066	Uranium
.250	1.148	
.375	1.375	Flux in
.444	1.484	Water
.513	1.583	(Diagonal)
.582	1.588	
.654	1.612	
.723	1.580	
.793	1.585	
.866	1.634	
.934	1.603	
.370	1.380	Flux in
.441	1.474	Water
.512	1.543	(Center-to-center)
.581	1.567	
.651	1.537	
.721	1.502	
.791	1.415	

Table V

Intracell Flux Distribution, .600" Diameter Rods of 1.027% Enriched Uranium in Light Water. Water-to-Metal Volume Ratio = 4:1.

Distance from rod center (inches)	Measured relative flux	Remarks
.000	.986	Flux
.084	1.019	in
.167	1.076	Uranium
.250	1.171	
.380	1.412	Flux in
.473	1.608	Water
.563	1.684	(Diagonal)
.653	1.716	
.743	1.734	
.833	1.738	
.923	1.695	
1.013	1.684	
1.103	1.709	
.390	1.420	Flux in
.479	1.594	Water
.569	1.653	(Center-to-center)
.659	1.683	
.749	1.643	
.839	1.568	
.932	1.429	

Table VI

Flux Averages Calculated from Measured Intracell Traverses. .600" Diameter Rods of 1.027% Enriched Uranium in Light Water.

Volume Ratio	$\bar{\phi}_m$	$\bar{\phi}_w$	$\bar{\phi}_a$
1:1	1.079	1.271	1.172
1.5:1	1.105	1.381	1.211
2:1	1.121	1.443	1.246
3:1	1.107	1.505	1.211
4:1	1.121	1.610	1.252

Table VII

Absorption Cross-sections* Used for Computing f.

Medium	σ (barns)	Σ (cm^{-1})
U^{235}	591	28.2
U^{238}	2.46	.118
1.027% Enriched Uranium	8.57	.4096
H_2O	.585	.0195
Al	.191	.0115

* These cross-sections have been computed by S. Oleska, and are reported in BNL Log No. C-7174. They are all averages over a Maxwell distribution.

Table VIII

Values of Thermal Utilization Implied by Measured Intracell Flux Traverses. .600" Diameter Rods of 1.027% Enriched Uranium in Light Water.

Volume Ratio	f
1:1	.941
1.5:1	.913
2:1	.886
3:1	.833
4:1	.781

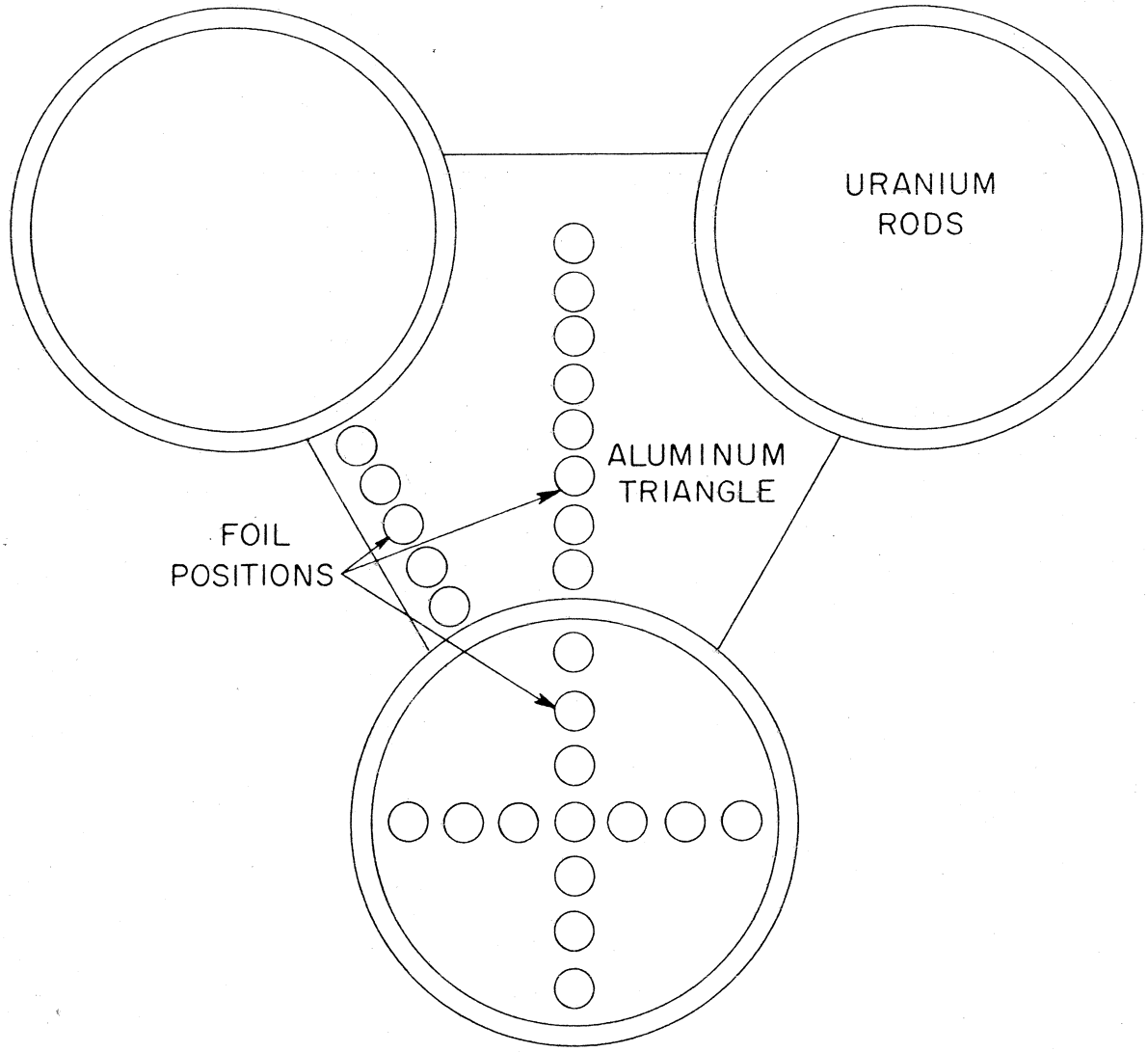


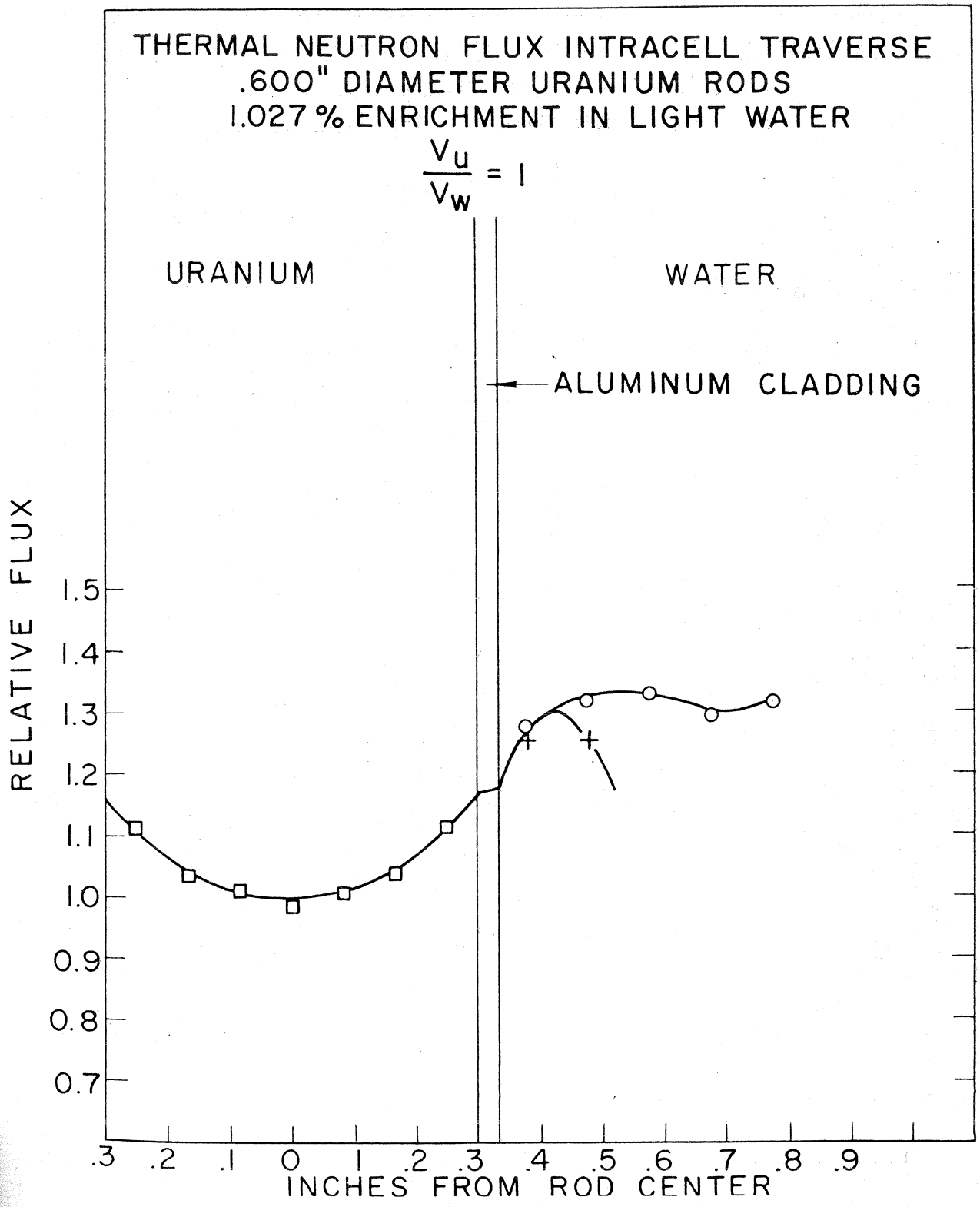
FIG. 1

FOIL POSITIONS FOR 2:1 LATTICE

SCALE 4" = 1"

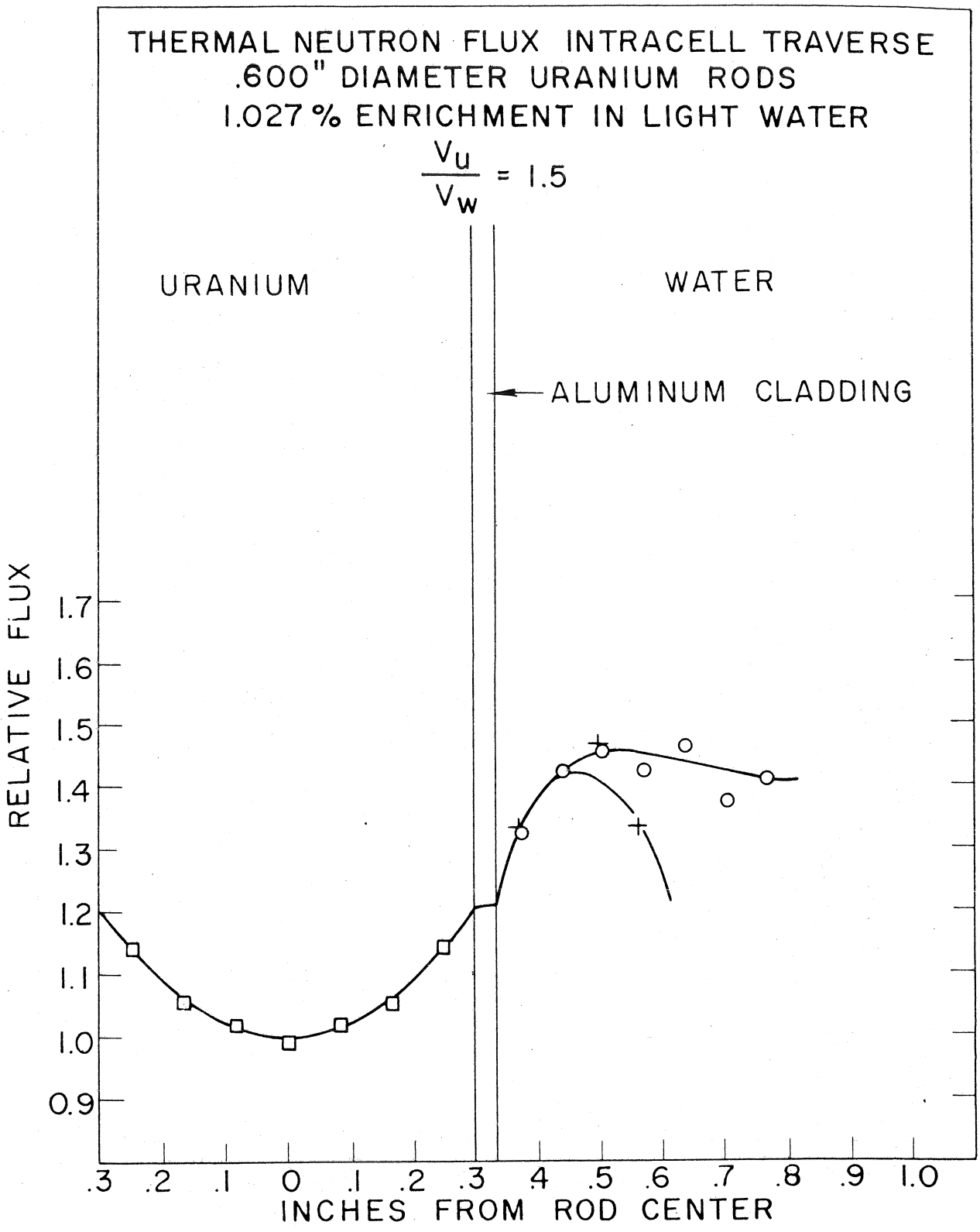
BNL LOG NO. D-2722

FIG. 2



BNL LOG NO. D-2723

FIG. 3



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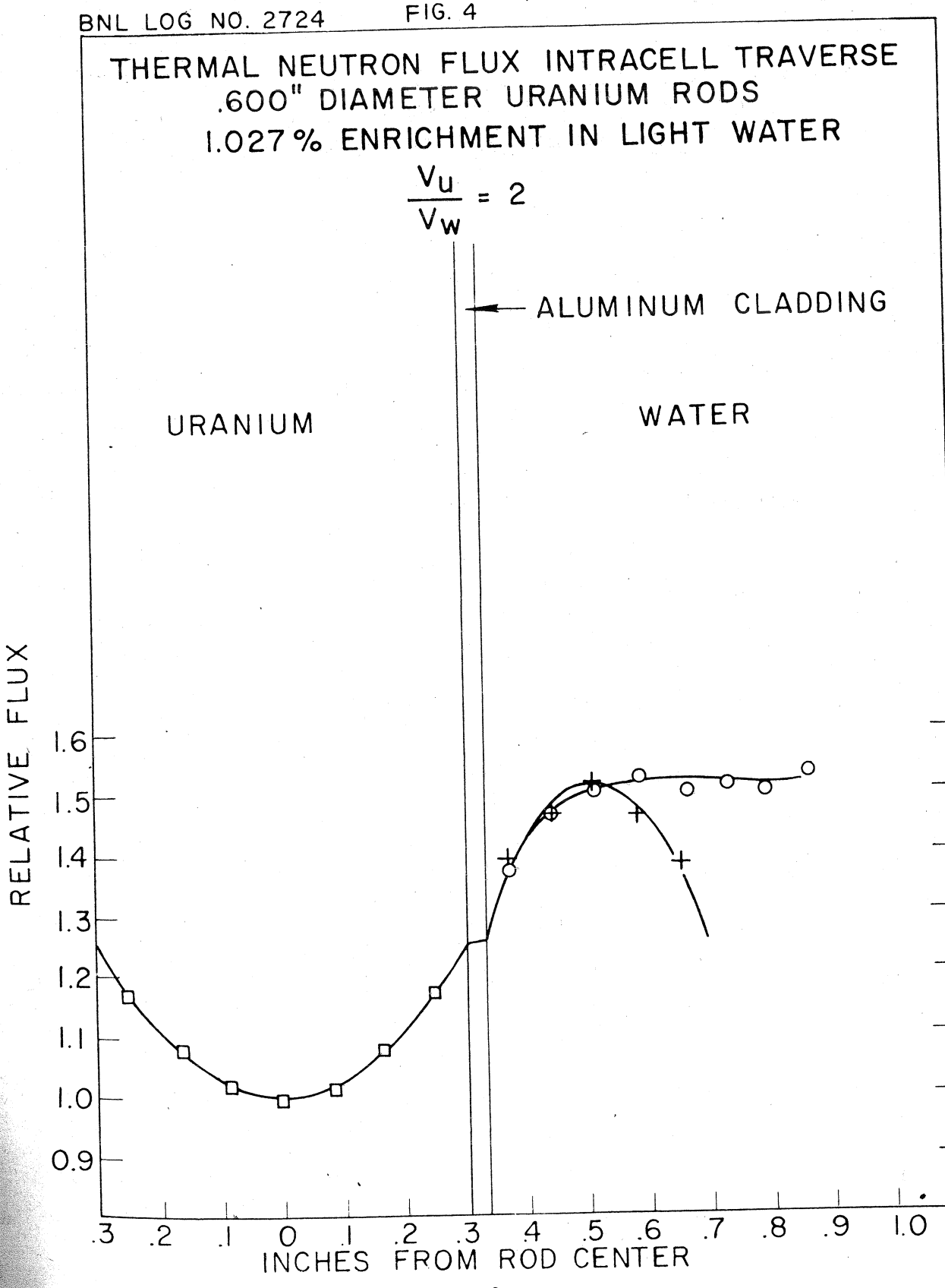
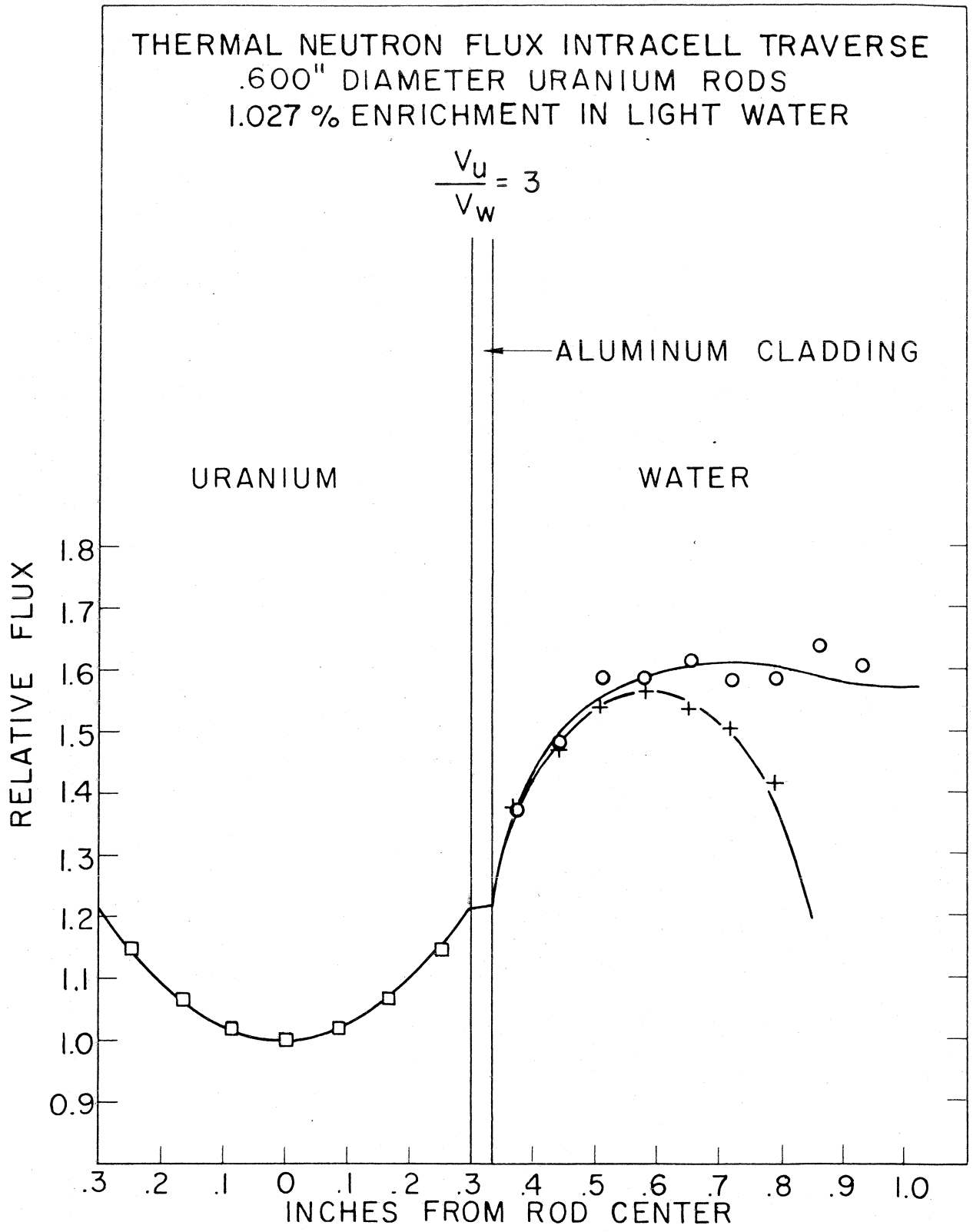
BNL LOG NO. 2724 FIG. 4



BNL LOG NO.D-2725

FIG. 5



BNL LOG NO. D-2726 FIG. 6

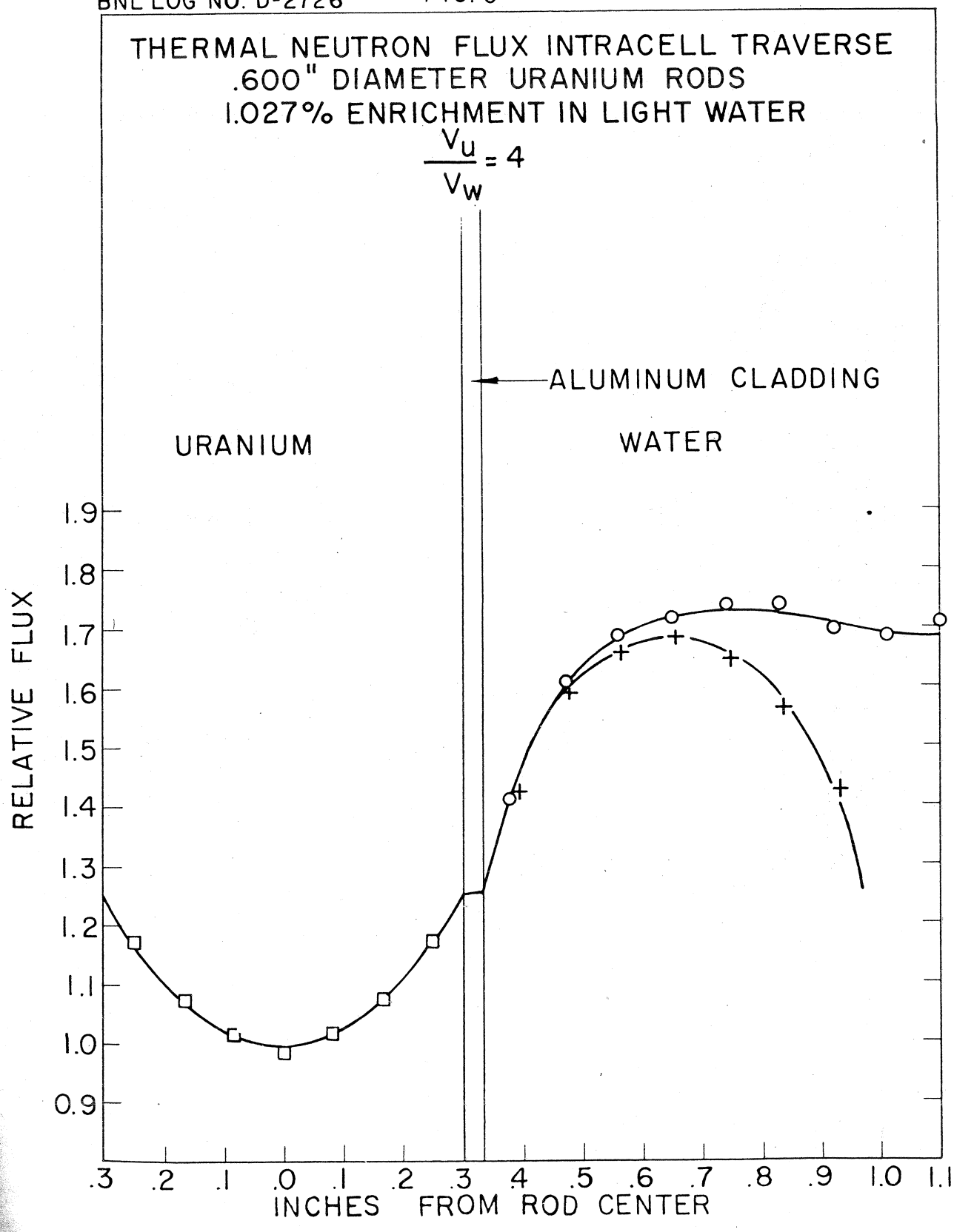


FIG. 7

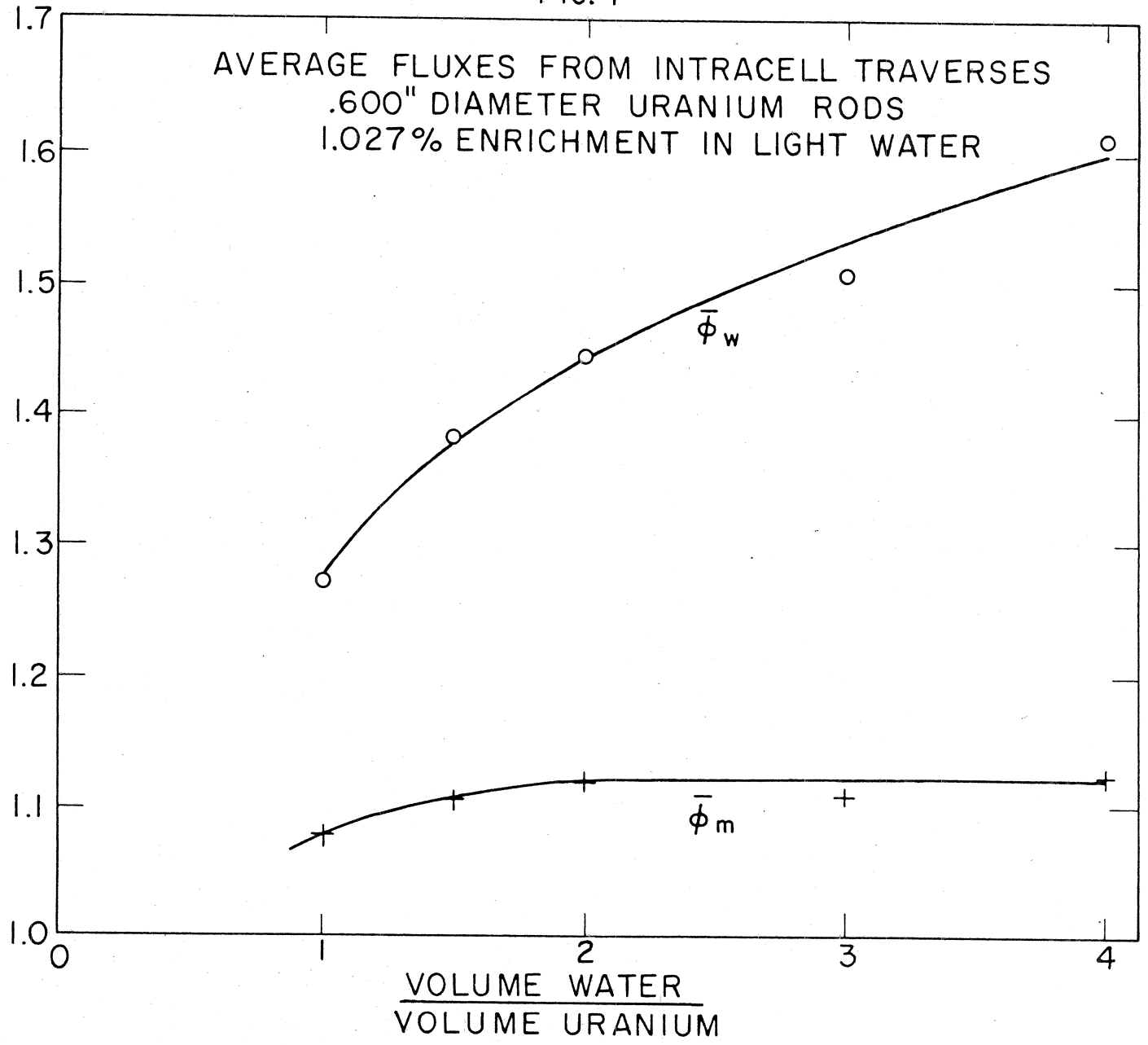


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FIG. 8