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Criticality Experiments with Subcritical Clusters of 2.35 Wt% and 4.31 Wt% ^{235}U Enriched UO_2 Rods in Water at a Water-to-Fuel Volume Ratio of 1.6

Prepared by S. R. Bierman, E. D. Clayton

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ABSTRACT

The fourth in a series of Nuclear Regulatory Commission funded criticality experiments have provided data for 2.35 wt% and 4.31 wt% ^{235}U enriched UO_2 rods at a water-to-fuel volume ratio of 1.6. The results from some 147 critical experiments are presented. They include for each enrichment:

- The critical size of single lattices or clusters of fuel
- The critical separation between sub-critical clusters of fuel
- The critical separation between sub-critical clusters of fuel having fixed neutron absorbers between the fuel clusters
- The isolation distance between fuel clusters
- The critical size of fuel clusters containing water holes and voids
- The critical size of fuel clusters separated by flux traps

The fixed neutron absorbers for which data were obtained include 304-L steel, borated 304-L steel, copper, copper containing 1 wt% cadmium, cadmium, aluminum, zirconium and two trade name materials containing boron (Boral and Boroflex).

SUMMARY

The results from the fourth in a series of criticality experiments funded by the United States Nuclear Regulatory Commission are presented in this paper. The initial three series of experiments in this program were concerned with determining the critical separation between clusters of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 fuel rods immersed in water at near optimum neutron moderation. The effect that various neutron absorber plates positioned between the fuel clusters had on the critical separation was investigated. Also the effect that lead and depleted uranium reflecting walls had on this critical separation was investigated in these earlier experiments. This fourth series of experiments involve the same fuel immersed in water as before but at a neutron moderation approximating that found typically in Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) fuel assemblies. Measurements similar to those performed at near optimum neutron moderation were repeated with the same neutron absorber material (Boral, 304-L steel, borated 304-L steel, copper, copper containing 1 wt% cadmium, aluminum and zirconium) plus a new material called Boroflex and two additional types of Boral. Measurements were also made to determine the effect that water holes, voids, and flux traps in fuel clusters have on the critical size of the fuel cluster.

The objective of these experiments, as in the previous experiments, is to provide clean, definable, integral data that can be described in calculations exactly as-run without corrections or approximations having to be made.

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CRITICALITY EXPERIMENTS WITH SUBCRITICAL CLUSTERS OF 2.35 WT% AND 4.31 WT% ^{235}U ENRICHED UO_2 RODS IN WATER AT A WATER-TO-FUEL VOLUME RATIO OF 1.6

INTRODUCTION

A research program, funded by the United States Nuclear Regulatory Commission, to provide experimental criticality data on conditions simulating Light Water Reactor (LWR) fuel shipping and storage configurations was begun in 1976 at the Battelle operated Critical Mass Laboratory at Hanford. The initial three series [1-5] of experiments in this program were concerned with determining the critical separation between clusters of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 fuel rods immersed in water at near optimum neutron moderation. The effect that various neutron absorber plates positioned between the fuel clusters had on the critical separation was investigated. Also the effect that lead and depleted uranium reflecting walls had on this critical separation was investigated in these earlier experiments.

The fourth series of experiments in this NRC program are covered in this paper and involve the same fuel immersed in water as before but at a neutron moderation approximating that found typically in Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) fuel assemblies.

Measurements similar to those performed at near optimum neutron moderation were repeated with the same neutron absorber materials plus a new material called Boroflex[tm] and two different types of Boral.[tm]

The objective of these experiments, as in the previous experiments, is to provide clean, definable, integral data that can be described in calculations exactly as-run without corrections or approximations having to be made.

Boroflex is a trademark product of Brand Industrial Services, Inc.
Boral is a trademark product of Brooks and Perkins, Inc.

EXPERIMENTS

In these latest experiments, as in the previous experiments, [1-5] the primary parameter measured was the critical separation between subcritical rectangular shaped clusters of fuel rods immersed in water. In the previous measurements three fuel clusters were aligned in a row. In these latest experiments, when the amount of fuel and neutron absorber plates available permitted, the critical separation between four fuel clusters in a rectangular arrangement was measured to obtain interaction data in two dimensions. Whenever there was insufficient fuel or absorber plates to achieve criticality in this four cluster geometry, measurements were made as before with three fuel clusters aligned in a row.

A photograph of a water flooded four cluster experimental assembly is shown in Figure 1 with a set of absorber plates in position. For clarity an artist sketch of a typical four cluster arrangement is shown in Figure 2. The neutron absorber plates are described in Table I. The fuel is described in Figure 3, and the water impurities are presented in Table II.

The primary neutron absorbing nuclei are homogeneously distributed throughout the absorber plates listed in Table I. However, in the Borals and in the Boroflex these nuclei are contained in B_4C particles uniformly distributed throughout either an aluminum (Boral) or a rubber material

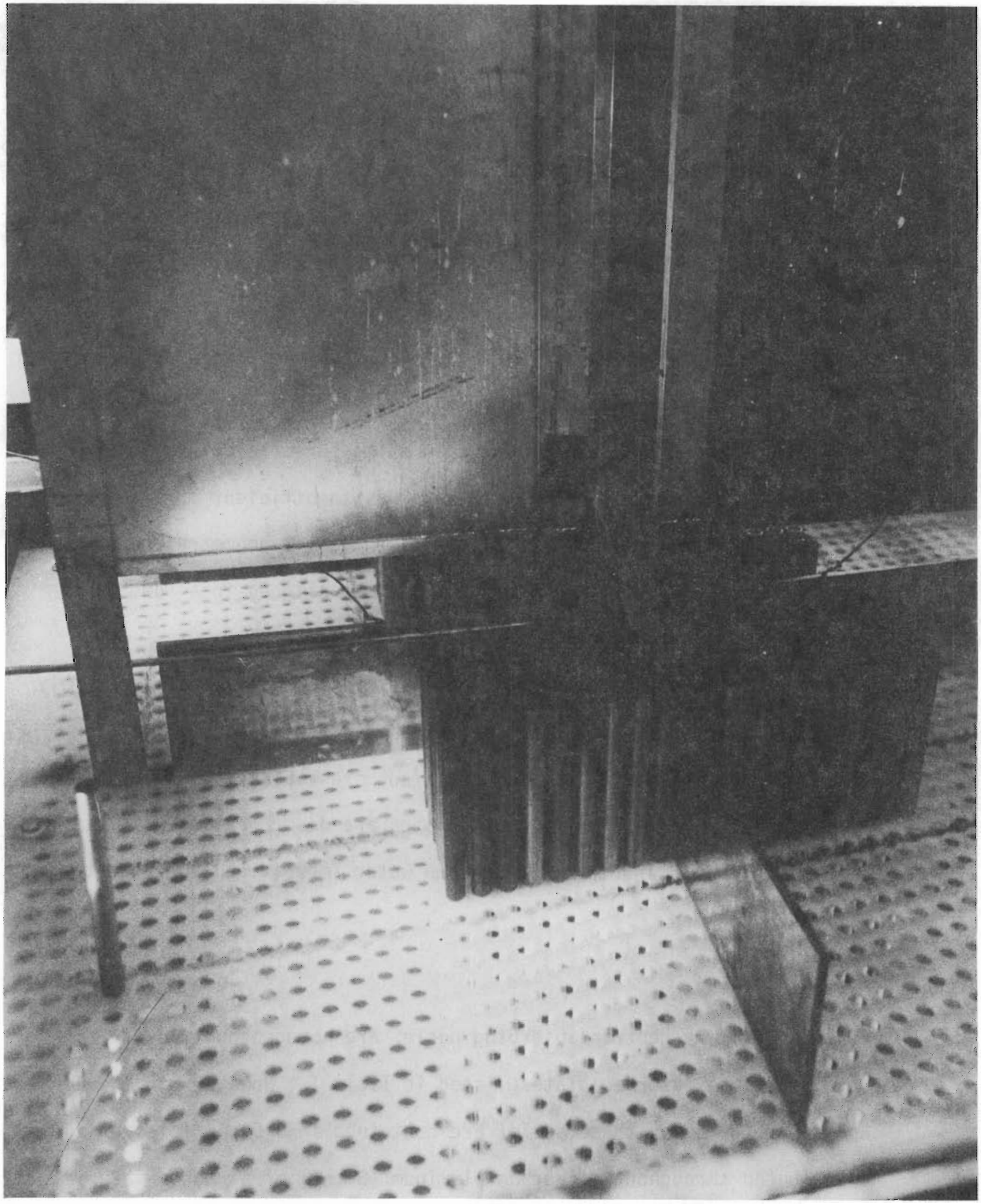


FIGURE 1. PHOTOGRAPH OF A TYPICAL FOUR CLUSTER EXPERIMENTAL ASSEMBLY

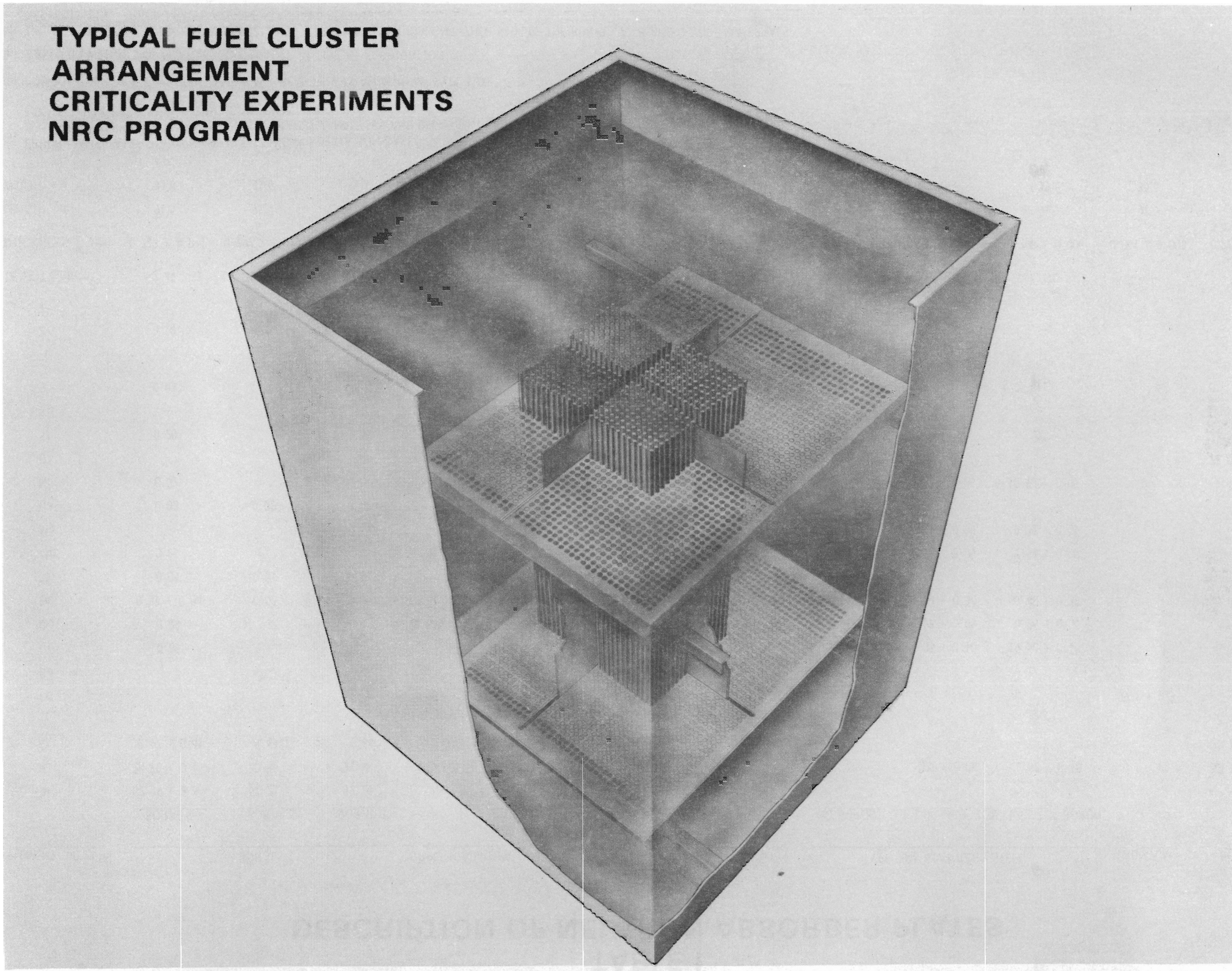


FIGURE 2. FUEL ARRANGEMENT IN A FOUR CLUSTER EXPERIMENTAL ASSEMBLY

TABLE I
DESCRIPTION OF NEUTRON ABSORBER PLATES

ELEMENT, WT.%[a]	BORAL[b]			COPPER-CADMIUM	COPPER	6061 ALUMINUM	ZIRCALOY-4	TYPE 304L STAINLESS STEEL			CADMIUM	BOROFLEX
	BORAL A	BORAL B	BORAL C					NO BORON	1.1 WT.% BORON	1.6 WT.% BORON		
Al	62.39 ± 2.8	61.21[c]	59.26[c]	- -	- -	97.15 ± 0.21	- - -	- - -	- -	- - -	- -	- -
B	28.70 ± 0.25	30.36[c]	31.88[c]	0.005	- - -	- - -	- - -	- - -	1.05 ± 0.08	1.62 ± 0.10	-	32.74 ± 0.05
C	7.97 ± 0.41	8.43[c]	8.86[c]	0.002	0.340	- - -	- - -	-	-	-	-	21.13 ± 0.03
H	- - -	- - -	- -	- - -	- -	- - -		-	- -	-	-	2.65 ± 0.31
Cd	- - -	- - -	- -	0.989 ± 0.003	-			- - -	- -	- - -	99.7 ± 0.3	- - -
Ca	- - -	- -	-	-				-	- -			- - -
Cr	0.05	- -	- -	-		0.21	0.13 ± 0.04	18.56 ± 0.10	19.03 ± 0.10	19.60 ± 0.10		0.03 ± 0.02
Cu	0.09	- -		98.685 ± 0.300	99.60 ± 0.14	0.12		0.27 ± 0.05	0.28 ± 0.05	0.26 ± 0.05		- -
Fe	0.33 ± 0.04	0.02	0.05	0.020	0.004	0.82	0.21 ± 0.03	68.24 ± 0.34	68.04 ± 0.34	66.40 ± 0.33		0.05 ± 0.06
Mg	0.05	0.01	0.01		0.002							- -
Mn	0.05			0.009		0.21		1.58 ± 0.05	1.58 ± 0.05	1.69 ± 0.05		-
Mo	-							0.26 ± 0.05	0.49 ± 0.05	0.31 ± 0.05	-	- - -
Na	0.02	0.02	0.02		0.002							- - -
Ni	0.02			0.010				11.09 ± 0.06	9.53 ± 0.05	10.12 ± 0.05		- -
O	-			0.019	0.030							21.01 ± 0.01
Si	0.20		0.06	0.004	0.020	0.82						22.39 ± 0.24
Sn				0.250			1.50 ± 0.27					- - -
S	0.03				0.002	0.06						
Ti	- -					0.61						-
Zn	0.10			0.007							0.3	- -
Zr	- -						98.16 ± 0.35					- - -
DENSITY, g/cm^3	2.49	2.50	2.47	8.910	8.913	2.692	6.32	7.930	7.900	7.770	8.650	1.731
THICKNESS,[d] cm	0.713 ± 0.011	0.292 ± 0.013	0.231 ± 0.013	0.357 ± 0.008	0.646 ± 0.008 0.337 ± 0.008	0.625 ± 0.001	0.652 ± 0.008	0.485 ± 0.015 0.302 ± 0.013	0.298 ± 0.006	0.298 ± 0.006	0.061 ± 0.003	0.22 ± 0.004 0.452 ± 0.006
LENGTH, cm	91.5	91.5	91.5	91.5	91.5	91.5	91.5	91.5	91.5	91.5	91.5	91.5
WIDTH, cm	35.6	35.6	35.6	35.6	35.6 (e)	35.6	35.6	35.6	35.6	35.6	35.6	35.6

(a) ERROR LIMITS WHERE SHOWN ARE ONE STANDARD DEVIATION BASED ON MULTIPLE CHEMICAL ANALYSES. IMPURITIES DISTRIBUTION BASED ON SPARK SOURCE MASS SPECTROGRAPHIC ANALYSES AND REPRESENT BEST ESTIMATE OF MAXIMUM CONCENTRATION FOR EACH ELEMENT PRESENT IN SIGNIFICANT QUANTITY.

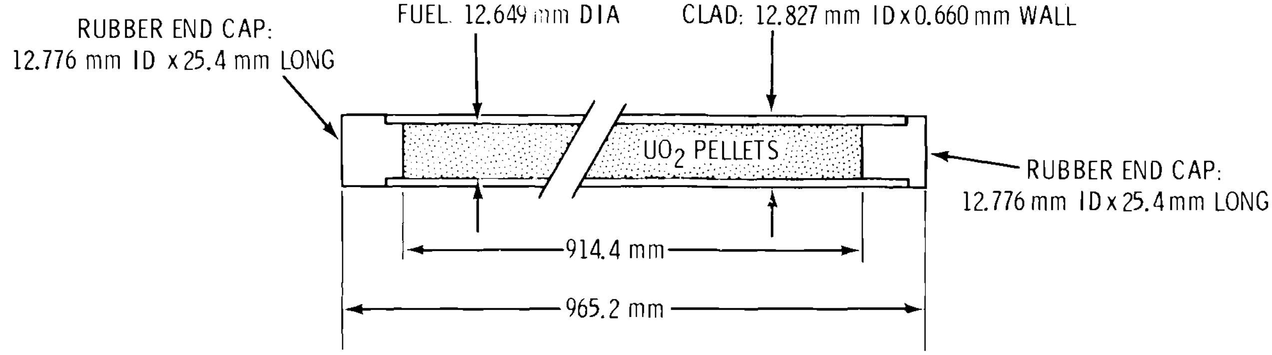
(b) COMPOSITION OF B_4C-Al CORE MATERIAL. CLADDING IS ALUMINUM, TYPE 1100.

(c) BASED ON WEIGHTS OF MIXTURE COMPONENTS AT TIME OF FABRICATION.

(d) INCLUDES 0.102 cm, 0.038 cm, AND 0.025 cm OF TYPE 1100 ALUMINUM ON EITHER SIDE OF THE BORAL, A, B AND C CORE MATERIALS RESPECTIVELY. ERROR LIMITS ARE ONE STANDARD DEVIATION.

(e) PLATES 0.337 cm THICK ARE 30.6 cm WIDE.

4.31 wt% ^{235}U ENRICHED UO_2 RODS



CLADDING: 6061 ALUMINUM TUBING

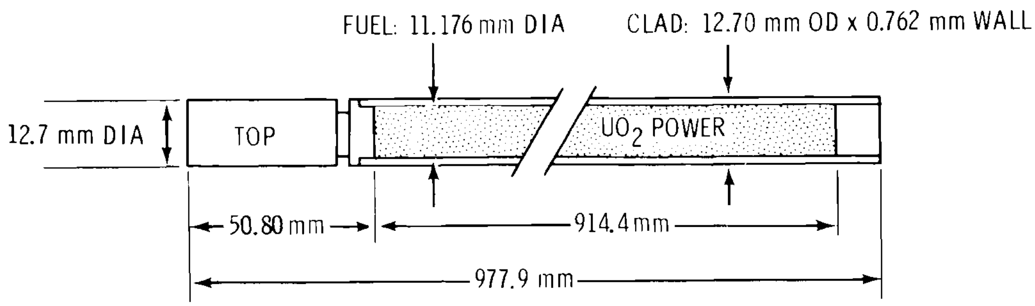
LOADING:

ENRICHMENT - 4.31 ± 0.01 wt% ^{235}U
FUEL DENSITY - 94.9 ± 0.55% OF THEORETICAL DENSITY
URANIUM ASSAY - 88.055 ± 0.261 wt% OF TOTAL FUEL COMPOSITION
UO_2 - 1203.38 ± 4.12 g / ROD

END CAP:

DENSITY - 1.321 g/cm^3
COMPOSITION- C - 58 ± 1 wt%   S - 1.7 ± 0.2 wt%
H - 6.5 ± 0.3 wt%   O - 22.1 wt% (BALANCE)
Ca - 11.4 ± 1.8 wt%   Si - 0.3 ± 0.1 wt%

2.35 wt% ^{235}U ENRICHED UO_2 RODS



CLADDING: 6061 ALUMINUM TUBING SEAL WELDED WITH A LOWER END PLUG OF 5052-H32 ALUMINUM AND A TOP PLUG OF 1100 ALUMINUM

LOADING:

ENRICHMENT - 2.35 ± 0.05 wt% ^{235}U
FUEL DENSITY - 9.20 mg / mm^3 (84% THEORETICAL DENSITY)
URANIUM ASSAY - 88.0 wt%
UO_2 - 825 g / ROD (AVERAGE)

FIGURE 3. DESCRIPTION OF FUEL RODS

TABLE II
WATER IMPURITIES

COMPONENT	CONCENTRATION [1] g/m^3 (ppm)
Cl	1.7 ± 0.6
NO_3	0.02 ± 0.01
Cr^{+6}	< 0.01
Zn	0.9 ± 1.1
Mn	< 0.01
Pb	0.008 ± 0.001
F	0.15 ± 0.04
Fe	< 0.03
Cu	< 0.01
Cd	0.020 ± 0.006
Gd	10.4 ± 3.6
SO_3	13.4 ± 5.0
DISSOLVED SOLIDS	113 ± 28

(1) ERROR LIMITS ARE STANDARD DEVIATIONS OBSERVED IN THREE SAMPLES

(Boroflex). According to the manufacturer, these particles have the following size distribution:

Particle Size (mm)	Wt% Particle Distribution	
	Boral	Boroflex
> 0.297	0.6	-----
> 0.250	8.0	-----
> 0.149	-----	Trace
> 0.125	73.6	-----
> 0.074	98.6	2.1
< 0.074	1.4	-----
> 0.044	100.0	21.2
< 0.044	-----	78.8

In addition to measuring the critical separation between multiple fuel clusters, experiments, with both the 2.35 wt% and the 4.31 wt% ^{235}U enriched UO_2 rods, were also performed to determine the critical size of single lattices containing voids and water holes. Experiments were also performed at each enrichment to measure the reactivity effect that a flux trap of varying thickness between two fuel clusters has on the critical size of the fuel clusters. The details of these measurements and those with the neutron absorber plates are covered in the specific sections on experimental data that follow.

All of the experiments were performed with rectangular lattices of rods having a water-to-fuel volume ratio of 1.6. This ratio lies within the neutron moderation range of the BWR and PWR type fuels. The typical BWR fuel elements have rod diameters and rod spacings that result in water-to-fuel volume ratios between 1.55 and 1.61. The PWR fuel elements have a range of 1.53 to 1.72. All of the experimental assemblies were water flooded and fully reflected on all six faces by at least 15 cm of water.

EXPERIMENTAL DATA

In each experiment the critical approach was made either by decreasing the water separation between a fixed amount of fuel or by adding fuel to fuel clusters separated by a fixed amount of water. In the latter, fuel additions to the fuel clusters were made to facilitate uniformity of neutron multiplication (fuel rods were added to the assembly symmetrically with respect to the neutron flux). Consequently, any partial row of fuel rods can and should be described as a full row of fractional fuel cells in calculations. Since these are rectangular lattices, the reactivity worth of a fuel rod is dependent on its position in the row of fuel. Although current calculational techniques are probably not sensitive enough to observe this in terms of neutron multiplication (k_{eff}), it is observable experimentally.

In the experiments involving four fuel clusters, data were obtained on assemblies in which the water separation between each fuel cluster was equal, and on assemblies in which each fuel cluster was of the same size. Additional data also was obtained in which both the separation and cluster sizes were unequal to measure the sensitivity of systems to either water separation or fuel loading.

SINGLE LATTICES OF FUEL RODS

The critical size of single rectangular lattices of both the 2.35 wt% and the 4.31 wt% ^{235}U enriched UO_2 rods was determined for several fuel lattices having sides of different length. The results of these measurements are tablulated in Table III and plotted in Figure 4. Both sets of fuel rods were in a square lattice pitch corresponding to a water-to-fuel volume ratio of 1.6. The pitch was 1.684 cm for the 2.35 wt% ^{235}U enriched UO_2 rods, and 1.892 cm for the 4.31 wt% enriched rods. All structural supports, except the lattice grid plates, were of aluminum (Type 6061) and outside the fuel region of each lattice. The grid plates were of 1.27 cm thick polypropylene (0.904 g/cm^3) located about 15 cm below the top of the fuel region and at the bottom of the fuel similar to that shown in Figure 9 for multiple fuel clusters. The fuel was supported on a 2.54 thick acrylic plate (1.185 g/cm; 8 wt% H, 60 wt% C, 32 wt% O) resting on two aluminum channels at least 15 cm above the floor of the epxerimental vessel (see Figure 9 for illustration).

TABLE III
EXPERIMENTAL CRITICALITY DATA FOR SINGLE LATTICES

2.35 WT. % ^{235}U ENRICHED FUEL 1.684cm SQUARE LATTICE PITCH

EXPERIMENT NUMBER	LATTICE WIDTH IN RODS	CRITICAL NUMBER OF RODS[a]
105	17	614.4 ± 0.2
094	21	529.3 ± 0.1
---	22.87	523[b]
096	23	523.9 ± 0.4
095	24	525.3 ± 0.2
106	34	595.4 ± 0.1

4.31 WT. % ^{235}U ENRICHED FUEL 1.892cm SQUARE LATTICE PITCH

EXPERIMENT NUMBER	LATTICE WIDTH IN RODS	CRITICAL NUMBER OF RODS[a]
046	12	225.8 ± 0.1
045	14	216.2 ± 0.2
---	14.66	215[b]
044	16	216.7 ± 0.1
130	16	216.5 ± 0.5 (c)
043	17	218.6 ± 0.2

(a) ERROR LIMITS ARE ONE STANDARD DEVIATION
(b) SQUARE ARRAY OBTAINED FROM INTERPOLATION OF OTHER DATA
(c) RERUN OF 044 TO CHECK REPRODUCIBILITY OF MEASUREMENTS

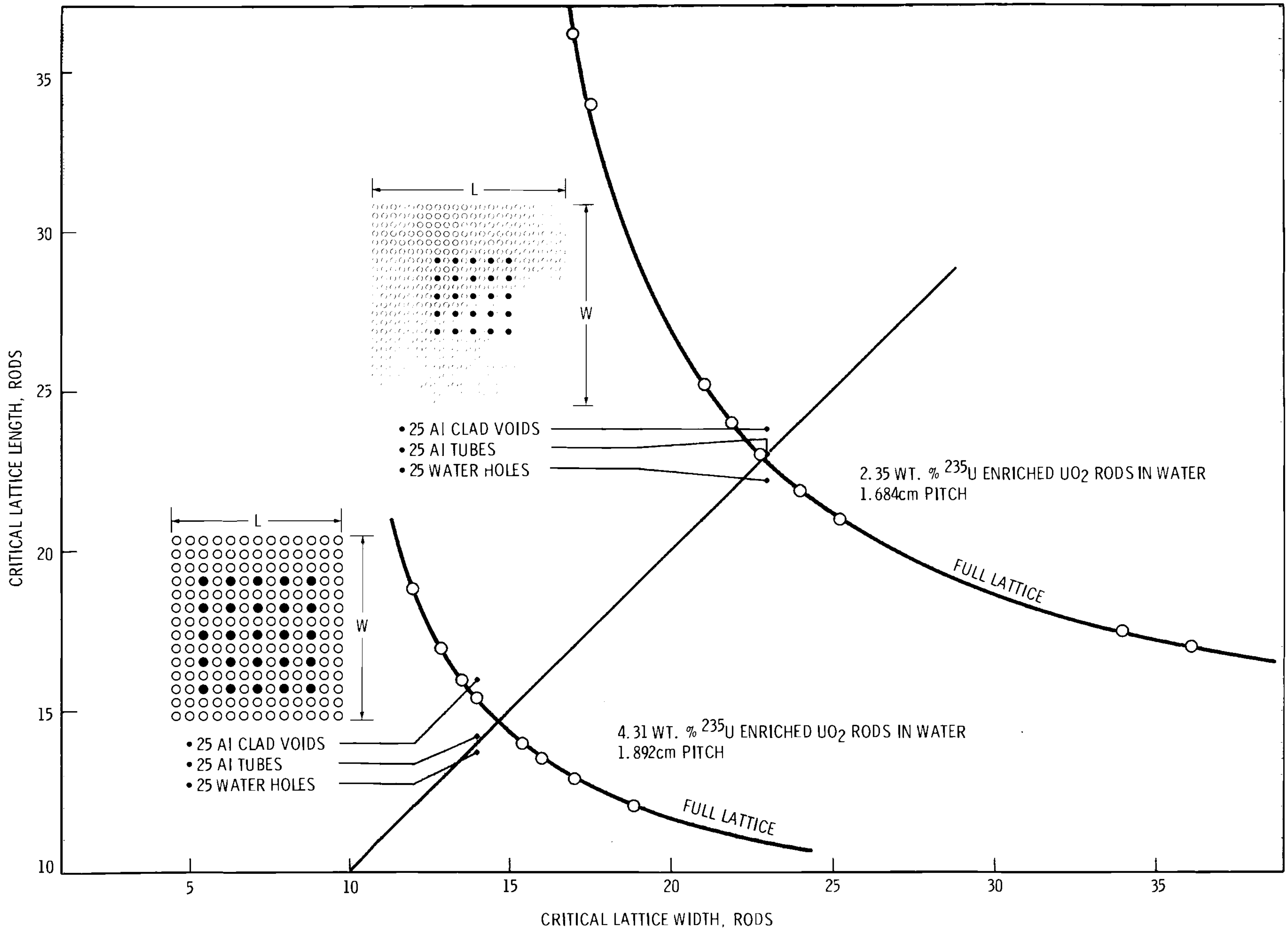


FIGURE 4. EXPERIMENTAL CRITICALITY DATA FOR SINGLE LATTICES

For rectangular lattices the minimim size occurs, of course, for the square. By interpolation of the data shown in Figure 4, the minimum sized lattice for the 2.35 wt% ^{235}U enriched UO_2 rods was determined to be 523 rods (a square 22.87 rods on a side). Similarly, for the 4.31 wt% enriched rods, the minimum size was determined to be 215 rods (14.66 rods on a side). These points have been added to the previously reported data (1) (2) (3) (6) shown in Figure 5, which presents the number of rods required for criticality as a function of neutron moderation.

Some LWR fuel elements have rod positions that are void of fuel to accomodate control rod and instrumentation clusters. These voided rod positions occur roughly in a 5 x 5 rod matrix arrangement and are typically on a 3.5 cm to 4.5 cm center-to-center spacing. When flooded these void regions become water holes in a matrix of fuel-water cells, and thus create zones richer in thermalized neutrons than the surrounding relatively under-moderated fuel-water cells. Experiments, simulating these conditions, were performed to obtain some integral data that could be used for evaluating the validity of calculational techniques when applied to systems with these types of water holes. The experiments were performed with single lattices of both the 2.35 wt% and the 4.31 wt% ^{235}U enriched fuel containing 25 vacant fuel positions on a 5 x 5 rod matrix approximately centered in the fuel lattice as shown in Figure 4. The center-to-center spacings between vacant fuel positions that could be achieved in the measurements was limited by the lattice pitch of each fuel. For the 2.35 wt% enriched fuel, the center-to-center closest to that typically present in

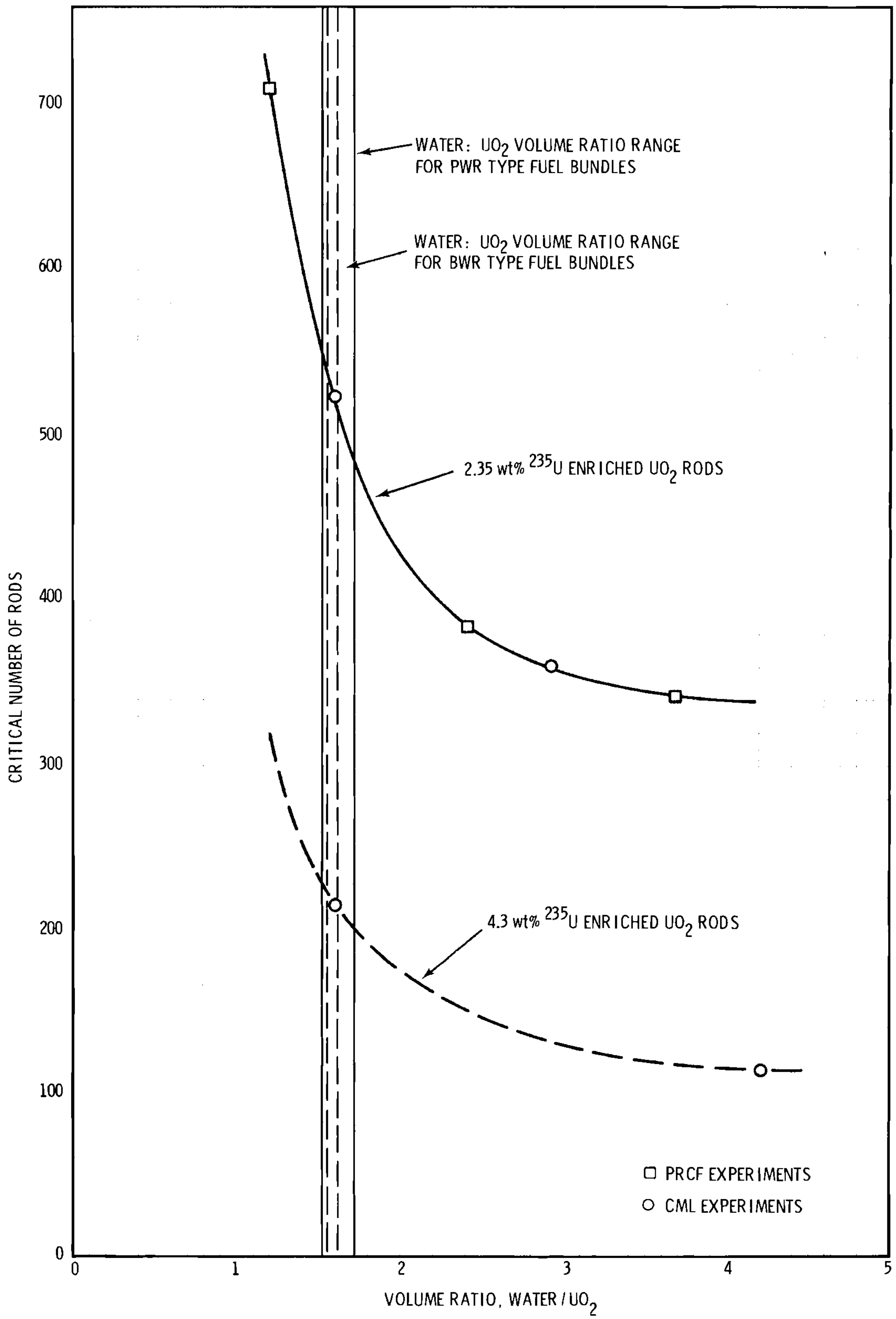


FIGURE 5. MINIMUM CRITICAL NUMBER OF RODS AS A FUNCTION OF NEUTRON MODERATION

LWR fuel elements was 3.368 cm. For the 4.31 wt% enriched fuel, the spacing was 3.784 cm.

The results of the "water hole" measurements are tabulated in Table IV. The results are also presented in Figure 4 for comparison with the data on single fuel lattices without the vacant fuel spaces. Diagram plans indicating the location of the vacant fuel spaces in each lattice are also shown in Figure 4. Measurements also were made with each vacant fuel space occupied by an air filled aluminum tube having the same outside diameter and length as the fuel rods in the lattice. To obtain data on the effect of the aluminum tubing, the tubes were unsealed and allowed to fill with water. These data are also presented in Table IV and Figure 4.

Some interesting dissimilarities are obvious in these "water hole" data. The presence of water holes in each of the two fuel lattices had a positive effect on the reactivity. To a lesser extent the same was true for the water filled aluminum tubes; however, the presence of aluminum tubes in the water holes of the 4.31 wt% enriched fuel lattice has a less of an effect on the critical size than in the 2.35 wt% enriched fuel lattice. Also the air filled aluminum tubes had no effect on the critical size of the 2.35 wt% enriched fuel lattice and very little (6.5%) on the critical size of the 4.31 wt% enriched fuel lattice. Because of these differences the measurements with 25 "water holes" were repeated (experiment 122) immediately following the measurements with the aluminum tubes (experiment 121). As can be seen in Table IV there is essentially no difference

TABLE IV

EXPERIMENTAL CRITICALITY DATA FOR SINLGE LATTICES CONTAINING VOIDS AND WATER HOLES

LATTICE CONDITION	2.35 WT. % ^{235}U ENRICHED FUEL 1.684cm SQUARE LATTICE PITCH LATTICES 23 RODS WIDE		4.31 WT. % ^{235}U ENRICHED FUEL 1.892cm SQUARE LATTICE PITCH LATTICES 14 RODS WIDE	
	EXPERIMENT NUMBER	CRITICAL NUMBER OF RODS[a]	EXPERIMENT NUMBER	CRITICAL NUMBER OF RODS[a]
25 WATER HOLES	097	485.8 ± 0.2	047	167.6 ± 0.1
25 WATER HOLES	---	---	122	168.1 ± 0.2[b]
25 Al CLAD VOIDS	099	523.8 ± 0.2	048	203.0 ± 0.1
25 Al TUBES	098	505.4 ± 0.2	121	173.5 ± 0.1
FULL LATTICE	096	523.9 ± 0.4	045	216.2 ± 0.2

(a) ERROR LIMITS ARE ONE STANDARD DEVIATION
(b) RERUN OF EXP 047 TO CHECK REPRODUCIBILITY

between the results obtained in these measurements (experiment 122) and the one (experiment 047) performed earlier with a different set of fuel lattice plates.

FUEL CLUSTERS SEPARATED BY A FLUX TRAP

Fuel element storage racks in shipping casks or fuel basin storage pools are generally designed and built such that either structural materials and, or fixed neutron poisons create neutron flux traps between the stored fuel elements. Epi-thermal neutrons escaping from the fuel elements pass through any structural and neutron absorber materials present between the fuel elements and tend to become thermalized in the water. These thermalized neutrons have a very low probability of being scattered back into the fuel elements because the structural and absorber materials, between which the neutrons are "trapped," generally have a very high probability for absorbing thermal neutrons. To provide some experimental data for comparison with calculations, a series of measurements were performed in which a flux trap was created between two clusters of fuel rods. An artist rendition of the experimental assembly is shown in Figure 6.

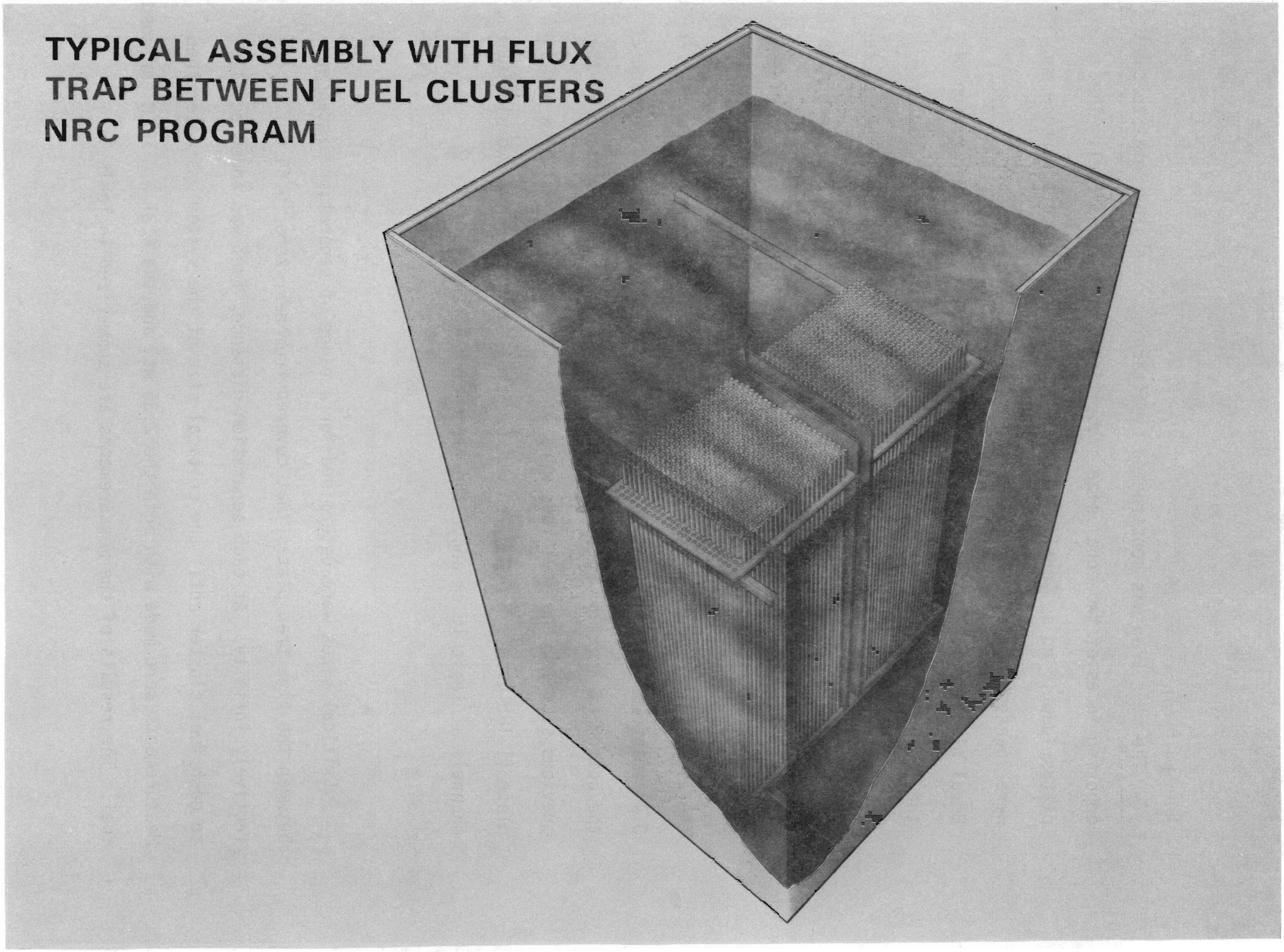


FIGURE 6. TYPICAL ASSEMBLY WITH FLUX TRAP

The flux trap was constructed by attaching sheets of Boral to the opposing faces of two equal size subcritical clusters of fuel. The plates identified as Boral C in Table I were used for this purpose and were located at the outer cell boundary of each fuel cluster. The Boral plates were positioned such that they covered the fuel region of the fuel rods and had one vertical edge aligned with an edge (outer cell boundary) of the fuel cluster. The remaining portion of the plates extended into the water reflector region as indicated in the photograph of an experimental assembly shown in Figure 7. As can be seen in Figures 6 and 7, there was no structural material inside the core boundaries of the assemblies except for the 0.904 g/cm^3 polypropylene grid plates (1.27 ± 0.4 cm thick) located about 15 cm from the top of the fuel regions and at the bottom of the fuel rods. As in the single lattices discussed in the previous section, the fuel rods were supported on a 2.54 cm thick acrylic plate (1.185 g/cm^3, 8 wt% H, 60 wt% C, 32 wt% O) resting on two aluminum channels at least 15 cm above the floor of the tank.

Critical sizes were determined for a range of separation distances between the flux trap plates that covered from near zero (0.64 cm) to effectively infinity. At each separation distance, fuel was added equally to each fuel cluster until the critical size of the system was determined. Measurements were made with both the 2.35 wt% and the 4.31 wt% ^{235}U enriched fuel. The results of the measurements are summarized in Table V.

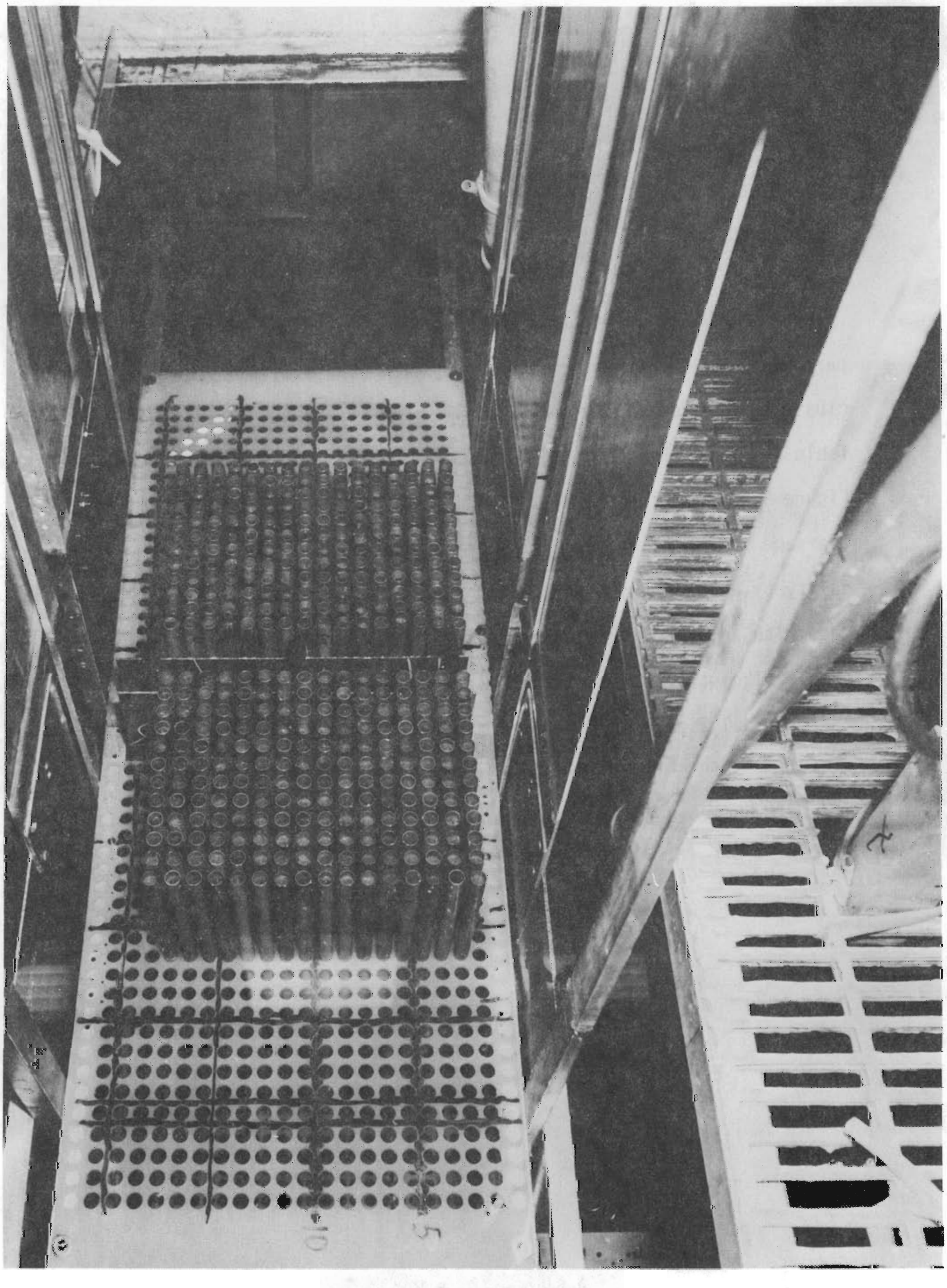


FIGURE 7. PHOTOGRAPH OF AN EXPERIMENTAL ASSEMBLY WITH A FLUX TRAP

A plot of the data showing the total number of rods required for criticality as a function of the water gap between the fuel clusters is presented in Figure 8.

At a separation distance of 3.804 cm, an additional experiment was performed in which the Boral plates between the 4.31 wt% enriched fuel clusters were replaced with 0.302 cm thick Type 304-L steel plates (see Table I for description). These data are also shown in Table V and Figure 8. Replacing the Boral with Type 304-L steel of approximately the same thickness reduced the total number of rods required for criticality by about a third (451.2 to 296.2 rods). The replacement also was made with an effectively infinite separation between the fuel clusters (one fuel cluster and flux trap plate was removed from the system, and the critical size determined for a single fuel cluster and its associated plate). At the effectively infinite separation, the reduction in critical size was observed to be only about 10% (494.6 to 448.8 rods).

TABLE V
EXPERIMENTAL CRITICALITY DATA WITH FLUX TRAP BETWEEN TWO EQUAL SIZED FUEL CLUSTERS

DISTANCE BETWEEN FLUX TRAP PLATES (cm) (a) (b)	2.35 WT. % ^{235}U ENRICHED FUEL 1.684cm SQUARE LATTICE PITCH LATTICES 21 RODS WIDE		4.31 WT. % ^{235}U ENRICHED FUEL 1.892cm SQUARE LATTICE PITCH LATTICES 16 RODS WIDE	
	EXPERIMENT NUMBER	CRITICAL NUMBER OF RODS (a)	EXPERIMENT NUMBER	CRITICAL NUMBER OF RODS (a)
0.640 ± 0.015	100	963.1 ± 0.2	127	380.5 ± 0.1
1.542 ± 0.005	104	1008.6 ± 0.3	126	405.1 ± 0.2
2.593 ± 0.010	103	1049.4 ± 0.3	---	---
3.804 ± 0.008	101	1080.2 ± 0.4	123	451.2 ± 0.1 (c)
5.156 ± 0.020	---	---	125	461.7 ± 0.1
∞	102	1151.4 ± 0.4	124	494.6 ± 0.4 (d)

(a) ERROR LIMITS ARE ONE STANDARD DEVIATION

(b) TYPE C BORAL PLATES, 0.231 cm THICK, AT CELL BOUNDARY OF EACH FUEL CLUSTER

(c) REPLACING 0.231cm THICK BORAL PLATES WITH 0.302cm THICK 304-L STEEL PLATE DECREASED THE NUMBER OF RODS TO 296.2 ± 0.2

(d) REPLACING 0.231cm THICK BORAL PLATES WITH 0.302cm THICK 304-L STEEL PLATES DECREASED THE NUMBER OF RODS TO 448.8 ± 0.8

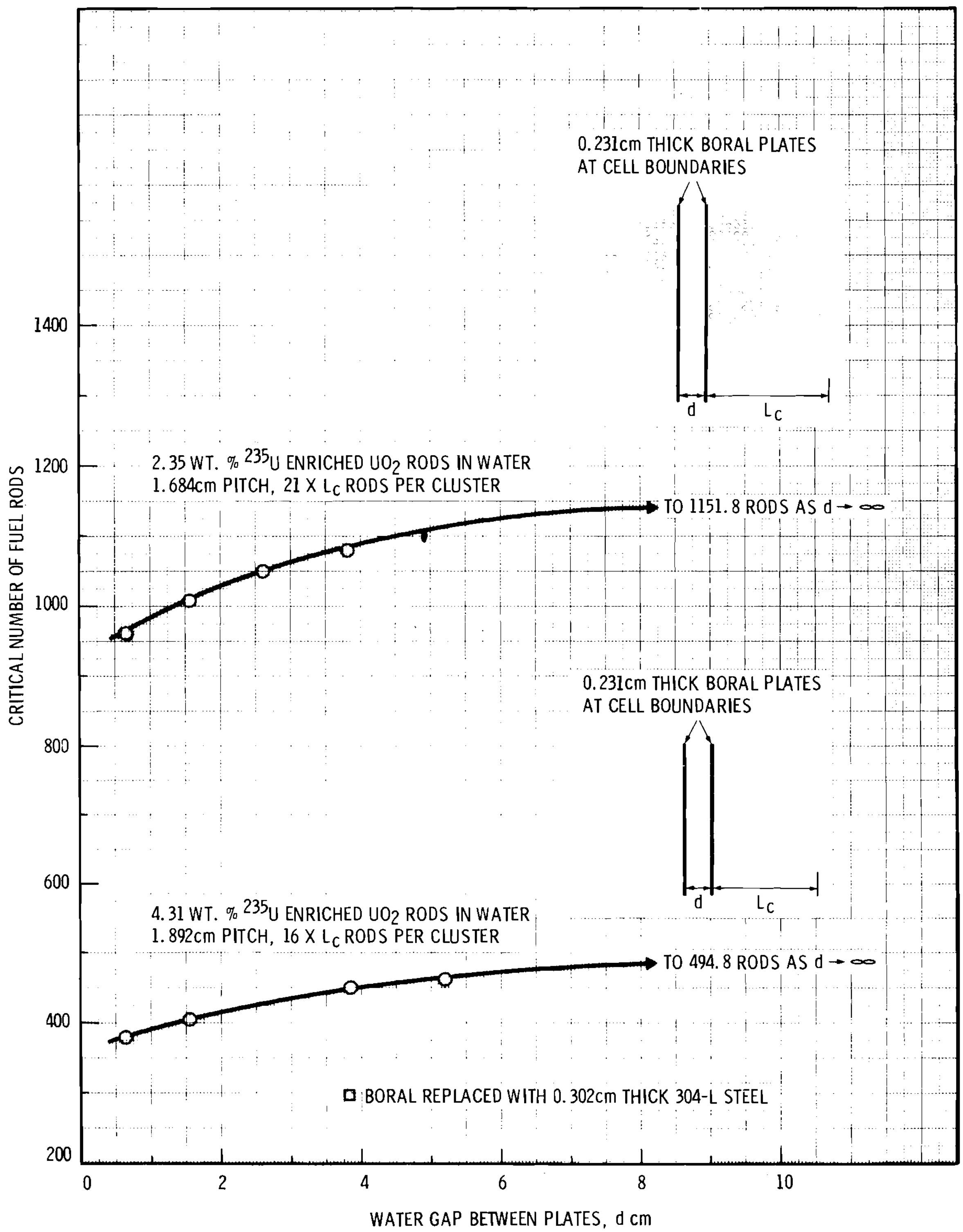


FIGURE 8. EXPERIMENTAL CRITICALITY DATA WITH FLUX TRAP BETWEEN TWO EQUAL SIZED FUEL CLUSTERS

MULTIPLE LATTICES OF FUEL RODS

To the extent that fuel and neutron absorber plates permitted, the critical size and separation between four subcritical clusters of fuel rods in a rectangular arrangement was determined for both the 4.31 wt% and the 2.35 wt% ^{235}U enriched UO_2 fuel rods. Measurements were made on assemblies having neutron absorber plates between the fuel clusters and on assemblies with no absorber plates. However there was an insufficient number of the borated steel and the copper cadmium plates to perform the experiments in a four cluster rectangular geometry. Also there was an insufficient amount of the 2.35 wt% enriched fuel to perform the experiments in this geometry with the borated and cadmium plates. Consequently these measurements were carried out with assemblies of three subcritical fuel clusters aligned in a row.

In both the four and three cluster assemblies there was no structural material inside the core boundaries of the assemblies except for the control blade guides and the 0.904 g/cm^3 polypropylene grid plates (1.27 ± 0.4 cm thick) located about 15 cm from the top of the fuel regions and at the bottom of the fuel rods as indicated in Figures 9 and 10. As in the previous assemblies the acrylic support plate was 2.54 cm thick, had a density of 1.185 g/cm^3, and a composition of 8 wt% H, 60 wt% C and 32 wt% O.

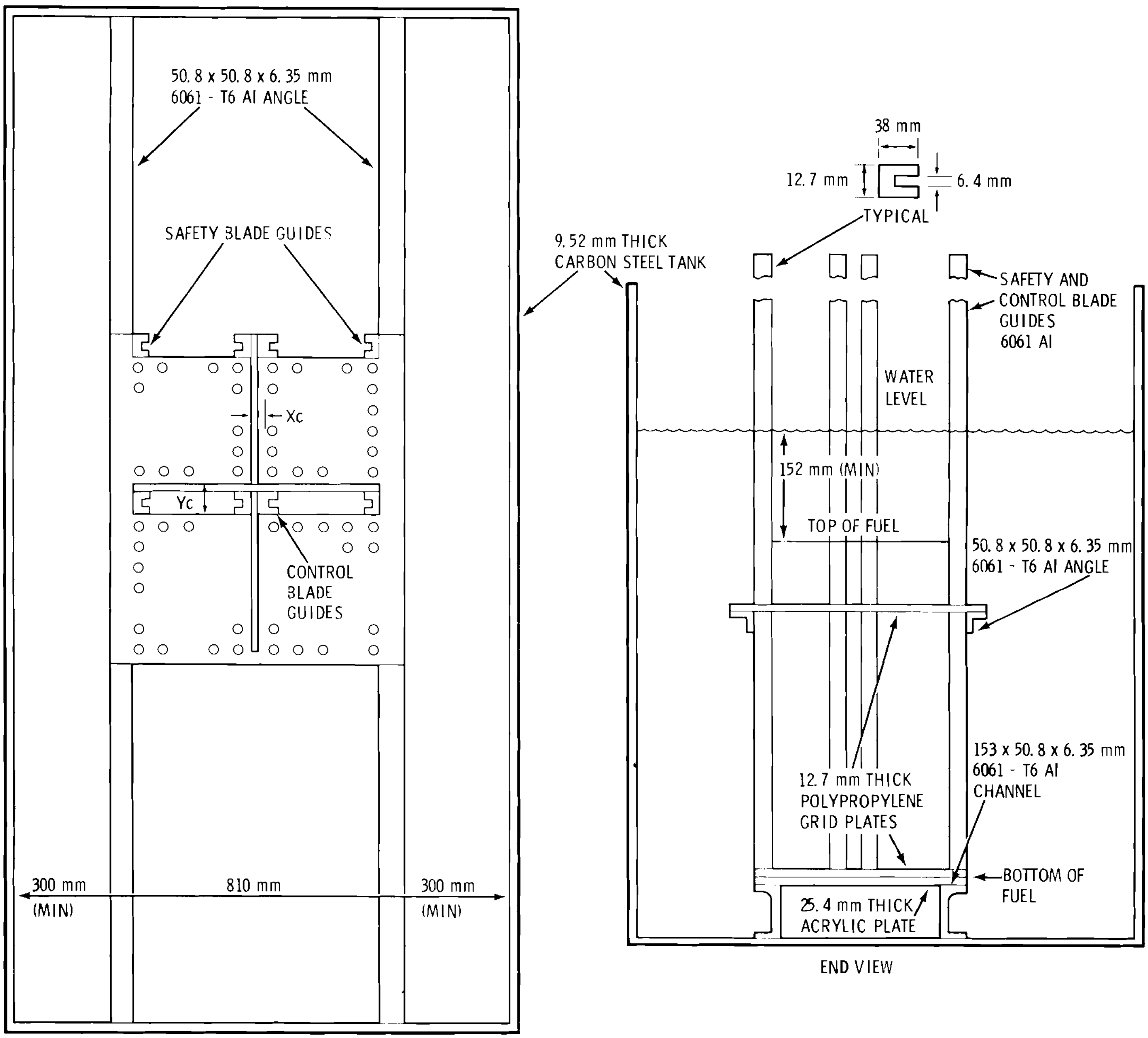


FIGURE 9. GRAPHICAL DESCRIPTION OF SIMULATED SHIPPING CONTAINER CRITICAL EXPERIMENTS - FOUR CLUSTER GEOMETRY

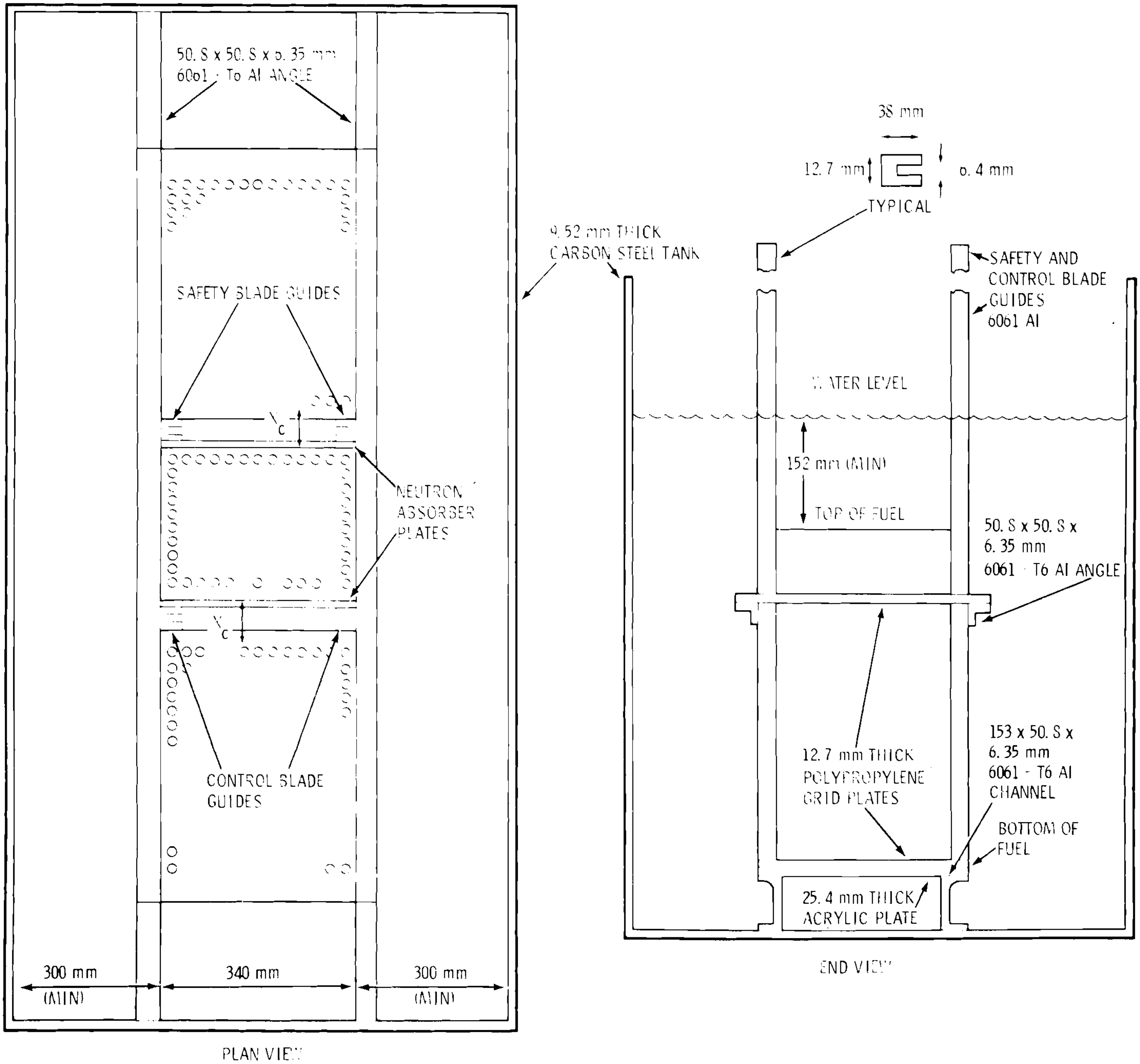


FIGURE 10. GRAPHICAL DESCRIPTION OF SIMULATED SHIPPING CONTAINER CRITICAL EXPERIMENTS - THREE CLUSTER GEOMETRY

MULTIPLE LATTICES OF 4.31 WT% ^{235}U ENRICHED UO_2 RODS

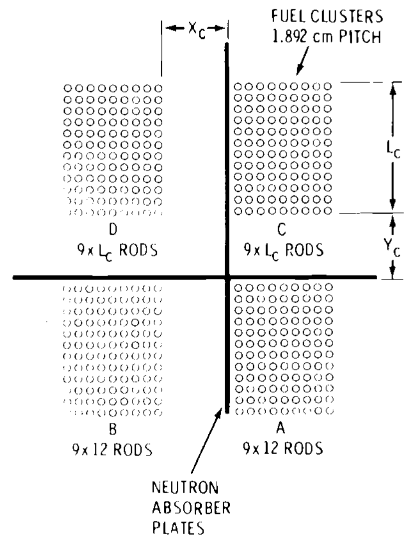
The measurement data obtained with the 4.31 wt% enriched fuel rods in a four cluster rectangular arrangement are summarized in Tables VI and VII. The measurement data obtained with three fuel clusters aligned in a row are summarized in Table VIII. A plan diagram is given in each table to indicate the sizes of the fuel clusters and the shape and location of neutron absorber plates when they are present. When present, the absorber plates were positioned outside of the fuel clusters, with the near surface at the cell boundaries, as indicated in Table VI, VII and VIII.

In the experiments with four fuel clusters, the size of two of the fuel clusters was always constant for a given neutron absorbing material. For the less effective neutron absorbers these fuel clusters were 9 rods wide by 12 rods long as shown in Table VI. For the more effective neutron absorbers (borated materials and cadmium) these two fuel clusters were 11 rods wide by 14 rods long as shown in Table VII. For each type of neutron absorber, the widths of the other two fuel clusters were the same as the two respective constant size fuel clusters; however, the length of these two clusters of fuel were allowed to vary in achieving criticality after a parameter change (i.e., separation or absorber plate).

With no neutron absorber plates in the four cluster assemblies, the separation distance between the fuel clusters was varied equally. At each separation the total number of fuel rods required for criti-

TABLE VI
EXPERIMENTAL CRITICALITY DATA FOR MULTIPLE FUEL CLUSTERS OF 4.31 WT% ^{235}U ENRICHED UO^2 RODS IN WATER

EXPERIMENT NUMBER	NEUTRON ABSORBER		CRITICAL SEPARATION [b]		CRITICAL SIZE (TOTAL RODS) [a]
	MATERIAL	THICKNESS (cm) [a]	Xc (cm) [a]	Yc (cm) [a]	
(c)	NONE	---	0.0 ± 0.01	0.0 ± 0.1	223 ± 1
(d)	NONE	---	2.83 ± 0.02	2.83 ± 0.02	221.3 ± 0.2
051	NONE	---	4.72 ± 0.03	4.72 ± 0.03	253.8 ± 0.1
053	NONE	---	6.61 ± 0.03	6.61 ± 0.03	432.7 ± 0.1
062	NONE	---	2.83 ± 0.02	0.0 ± 0.01	219.2 ± 0.1
061	NONE	---	2.83 ± 0.02	8.38 ± 0.02	225.0
060	NONE	---	2.83 ± 0.02	10.86 ± 0.04	234.0
059	NONE	---	2.83 ± 0.02	11.29 ± 0.02	252.0
058	NONE	---	2.83 ± 0.02	12.02 ± 0.02	288.0
057	NONE	---	2.83 ± 0.02	13.64 ± 0.04	360.0
055	NONE	---	2.83 ± 0.02	14.98 ± 0.02	396.0
056	NONE	---	2.83 ± 0.02	19.81 ± 0.05	432.0
115	ALUMINUM	0.625 ± 0.001	2.83 ± 0.02	8.50 ± 0.04	233.7 ± 0.04
116			2.83 ± 0.02	9.04 ± 0.04	234.0
117	ZIRCALOY-4	0.652 ± 0.008	2.83 ± 0.02	11.04 ± 0.03	234.0
118			2.83 ± 0.02	8.50 ± 0.04	333.8 ± 0.1 [e]
119	NONE	--	2.83 ± 0.02	8.50 ± 0.04	347.4 ± 0.1 [e]
064	304-L STEEL	0.302 ± 0.013	2.83 ± 0.02	2.83 ± 0.02	247.1 ± 0.1
066			2.83 ± 0.02	3.38 ± 0.06	252.0
065			2.83 ± 0.02	4.54 ± 0.03	270.0
067			2.83 ± 0.02	6.49 ± 0.02	342.0
120			2.83 ± 0.02	6.45 ± 0.02	342.0 [f]
070			2.83 ± 0.02	8.10 ± 0.04	396.0
068			2.83 ± 0.02	9.96 ± 0.04	432.0
069			2.83 ± 0.02	11.55 ± 0.05	450.0
069A			2.83 ± 0.02	12.29 ± 0.05	453.7 ± 0.1
071	304-L STEEL	0.485 ± 0.015	2.83 ± 0.02	2.83 ± 0.02	271.8 ± 0.1
072			2.83 ± 0.02	4.47 ± 0.04	306.0
073			2.83 ± 0.02	8.36 ± 0.02	432.0
074	COPPER	0.337 ± 0.008	2.83 ± 0.02	2.83 ± 0.02	257.2 ± 0.1
075			2.83 ± 0.02	5.94 ± 0.08	342.0
076			2.83 ± 0.02	9.02 ± 0.04	432.0
113	COPPER	0.646 ± 0.008	2.83 ± 0.02	2.67 ± 0.05	306.0
112			2.83 ± 0.02	2.83 ± 0.02	309.9 ± 0.1
114			2.83 ± 0.02	3.47 ± 0.05	324.0
111			2.83 ± 0.02	4.72 ± 0.03	366.6 ± 0.2
110			2.83 ± 0.02	7.10 ± 0.05	432.0
108			2.83 ± 0.02	8.12 ± 0.04	450.0
109			2.83 ± 0.02	10.21 ± 0.02	468.0



(a) ERROR LIMITS ARE ONE STANDARD DEVIATION. ERROR LIMITS ARE GIVEN FOR TOTAL RODS ONLY WHEN APPROACH TO CRITICAL WAS MADE BY FUEL ADDITION.

(b) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARIES OF THE FUEL CLUSTERS.

(c) INTERPOLATION BETWEEN DATA FROM EXPERIMENTS 043 AND 046.

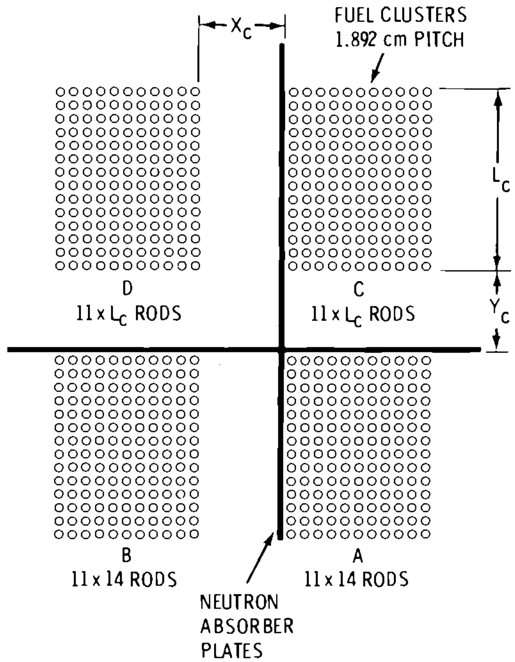
(d) INTERPOLATION BETWEEN DATA FROM EXPERIMENTS 061 AND 062.

(e) FUEL CLUSTERS A AND B REDUCED TO 9 X 10 RODS TO OBTAIN ZIRCALOY-4 AND ALUMINUM AT THE SAME WATER GAP.

(f) RERUN OF EXPERIMENT 067 TO CHECK REPRODUCABILITY AND SYMMETRY OF CRITICAL APPROACH LOADINGS.

TABLE VII
EXPERIMENTAL CRITICALITY DATA FOR MULTIPLE FUEL CLUSTERS OF 4.31 WT% ^{235}U ENRICHED UO_2 RODS IN WATER

EXPERIMENT NUMBER	NEUTRON ABSORBER MATERIAL	NEUTRON ABSORBER THICKNESS (cm)[a]	CRITICAL SEPARATION X_C (cm)[a]	CRITICAL SEPARATION Y_C (cm)[a]	CRITICAL SIZE (TOTAL RODS)[a]
079	BORAL-A	0.713 ± 0.011[c]	2.83 ± 0.02	2.83 ± 0.02	638.5 ± 0.1
080			2.83 ± 0.02	4.80 ± 0.10	660.0
082			2.83 ± 0.02	8.50 ± 0.04	675.3 ± 0.1
081			2.83 ± 0.02	10.39 ± 0.03	679.8 ± 0.1
087	BORAL-B	0.292 ± 0.013[c]	2.83 ± 0.02	2.83 ± 0.02	604.4 ± 0.1
088			2.83 ± 0.02	3.17 ± 0.08	616.0
089			2.83 ± 0.02	4.72 ± 0.03	633.6 ± 0.1
086			2.83 ± 0.02	5.24 ± 0.05	638.0
090			2.83 ± 0.02	8.50 ± 0.04	659.7 ± 0.2
093	BORAL-C	0.231 ± 0.013[c]	2.83 ± 0.02	2.83 ± 0.02	606.0 ± 0.1
092			2.83 ± 0.02	3.53 ± 0.02	616.0
091			2.83 ± 0.02	8.50 ± 0.02	661.6 ± 0.2
097	BOROFLEX	0.546 ± 0.018[d]	2.83 ± 0.02	2.83 ± 0.02	601.0 ± 0.01
096			2.83 ± 0.02	3.60 ± 0.03	616.0
095			2.83 ± 0.02	4.72 ± 0.03	633.5 ± 0.1
094			2.83 ± 0.02	8.50 ± 0.04	663.3 ± 0.3
098	BOROFLEX	0.408 ± 0.034[e]	2.83 ± 0.02	2.83 ± 0.02	597.9 ± 0.1
100			2.83 ± 0.02	4.72 ± 0.02	631.2 ± 0.1
101			2.83 ± 0.02	6.61 ± 0.03	650.8 ± 0.1
105	BOROFLEX	0.772 ± 0.019[f]	2.83 ± 0.02	2.83 ± 0.02	643.1 ± 0.1
106			2.83 ± 0.02	4.94 ± 0.09	660.0
107			2.83 ± 0.02	6.61 ± 0.03	672.2 ± 0.1
083	BOROFLEX	0.634 ± 0.034[g]	2.83 ± 0.02	2.83 ± 0.02	642.5 ± 0.1
084			2.83 ± 0.02	6.61 ± 0.03	669.8 ± 0.1
085			2.83 ± 0.02	8.50 ± 0.04	675.9 ± 0.1
104	CADMIUM	0.061 ± 0.003[h]	2.83 ± 0.02	2.83 ± 0.02	504.8 ± 0.2
103			2.83 ± 0.02	5.30 ± 0.04	594.0
102			2.83 ± 0.02	6.43 ± 0.02	616.0



(a) ERROR LIMITS ARE ONE STANDARD DEVIATION. ERROR LIMITS ARE GIVEN FOR TOTAL RODS ONLY WHEN APPROACH TO CRITICAL WAS MADE BY FUEL ADDITION

(b) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARIES OF THE FUEL CLUSTERS

(c) INCLUDES 0.102 cm, 0.038 cm, AND 0.025 cm OF TYPE 1100 ALUMINIUM ON EITHER SIDE OF THE BORAL A, B, AND C CORE MATERIALS RESPECTIVELY

(d) INCLUDES 0.160 cm THICK PLEXIGLAS ON EITHER SIDE OF 0.226 ± 0.004 cm THICK BOROFLEX

(e) INCLUDES 0.091 cm THICK TYPE 304-L STEEL ON EITHER SIDE OF 0.226 ± 0.004 cm THICK BOROFLEX

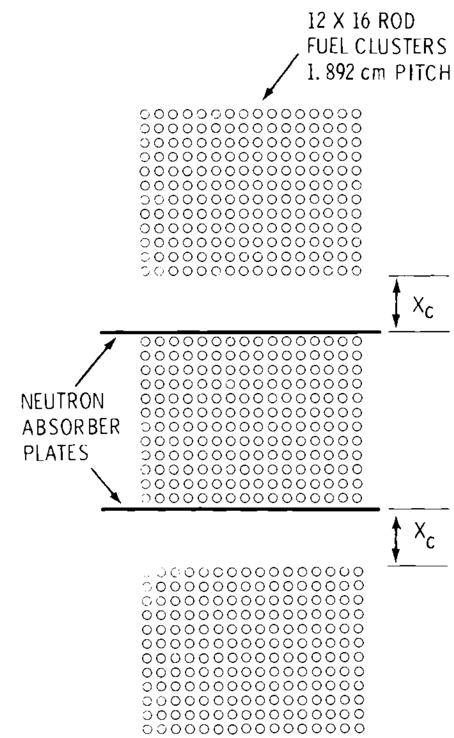
(f) INCLUDES 0.160 cm THICK PLEXIGLAS ON EITHER SIDE OF 0.452 ± 0.006 cm THICK BOROFLEX

(g) INCLUDES 0.091 cm THICK TYPE 304-L STEEL ON EITHER SIDE OF 0.452 ± 0.006 cm THICK BOROFLEX

(h) CADMIUM MOUNTED ON 0.296 cm THICK PLEXIGLAS

TABLE VIII
EXPERIMENTAL CRITICALITY DATA FOR MULTIPLE FUEL CLUSTERS OF 4.31 WT% ^{235}U ENRICHED UO_2 RODS IN WATER

EXPERIMENT NUMBER	NEUTRON ABSORBER MATERIAL	NEUTRON ABSORBER THICKNESS (cm) (a)	CRITICAL SEPARATION (b) X_C, (cm) (a)	1.892 cm SQUARE PITCH FUEL CLUSTERS (c)
131	NONE	- - -	12.27 ± 0.02	3 - 12 X 16
132	304-L STEEL	0.302 ± 0.013	10.52 ± 0.02	3 - 12 X 16
135	304-L STEEL WITH 1.1 WT. % B	0.298 ± 0.006	7.23 ± 0.02	3 - 12 X 16
136	304-L STEEL WITH 1.6 WT. % B	0.298 ± 0.006	6.63 ± 0.03	3 - 12 X 16
133	COPPER	0.337 ± 0.008	10.36 ± 0.02	3 - 12 X 16
134	COPPER-CADMIUM	0.357 ± 0.008	7.61 ± 0.02	3 - 12 X 16



(a) ERROR LIMITS ARE ONE STANDARD DEVIATION.

(b) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARIES OF THE FUEL CLUSTERS.

(c) NUMBER AND SIZE OF FUEL CLUSTERS, RODS LONG BY RODS WIDE, ALIGNED IN A ROW.

cality was determined by incrementally adding rods to the fuel clusters identified as C and D in Table VI. This data are plotted in Figure 11 and illustrates the sensitivity of the unpoisoned assembly to the separation distance between the fuel clusters. As can be seen in Figure 11, the criticality of the assemlby is essentially insensitive to separation below 3 cm. At separations above 3 cm, the total number of fuel rods required for criticality rises very rapidily.

Measurements with no absorber in the four cluster assemblies were also made in which the separation distance (X_c in Table VI and Figure 11) in one direction was held constant at 2.83 cm, and the separation distance in the other direction (Y_c in Table VI and Figure 11) was varied to determine criticality with a fixed amount of fuel at each separation. With an equal amount of fuel in each cluster (108 rods per fuel cluster), the critical separation in the Y direction was 19.81 ± 0.05 cm. As the amount of fuel in the C and D clusters was decreased the critical separation, in the Y direction, decreased uniformily, as shown in Figure 11, down to a separation of about 11 cm. Below 11 cm, the number of fuel rods required for criticality was relatively insensitive to separation in the Y direction.

With neutron absorber plates in the four cluster assemblies, measurements were made similar to those without the absorber plates in which the X_c dimension was held constant at 2.83 cm. These data are presented in Table VI and Figure 11 for the less effective absorbers

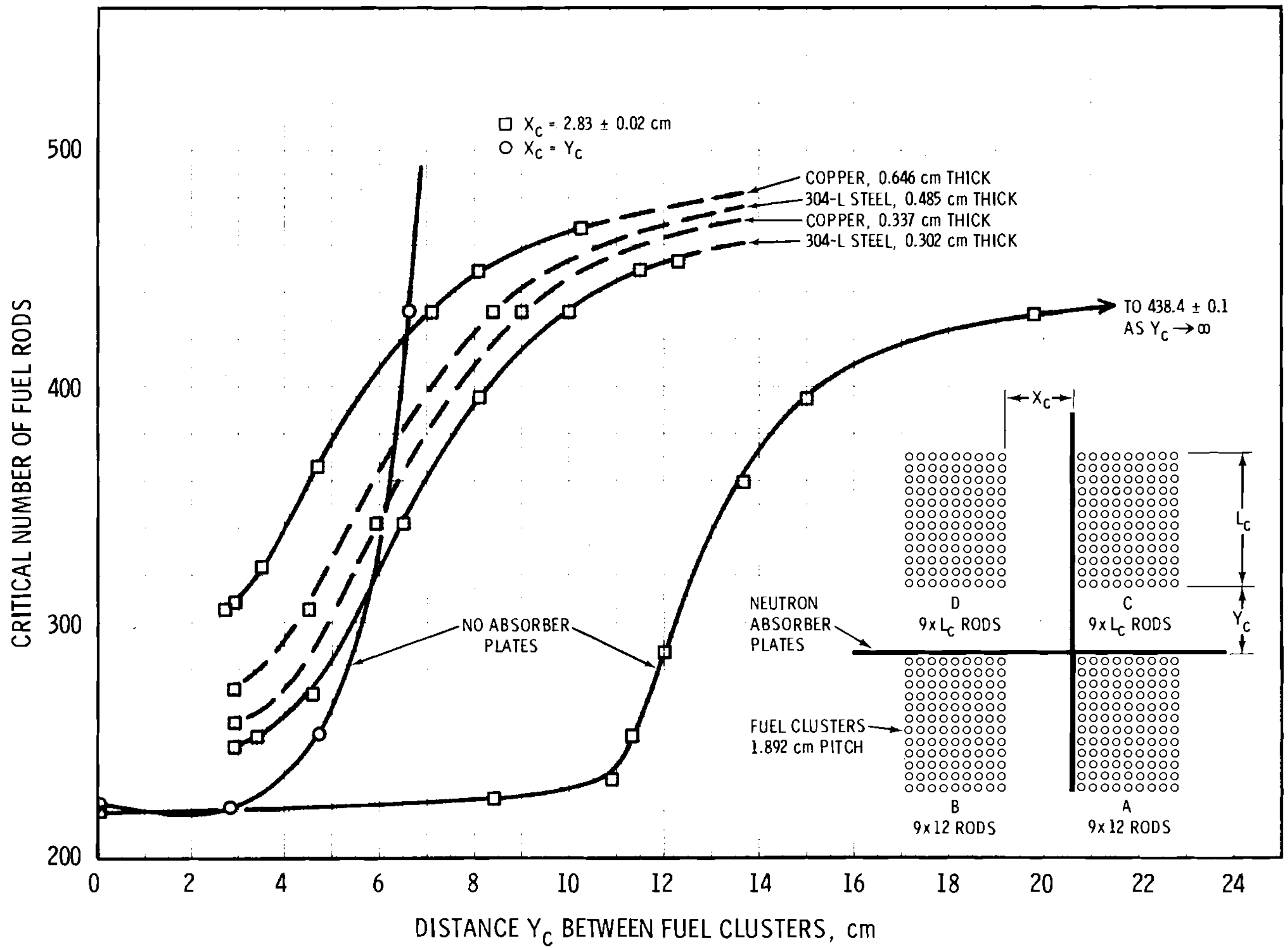


FIGURE 11. EXPERIMENTAL CRITICALITY DATA FOR MULTIPLE FUEL CLUSTERS OF 4.31 WT% ^{235}U ENRICHED UO_2 RODS IN WATER

and in Table VII and Figures 12 and 13 for the more effective borated and cadmium absorber plates. To achieve criticality with these latter plates, the size of the fuel clusters had to be increased as indicated in Table VII and Figures 12 and 13. Measurements were made in the four cluster arrangement with the following plates:

- Two different thicknesses of Type 304-L steel
- Two different thicknesses of copper
- Three different types of Boral
- Two different thicknesses of Boroflex, with and without steel cladding
- One thickness of cadmium
- One thickness of aluminum
- One thickness of Zircaloy

The three types of Boral were of different thicknesses and slightly different boron loadings. The Boral identified in Table I as type A was the same material used in previous experiments[2][3] and has a ^{10}B loading of 0.092 g/cm^2. The other two Borals, B and C, identified in Table I were supplied by the same manufacturer and had ^{10}B loadings of 0.023 g/cm^2 and 0.020 g/cm^2 respectively. These latter two Borals were supplied by the manufacturer from a production then in progress for use in fabricating spent fuel storage racks.

Boroflex is a borated flexible rubber type material that is normally clad in steel for support and stability. Consequently the measurements were made with the Boroflex sandwiched between two 0.091 cm thick sheets of

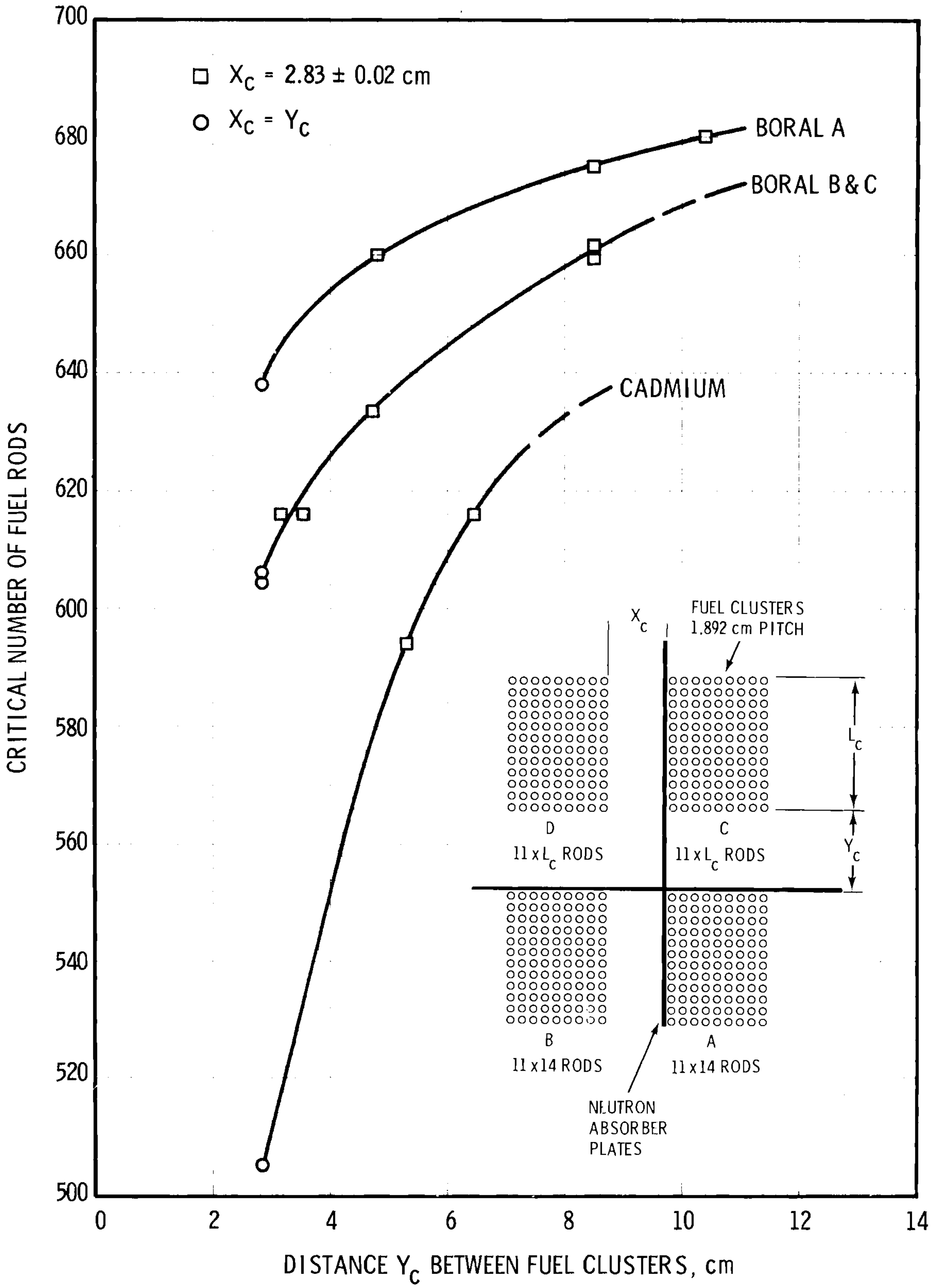


FIGURE 12. EXPERIMENTAL CRITICALITY DATA FOR MULTIPLE FUEL CLUSTERS OF 4.31 WT% ^{235}U ENRICHED UO_2 RODS IN WATER WITH BORAL OR CADMIUM PLATES

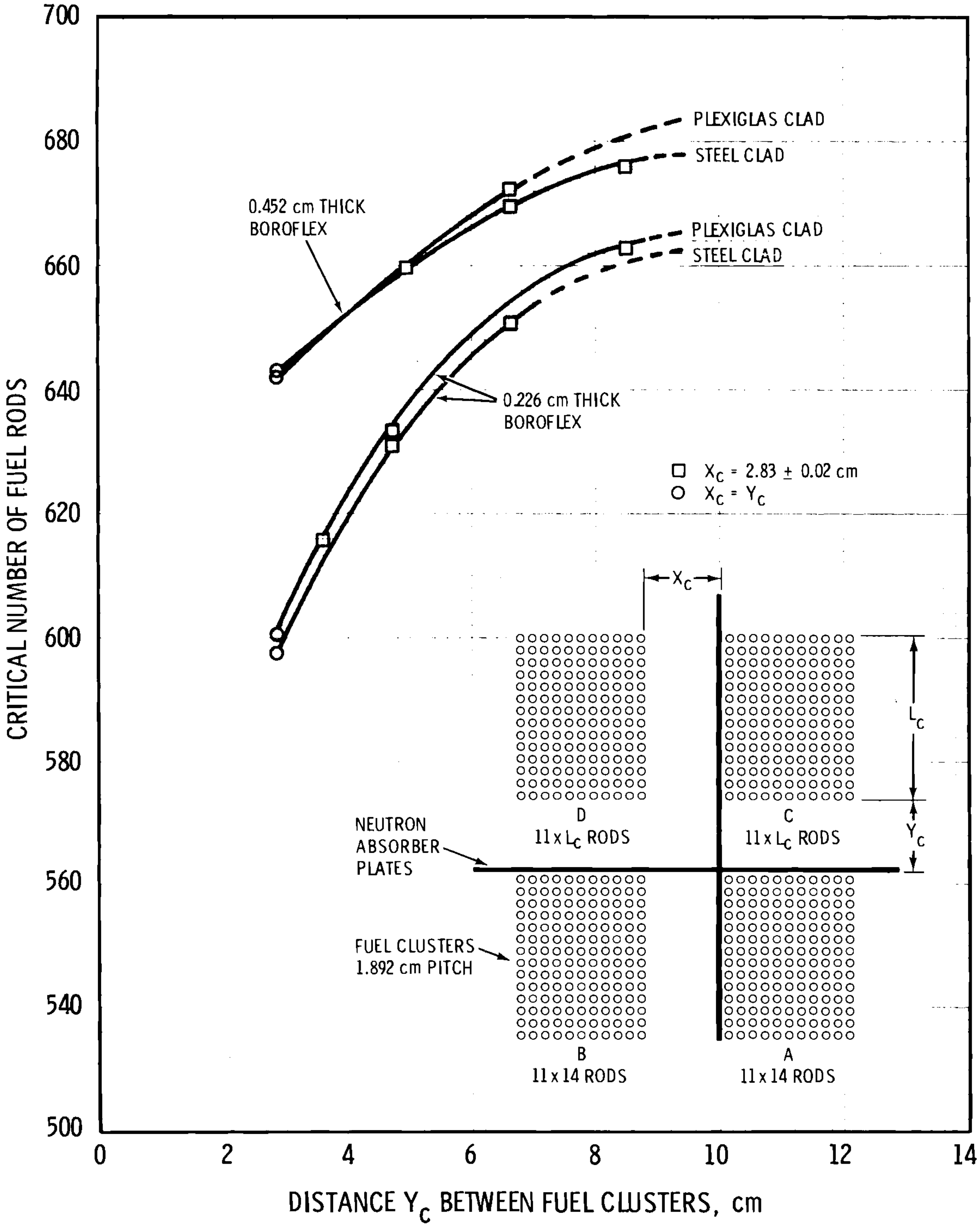


FIGURE 13. EXPERIMENTAL CRITICALITY DATA FOR MULTIPLE FUEL CLUSTERS OF 4.31 WT% ^{235}U ENRICHED UO_2 RODS IN WATER WITH BOROFLEX PLATES

Type 304-L steel. However, to provide data on the Boroflex alone, the same plates were sandwiched between 0.16 cm thick acrylic sheets (Plexiglas^{tm}) also. The Boroflex, like Boral B and C, was obtained from a production run the manufacturer was then making for use in fabricating spent fuel storage racks.

By referring to Figures 11, 12 and 13, it can be seen that the critical size of the four cluster assembly with any of the neutron absorbers was much more sensitive to the separation distance between fuel clusters then was the unpoisoned assembly. In each poisoned case the critical size increased rapidly for separation distance above 2.83 cm whereas very little change was observed in the comparable unpoisoned system at separation distances below about 11 cm.

Although zirconium and aluminum are not generally considered neutron absorbers they are frequently encountered in shipping cask and fuel storage systems. Consequently some measurements were made with these materials in the four cluster assembly also. The results of the measurements are included in Table VI. The alumnium appeared to have a poisoning effect on the reactivity of the assembly. With 234 fuel rods in the assembly and a fixed separation distance of 2.83 cm in one direction (dimension X_c in Table VI) the critical separation in the other direction (Y_c in Table VI) decreased from 10.86 cm with no aluminum to 9.04 cm (8.415 cm of water) with the aluminum. The Zircaloy appeared to have an opposite effect on the reactivity in that its presence caused an increase in the Y_c dimension to 11.04 cm for the critical condition. However, if the thickness of

Plexiglas is a trademark product of Rho and Haas.

the Zircaloy (0.652 cm) is subtracted from this critical separation, the total water separation (10.39 cm) is less with the Zircaloy in the assembly than without it. To obtain data on the aluminum and Zircaloy at the same critical separation distance the fuel clusters identfied as A and B in Table VI had to be reduced to 9 rods wide by 10 rods long. These measurements also indicated that effectively the Zircaloy plates had a non-poisoning influence on the critical separation between the fuel clusters. With the separation distances held constant (X_c at 2.83 cm and Y_c at 8.50 cm), the total number of fuel rods required for criticality decreased from 347.4 rods with no Zircaloy to 333.8 rods with the Zircaloy plates in the assembly.

Measurements with the two borated steels and the copper-cadmium plates had to be made in a three cluster geometry because a sufficient number of these neutron absorber plates were not available to construct the curciform required in the four cluster arrangement. The results of these experiments are summarized in Table VIII. For comparison purposes, experiments also were performed in this three cluster arrangement with copper plates, Type 304-L steel plates, and without any neutron absorbers present in the assembly. As indicated the fuel clusters were all of equal size (12 rods by 16 rods) and aligned in a row. The neutron absorber plates were located at the cell boundary on either side of the center fuel cluster as indicated in Table VIII.

MULTIPLE LATTICES OF 2.35 WT% ^{235}U ENRICHED UO_2 RODS

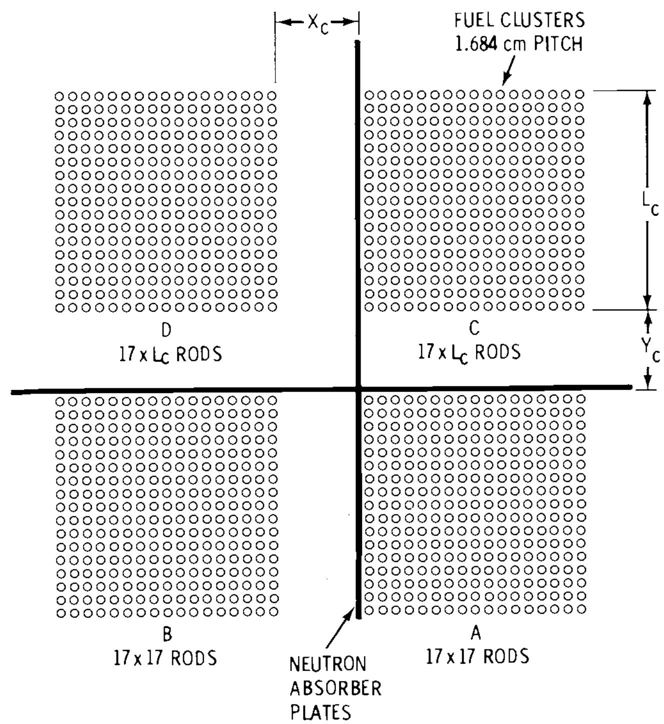
The measurement data obtained with the 2.35 wt% enriched fuel rods in a four cluster rectangular arrangement are summarized in Table IX. The measurement data obtained with three fuel clusters aligned in a row are summarized in Table X. A plan diagram is given in each table to indicate the fuel and absorber plate arrangement.

The experiments with the 2.35 wt% enriched fuel rods were performed in the samme manner, and with the same absorber materials, as those with the 4.31 wt% enriched fuel rods discussed in the previous section of this report. The measurements were performed in a four cluster arrangement only for the less effective neutron absorber materials. The experiments with more effective neutron absorber materials (the borated and cadmium materials) had to be performed in a three fuel cluster geometry because there was insufficient fuel for the four cluster geometry.

A plot of the data obtained in the four cluster geometry is presented in Figure 14. As can be seen the results are very similar to those obtained with the 4.31 wt% enriched fuel (Figure 11).

TABLE IX
EXPERIMENTAL CRITICALITY DATA FOR MULTIPLE FUEL CLUSTERS OF 2.35 WT% ^{235}U ENRICHED UO_2 RODS IN WATER

EXPERIMENT NUMBER	NEUTRON ABSORBER MATERIAL	NEUTRON ABSORBER THICKNESS (cm) [a]	CRITICAL SEPARATION [b] Xc (cm) [a]	CRITICAL SEPARATION [b] Yc (cm) [a]	CRITICAL SIZE (TOTAL RODS) [a]
106	NONE	---	0 ± 0.01	0 ± 0.01	595.4 ± 0.1
069	NONE	---	2.59 ± 0.08	2.59 ± 0.08	600.0 ± 0.1
108	NONE	---	1.68 ± 0.02	0 ± 0.0	587 ± 1
070	NONE	---	4.27 ± 0.08	4.27 ± 0.08	709.2 ± 0.4
071	NONE	---	5.95 ± 0.08	5.95 ± 0.08	1091.9 ± 0.2
078	NONE	---	2.59 ± 0.08	5.11 ± 0.02	612.0
077	NONE	---	2.59 ± 0.08	6.66 ± 0.02	646.0
076	NONE	---	2.59 ± 0.08	7.53 ± 0.02	714.0
075	NONE	---	2.59 ± 0.08	9.00 ± 0.03	884.0
074	NONE	---	2.59 ± 0.08	9.97 ± 0.02	986.0
073	NONE	---	2.59 ± 0.08	11.45 ± 0.03	1088.0
072	NONE	---	2.59 ± 0.08	13.87 ± 0.04	1156.0
079	ALUMINUM	0.625 ± 0.001	2.59 ± 0.08	2.59 ± 0.08	603.2 ± 0.3
080	ZIRCALOY-4	0.652 ± 0.008	2.59 ± 0.08	2.59 ± 0.08	598.4 ± 0.1
081	304-L STEEL	0.302 ± 0.013	2.59 ± 0.08	2.59 ± 0.08	706.8 ± 0.3
082			2.59 ± 0.08	5.95 ± 0.08	974.3 ± 0.1
083			2.59 ± 0.08	7.64 ± 0.09	1118.2 ± 0.2
084			2.59 ± 0.08	9.32 ± 0.09	1187.8 ± 0.3
086	304-L STEEL	0.485 ± 0.015	2.59 ± 0.08	2.59 ± 0.08	776.9 ± 0.3
087			2.59 ± 0.08	4.27 ± 0.08	898.1 ± 0.4
085			2.59 ± 0.08	9.32 ± 0.09	1223.0 ± 1.0
088	COPPER	0.337 ± 0.008	2.59 ± 0.08	2.59 ± 0.08	746.8 ± 0.5
089			2.59 ± 0.08	4.27 ± 0.08	860.9 ± 0.3
090			2.59 ± 0.08	7.64 ± 0.09	1155.1 ± 0.3
091	COPPER	0.646 ± 0.008	2.59 ± 0.08	2.59 ± 0.08	866.7 ± 0.7
092			2.59 ± 0.08	5.95 ± 0.08	1142.3 ± 0.1

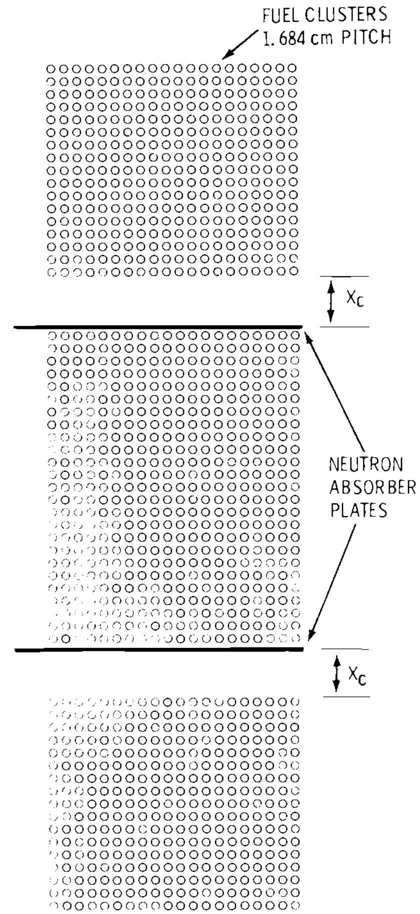


[a] ERROR LIMITS ARE ONE STANDARD DEVIATION. ERROR LIMITS ARE GIVEN FOR TOTAL RODS ONLY WHEN APPROACH TO CRITICAL WAS MADE BY FUEL ADDITION.

[b] PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARIES OF THE FUEL CLUSTERS.

TABLE X
EXPERIMENTAL CRITICALITY DATA FOR MULTIPLE FUEL CLUSTERS OF 2.35 WT% ^{235}U ENRICHED UO_2 RODS IN WATER

EXPERIMENT NUMBER	NEUTRON ABSORBER MATERIAL	NEUTRON ABSORBER THICKNESS (cm) (a)	CRITICAL SEPARATION (b) X_C, cm (a)	1.684 cm SQUARE PITCH FUEL CLUSTERS (c)
112	NONE	- - -	9.88 ± 0.03	1 - 25 X 20 2 - 17 X 20
120	NONE	- - -	6.78 ± 0.02	1 - 18 X 25 2 - 18 X 20
113	304-L STEEL	0.302 ± 0.013	7.80 ± 0.03	1 - 25 X 20 2 - 17 X 20
114	304-L STEEL WITH 1.1 WT. % B	0.298 ± 0.006	3.86 ± 0.02	1 - 25 X 20 2 - 17 X 20
115	304-L STEEL WITH 1.6 WT. % B	0.298 ± 0.006	3.46 ± 0.02	1 - 25 X 20 2 - 17 X 20
117	BORAL B	0.292 ± 0.013	1.68 ± 0.09	1 - 25 X 20 2 - 17 X 20
116	BORAL C	0.231 ± 0.013	1.93 ± 0.07	1 - 25 X 20 2 - 17 X 20
118	BOROFLEX	0.546 ± 0.018 (d)	1.84 ± 0.05	1 - 25 X 20 2 - 17 X 20
119	BOROFLEX	0.408 ± 0.034 (e)	1.73 ± 0.07	1 - 25 X 20 2 - 17 X 20
123	CADMIUM	0.061 ± 0.003	3.04 ± 0.02	1 - 25 X 20 2 - 17 X 20
121	COPPER	0.337 ± 0.008	5.24 ± 0.02	1 - 25 X 18 (f) 2 - 20 X 18
122	COPPER-CADMIUM	0.357 ± 0.008	2.60 ± 0.02	1 - 25 X 18 (f) 2 - 20 X 18



(a) ERROR LIMITS ARE ONE STANDARD DEVIATION.

(b) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARIES OF THE FUEL CLUSTERS.

(c) NUMBER AND SIZE OF FUEL CLUSTERS, RODS LONG BY RODS WIDE, ALIGNED IN A ROW.

(d) INCLUDES 0.160 cm THICK PLEXIGLAS ON EITHER SIDE OF 0.226 ± 0.004 cm THICK BOROFLEX.

(e) INCLUDES 0.091 ± 0.023 cm THICK TYPE 304-L STEEL ON EITHER SIDE OF 0.226 ± 0.004 cm THICK BOROFLEX.

(f) FUEL CLUSTER WIDTH REDUCED TO ACCOMODATE THE WIDTH OF THE COPPER-CADMIUM PLATES.

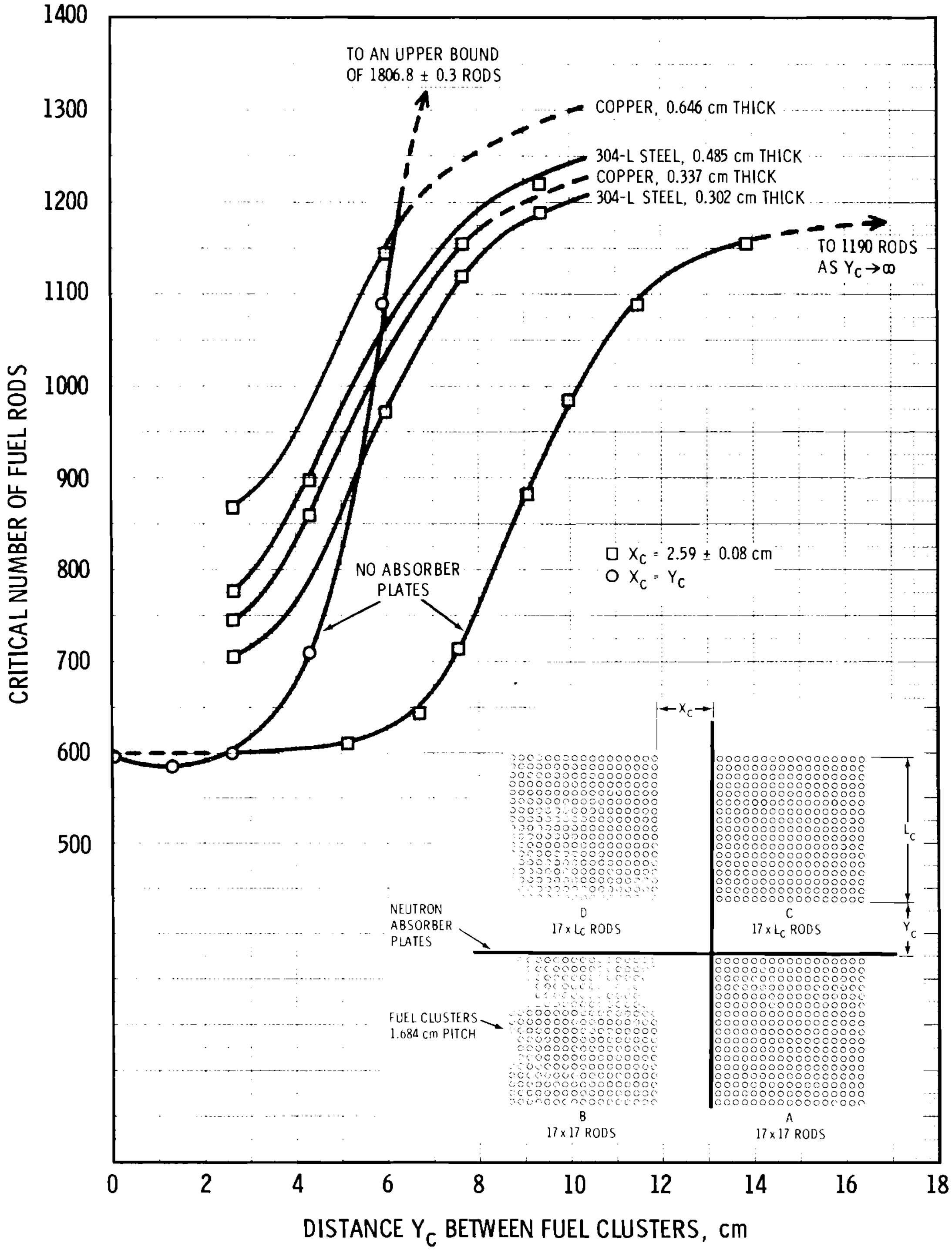


FIGURE 14. EXPERIMENTAL CRITICALITY DATA FOR MULTIPLE FUEL CLUSTERS OF 2.35 WT% ^{235}U ENRICHED UO_2 RODS IN WATER

ISOLATION BETWEEN FUEL CLUSTERS

During the course of the measurements with three fuel clusters aligned in a row, neutron count rates were recorded as the fuel clusters were moved together. A plot of one of these sets of data is shown in Figure 15 for each fuel enrichment. The neutron count rate observed for a three cluster assembly relative to the count rate observed with a single cluster assembly is shown in Figure 15 as a function of the separation between the fuel clusters. For the 2.35 wt% ^{235}U enriched fuel, the fuel clusters were essentially isolated from one another at a separation distance between the cluster of about 12 cm. For the 4.31 wt% ^{235}U enriched fuel a comparable degree of isolation required about 20 cm of separation between the fuel clusters. The surface area of the opposing, or interacting, faces were approximately equal for both sets of data shown in Figure 15. However, it should be noted that the two outside fuel clusters in the 2.35 wt% ^{235}U enriched fuel assembly each contained only about 62% of the number of rods required for a single fuel cluster to be critical whereas each of the fuel clusters in the 4.31 wt% enriched assembly contained about 88% of the critical number of rods. Also the $H/^{235}U$ atomic ratio is 220 for the 2.35 wt% ^{235}U enriched fuel assembly and 106 for the 4.31 wt% ^{235}U enriched assembly.

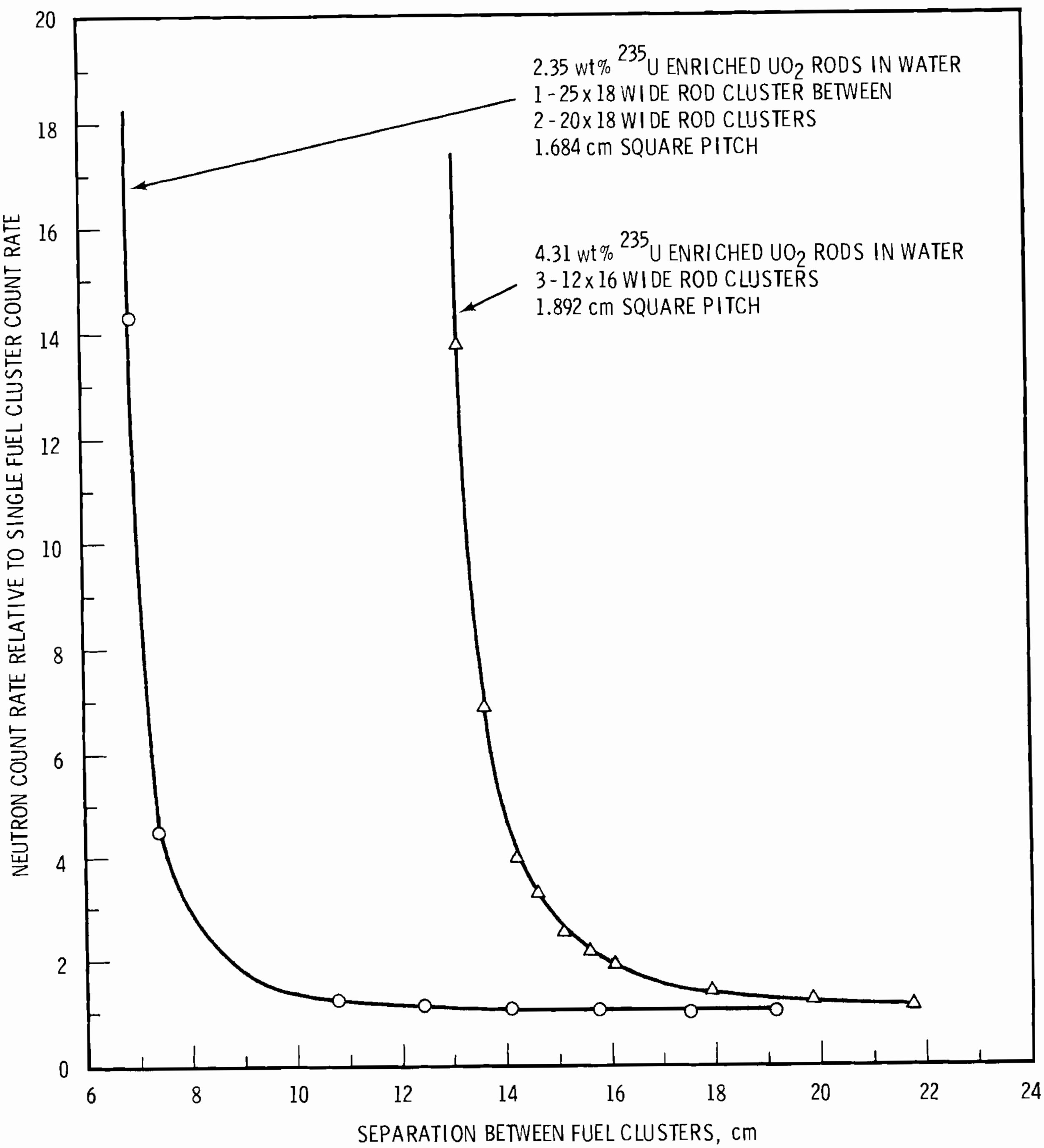


FIGURE 15. ISOLATION DISTANCE BETWEEN WATER FLOODED SUBCRITICAL FUEL CLUSTERS OF UO_2 RODS

CONCLUSIONS

The minimum of fuel rods required for criticality in a rectangular array having a 1.6 water-to-fuel volume ratio is 523 for the 2.35 wt% ^{235}U enriched UO_2 rods and 215 for the 4.31 wt% ^{235}U enriched UO_2 rods. As would be expected, the presence of water holes in these undermoderated fuel assemblies have a positive reactivity effect. Replacing the water holes with voids in the 4.31 wt% enriched fuel lattices also has a positive reactivity effect; however, voids in the 2.35 wt% enriched fuel lattices have no effect on the number of fuel rods required for criticality.

The measurements with flux traps between fuel clusters indicate that the criticality of the lower enriched fuel is slightly more sensitive to the distance between the material creating the flux trap. At either the 2.35 wt% or the 4.31 wt% ^{235}U enrichment, the critical number of rods slowly and uniformly increases as the distance across the flux trap increases from near zero to infinity. The measurement data also indicates, that as the thickness of the flux trap increases the type of materials creating the trap becomes less important. The difference in critical size between a flux trap created by either Boral plates or steel plates was about 35% at a separation distance of 3.8 cm but approached a difference of only 10% as the distance approached infinity.

The critical size of unpoisoned fuel clusters in a rectangular arrangement was observed to be relatively insensitive to separation distances up to about 3 cm between the fuel clusters. Above 3 cm the total number of fuel rods required for criticality increases rapidly for either fuel enrichment. Also for either the 2.35 wt% or the 4.31 wt% ^{235}U enriched fuel, an optimum critical separation of about 1.5 cm exists. The critical size of the fuel assembly with any of the neutron absorber plates between the fuel clusters was much more sensitive to the separation distance between fuel clusters than was the unpoisoned assembly. In each poisoned assembly the critical size increased rapidly for separation distances above about 3 cm. Very little change was observed in the critical size of the unpoisoned systems until separation distances exceeded about 11 cm for the 4.31 wt% ^{235}U enriched fuel and 5 cm for the 2.35 wt% ^{235}U enriched fuel.

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16. ABSTRACT *(200 words or less)*

The results from the fourth in a series of criticality experiments, are presented in this paper. This fourth set of experiments involve clusters of either 2.35 wt% or 4.31 wt% ^{235}U enriched UO_2 fuel rods immersed in water as in previous experiments but a neutron moderation approximating that found typically in Boiling Water Reactor and Pressurized Water Reactor type fuel assemblies. (Previous experiments were performed near optimum neutron moderation). The critical separation between multiple subcritical fuel assemblies, both with and without fixed neutron poisons, was determined.

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