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PNL-2438

Critical Separation Between Subcritical Clusters of 2.35 Wt% ^{235}U Enriched UO_2 Rods in Water with Fixed Neutron Poisons

October 1977

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U.S. Nuclear Regulatory Commission

Battelle
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Critical Separation Between Subcritical Clusters of 2.35 Wt% ^{235}U Enriched UO_2 Rods in Water with Fixed Neutron Poisons

by
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October 1977

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SUMMARY

A research program, funded by the U. S. Nuclear Regulatory Commission, to provide experimental criticality data on systems simulating conditions associated with fuel element shipping packages and fuel storage pools was begun in 1976 at the Battelle operated Critical Mass Laboratory. The objective of this program is to provide experimental data for validating calculational techniques and nuclear data used in criticality assessments of LWR type fuel element shipping packages and similiar type systems. Consequently the experiments are designed to permit easy and accurate definition in Monte Carlo computer codes currently used in these criticality assessments.

Basically the experiments are concerned with the critical separation between water flooded subcritical clusters of fuel rods in the presence of various fixed neutron poisons. The experiments are carried out in a 1.8m x 3m x 2.1m deep tank provided with features specifically designed and built for these experiments. The initial series of experiments in this program are covered in this report and involve aluminum clad 2.35 wt% ^{235}U enriched UO_2 rods about 12mm in diameter by 914mm in length. The critical separation between three subcritical clusters of these rods aligned in a row was determined with and without the following neutron absorber materials (neutron poisons) located between the clusters:

304L Steel with 0, 1.1, and 1.6 wt% Boron

Boral

Copper with 0 and 1 wt% Cadmium

Cadmium

Aluminum

Zircaloy-4

The neutron poisons were in the form of plates slightly larger than the length and width of the opposing faces of the fuel clusters.

CONTENTS

CRITICAL SEPARATION BETWEEN SUBCRITICAL CLUSTERS OF 2.35 WT% ^{235}U ENRICHED UO_2 RODS IN WATER WITH FIXED NEUTRON POISONS

S. R. Bierman, E. D. Clayton and B. M. Burst

INTRODUCTION

A research program, funded by the U. S. Nuclear Regulatory Commission, to provide experimental criticality data on systems simulating conditions associated with fuel element shipping packages and fuel storage pools was begun in 1976, at the Battelle operated Critical Mass Laboratory. The objective of this program is to provide experimental data suitable for use in determining the validity of calculational techniques and nuclear data used in criticality assessments of light water reactor (LWR) type fuel element shipping packages. It is anticipated that the data would be applicable to criticality assessments of similiar conditions encountered in such areas as fuel element handling and storage facilities.

Conditions that must be considered, and thus simulated by the experiments, in making criticality assessments of fuel element shipping packages involve subcritical clusters of rods (fuel elements) separated in space with and without neutron absorbing materials between them. Since the fuel elements are designed such that they are more reactive in the presence of a moderating medium, water flooding must be assumed as a worst-case condition. Also, especially in spent fuel shipping casks, biological shielding materials are generally present and their effect on criticaliy must be considered in any assessment. Consequently, the experimental data should be obtained in a manner such that calculational assessments of these parameters can be verified by the data.

A detailed description of the experimental system, designed and built specifically for these experiments, is presented in this report. Also the first experiments and the results from the initial series of measurements in this system are covered in this report.

EXPERIMENTAL SYSTEM

The experimental measurements are carried out in the critical assembly room of the Critical Mass Laboratory. An overall photograph of the equipment in place is shown in Figure 1. Basically the system consists of a 1.8m x 3m x 2.1m deep carbon steel tank provided with grid plates, a control blade, a safety blade, a water dump valve, and associated electronic detection and interlock devices. The tank, safety blade, and control blade are designed to easily facilitate variable width grid plates. The location of the safety and control blades can also be varied with little difficulty. The control and safety blades will normally consist of some type of neutron absorbing material and can be easily replaced. Both blades are magnetically coupled to individual, belt driven, worm screw drive systems. Upon a scram of the system magnetic power is interrupted and the blades fall by gravity,via guides, into the grid plate region of the system. The blades are shown partially withdrawn in Figure 1.

The grid plates used for latticing the fuel rods into clusters will normally be an acrylic material since it is of about the same density as water and has neutron moderating characteristics almost identical to water. A close-up photograph of the interior of the tank and three sets of grid plates arranged in a row is shown in Figure 2. All of the grid plate support structures and the control

EQUIPMENT USED IN EXPERIMENTS

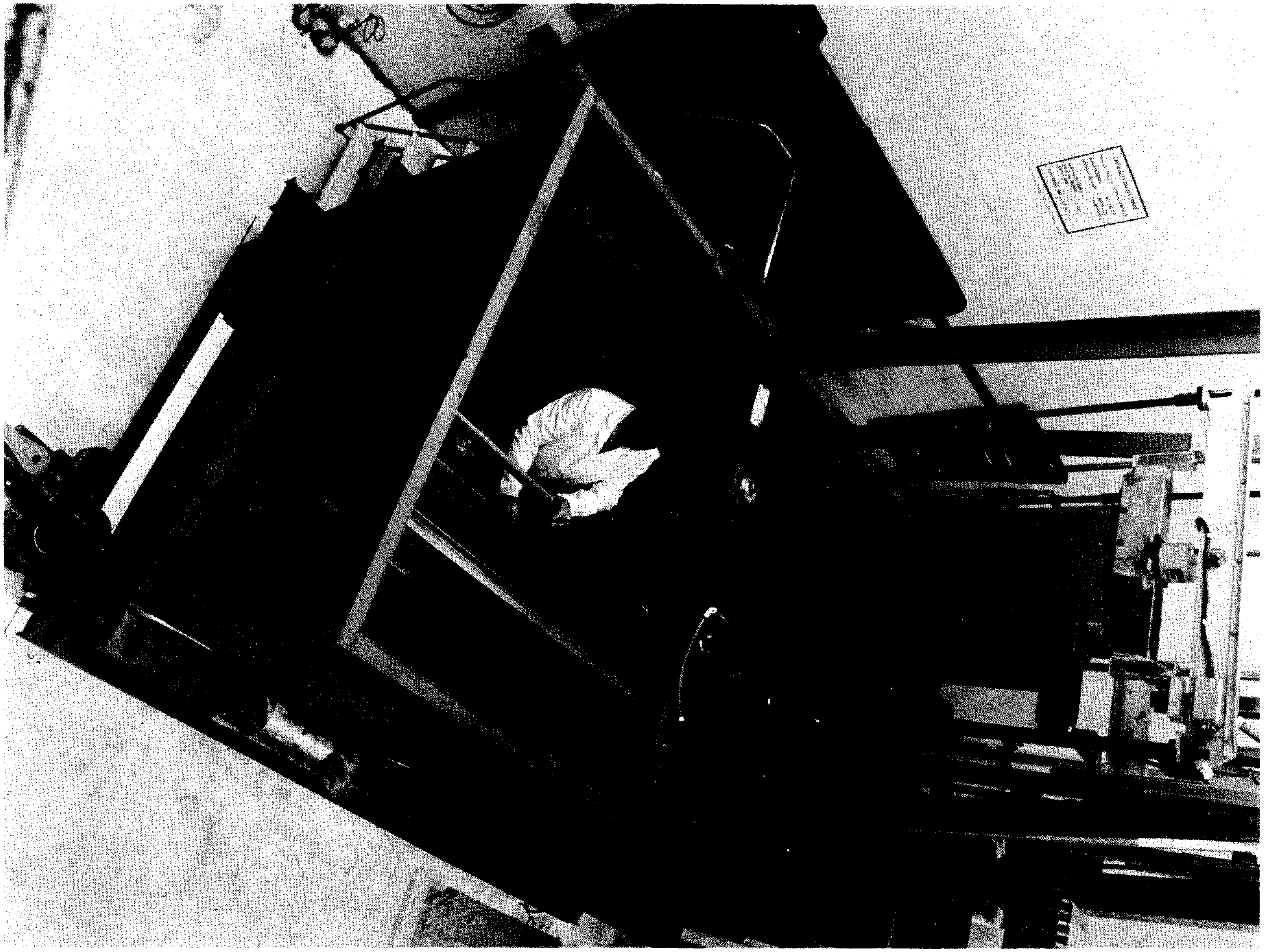


FIGURE 1

LATTICE ARRANGEMENT

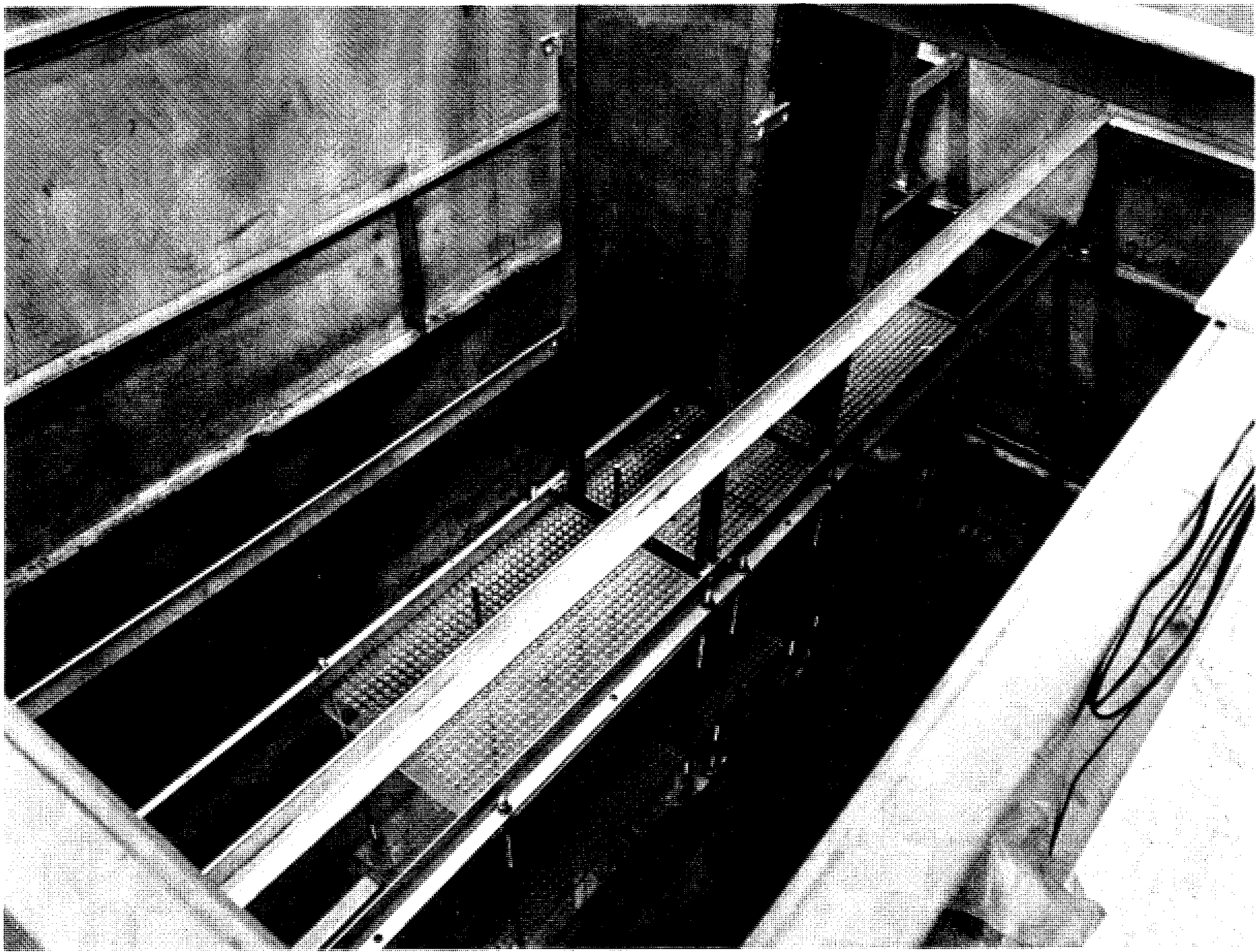


FIGURE 2

and safety blade guides are of 6061 type aluminum. Although not discernible in Figure 2, a fuel rod support plate is provided and is elevated at least 150mm above the floor of the tank by 6061 type aluminum channel. The rod support plate is also of acrylic plastic.

The system is shown in operation in Figure 3. Neutron detection and electronic equipment are located on the periphery of the fuel rod clusters to prevent perturbing the measurements. A californium source is used in the experiments when needed and is positioned in the geometrical center of the array of fuel. In Figure 3, a typical fuel change is shown being made to three subcritical water flooded clusters of fuel rods. The control blade is shown in the "full-in" position in this Figure, but would be fully withdrawn following the fuel change and preceding data accumulation. The safety blade is shown fully withdrawn and remains in this position during normal operations.

EXPERIMENTS WITH 2.35 WT% ^{235}U ENRICHED UO_2 RODS IN WATER

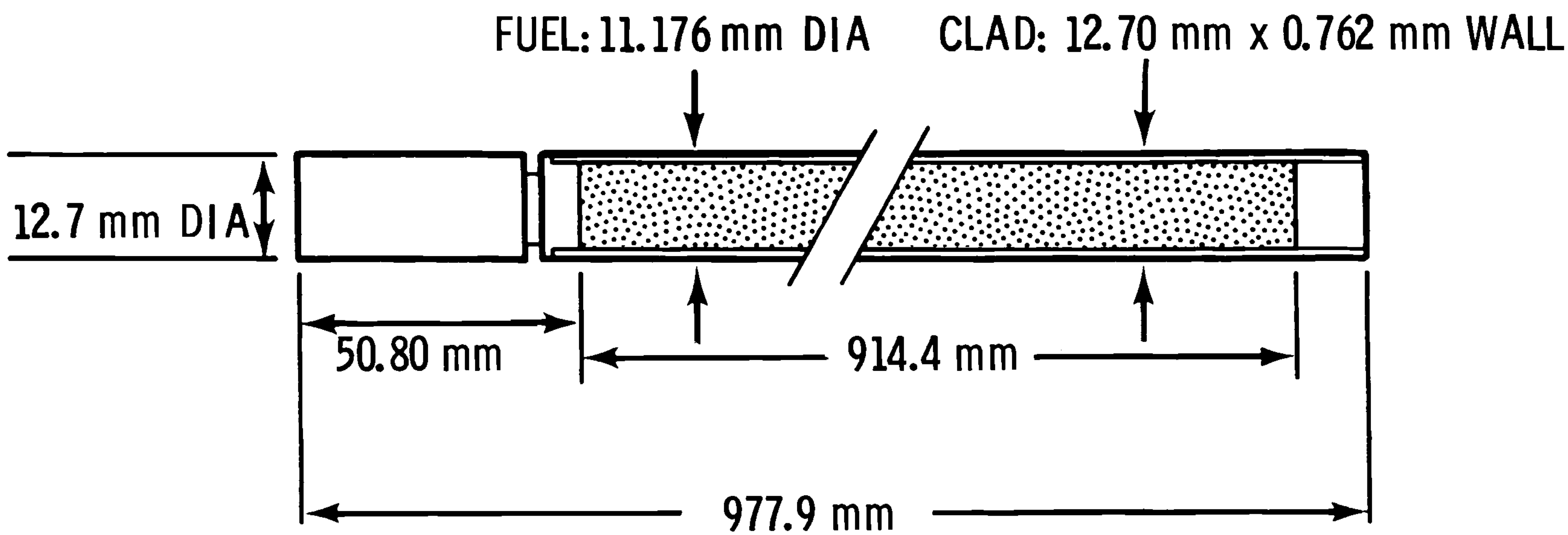
The initial series of experiments under this program were performed with water flooded aluminum clad UO_2 fuel rods about 12mm in diameter, 914mm in length, and enriched to 2.35 wt% ^{235}U. A complete description of the fuel rods is given in Figure 4, and the chemical analysis of the water is given in Table I. The experiments consisted of determining the number of these rods required for criticality at near optimum moderation, and then measuring the critical separation between three subcritical clusters of these rods aligned in a row. The effect that the following fixed neutron absorbers (neutron poisons) had on the critical separation between these clusters of rods was also investigated:

FULLY LOADED EXPERIMENTAL ASSEMBLY

FIGURE 3

FIGURE 4

DESCRIPTION OF 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

TOTAL WEIGHT OF LOADED FUEL RODS: 917 gm (AVERAGE)

LOADING:

825 gm OF UO_2 POWDER/ROD, 726 gm OF U/ROD, 17.08 gm OF U-235/ROD
ENRICHMENT - 2.35 ± 0.05 w/o U-235
FUEL DENSITY - 9.20 mg/mm^3 (84% THEORETICAL DENSITY)

TABLE I

CHEMICAL ANALYSIS OF WATER

2.35 wt% ^{235}U ENRICHED UO_2 RODS IN WATER EXPERIMENTS

COMPONENT	CONCENTRATION[(1)] g/m^3 (ppm)
Cl	26.2 ± 5.4
NO_3^-	0.24 ± 0.12
Cr^{+6}	< 0.028
Zn	0.35 ± 0.05
Mn	< 0.55
Pb	< 0.015
Fl	0.21 ± 0.02
Fe	< 0.06
Cu	< 0.06
Cd	0.004 ± 0.001
SO_3	6.7 ± 0.4

(1) AVERAGE OF SAMPLES TAKEN AT THE BEGINNING OF THE EXPERIMENTS AND NEAR THE END OF THE EXPERIMENTS

Boral

304L Steel

1.1 wt% B-304L Steel

1.6 wt% B-304L Steel

Copper

1 wt% Cd-Copper

Aluminum

Zircaloy-4

Cadmium

The composition of each neutron absorber material is given in Table II.

Based on past experiments[1] [2] with these fuel rods, all of the current measurements were performed with the rods arranged in a 20.32mm square lattice pitch. Plan and end views diagraming the layout of the experiments are shown in Figure 5. Measurements with a near square array of rods in only the center unit shown in Figure 5 resulted in 261.5 ± 0.5 rods being required for criticality in the absence of any poison plates. This is in agreement with an interpolation between the previously obtained data points[1].

In measuring the critical separation between three subcritical clusters of these rods, the length of each cluster was held constant at 20 rods in all but a few experiments. As will be covered later, some measurements with boral and some with copper, as neutron poison plates, were performed with the outer two rod clusters elongated. The width of all the rod clusters was the same in each experiment.

The critical separation between the rod clusters is indicated as Xc in Figure 5. This separation is not rod-to-rod distance but unit cell boundary-to-unit cell boundary for direct input to computer codes.

TABLE II

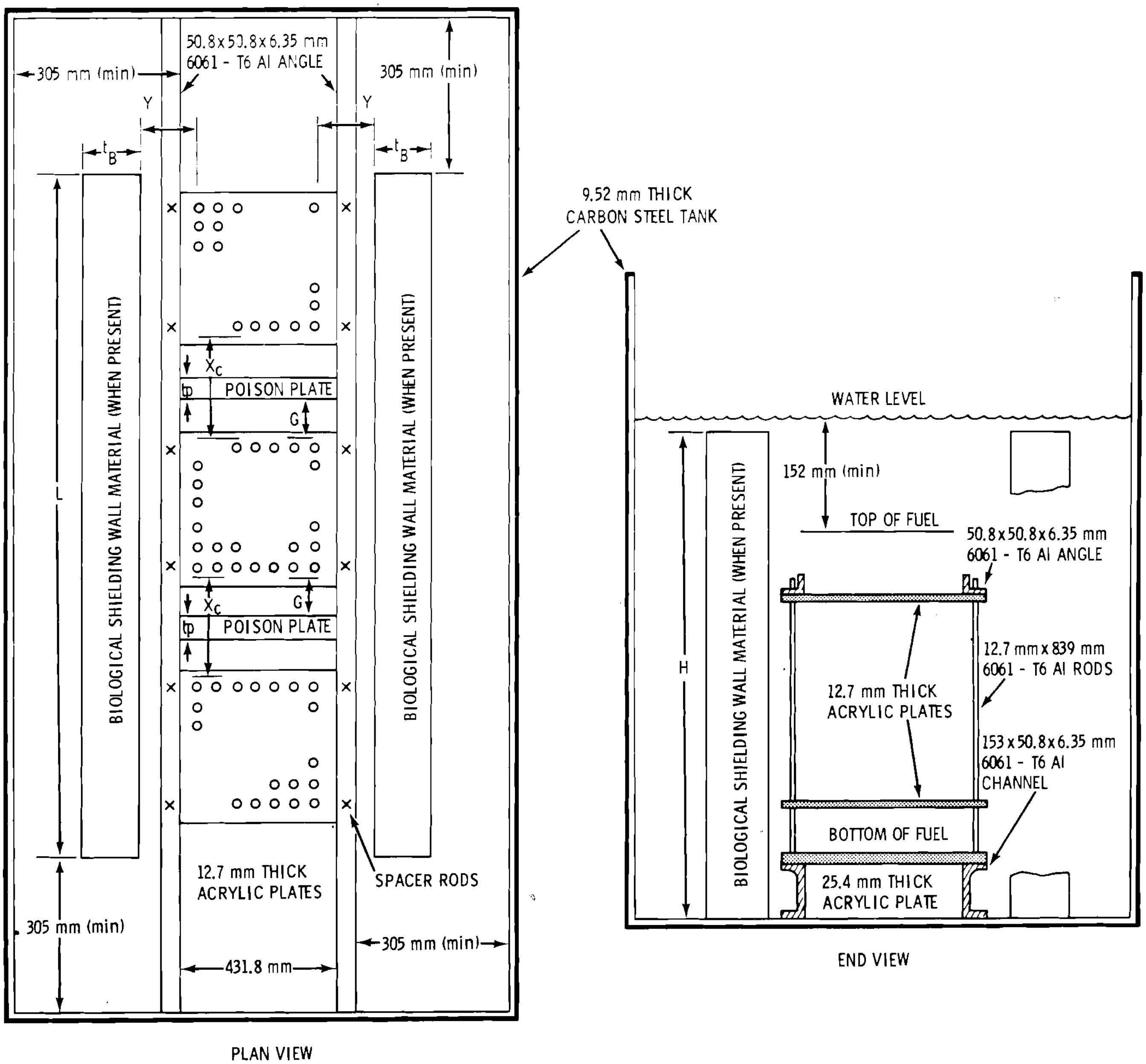
COMPOSITION OF NEUTRON ABSORBER PLATES (1)

ELEMENT	BORAL (2.49 mg/mm^3) wt%	COPPER-CADMIUM (8.910 mg/mm^3) wt%	COPPER (8.913 mg/mm^3) wt%	6061 ALUMINUM (2.692 mg/mm^3) wt%	ZIRCALOY-4 (6.32 mg/mm^3) wt%	304-L STEEL (7.930 mg/mm^3) NO BORON wt%	304-L STEEL (7.900 mg/mm^3) 1.1 wt% BORON wt%	304-L STEEL (7.770 mg/mm^3) 1.6 wt% BORON wt%	CADMIUM (8.650 mg/mm^3) wt%
Al	62.39 ± 2.8	-	-	97.15 ± 0.21	-	-	-	-	-
B	28.70 ± 0.25	0.005	-	-	-	-	1.05 ± 0.08	1.62 ± 0.10	-
C	7.97 ± 0.41	0.002	0.340	-	-	-	-	-	-
Cd	-	0.989 ± 0.003	-	-	-	-	-	-	99.7 ± 0.3
Cr	0.05	-	-	0.21	0.13 ± 0.04	18.56 ± 0.10	19.03 ± 0.10	19.60 ± 0.10	-
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	0.020	0.004	0.82	0.21 ± 0.03	68.24 ± 0.34	68.04 ± 0.34	66.40 ± 0.33	-
Mg	0.05	-	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	-	0.002	-	-	-	-	-	-
Ni	0.02	0.010	-	-	-	11.09 ± 0.06	9.53 ± 0.05	10.12 ± 0.05	-
O	-	0.019	0.030	-	-	-	-	-	-
Si	0.20	0.004	0.020	0.82	-	-	-	-	-
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	-	-	-	-

(1) ERROR LIMITS WHERE SHOWN ARE ONE STANDARD DEVIATION BASED ON MULTIPLE CHEMICAL ANALYSES. ERROR LIMITS NOT SHOWN FOR MINOR IMPURITIES. IMPURITIES DISTRIBUTION BASED ON SPARK SOURCE MASS SPECTROGRAPHIC ANALYSES AND REPRESENT BEST ESTIMATE OF MAXIMUM CONCENTRATION FOR EACH ELEMENT PRESENT IN SIGNIFICANT QUANTITY

FIGURE 5

GRAPHICAL ARRANGEMENT OF SIMULATED SHIPPING PACKAGE CRITICAL EXPERIMENTS



The neutron poison plates, when present, are positioned between each rod cluster at a fixed distance, from the center rod cluster cell boundary, indicated as G in Figure 5. Each plate was paralleled to the fuel rods as indicated in Figure 5. The dimensions of the plates will be given later with the respective measurement data; however each plate was slightly longer and wider than the rod clusters involved in the measurements with that plate. Measurements for each of the poison plates were made with the plates positioned at two locations in the water gap between the fuel rod clusters. One location was near the unit cell boundary of the center fuel rod cluster, and the other was near the midpoint between the fuel rod clusters.

Unpoisoned Assemblies

Measurement data are presented in Table III for systems having no neutron poison plates, and in Tables IV through VIII for fuel rod clusters with neutron poison plates. A plot of critical separations as a function of the width of the unpoisoned rod clusters is shown in Figure 6.

304L Steel Poisoned Assemblies

Experimental data obtained with 304L steel plates between the fuel rod clusters are presented in Table IV. Measurements were performed with 304L steel plates having thicknesses of about 3mm and 5mm. At the 3mm thickness, the critical separation between fuel rod clusters was also determined for three boron contents in the steel, 0, 1.05, and 1.62 wt%. To obtain meaningful data the borated steel measurements were performed on more reactive fuel rod clusters (20 x 17 rods) than the measurements with the unborated steel at different thicknesses. The critical separation as a function of boron content is plotted in figure 7 and as a function of steel thickness in Figure 8.

TABLE III

EXPERIMENTAL DATA ON CLUSTERS OF 2.35 wt% ^{235}U ENRICHED UO_2 RODS IN WATER

FUEL CLUSTERS			
NUMBER IN ARRAY (1)	LENGTH x WIDTH 20.32mm SQ. PITCH (FUEL RODS)	CRITICAL SEPARATION BETWEEN FUEL CLUSTERS (2) (Xc, mm)	EXPERIMENT NUMBER
1	20 x 18.08 ± 0.02	∞	002
3	20 x 17	119.2 ± 0.4	015
3	20 x 16	83.9 ± 0.5	005
3	20 x 16	84.1 ± 0.5	014 (3)
3	20 x 16	84.2 ± 0.5	013 (4)
3	20 x 16	84.4 ± 0.5	049 (3)
3	22 x 16 (5)	100.5 ± 0.5	018
3	20 x 15	63.9 ± 0.6	022
3	24 x 15 (6)	80.1 ± 0.6	045
3	20 x 14	44.6 ± 1.0	021

(1) CLUSTERS OF FUEL RODS ALIGNED IN A SINGLE ROW

(2) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARIES OF THE FUEL CLUSTERS. ERROR LIMITS ARE ONE STANDARD DEVIATION

(3) RERUN OF EXPERIMENT 005

(4) EXTRA THICKNESS OF ALUMINUM ON CONTROL AND SAFETY BLADE GUIDES

(5) CENTER FUEL CLUSTER AT 20 x 16 RODS. TWO OUTER FUEL CLUSTERS AT 22 x 16 RODS EACH

(6) CENTER FUEL CLUSTER AT 20 x 15 RODS. TWO OUTER FUEL CLUSTERS AT 24 x 15 RODS EACH

FIGURE 6

CRITICAL SEPARATION AS FUNCTION OF FUEL CLUSTER WIDTH

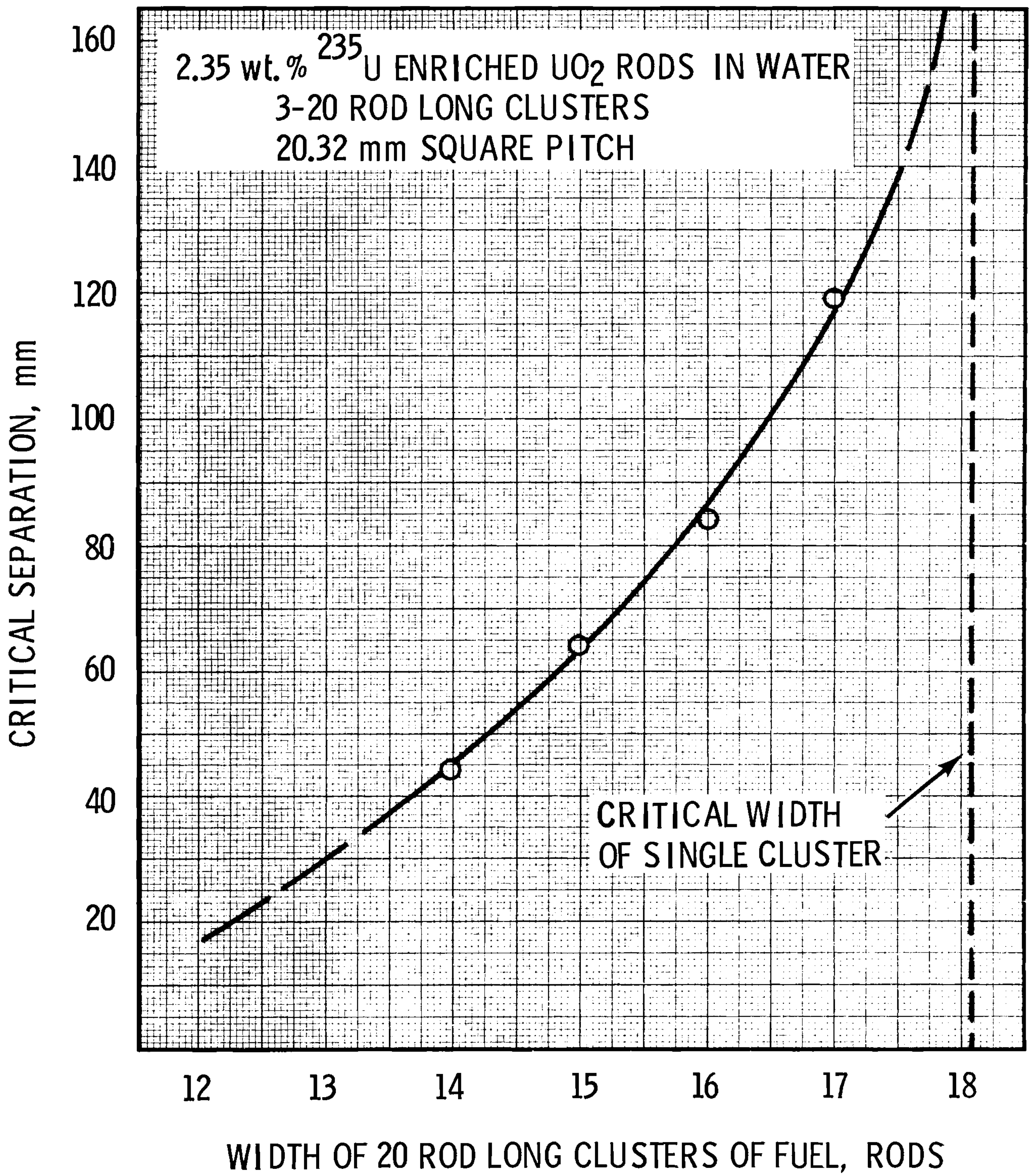


TABLE IV

EXPERIMENTAL DATA ON CLUSTERS OF 2.35 wt% ^{235}U ENRICHED UO_2 RODS IN WATER WITH 304L STEEL PLATES BETWEEN FUEL CLUSTERS (1)

FUEL CLUSTERS		304L STEEL PLATES (3)				
NUMBER IN ARRAY (2)	LENGTH x WIDTH 20.32mm SQ. PITCH (FUEL RODS)	BORON CONTENT wt%	THICKNESS (tp, mm)	DISTANCE TO FUEL CLUSTER (4) (G, mm)	CRITICAL SEPARATION BETWEEN FUEL CLUSTERS (5) (Xc, mm)	EXPERIMENT NUMBER
3	20 x 16	0	4.85 ± 0.15	6.45 ± 0.06	68.8 ± 0.2	028
3	20 x 16	0	4.85 ± 0.15	27.32 ± 0.50	76.4 ± 0.4	005
3	20 x 16	0	4.85 ± 0.15	40.42 ± 0.70	75.1 ± 0.3	029
3	20 x 16	0	3.02 ± 0.13	6.45 ± 0.06	74.2 ± 0.2	027
3	20 x 16	0	3.02 ± 0.13	40.42 ± 0.70	77.6 ± 0.3	026
3	20 x 17	0	3.02 ± 0.13	6.45 ± 0.06	104.4 ± 0.3	034
3	20 x 17	0	3.02 ± 0.13	40.42 ± 0.70	114.7 ± 0.3	035
3	20 x 17	1.05	2.98 ± 0.06	6.45 ± 0.06	75.6 ± 0.2	032
3	20 x 17	1.05	2.98 ± 0.06	40.42 ± 0.70	96.2 ± 0.3	033
3	20 x 17	1.62	2.98 ± 0.05	6.45 ± 0.06	73.6 ± 0.3	038
3	20 x 17	1.62	2.98 ± 0.05	40.42 ± 0.70	95.2 ± 0.3	039

(1) ERROR LIMITS SHOWN ARE ONE STANDARD DEVIATION

(2) CLUSTERS OF FUEL RODS ALIGNED IN A ROW

(3) PLATES ARE 356 mm WIDE BY 915mm LONG.

(4) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARY OF THE CENTER FUEL CLUSTER AND THE NEAR SURFACE OF THE STEEL PLATE

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

FIGURE 7

CRITICAL SEPARATION AS FUNCTION OF BORON CONTENT IN 304-L STEEL PLATES

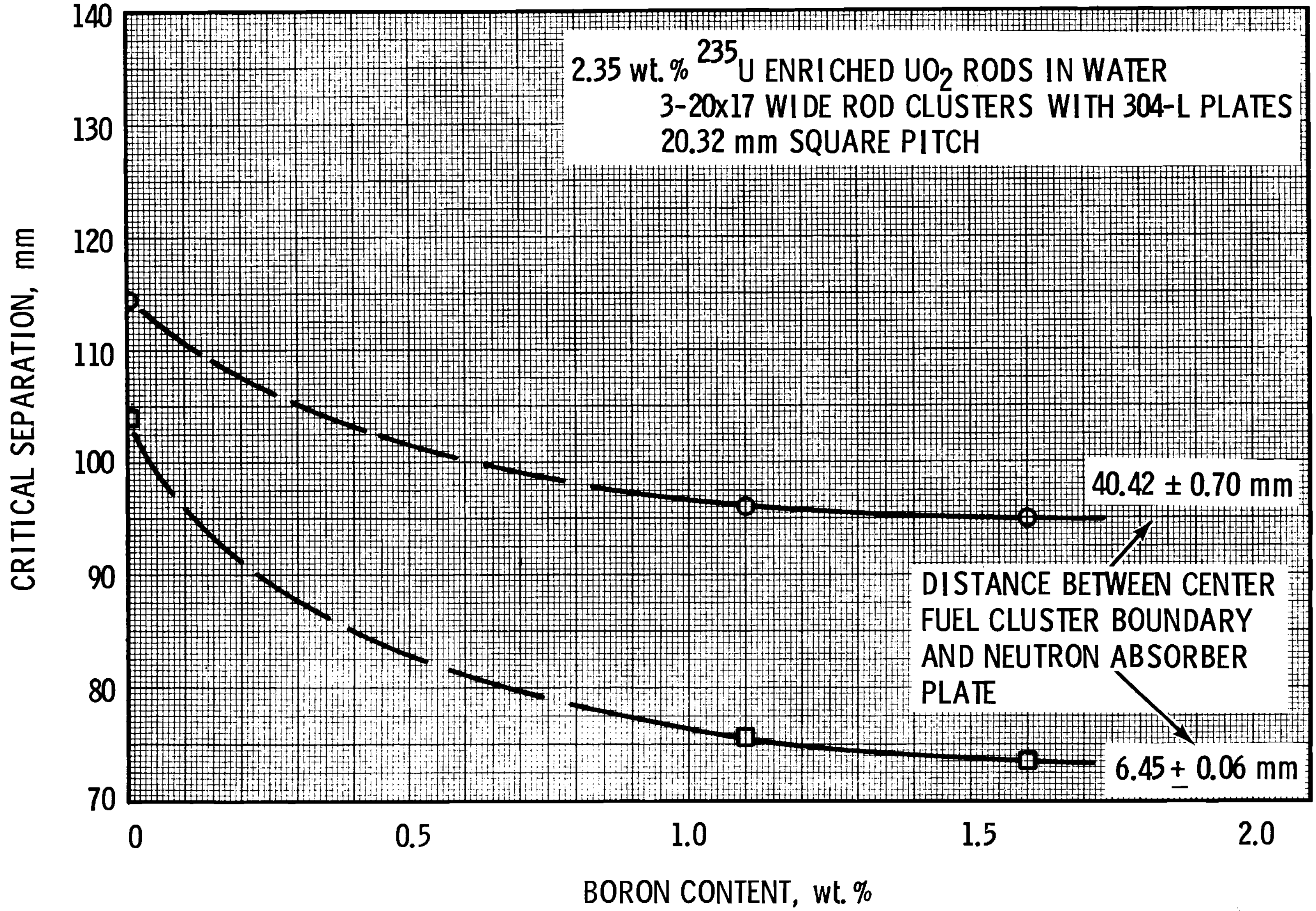
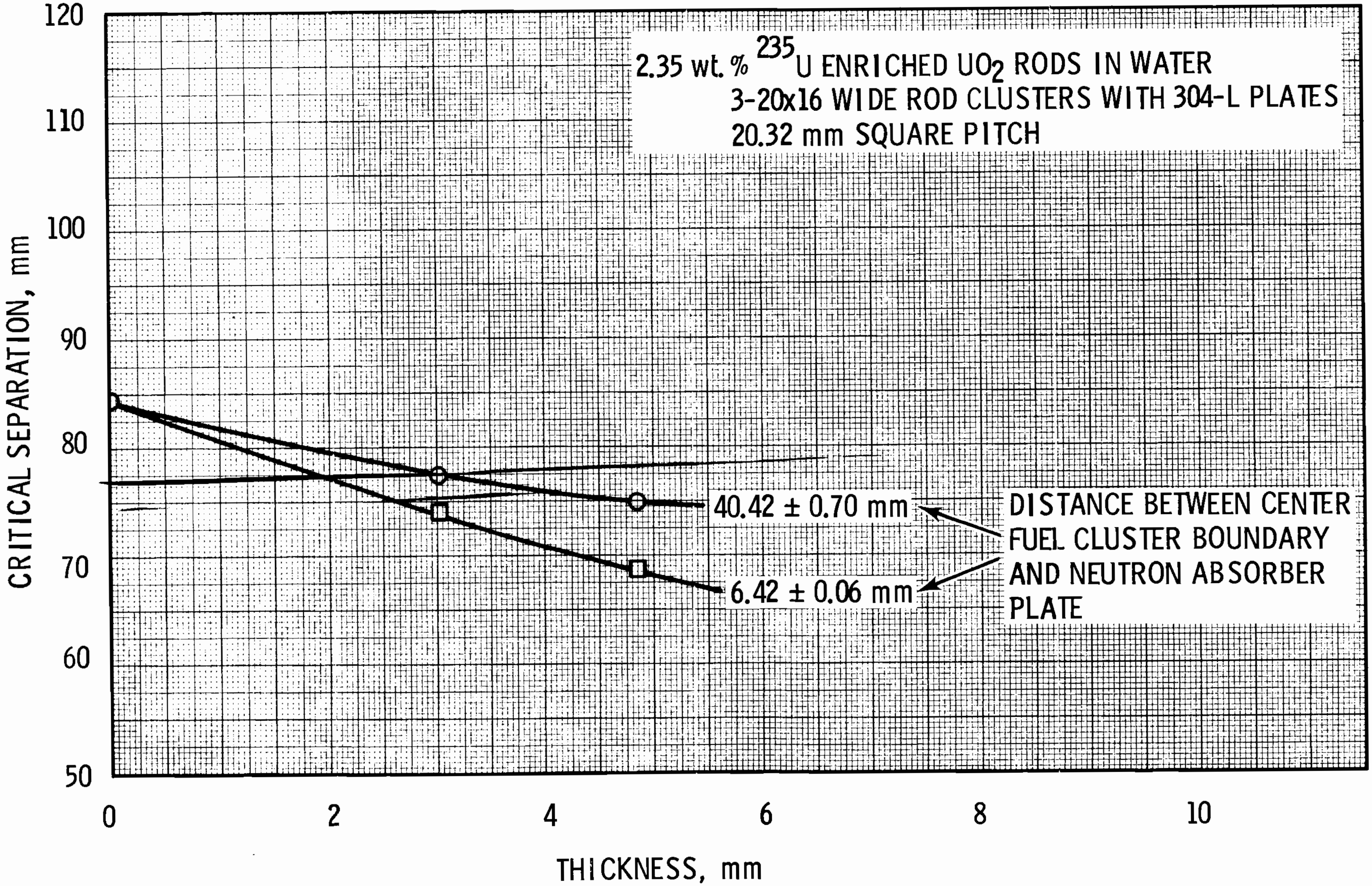


FIGURE 8

CRITICAL SEPARATION AS FUNCTION OF THICKNESS OF 304-L STEEL PLATES



In each case the steel is more effective as a neutron poison when positioned nearer the center fuel rod cluster.

Boral Poisoned Assemblies

Experimental data with boral as the neutron poison material between three clusters of rods are presented in Table V. Since the boral plates were used as the control and safety blades during the experiments, data were also obtained on their reactivity worth as a fixed neutron poison positioned in water adjacent to a single cluster of rods. A single unpoisoned 20 x 18.08 rod cluster is required for criticality (Table III). With a 7.13mm thick boral plate, 27.32mm from the cluster boundary, a width of 18.48 rods is required for criticality. With a second plate at 27.32mm from the opposite cluster boundary, a width of 18.88 rods is required for criticality. Based on these data, a single cluster of these rods enclosed on all four sides with 7.13mm thick boral, 27.32mm out in the water reflector, would be critical with 20 x 19.68 rods.

Throughout these experiments the fuel rod clusters are generally identical in each experiment and only the separation between clusters is varied. However, to obtain additional data with these boral plates, which are very sensitive to thermal neutrons, the water separation between the clusters was held constant at the minimum distance physically possible in this system, (52.2mm) and fuel rods were added to the outside two clusters to achieve criticality. Also, as shown in Table V, the critical separation between a center 20 x 16 rod cluster and two outside 22 x 16 rod clusters was determined to provide data on a slightly smaller water separation and more easily defined fuel arrangement.

TABLE V

EXPERIMENTAL DATA ON CLUSTERS OF 2.35 wt% ^{235}U ENRICHED UO_2 RODS IN WATER WITH BORAL PLATES BETWEEN FUEL CLUSTERS (1)

FUEL CLUSTERS		BORAL PLATES			
NUMBER IN ARRAY (2)	LENGTH x WIDTH 20.32mm SQ. PITCH (FUEL RODS)	THICKNESS (3) (tp, mm)	DISTANCE TO FUEL CLUSTER (4) (G, mm)	CRITICAL SEPARATION BETWEEN FUEL CLUSTERS (5) (Xc, mm)	EXPERIMENT NUMBER
3	20 x 17	7.13 ± 0.11	6.45 x 0.06	63.4 ± 0.2	020
3	20 x 17	7.13 ± 0.11	6.45 ± 0.06	63.2 ± 0.5	023 (6)
3	20 x 17	7.13 ± 0.11	44.42 ± 0.60	90.3 ± 0.5	016
3	22.21 ± 0.02 x 16 (7)	7.13 ± 0.11	6.45 ± 0.06	52.2 ± 0.3	017
3	22 x 16 (8)	7.13 ± 0.11	6.45 ± 0.06	50.5 ± 0.3	017
1	20 x 18.88 ± 0.10	7.13 ± 0.11	27.32 ± 0.50	∞	002
1	20 x 18.48 ± 0.05	7.13 ± 0.11	27.32 ± 0.50 (9)	∞	002

(1) ERROR LIMITS SHOWN ARE ONE STANDARD DEVIATION

(2) CLUSTERS OF FUEL RODS ALIGNED IN A SINGLE ROW

(3) INCLUDES 1.02 mm THICK CLADDING OF TYPE 1100 Al ON EITHER SIDE OF THE B_4C-Al CORE MATERIAL. PLATES 365mm WIDE BY 915 mm LONG.

(4) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARY OF THE CENTER FUEL CLUSTER AND THE NEAR SURFACE OF THE BORAL PLATE

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

(6) RERUN OF EXPERIMENT 020

(7) CENTER FUEL CLUSTER AND SEPARATION BETWEEN CLUSTERS HELD CONSTANT AT 20 x 16 RODS AND 52.2 ± 0.3 mm RESPECTIVELY. TWO OUTER CLUSTERS LOADED TO CRITICAL AT 22.21 ± 0.02 x 16 RODS EACH

(8) CENTER FUEL CLUSTER AT 20 x 16 RODS. TWO OUTER FUEL CLUSTERS AT 22 x 16 RODS EACH

(9) BORAL PLATE ON ONE SIDE OF FUEL CLUSTER ONLY

Copper Poisoned Assemblies

Experiments were performed with copper and with copper containing about 1 wt% cadmium as the neutron poison material between the rod clusters. The measurement data from these experiments are presented in Figure VI.

The copper plates available with 1 wt% Cd were only 306mm in width. Consequently the measurements with these neutron poison plates were performed with fuel rod clusters only 15 rods wide (304.8mm) to avoid a direct line of sight between rods of different clusters. To offset this decrease in reactivity in each of the rod clusters, the two outer fuel rod clusters were lengthened as indicated in Table VI. (The center cluster was held constant at 20 rods in length). For direct comparison a corresponding experiment was run with these same rod clusters using copper plates of the same width and approximate thickeness (3.37mm versus 3.57mm), but containing no cadmium.

Measurement data were also obtained on copper plates about 6.5mm thick to provide data on copper which were directly comparable to data on most of the other neutron absorbing materials covered in this report.

Cadmium Poisoned Assemblies

Measurement data obtained in the experiments with cadmium are presented in Table VII. The absorption cross section of cadmium is very high for low energy neutrons and decreases sharply in the vicintiy of about 0.5 ev. This point of decrease, cadmium cutoff, is dependent on the thickness of the cadmium. Also the transmission of thermal neutrons through cadmium is a function of the cadmium thickness and is most sensitive between thicknesses of about 0.1mm and 1mm.

TABLE VI

EXPERIMENTAL DATA ON CLUSTERS OF 2.35 wt% ^{235}U ENRICHED UO_2 RODS IN WATER WITH COPPER PLATES BETWEEN FUEL CLUSTERS (1)

FUEL CLUSTERS		COPPER PLATES (3)				
NUMBER IN ARRAY (2)	LENGTH x WIDTH 20.32 mm SQ. PITCH (FUEL RODS)	CADMIUM CONTENT wt%	THICKNESS (t_p, mm)	DISTANCE TO FUEL CLUSTERS (4) (G, mm)	CRITICAL SEPARATION BETWEEN FUEL CLUSTERS (5) (X_c, mm)	EXPERIMENT NUMBER
3	20 x 16	0	6.46 ± 0.08	6.45 ± 0.06	66.2 ± 0.2	031
3	20 x 16	0	6.46 ± 0.08	27.32 ± 0.50	77.2 ± 0.6	006
3	20 x 16	0	6.46 ± 0.08	44.42 ± 0.60	75.1 ± 0.2	012
3	24 x 15 (6)	0	3.37 ± 0.08	6.45 ± 0.06	68.8 ± 0.5	043
3	24 x 15 (6)	0	3.37 ± 0.08	40.42 ± 0.70	70.0 ± 0.4	044
3	24 x 15 (6)	0.989	3.57 ± 0.08	6.45 ± 0.06	51.5 ± 0.6	041
3	24.21 ± 0.02 x 15 (7)	0.989	3.57 ± 0.08	6.45 ± 0.06	52.2 ± 0.3	040
3	24.83 ± 0.08 x 15 (8)	0.989	3.57 ± 0.08	40.42 ± 0.70	52.2 ± 0.3	042

(1) ERROR LIMITS SHOWN ARE ONE STANDARD DEVIATION

(2) CLUSTERS OF FUEL RODS ALIGNED IN A ROW

(3) PLATES 6.46mm THICK ARE 356mm WIDE BY 915mm LONG. OTHERS ARE 306mm BY 915mm.

(4) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARY OF THE CENTER FUEL CLUSTER AND THE NEAR SURFACE OF THE PLATE

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

(6) CENTER FUEL CLUSTER AT 20 x 15 RODS. TWO OUTER FUEL CLUSTERS AT 24 x 15 (NECESSITATED BY Cd-Cu PLATES AVAILABLE)

(7) CENTER FUEL CLUSTER AND SEPARATION BETWEEN CLUSTERS HELD CONSTANT AT 20 x 15 RODS AND 52.2 mm RESPECTIVELY. TWO OUTER FUEL CLUSTERS LOADED TO CRITICAL AT 24.21 ± 0.02 x 15 RODS EACH

(8) CENTER FUEL CLUSTER AND SEPARATION BETWEEN CLUSTERS HELD CONSTANT AT 20 x 15 RODS AND 52.2 mm RESPECTIVELY. TWO OUTER FUEL CLUSTERS LOADED TO CRITICAL AT 24.83 ± 0.08 x 15 RODS EACH

TABLE VII

EXPERIMENTAL DATA ON CLUSTERS OF 2.35 wt% ^{235}U ENRICHED UO_2 RODS IN WATER WITH CADMIUM PLATES BETWEEN FUEL CLUSTERS (1)

FUEL CLUSTERS		CADMIUM PLATES (3)			
NUMBER IN ARRAY (2)	LENGTH x WIDTH 20.32mm SQ. PITCH	THICKNESS (tp, mm)	DISTANCE TO FUEL CLUSTERS (4) (g, mm)	CRITICAL SEPARATION BETWEEN FUEL CLUSTERS (5) (Xc, mm)	EXPERIMENT NUMBER
3	20 x 17	0.610 ± 0.025	6.45 ± 0.06	67.4 ± 0.6	036
3	20 x 17	0.610 ± 0.025	14.82 ± 0.70	76.0 ± 0.2	054
3	20 x 17	0.610 ± 0.025	40.42 ± 0.70	93.7 ± 0.3	037
3	20 x 17	0.291 ± 0.010	14.82 ± 0.70	77.8 ± 1.0	050
3	20 x 17	0.291 ± 0.010	40.42 ± 0.70	94.0 ± 0.3	051
3	20 x 17	0.901 ± 0.027	14.82 ± 0.70	75.4 ± 0.3	052
3	20 x 17	0.901 ± 0.027	40.42 ± 0.70	93.9 ± 0.3	053

(1) ERROR LIMITS SHOWN ARE ONE STANDARD DEVIATION.

(2) CLUSTERS OF FUEL RODS ALIGNED IN A ROW.

(3) PLATES ARE 356 mm WIDE BY 915 mm LONG.

(4) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARY OF THE CENTER FUEL CLUSTER AND THE NEAR SURFACE OF THE PLATE

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

Consequently the critical separation between fuel rod clusters was determined for several thicknesses of cadmium plates between the clusters of rods. According to the published data[3], the thicknesses of about 0.3mm, 0.6mm, and 0.9mm investigated in the experiments should result in an overall difference in thermal neutron transmission of about a thousand. Over this same change in thicknesses the cadmium cutoff energy should vary about a 0.1 ev[3].

The results of the measurements are also shown graphically in Figures 9 and 10 to illustrate the sensitivity of the measurements to the thickness of the cadmium and to its location between the fuel rod clusters.

Aluminum and Zircaloy Plates

Although not generally considered as neutron poisons or absorbers, aluminum and zirconium are commonly encountered as fuel basket or fuel cladding materials, and thus serve, essentially, as voiding materials in flooded conditions. Consequently a series of experiments were performed with aluminum and Zircaloy-4 plates positioned between the three clusters of fuel rods. The results of these measurements are presented in Table VIII and Figure 11.

As can be seen in Figure 11, some spatial dependence is indicated by the data for aluminum; whereas little if any spatial dependence was observed in the measurements with Zircaloy-4. As expected neither the aluminum or the Zircaloy-4 was observed to be a very good neutron absorber. The critical water separation between the fuel clusters was decreased by less than 5% by either of these materials.

FIGURE 9

CRITICAL SEPARATION AS FUNCTION OF THICKNESS OF CADMIUM PLATES

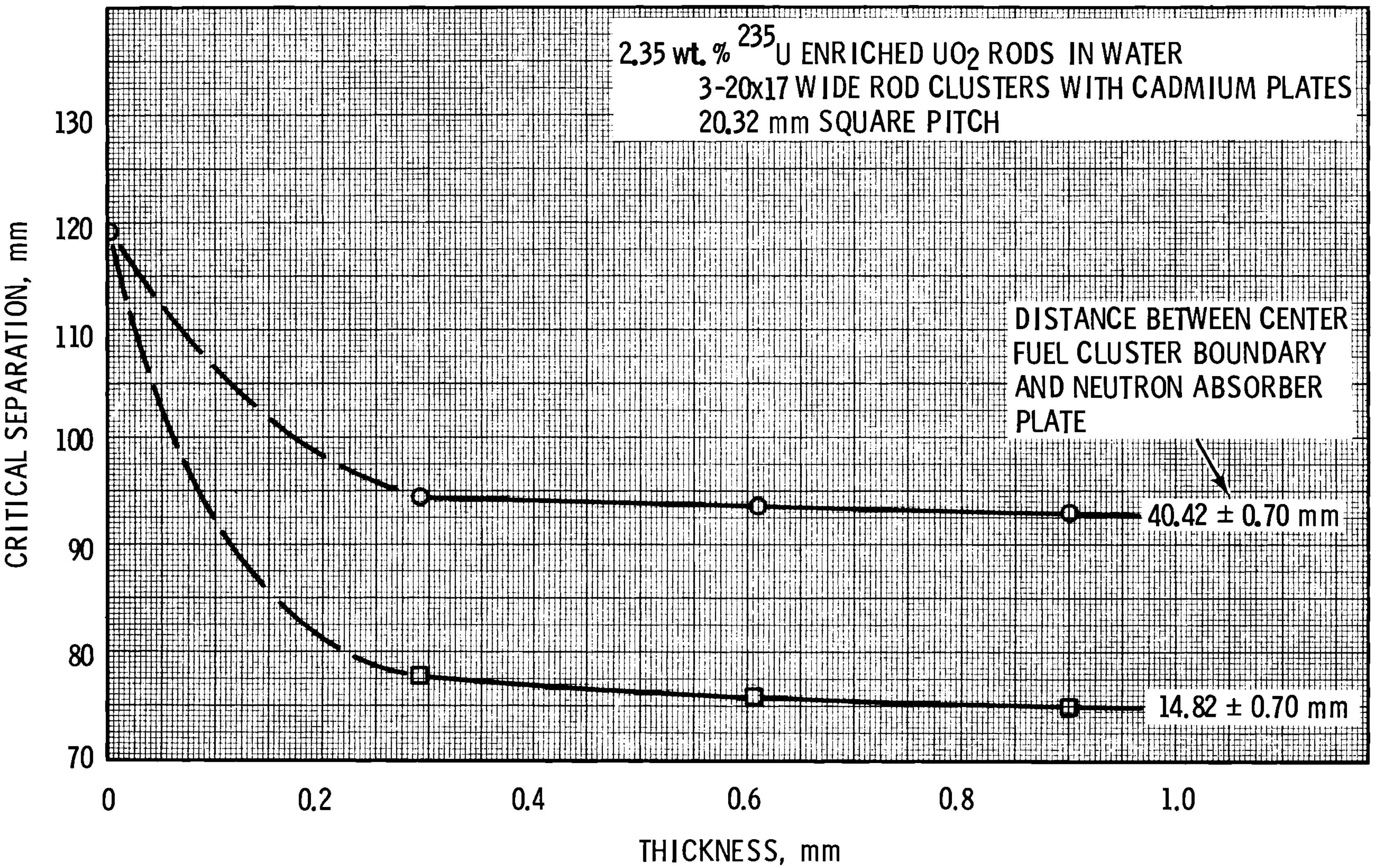


FIGURE 10

CRITICAL SEPARATION AS FUNCTION OF DISTANCE BETWEEN CENTER FUEL CLUSTER AND CADMIUM PLATES

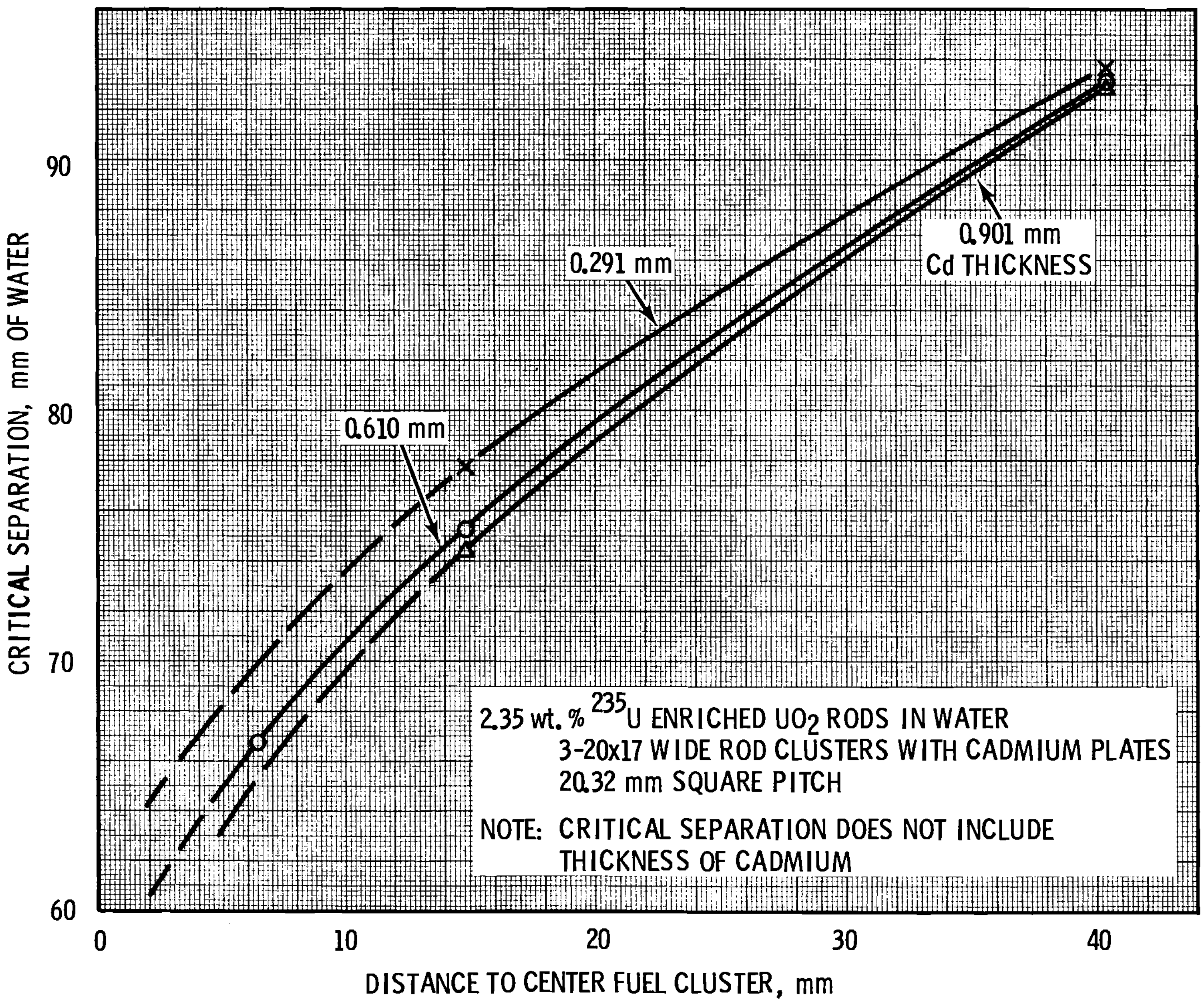


TABLE VIII

EXPERIMENTAL DATA ON CLUSTERS OF 2.35 wt% ^{235}U ENRICHED UO_2 RODS IN WATER WITH ALUMINUM OR ZIRCALOY-4 PLATES BETWEEN FUEL CLUSTERS (1)

FUEL CLUSTERS		NEUTRON ABSORBER PLATES (3)				
NUMBER IN ARRAY (2)	LENGTH x WIDTH 20.32 mm SQ. PITCH	TYPE	THICKNESS (t_p, mm)	DISTANCE TO FUEL CLUSTER (4) (G, mm)	CRITICAL SEPARATION BETWEEN FUEL CLUSTERS (5) (X_c, mm)	EXPERIMENT NUMBER
3	20 x 16	ALUMINUM	6.25 ± 0.01	6.45 ± 0.06	86.7 ± 0.3	024 (6)
3	20 x 16	ALUMINUM	6.25 ± 0.01	40.42 ± 0.7	87.8 ± 0.3	048
3	20 x 16	ALUMINUM	6.25 ± 0.01	44.42 ± 0.60	88.3 ± 0.3	010
3	20 x 16	ZIRCALOY-4	6.52 ± 0.08	6.45 ± 0.06	87.9 ± 0.3	046
3	20 x 16	ZIRCALOY-4	6.52 ± 0.08	40.42 ± 0.70	87.8 ± 0.4	047

(1) ERROR LIMITS SHOWN ARE ONE STANDARD DEVIATION.

(2) CLUSTERS OF FUEL RODS ALIGNED IN A ROW

(3) PLATES ARE 356 mm WIDE BY 915 mm LONG

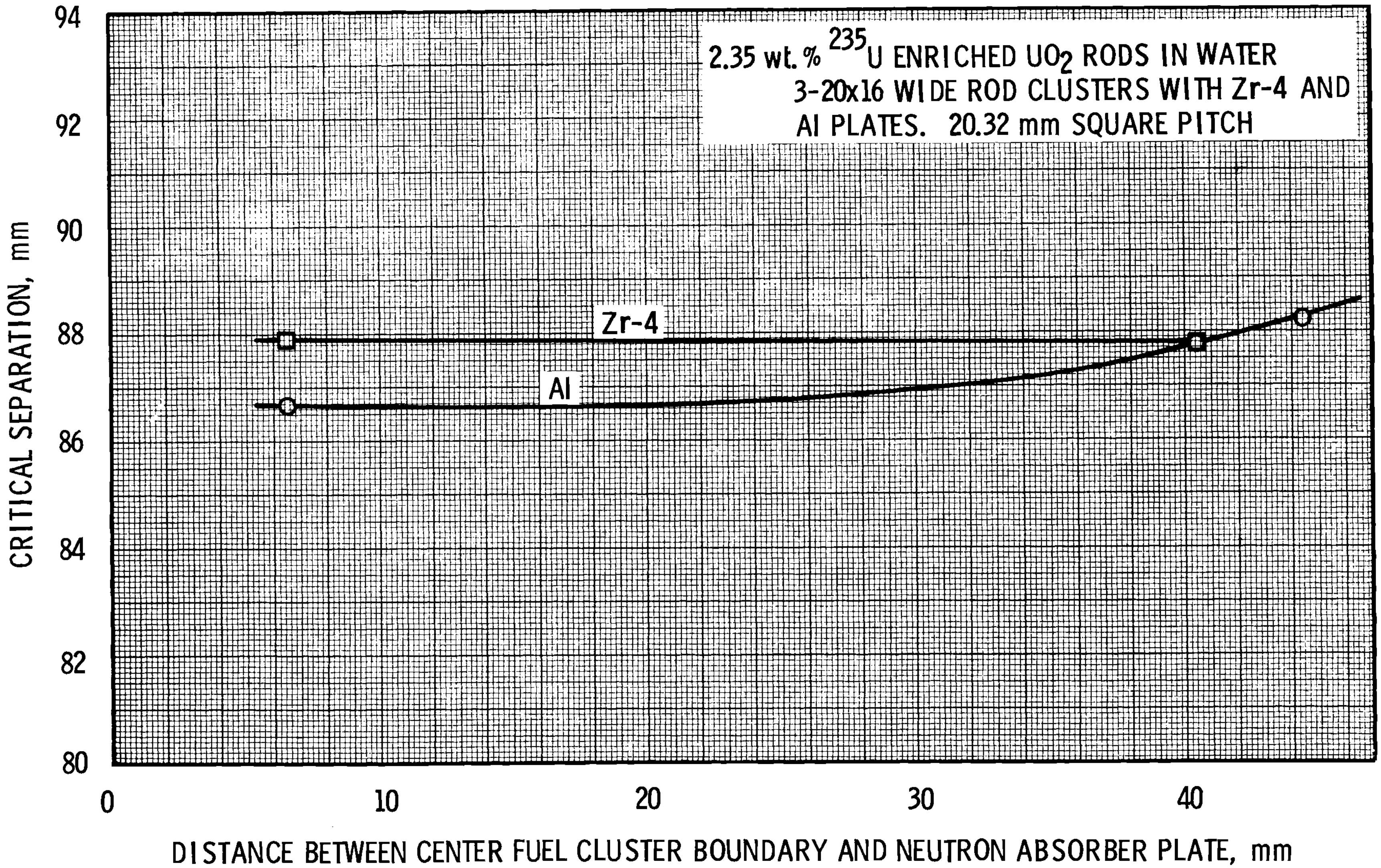
(4) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARY OF THE CENTER FUEL CLUSTER AND THE NEAR SURFACE OF THE PLATE

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

(6) THE ALUMINUM ANGLE GRID SUPPORTS WERE DOUBLED DURING THIS EXPERIMENT AND HAD NO EFFECT ON THE CRITICAL SEPARATION

FIGURE 11

CRITICAL SEPARATION AS FUNCTION OF ABSORBER PLATE LOCATION



REPRODUCIBILITY OF MEASUREMENT DATA

During the course of the measurements several experiments were repeated using different but identical (within the quality control applied during fabrication) fuel rods and different fuel loading arrangements on the approach to critical. All of the measurement data thus checked was reproduced to within a one sigma limit of 0.3%. (Some of the data given in Table III through VIII show larger deviations than 0.3% on the critical separation. Because of scatter in the approach to critical data, better accuracy could not be claimed for these measurements)

EFFECTS OF STRUCTURAL MATERIALS

Measurements were performed to determine the effect the safety and control blade guides, seen in Figures 1, 2, and 3, had on the critical separation between the fuel rod clusters (See Table III). Measurements were also made to determine the effect that the aluminum angles supporting the grid plates had on the critical separation (See Table VIII). Doubling the amount of these materials resulted in no change in the predicted critical separation between fuel rod clusters. It is therefore concluded that these materials, which are in the reflector outside the fuel clusters, had no effect on the critical separation.

APPLICABILITY OF MEASUREMENT DATA

The measurement results presented in this report should be applicable for use in validating calculations on lower enriched LWR type rods at or near optimum neutron moderation.

Although the fuel available for performing these experiments had a fuel density (84% of theoretical UO_2 density) less than that generally used in commercial light water reactors, calculations reproducing these measurements results should reproduce measurements with this same fuel at a higher density. The density effect is relatively straight forward (especially over the small range involved here), and a technique which adequately calculates 84% theoretical density fuel should do so for this fuel at 95% theoretical density also.

Currently, commercial fuels are clad in zircaloy whereas the fuel rods used in the experiments were clad in aluminum. Neutronically, these two materials should be interchangeable as cladding in these experiments. For Zr the thermal neutron absorption cross section is 0.18b whereas for Al it is 0.23b. The measurement data is from "thermal systems" and is not sufficiently accurate to resolve differences of this magnitude.

The fuel used in these experiments also differed slightly from typical commercial fuels by being about 3 ft. in length as compared to about 6 ft., generally, for commercial fuels. However pre - experiment calculations indicated that this would amount to less than a 1% effect on k_{eff}. If the calculational techniques can adequately reproduce this higher neutron leakage experimental system, it should just as accurately, at least, reproduce the same system with slightly less neutron leakage in the axial dimensions.

As will be demonstrated in the section on correlation of measurement data with theory, the experiments as performed can be described exactly by the geometry routines of Monte Carlo type codes. Although it was determined experimentally that some of the equipment structural materials did not effect the measurements for these particular experiments, they can be described, if need be, in calculations on future measurements.

CORRELATION OF MEASUREMENT DATA WITH THEORY

In conjunction with the experiments, a series of calculations were also performed for the purpose of correlating the experiments with theory and for code and cross section validation. The calculations also served to verify that the experimental arrangement could be accurately described for computer code input.

Due to the complex geometry of the experiments, the Keno IV[4] computer code was used. The calculations were made using 17 epithermal broad group cross sections, generated using the Eggnit code[5] and FLANGE - ETOG[6, 7] processed ENDF/B-4 data, and a single thermal group generated using THERMOS[8] with ENDF/B-3 library.

Results of calculations for experiments where only water was between the clusters of rods are summarized in Table IX. The experiment geometry was closely modeled in Keno IV; the aluminum supports and the individual rods, including cladding and aluminum end pieces, were described. The calculations of this discreet model indicated a conservative bias of $\sim$ 2% in terms of k_{eff}.

At one of the experiment points, three 20 x 17 lattices were modeled using both a discreet - fuel rod model, as described in the preceding paragraph, and a smeared rod in water geometry, (homogenized unit cell cross sections used in the fuel cluster regions). Multiple cases were run, using different random number sequencing, in order to obtain a meaningful statistical comparison. As indicated in Table X, the smeared model agreed more closely with the experiment, being conservative by only about 1%, compared to the 2% bias obtained for the discreet case. Hence, there appears to be no particular advantage to modeling the core discreetly.

Calculations were also made for a few of the more complex experiments involving neutron absorber plates. These calculations were performed using the smeared rod model. The cases calculated and the results are shown in Table XI. A conservative bias of about 1% was also obtained on these neutron poisoned systems.

TABLE IX

RESULTS OF BENCHMARK CALCULATIONS FOR SUBCRITICAL CLUSTERS OF 2.35 w/o ^{235}U ENRICHED UO_2 RODS IN WATER

FUEL CLUSTERS			
NUMBER IN ARRAY	LATTICE CONFIGURATION (20.32 mm SQ PITCH) NUMBER OF RODS	CRITICAL SEPARATION BETWEEN FUEL CLUSTERS (mm) (1)	K_{eff} (3) (4)
3 (2)	20 x 17	119.2 ± 0.4	1.022 ± 0.005
3 (2)	20 x 16	83.9 ± 0.5	1.019 ± 0.007
3 (2)	20 x 15	63.9 ± 0.6	1.017 ± 0.006
3 (2)	20 x 14	44.6 ± 1.0	1.016 ± 0.005
			AVE 1.019
1 (5)	20 x 18.08	0.0	1.010 ± 0.003

(1) SEPARATION DISTANCE AS MEASURED FROM OUTER CELL BOUNDARY TO OUTER CELL BOUNDARY

(2) GEOMETRY MODELED DISCREETLY

(3) KENO IV CALCULATIONS USING 18 GROUP AVERAGED CROSS SECTIONS FROM FLANGE-ETOG PROCESSED ENDF/B-4 DATA. ONE SIGMA LIMITS ON MONTE CARLO CALCULATIONS

(4) 103 BATCHES, 500 NEUTRONS PER BATCH

(5) A SMEARED RODS IN WATER GEOMETRY USED

TABLE X

COMPARISON OF DISCREET MODEL AND SMEARED MODEL FOR THREE 20 x 17 ROD LATTICES ISOLATED BY 119.2 mm H_2O

NUMBER OF BATCHES	NEUTRONS PER BATCH	NUMBER OF INITIAL BATCHES SKIPPED TO OBTAIN CONVERGENCE	K_{eff} (1)
	SMEARED GEOMETRY		
103	498	57	1.015 ± 0.004
103	499	17	1.007 ± 0.003
103	500	42	1.003 ± 0.004
103	501	22	1.012 ± 0.003
103	502	27	1.005 ± 0.004
		AVERAGE	1.008
	DISCREET GEOMETRY		
103	498	37	1.024 ± 0.006
103	499	27	1.027 ± 0.006
103	500	11	1.022 ± 0.005
103	501	27	1.026 ± 0.006
103	502	67	1.028 ± 0.008
		AVERAGE	1.025

(1) KENO IV CALCULATIONS USING 18 GROUP AVERAGED CROSS SECTIONS FROM FLANGE-ETOG PROCESSED ENDF/B-4 DATA. ONE SIGMA LIMITS ON MONTE CARLO CALCULATIONS

TABLE XI

RESULTS OF BENCHMARK CALCULATIONS
FOR SUBCRITICAL CLUSTERS OF UO_2 RODS SEPARATED BY WATER AND NEUTRON ABSORBER PLATES[1]

NUMBER OF FUEL ROD CLUSTERS	CLUSTER CONFIGURATION[2] (20.32 mm SQ. PITCH) NUMBER OF RODS	ABSORBER PLATE MATERIAL	ABSORBER PLATE[3] THICKNESS (mm)	CRITICAL SEPARATION[5] BETWEEN FUEL CLUSTERS (mm)	DISTANCE FROM[6] ABSORBER PLATE TO FUEL CLUSTERS	Keff[2][7][8]
3	20 x 16	304L STAINLESS STEEL	4.85 ± 0.15	68.2 ± 0.2	6.45 ± 0.06	1.008 ± 0.003
3	20 x 16	304L STAINLESS STEEL	4.85 ± 0.15	75.1 ± 0.3	40.42 ± 0.70	1.008 ± 0.004
3	20 x 16	6061 ALUMINUM	6.25 ± 0.01	88.3 ± 0.3	44.42 ± 0.60	1.006 ± 0.003
3	20 x 16	6061 ALUMINUM	6.25 ± 0.01	87.8 ± 0.3	40.42 ± 0.70	1.011 ± 0.003
3	20 x 17	BORAL	7.13 ± 0.11[4]	90.3 ± 0.5	44.42 ± 0.60	1.012 ± 0.004
3	20 x 17	Cd	0.610 ± 0.025	93.7 ± 0.3	40.42 ± 0.70	1.013 ± 0.004
3	20 x 16	ZIRCALOY-4	6.52 ± 0.08	87.8 ± 0.4	40.42 ± 0.70	1.005 ± 0.003
					AVERAGE	1.009

(1) ERROR LIMITS SHOWN ARE ONE STANDARD DEVIATION

(2) A SMEARED RODS IN WATER GEOMETRY USED IN CALCULATIONS

(3) PLATE HEIGHT OF 915 mm AND WIDTH OF 356 mm

(4) INCLUDES 1.02 mm THICK CLADDING OF 1100 Al ON EITHER SIDE OF THE B_4C-Al CORE MATERIAL

(5) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARIES OF ADJACENT FUEL CLUSTERS

(6) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARY OF THE CENTER FUEL CLUSTER AND THE NEAR SURFACE OF THE ABSORBER PLATE

(7) KENO IV CALCULATIONS USING 18 GROUP AVERAGED CROSS SECTIONS FROM FLANGE-ETOG

(8) 103 BATCHES, 500 NEUTRONS/ BATCH INPUT TO KENO IV

CONCLUSIONS AND RECOMMENDATIONS

The objective of this research program is to provide experimental data for validating calculational techniques and nuclear data used in criticality assessments of LWR type fuel element shipping packages and similiar systems. To accomplish this objective it was necessary that the experiments be designed to permit easy and accurate definition in Monte Carlo computer codes currently used in these assessments. In the process of correlating some of the measurement data with calculations, it was verified that the experimental assemblies could be described exactly in at least one of these codes, KENO IV[4]. It was further concluded from the calculations - data correlations that the fuel regions did not have to be discreetly modeled in the calculations. (That is, cell averaged cross section data can be used for the fuel regions).

The fuel used in these experiments is typical of relatively low enriched LWR type UO_2 fuel rods except for three minor differences.

1. The experimental fuel had a slightly lower density then generally achieved in commercial reactor grade fuel (84% vs $\sim$ 95% of theoretical density).

2. The experimental fuel was clad in Al whereas commercial fuels are generally clad in a Zr alloy.

3. The experimental fuel was $\sim$ 3 ft. in length as compared to $\sim$ 6 ft. for commercial fuels.

These differences should not effect the applicability of the measurement data for validating calculations involving the lower enriched LWR UO_2 fuel rods at or near optimum moderation. Additional experimental data are needed to extend the capability for validating calculations to the higher LWR enrichments (5 wt% maximum) and to lower moderation ranges (water to fuel volume ratios of 1.5 to 2).

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