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FISSION REACTORS

CRITICALITY EXPERIMENTS WITH SUBCRITICAL CLUSTERS OF 2.35 AND 4.31 wt% ^{235}U-ENRICHED UO_2 RODS IN WATER WITH STEEL REFLECTING WALLS

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A series of criticality experiments with 2.35 and 4.31 wt% ^{235}U-enriched UO_2 rods in water was performed to provide well-defined benchmark-type data on thick steel reflecting walls. For each fuel enrichment, the critical separation between three subcritical fuel clusters was observed to increase as 178.5-mm-thick reflecting walls of reactor-grade steel was moved toward the fuel. This increase was observed for fuel clusters having an undermoderated water-to-fuel volume ratio of 1.6 and for fuel clusters having near optimum neutron moderation (2.92 for the 2.35 wt% ^{235}U-enriched fuel and 3.88 for the 4.31 wt% ^{235}U-enriched fuel). In all cases the critical separation between fuel clusters increased to a maximum as the steel walls were moved toward the fuel clusters. This maximum effect was observed with ~10 mm of water between the fuel clusters and the steel reflecting walls. As this water gap was decreased, the critical separation between the fuel clusters also decreased slightly.

Measurement data were also obtained for each enrichment with neutron absorber plates between the fuel clusters having the 1.6 water-to-fuel volume ratio. During these measurements, the steel reflecting walls were at the near optimum distance from the fuel clusters. The fixed neutron absorbers for which data were obtained include Type 304L stainless steel, borated Type 304L stainless steel, copper, copper containing 1 wt% cadmium, cadmium, and two trade-name materials containing boron (Boral and Boroflex).

INTRODUCTION

A research program, funded by the U.S. Nuclear Regulatory Commission (NRC), 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 results of four sets of experiments in this program have been reported in previous NRC documents.[1-6] These four sets of experiments were concerned with

1. fuel clusters of 2.35 wt% ^{235}U-enriched UO_2 rods immersed in water at near optimum neutron moderation with neutron absorber plates between the fuel clusters
2. fuel clusters of 4.31 wt% ^{235}U-enriched UO_2 rods immersed in water at near optimum neutron moderation with neutron absorber plates between the fuel clusters
3. fuel clusters of 2.35 and 4.31 wt% ^{235}U-enriched UO_2 rods immersed in water at near optimum neutron moderation with lead and depleted uranium reflecting walls on either side of the fuel clusters
4. fuel clusters of 2.35 and 4.35 wt% ^{235}U-enriched UO_2 rods immersed in water at a 1.6 water-to-fuel volume ratio with neutron absorber plates and flux traps between the fuel clusters (measurements also made with some fuel clusters containing water holes).

The results from a fifth set of experiments are covered in this paper and involve the same two fuels immersed in water as before. In this fifth series of

experiments, the effect of reactor-grade steel on the critical separation between fuel clusters is investigated at an undermoderated water-to-fuel volume ratio of 1.6 and at a neutron moderation ratio near optimum for each of the fuels. In addition, some measurements in this fifth set of experiments are made with neutron absorber plates between the fuel clusters with the reflecting walls in place.

The objective of these latest 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. No particular attempt is made to obtain parametric correlations between different fuels or biological shielding material.

EXPERIMENTS

As in the previous experiments with lead and depleted uranium reflecting walls, these current experiments with steel walls consisted of determining the critical separation between three subcritical clusters of fuel rods aligned in a row with steel walls parallel on either side of, and at various distances from, the row of fuel clusters.

A photograph of a typical assembly, with the steel walls in place, is shown in Fig. 1. The system is provided with a safety and a control blade. Both of these are shown, one inserted and one withdrawn, on either side of the center fuel cluster in Fig. 1. Both blades would be fully withdrawn whenever data are being obtained. Also, of course, the entire system would be flooded with water to a depth of at least 150 mm above the top of the fuel before any measurements are made. A detailed graphic layout of the experimental system is given in Fig. 2. All structural materials are on the periphery of the experimental assembly except for four 51-mm-wide Type 6061 aluminum spacer bars between the fuel and reflecting walls, the lattice grid plates, and the aluminum guides

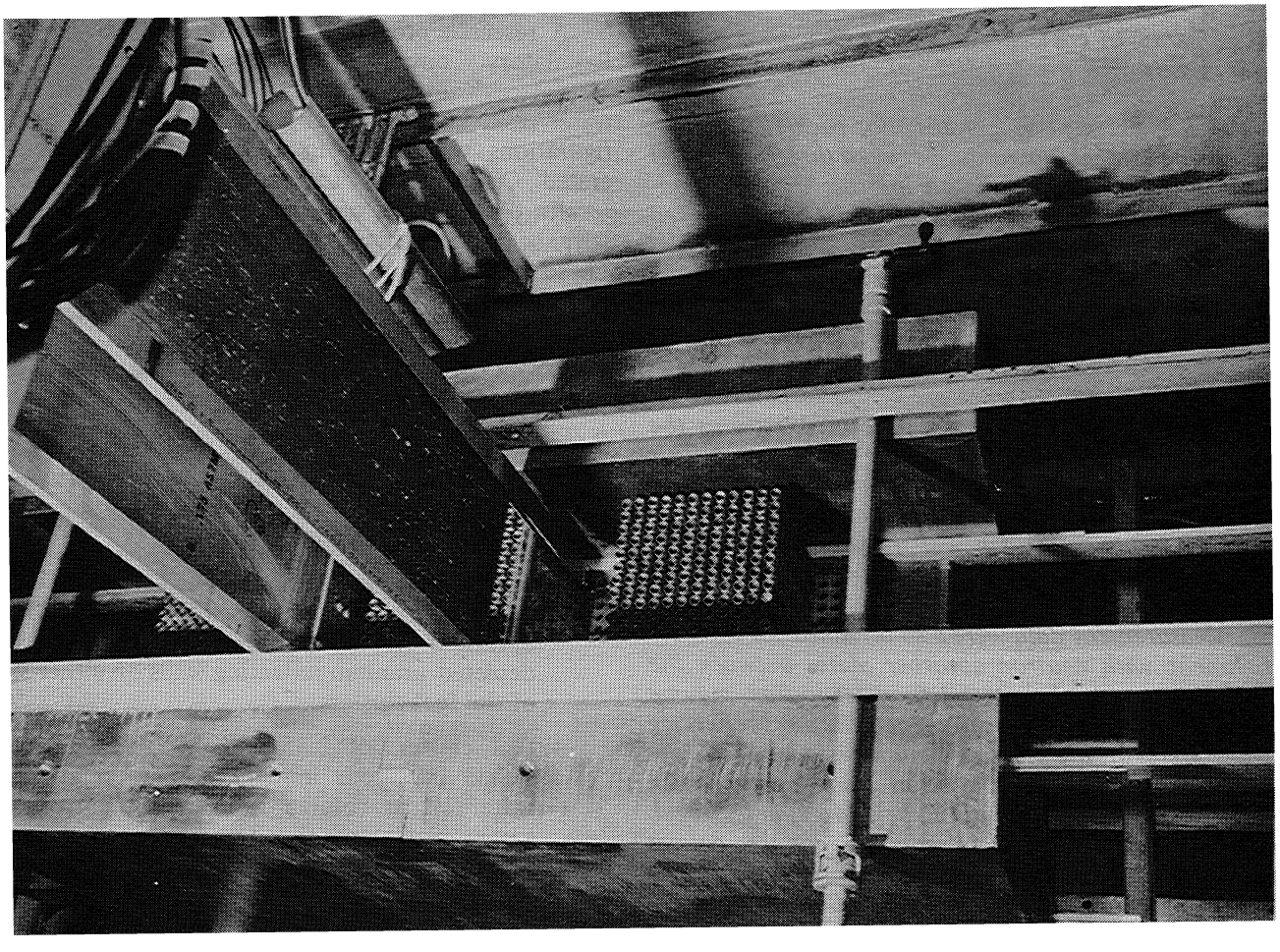


Fig. 1. Photograph of a typical experimental assembly.

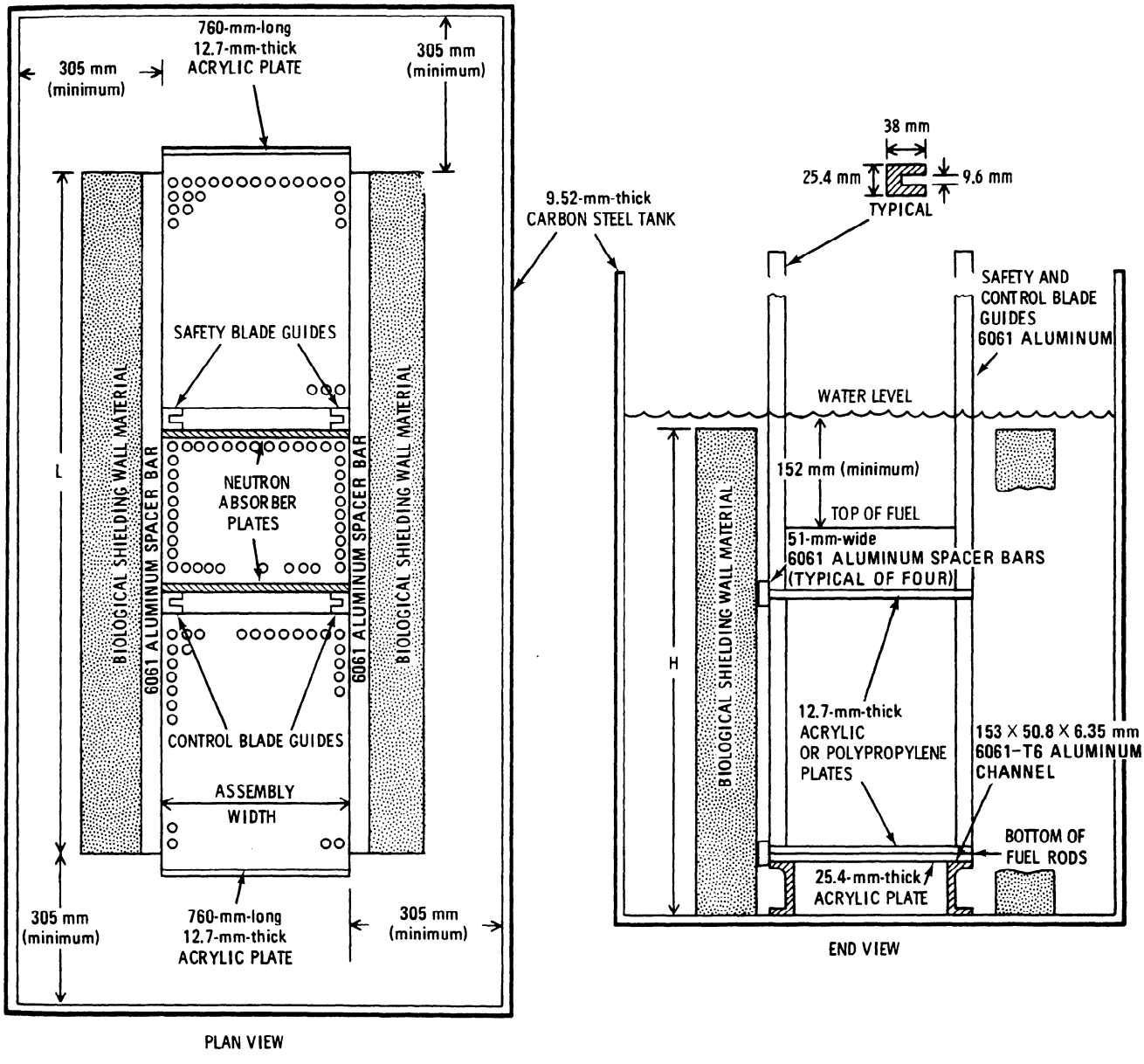


Fig. 2. Graphical arrangement of simulated shipping container critical experiments.

for the safety and control blades. The lattice grid plates for the near optimum neutron-moderated experiments were fabricated from 12.7-mm-thick acrylic (1.185 g/cm^3, 8 wt% hydrogen, 60 wt% carbon, 32 wt% oxygen) sheets. The lattice grid plates for the undermoderated experiments were fabricated from 12.7-mm-thick polypropylene (0.904 g/cm^3) sheets.

Measurement data were obtained for both the 2.35 and the 4.31 wt% ^{235}U-enriched UO_2 rods in square-pitched, water-flooded lattices. Data were obtained for each enrichment at neutron moderation in the fuel clusters near optimum for criticality (water-to-fuel volume ratios of 2.92 and 3.88 for the 2.35 and the 4.31 wt% fuel, respectively) and at neutron moderation approximating that found typically in boiling water reactor and pressurized water reactor fuel elements (1.6 water-to-fuel volume ratio). In the measurements, the distance between the outer cell boundaries of the fuel clusters and the near surface of the steel reflecting walls varied from zero to that approaching infinity (removal of the steel walls from the system).

The effect that the following neutron absorber plates positioned between the fuel clusters had on the

TABLE I

Water Impurities

Component	Concentration [g/m³ (ppm)]
Chlorine	≤5
NO_3	0.02
Cr^{+6}	<0.01
Zinc	16
Manganese	<0.01
Lead	<0.005
Fluorine	0.18
Iron	24
Copper	<0.01
Cadmium	0.001
SO_3	14.5
Dissolved solids	61 ± 3

critical separation between the clusters was also investigated for each enrichment at the 1.6 water-to-fuel volume ratio and one position of the reflecting walls:

1. Type 304L stainless steel
2. Type 304L stainless steel with 1.1 wt% boron
3. Boral™[a]
4. Boroflex™[b]
5. cadmium

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

TABLE

Description of Neutron

Element (wt%)[a]	Boral[b]			Copper-Cadmium	Copper
	Boral A	Boral B	Boral C		
Aluminum	62.39 ± 2.8	61.21[c]	59.26[c]	---	---
Boron	28.70 ± 0.25	30.36[c]	31.88[c]	0.005	---
Carbon	7.97 ± 0.41	8.43[c]	8.86[c]	0.002	0.340
Hydrogen	---	---	---	---	---
Cadmium	---	---	---	0.989 ± 0.003	---
Calcium	---	---	---	---	---
Chromium	0.05	---	---	---	---
Copper	0.09	---	---	98.685 ± 0.300	99.60 ± 0.14
Iron	0.33 ± 0.04	0.02	0.05	0.020	0.004
Magnesium	0.05	0.01	0.01	---	0.002
Manganese	0.05	---	---	0.009	---
Molybdenum	---	---	---	---	---
Sodium	0.02	0.02	0.02	---	0.002
Nickel	0.02	---	---	0.010	---
Oxygen	---	---	---	0.019	0.030
Silicon	0.20	---	0.06	0.004	0.020
Tin	---	---	---	0.250	---
Sulfur	0.03	---	---	---	0.002
Titanium	---	---	---	---	---
Zinc	0.10	---	---	0.007	---
Zirconium	---	---	---	---	---
Density (g/cm³)	2.49	2.50	2.47	8.910	8.913
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

[a]Error limits where shown are one standard deviation based on multiple chemical analyses. Impurities distribution based on spark quantity.
[b]Composition of B_4C-aluminum core material cladding is aluminum Type 1100.
[c]Based on weights of mixture components at time of fabrication.
[d]Includes 0.102, 0.038, and 0.025 cm of Type 1100 aluminum on either side of the Boral A, B, and C core materials, respectively.

6. copper

7. copper with 1 wt% cadmium.

In these measurements involving neutron absorber plates, single absorber plates of a kind were located between the fuel clusters at the cell boundary of the center fuel cluster as illustrated in Fig. 2 and in the data tables and figures. The plates were always centered on the fuel region of the fuel rods.

A detailed description of each type of fuel rod is given in Fig. 3. The chemical impurities of the water used in these experiments are given in Table I. The steel reflecting walls are described in Fig. 4 and, except for their length and width (915 and 302 mm, respectively), each of the absorber plates is described in Table II.

Since these experiments are intended to neutronically simulate systems using steel as a biological shielding material, the thickness of the steel walls used in the experiments was essentially infinite with respect to neutron reflection. This thickness was determined[7] to be ~175 mm (~7 in.) from calculations on an assembly representative of the experimental assemblies. Consequently, the measurements were performed with a steel plate having a nominal thickness of 7 in. (178.5 ± 0.4-mm actual thickness) and machined to obtain a plane surface within 0.127 mm.

In each of the neutron absorbing plates used in the experiments, the primary neutron absorbing nuclei are homogeneously distributed throughout the core of the plates. However, in the Boral and in the Boroflex, these nuclei are contained in B_4C particles uniformly distributed throughout either an aluminum (Boral) or a rubber (Boroflex) material. According to

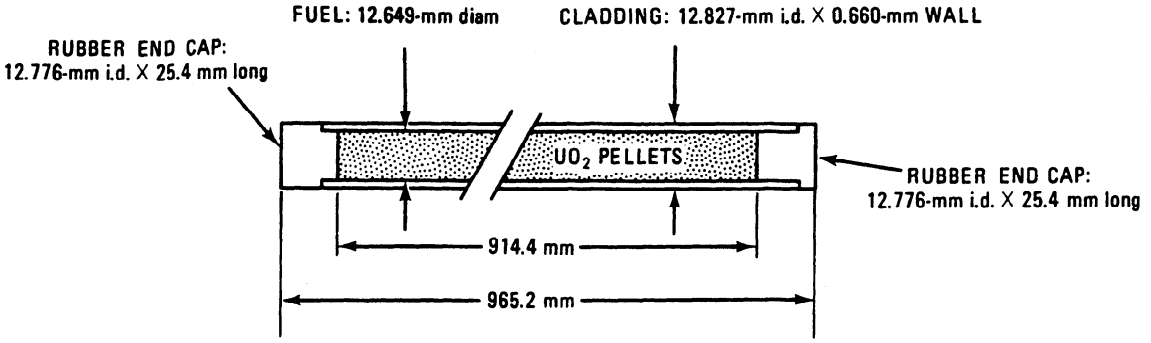
II

Absorber Plates

6061 Aluminum	Zircaloy-4	Type 304L Stainless Steel			Cadmium	Boroflex
		No Boron	1.1 wt% Boron	1.6 wt% Boron		
97.15 ± 0.21	---	---	---	---	---	---
---	---	---	1.05 ± 0.08	1.62 ± 0.10	---	32.74 ± 0.05
---	---	---	---	---	---	21.13 ± 0.03
---	---	---	---	---	---	2.65 ± 0.31
---	---	---	---	---	99.7 ± 0.3	---
---	---	---	---	---	---	---
0.21	0.13 ± 0.04	18.56 ± 0.10	19.03 ± 0.10	19.60 ± 0.10	---	0.03 ± 0.02
0.12	---	0.27 ± 0.05	0.28 ± 0.05	0.26 ± 0.05	---	---
0.82	0.21 ± 0.03	68.24 ± 0.34	68.04 ± 0.34	66.40 ± 0.33	---	0.05 ± 0.06
---	---	---	---	---	---	---
0.21	---	1.58 ± 0.05	1.58 ± 0.05	1.69 ± 0.05	---	---
---	---	0.26 ± 0.05	0.49 ± 0.05	0.31 ± 0.05	---	---
---	---	---	---	---	---	---
---	---	11.09 ± 0.06	9.53 ± 0.05	10.12 ± 0.05	---	---
---	---	---	---	---	---	21.01 ± 0.01
0.82	---	---	---	---	---	22.39 ± 0.24
---	1.50 ± 0.27	---	---	---	---	---
0.06	---	---	---	---	---	---
0.61	---	---	---	---	---	---
---	---	---	---	---	0.3	---
---	98.16 ± 0.35	---	---	---	---	---
2.692	6.32	7.930	7.900	7.770	8.650	1.731
0.625 ± 0.001	0.652 ± 0.008	0.485 ± 0.015	0.298 ± 0.006	0.298 ± 0.006	0.061 ± 0.003	0.226 ± 0.004
---	---	0.302 ± 0.013	---	---	---	0.452 ± 0.006

source mass spectrographic analyses and represent best estimate of maximum concentration for each element present in significant

Plates 0.337 cm thick are 30.6 cm wide.

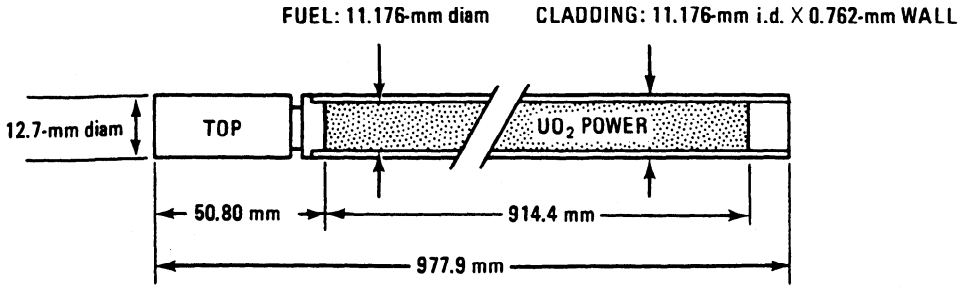


CLADDING: 6061 ALUMINUM TUBING

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 = CARBON: 58 ± 1 wt%; HYDROGEN: 6.5 ± 0.3 wt%; CALCIUM: 11.4 ± 1.8 wt%; SULFUR: 1.7 ± 0.2 wt%; OXYGEN: 22.1 wt% (BALANCE); SILICON: 0.3 ± 0.1 wt%

(a)



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)

(b)

Fig. 3. Description of fuel rods: (a) 4.31 wt% ^{235}U-enriched UO_2 rods, and (b) 2.35 wt% ^{235}U-enriched UO_2 rods.

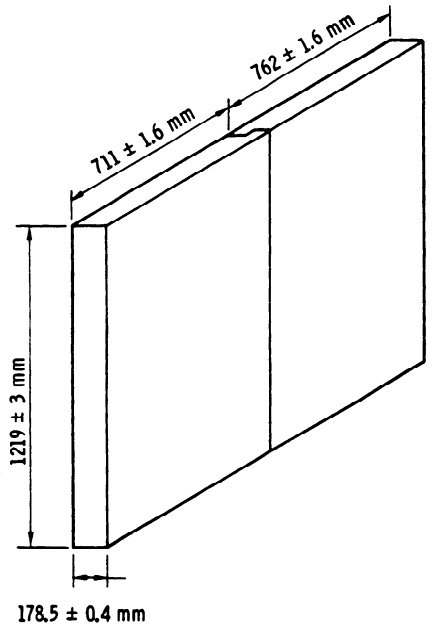
the manufacturer, these particles have the following size distribution.

Particle Size (mm)	Particle Distribution (wt%)	
	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

EXPERIMENTAL DATA

In each experiment, the approach to critical was made by decreasing the water separation between the fuel clusters while holding all the other parameters constant. To the extent possible, the fuel clusters were of equal size in a set of measurements. However, in the experiments with the 2.35 wt% ^{235}U-enriched UO_2 fuel rods, the center fuel cluster had to be made larger than the outer two clusters to achieve criticality (with the 1200 fuel rods available) in all of the assemblies having a 1.6 water-to-fuel ratio.

As indicated earlier, data were obtained for each fuel at a water-to-fuel volume ratio that was near optimum for neutron moderation and at an undermoderated water-to-fuel volume ratio. For the 2.35 wt% ^{235}U-enriched fuel, these water-to-fuel volume ratios were 2.92 (20.32-mm square lattice spacings) and 1.6 (16.84-mm square lattice spacings). For the 4.31 wt% ^{235}U-enriched fuel, the ratios were 3.88 (25.40-mm square lattice spacings) and 1.6 (18.92-mm square lattice spacings).



TYPE:	SA533 GrB C/1
DENSITY:	7.84 g/cm^3
IRON (wt%):	96.77 ± 0.13
CARBON (wt%):	0.19 ± ---
MANGANESE (wt%):	1.28 ± 0.03
PHOSPHORUS:	0.004 ± ---
SULFUR:	0.006 ± ---
SILICON:	0.22 ± ---
NICKEL:	0.79 ± 0.14
MOLYBDENUM:	0.49 ± 0.05
CHROMIUM:	0.12 ± 0.01
COPPER:	0.13 ± 0.01

Fig. 4. Description of steel wall.

Assemblies Without Neutron Absorber Plates

Each of the experiments without neutron absorber plates is described in Table III for the 2.35 wt% ^{235}U-enriched fuel and in Table IV for the 4.31 wt% ^{235}U-enriched fuel. The measurement data for the two respective fuels are summarized also in these two tables.

The data for the 2.35 wt% ^{235}U-enriched fuel are shown graphically in Fig. 5 for the near optimum moderated 20.32-mm lattice spacing and in Fig. 6 for the undermoderated 16.84-mm lattice spacing. By referring to the two figures, it can easily be seen that for either lattice spacing the critical separation between the fuel clusters increases as the steel reflecting walls are moved toward the fuel clusters. This increase in critical separation reaches a maximum for either lattice spacing with ~10 mm of water between the walls and the fuel clusters.

The data for the 4.31 wt% ^{235}U-enriched fuel are shown graphically in Fig. 7 for the near optimum moderated 25.40-mm lattice spacing and in Fig. 8 for the undermoderated 18.92-mm lattice spacing. As can be seen in the two figures, the effect that the steel walls have on the critical separation between the fuel clusters of 4.31 wt% ^{235}U-enriched fuel is very similar to that observed for the 2.35 wt% ^{235}U-enriched fuel. As the steel walls are moved toward the fuel clusters, the critical separation between the fuel clusters increases to a maximum and then decreases as the walls continue to be moved toward the fuel clusters. For the 25.40-mm lattice spacing, this maximum effect occurs with ~10 mm of water between the 4.31 wt% ^{235}U-enriched fuel and the steel walls, and thus is very similar to the observations made with the 2.35 wt% ^{235}U-enriched fuel. However, for the undermoderated 18.92-mm lattice spacing, with the 4.31 wt% ^{235}U-enriched fuel, the water separation

TABLE III

Experimental Data on Clusters of 2.35 wt% ^{235}U-Enriched UO_2 Rods in Water with Steel Reflecting Walls*

Distance Between Reflecting Walls and Fuel Clusters[a] (mm)	20.32-mm Square Pitch Fuel Clusters[b]	Critical Separation Between Fuel Clusters[c] (mm)	16.84-mm Square Pitch Fuel Clusters[b]	Critical Separation Between Fuel Clusters[c] (mm)
0	3-19 X 16	106.5 ± 0.3	1-25 X 18 2-20 X 18	89.8 ± 0.1
6.60 ± 1.02	3-19 X 16	112.0 ± 0.3	1-25 X 18 2-20 X 18	95.8 ± 0.7
13.21 ± 0.76	3-19 X 16	112.0 ± 0.2	1-25 X 18 2-20 X 18	95.1 ± 0.2
16.84 ± 0.13	---	---	1-25 X 18 2-20 X 18	96.6 ± 0.8
23.44 ± 1.03	---	---	1-25 X 18 2-20 X 18	92.8 + 0.3
26.16 ± 1.07	3-19 X 16	103.6 ± 0.2	---	---
30.05 ± 0.77	---	---	1-25 X 18 2-20 X 18	90.6 ± 0.2
39.12 ± 1.32	3-19 X 16	95.1 ± 0.5	1-25 X 18 2-20 X 18	85.4 ± 0.2
67.26 ± 1.27	---	---	1-25 X 18 2-20 X 18	76.7 ± 0.6
∞	3-19 X 16	83.1 ± 0.4[d]	1-25 X 18 2-20 X 18	72.4 ± 0.3
∞	3-19 X 16	82.3 ± 0.4	1-25 X 18 2-20 X 18	71.9 ± 0.2[d]

*Error limits shown are one standard deviation. Reflecting walls are 178.5 ± 0.4 mm thick.
[a]Perpendicular distance between the cell boundary of the fuel clusters and the reflecting walls.
[b]Number of fuel clusters, rods long X rods wide, aligned in a row.
[c]Perpendicular distance between fuel clusters, rod surface to rod surface.
[d]Critical separations previously reported in Refs. 4 and 6 for these assemblies.

TABLE IV

Experimental Data on Clusters of 4.31 wt% ^{235}U-Enriched UO_2 Rods in Water with Steel Reflecting Walls*

Distance Between Reflecting Walls and Fuel Clusters[a] (mm)	25.40-mm Square Pitch Fuel Clusters[b]	Critical Separation Between Fuel Clusters[c] (mm)	18.92-mm Square Pitch Fuel Clusters[b]	Critical Separation Between Fuel Clusters[c] (mm)
0	3-13 X 8	128.9 ± 0.2	3-12 X 16	148.7 ± 0.2
6.60 ± 1.02	3-13 X 8	142.5 ± 0.5	3-12 X 16	157.4 ± 0.2
13.21 ± 0.76	3-13 X 8	141.2 ± 0.1	3-12 X 16	158.7 ± 0.1
19.56 ± 1.02	---	---	3-12 X 16	158.4 ± 0.2
26.16 ± 1.07	3-13 X 8	124.4 ± 0.5	3-12 X 16	154.5 ± 0.1
54.05 ± 1.02	3-13 X 8	98.0 ± 0.5	3-12 X 16	138.2 ± 0.3
∞	3-13 X 8	82.3 ± 0.4	3-12 X 16	129.6 ± 0.3
∞	3-13 X 8	82.4 ± 0.3[d]	3-12 X 16	129.8 ± 0.2
∞	---	---	3-12 X 16	127.5 ± 0.1[d]

*Error limits shown are one standard deviation. Reflecting walls are 178.5 ± 0.4 mm thick.
[a]Perpendicular distance between the cell boundary of the fuel clusters and the reflecting walls.
[b]Number of fuel clusters, rods long X rods wide, aligned in a row.
[c]Perpendicular distance between fuel clusters, rod surface to rod surface.
[d]Critical separations previously reported in Refs. 4 and 6 for these assemblies.

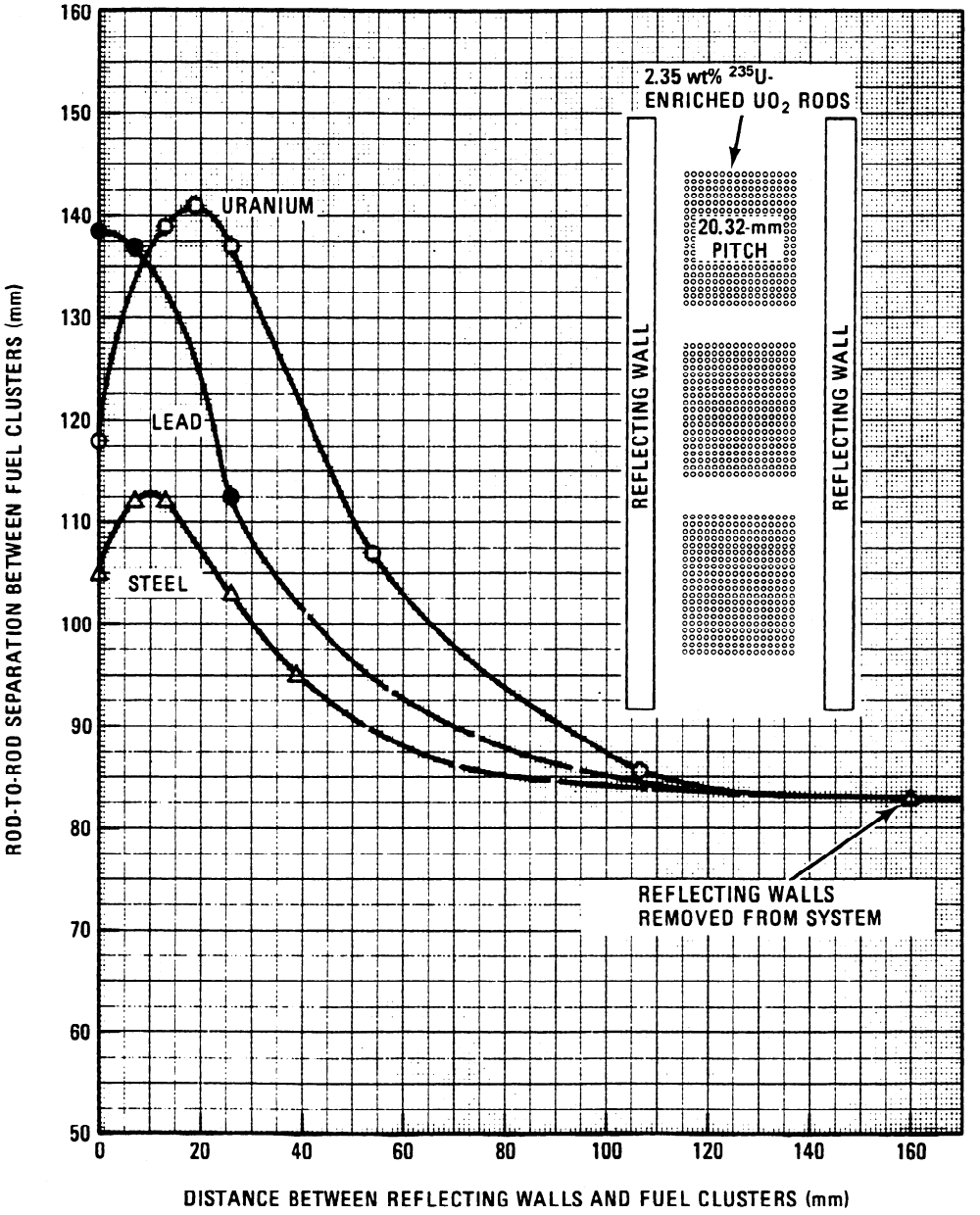


Fig. 5. Critical separation between near optimum moderated fuel clusters of 2.35 wt% ^{235}U-enriched UO_2 rods in water with steel, lead, or depleted uranium reflecting walls.

between fuel and reflecting walls, at which the maximum effect occurs, moved to ~15 mm (see Fig. 7).

The measurements with steel reflecting walls on either side of the near optimum moderated fuel clusters were made with fuel clusters identical to those on which measurements had been previously made with depleted uranium and lead reflecting walls.[4] The results of these previous measurements are shown with the steel wall results in Figs. 5 and 7 to permit easy comparison of the effects that these three types of biological shielding materials have on the critical separation between the fuel clusters. As can be seen in Figs. 5 and 7, the steel and depleted uranium reflecting walls have a similar effect on the critical separation between the fuel clusters. For all three materials, the critical separation between the fuel clusters increases as the reflecting walls are moved toward the fuel clusters. In both the steel and uranium cases, however, this increase in critical separation experiences a maximum with some water between the fuel and the walls. For the uranium walls this maximum occurred with the walls ~20 mm from the

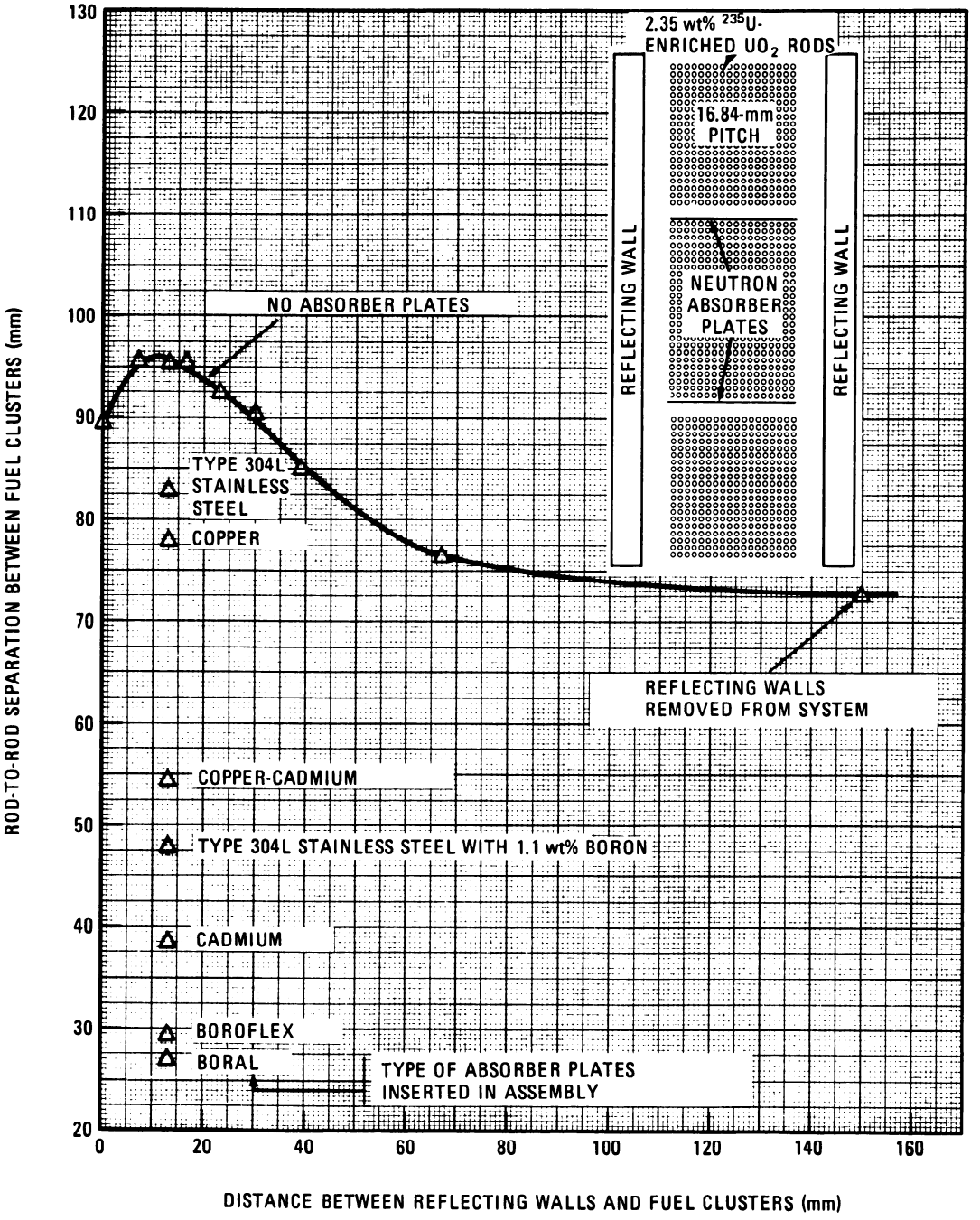


Fig. 6. Critical separation between undermoderated fuel clusters of 2.35 wt% ^{235}U-enriched UO_2 rods in water with steel reflecting walls and fixed neutron absorbers.

fuel cluster for both the 2.35 and the 4.31 wt% ^{235}U-enriched fuel. As discussed earlier, the maximum critical separation occurs with only ~ 10 mm of water between the steel and these same fuel clusters. By comparing the curves in Figs. 5 and 7, it can also be easily seen that, at all wall positions, the steel reflecting walls have less of an effect on the critical separation between the fuel clusters than either the lead or the uranium reflecting walls.

Assemblies with Neutron Absorber Plates

Each of the experiments with neutron absorber plates is described in Table V for the 2.35 wt%

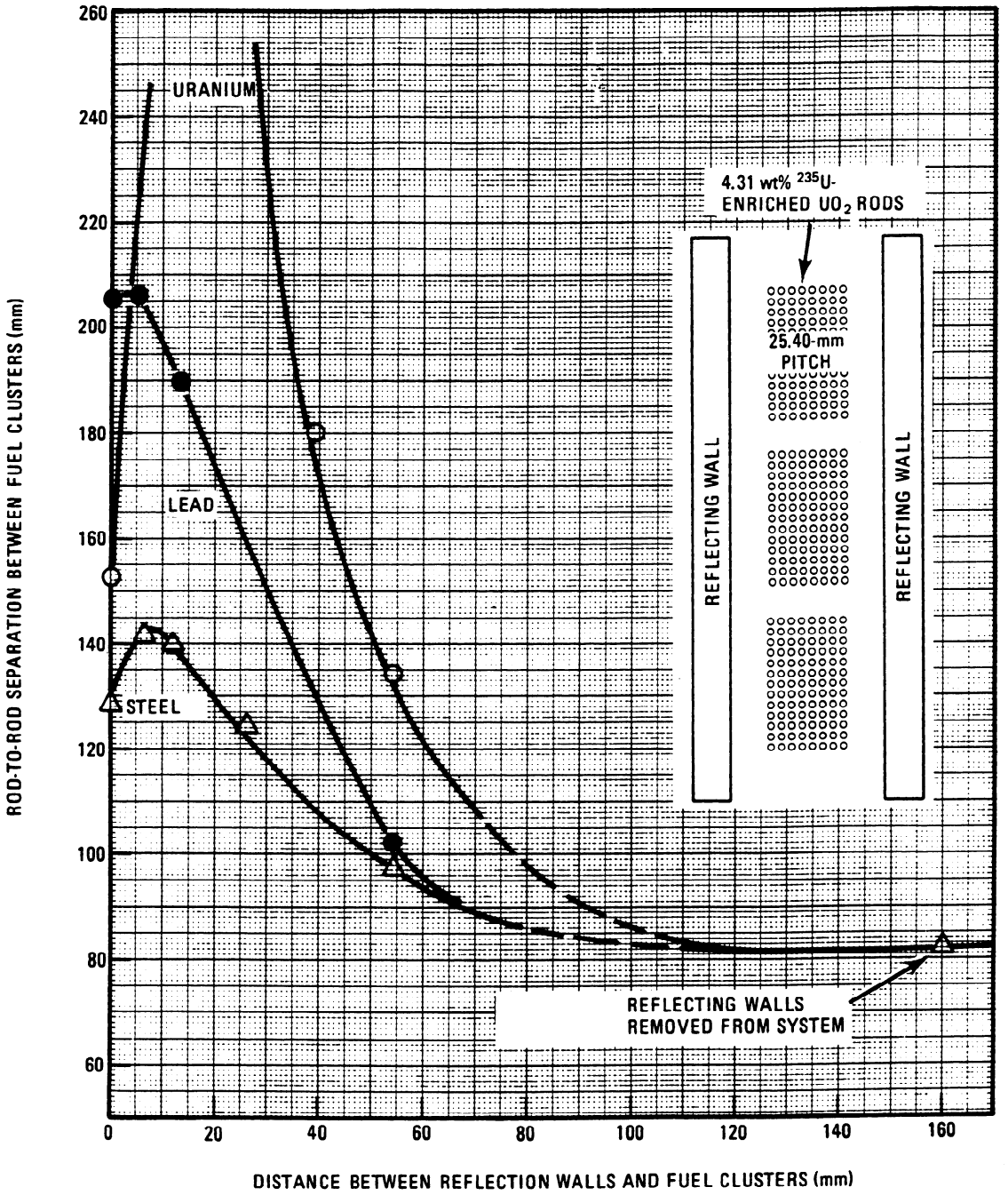


Fig. 7. Critical separation between near optimum moderated fuel clusters of 4.31 wt% ^{235}U-enriched UO_2 rods in water with steel, lead, or depleted uranium reflecting walls.

^{235}U-enriched fuel and in Table VI for the 4.31 wt% ^{235}U-enriched fuel. The measurement data for the two respective fuels are also summarized in these two tables.

Measurements were made for each fuel and absorber plate with the steel reflecting walls positioned at near optimum for criticality with no absorber plates present. For the 2.35 wt% ^{235}U-enriched fuel clusters, the distance between the steel walls and the outer cell boundary of the fuel clusters was 13.21 mm. For the 4.31 wt% ^{235}U-enriched fuel, the distance was 19.56 mm. As discussed earlier, the neutron absorber plates (302 mm wide X 915 mm long) were located between the fuel clusters at the cell boundary of the center fuel cluster. The plates were always centered on the fuel region of the fuel rods.

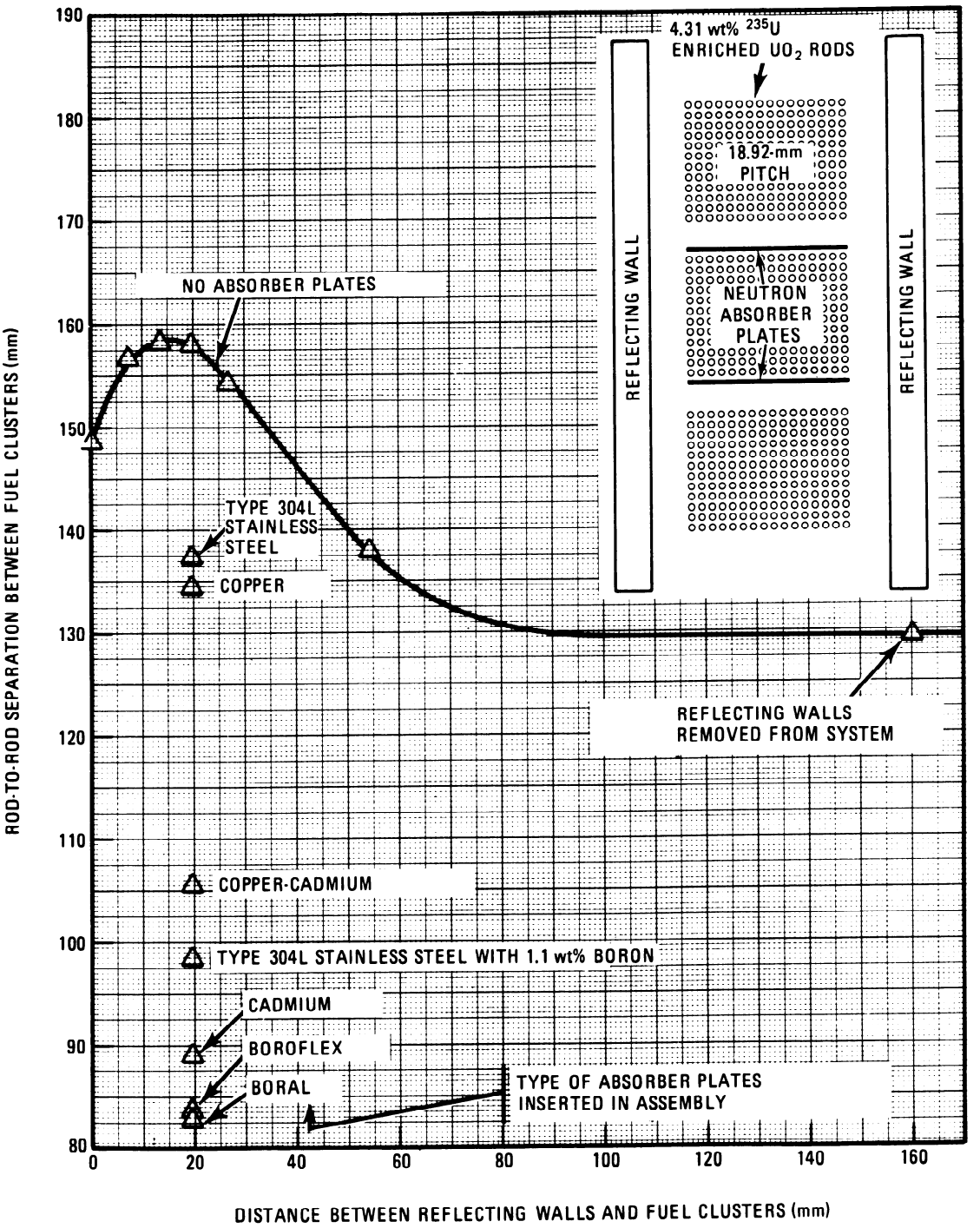


Fig. 8. Critical separation between undermoderated fuel clusters of 4.31 wt% ^{235}U-enriched UO_2 rods in water with steel reflecting walls and fixed neutron absorbers.

The results of the experiments with the 2.35 wt% ^{235}U-enriched fuel are shown in Fig. 6 to permit relative comparisons to be made between the absorber plates and the assembly with no absorber plates. The results with the 4.31 wt% ^{235}U-enriched fuel are similarly shown in Fig. 8.

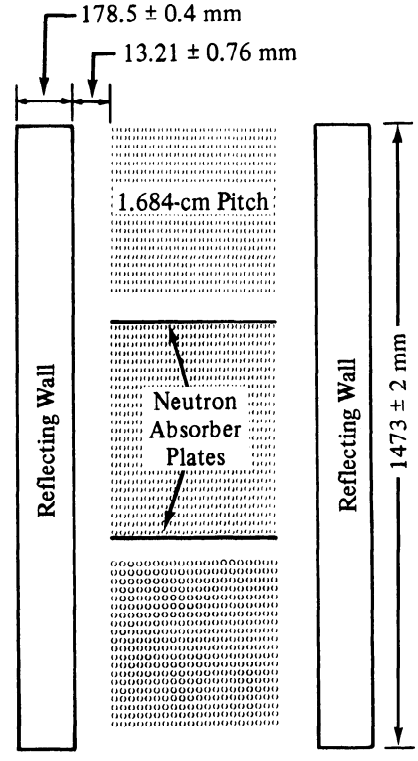
CONCLUSIONS

As with both the depleted uranium and the lead reflecting walls reported on previously,[4] thick steel walls submerged in a water reflecter are a better neutron reflector than water alone. It should be noted,

TABLE V

Experimental Data on Clusters of 2.35 wt% ^{235}U-Enriched UO_2 Rods in Water Reflecting Walls and Fixed Neutron Absorber Plates*

Neutron Absorber[a]		16.84-mm Square Pitch Fuel Clusters[b]	Critical Separation Between Fuel Clusters[c] (mm)
Material	Thickness (mm)		
None	---	1-25 X 18 2-20 X 18	95.1 ± 0.2
Type 304L stainless steel	3.02 ± 0.13	1-25 X 18 2-20 X 18	82.8 ± 0.3
Type 304L stainless steel with 1.1 wt% boron	2.98 ± 0.06	1-25 X 18 2-20 X 18	48.0 ± 0.2
Boral B	2.92 ± 0.13	1-25 X 18 2-20 X 18	26.9 ± 0.3
Boroflex	5.46 ± 0.18[d]	1-25 X 18 2-20 X 18	29.8 ± 0.8
Cadmium	0.61 ± 0.03	1-25 X 18 2-20 X 18	38.6 ± 0.2
Copper	3.37 ± 0.08	1-25 X 18 2-20 X 18	77.9 ± 0.2
Copper-cadmium	3.57 ± 0.08	1-25 X 18 2-20 X 18	54.3 ± 1.0



*Error limits are one standard deviation.
[a]Absorber plates, 302 mm wide X 915 mm long, each centered on middle fuel cluster at outer cell boundary.
[b]Number and size of fuel clusters, rods long X rods wide, aligned in a row.
[c]Perpendicular distance between the fuel clusters, rod surface to rod surface.
[d]Includes 1.60-mm-thick Plexiglas on either side of 2.26- ± 0.04-mm-thick Boroflex.

however, that thin sheets of steel next to fuel clusters submerged in water have a neutron poisoning effect on the system. The reactivity effect as a function of wall thickness was beyond the scope of the experiments reported on herein and was not investigated.

Although not as effective as either lead of depleted uranium in increasing the critical separation between fuel clusters, the effects of the steel reflecting walls are very similar to those observed previously[4] with the depleted uranium. For either, the critical separation between the fuel clusters increased as the reflecting walls were moved toward the fuel clusters. This is also true for lead; however, in the steel and uranium cases, this increase goes through a maximum. For the steel this maximum effect occurs with ~10 mm of water between the reflecting walls and the fuel, whereas the maximum occurs at ~20 mm for the depleted uranium walls.

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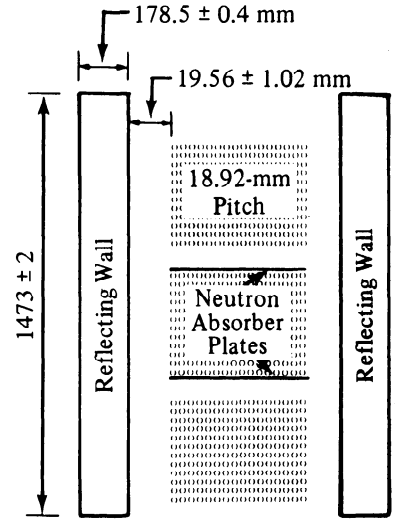
REFERENCES

1. S. R. BIERMAN, B. M. DURST, and E. D. CLAYTON, "Critical Separation Between Subcritical Clusters of 2.35 wt% ^{235}U Enriched UO_2 Rods in Water with Fixed Neutron Poisons," PNL-2438, Pacific Northwest Laboratory (1977).

TABLE VI

Experimental Data on Clusters of 4.31 wt% ^{235}U-Enriched UO_2 Rods in Water Reflecting Walls and Fixed Neutron Absorber Plates*

Neutron Absorber[a]		18.92-mm Square Pitch Fuel Clusters[b]	Critical Separation Between Fuel Clusters[c] (mm)
Material	Thickness (mm)		
None	---	3-12 X 16	158.4 ± 0.2
Type 304L stainless steel	3.02 ± 0.13	3-12 X 16	137.5 ± 0.6
Type 304L stainless steel with 1.1 wt% boron	2.98 ± 0.06	3-12 X 16	98.3 ± 0.4
Boral B	2.92 ± 0.13	3-12 X 16	83.0 ± 0.3
Boroflex	5.46 ± 0.18[d]	3-12 X 16	83.7 ± 0.2
Cadmium	0.61 ± 0.03	3-12 X 16	89.4 ± 0.6
Copper	3.37 ± 0.08	3-12 X 16	134.7 ± 0.4
Copper-cadmium	3.57 ± 0.08	3-12 X 16	105.7 ± 0.2



*Error limits are one standard deviation.
[a]Absorber plates, 302 mm wide X 915 mm long, each centered on middle fuel cluster at outer cell boundary.
[b]Number and size of fuel clusters, rods long X rods wide, aligned in a row.
[c]Perpendicular distance between the fuel clusters, rod surface to rod surface.
[d]Includes 1.60-mm-thick Plexiglas on either side of 2.26- ± 0.04-mm-thick Boroflex.

2. S. R. BIERMAN, B. M. DURST, and E. D. CLAYTON, "Critical Separation Between Subcritical Clusters of 4.31 wt% ^{235}U Enriched UO_2 Rods in Water with Fixed Neutron Poisons," NUREG/CR-0073, U.S. Nuclear Regulatory Commission (1978).

3. S. R. BIERMAN, B. M. DURST, and E. D. CLAYTON, "Critical Separations Between Subcritical Clusters of Low Enriched UO_2 Rods in Water with Fixed Neutron Poisons," *Nucl. Technol.*, **42**, 237 (1979).

4. S. R. BIERMAN, B. M. DURST, and E. D. CLAYTON, "Critical Experiments with Subcritical Clusters of 2.35 wt% and 4.31 wt% ^{235}U Enriched UO_2 Rods in Water with Uranium or Lead Reflecting Walls," NUREG/CR-0796, U.S. Nuclear Regulatory Commission (1979).

5. S. R. BIERMAN, B. M. DURST, and E. D. CLAYTON, "Critical Experiments with Subcritical Clusters of Low Enriched UO_2 Rods in Water with Uranium or Lead Reflecting Walls," *Nucl. Technol.*, **47**, 51 (1980).

6. S. R. BIERMAN and E. D. CLAYTON, "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," NUREG/CR-1547, U.S. Nuclear Regulatory Commission (1980).

7. R. M. WESTFALL, Oak Ridge National Laboratory, Private Communication.