Criticality Experiments with Subcritical Clusters of 2.35 Wt% and 4.31 Wt% ^{235}U Enriched UO_2 Rods in Water with Steel Reflecting Walls

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Pacific Northwest Laboratory
Operated by
Battelle Memorial Institute

Prepared for
U.S. Nuclear Regulatory
Commission

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Manuscript Completed: January 1981

Date Published: April 1981

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Prepared for

Division of Safeguards, Fuel Cycle and Environmental Research

Office of Nuclear Regulatory Research

U.S. Nuclear Regulatory Commission

Washington, D.C. 20555

NRC FIN B2094

ABSTRACT

A series of criticality experiments with 2.35 wt% and 4.31 wt% ^{235}U enriched UO_2 rods in water were performed to provide well defined benchmark type data on the effects of 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 towards 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 towards the fuel clusters. This maximum effect was observed with about 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 304-L steel, borated 304-L steel, copper, copper containing 1 wt% cadmium, cadmium, and two trade name materials containing boron (Boral and Boroflex). A comparison between these data and data from previous experiments indicates a slight reduction in the effectiveness of the absorber plates when the steel reflecting walls are present.

SUMMARY

The results from the fifth in a series of criticality experiments funded by the United States Nuclear Regulatory Commission are presented in this paper. The initial four 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 and at an undermoderated water-to-fuel volume ratio of 1.6. The effect that various neutron absorber plates, positioned between the fuel clusters, had on the critical separation was investigated in these previous experiments. Also the effect that lead and depleted uranium reflecting walls had on the critical separation was investigated at near optimum neutron moderation in these earlier experiments. This fifth series of experiments involve the same fuel immersed in water at the same neutron moderation as before but with 178.5 mm thick reactor grade steel reflecting walls parallel on either side of and at various distances from three subcritical fuel clusters aligned in a row.

Measurements similar to those performed previously with lead and depleted uranium reflecting walls were repeated with the steel walls. In addition, at the wall location having maximum effect on criticality, measurement data were obtained, for both enrichments, with neutron absorber plates between the fuel clusters having the 1.6 water-to-fuel volume ratio. The fixed neutron absorbers for which data were obtained include 304-L steel, borated

304-L steel, copper, copper containing 1 wt% cadmium, cadmium, and two trade name materials containing boron (Boral and Boroflex).

As was observed previously with the depleted uranium and the lead reflecting walls, the steel walls submerged in the water reflector were found to provide better neutron reflection than water alone. Although not as effective as either lead or depleted uranium in increasing the critical separation between the fuel clusters, the effects of the steel reflecting walls are very similar to those observed with the depleted uranium. For either the steel or depleted uranium, the critical separation between fuel clusters increased to a maximum as the reflecting walls were moved towards the fuel clusters. This maximum effect was observed with about 10 mm of water between the steel walls and the fuel clusters (compared to the about 20 mm previously observed for the depleted uranium reflecting walls). As this 10 mm water gap was decreased, the critical separation between the fuel clusters also decreased slightly.

The steel reflecting walls were found to have a negative effect on the neutron absorber plates positioned between the fuel clusters. A comparison between these data and data from previous experiments indicate that the effectiveness of the neutron absorber plates to reduce the critical separation between fuel clusters is reduced slightly by the presence of the steel reflecting walls.

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PREFACE

The results obtained in a fifth set of criticality experiments for the United States Nuclear Regulatory Commission (NRC) are presented herein. The primary objective in all of these NRC experiments has been to provide clean, well defined, integral data that could be described in calculations exactly as-run without corrections or approximations having to be made. The data are thus primarily intended for use in validating calculational techniques.

The same UO_2 fuel, lattice grid plates, neutron absorber plates, and reflecting walls have been used throughout these experiments. However, during this period of time, some of these parameters have become better defined as a result of repeated analysis. For example, the 4.31 wt% ^{235}U enriched UO_2 rods were originally identified as having a ^{235}U enrichment of 4.29 wt%. Multiple analysis of the rods during the course of these five sets of experiments have resulted in the more correct average of 4.31 wt% quoted in this and some of the more recent reports. Although there are no redefinitions of significance, the values quoted in this report should be considered the latest and, hopefully, the more correct values to use.

The authors wish to especially acknowledge the contributions of J. H. Smith, Senior Reactor Operator at the Hanford Critical Mass Laboratory,

for his assistance in the performance of these criticality experiments and of L. N. Terry in the typing of this document. The authors would also like to acknowledge the continuous support and guidance of Richard H. Odegarden and Donald E. Solberg of the U. S. Nuclear Regulatory Commission as well as G. E. Whitesides and R. M. Westfall of ORNL.

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

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 results of four sets of experiments in this program have been reported in previous NUREG documents.^(1,2,3,4) These earlier four sets of experiments were concerned with:

- 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,
- 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,

- fuel clusters of 2.35 wt% 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,
- fuel clusters of 2.35 wt% 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 were also made with some fuel clusters containing water holes.

The results from a fifth set of experiments are covered in this report 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. (Measurements involving both fixed poisons and reflecting walls simultaneously were never performed in previous experiments).

The objective of these latest experiments, as in the previous experiments, is to provide clean, well defined, 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 sub-critical 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 Figure 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 Figure 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 Figure 2. All structural materials are on the periphery of the experimental assembly except for four 51 mm wide type 6061 aluminium spacer bars between the fuel and reflecting walls, the lattice

FIGURE 1. PHOTOGRAPH OF A TYPICAL EXPERIMENTAL ASSEMBLY

FIGURE 2. GRAPHICAL ARRANGEMENT OF SIMULATED SHIPPING CONTAINER CRITICAL EXPERIMENTS

grid plates and the aluminum guides for the safety and control blades. The lattice grid plates for the near optimum neutron moderated experiments were fabricated from acrylic (1.185 g/cm^3 , 8 wt% H, 60 wt% C, 32 wt% O) sheets, 12.7 mm thick. 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 wt% 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 ratio of 2.92 and 3.88 for the 2.35 wt% 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 was 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 critical separation between the clusters was also investigated at the 1.6 water-to-fuel volume ratio and a single position of the reflecting walls for each enrichment:

- 304-L Steel
- 304-L Steel with 1.1 wt% B
- Boraltm
- Boroflextm
- Cadmium
- Copper
- Copper with 1 wt% Cd

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 Figure 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 fuel rod is given in Figure 3. The chemical impurities of the water used in these experiments are given in Table I. The steel reflecting walls are described in Figure 4 and, except for their length and width, which was respectively 915 mm and 302 mm, each of the absorber plates are 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

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

4.31 wt% ^{235}U ENRICHED UO_2 RODS

CLADDING: 6061 ALUMINUM TUBING

LOADING:

ENRICHMENT - 4.31 ± 0.01 wt% ^{235}U

FUEL DENSITY - $94.9 \pm 0.55\%$ 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/cm³

COMPOSITION- C - 58 ± 1 wt%

H - 6.5 ± 0.3 wt%

Ca - 11.4 ± 1.8 wt%

S - 1.7 ± 0.2 wt%

O - 22.1 wt% (BALANCE)

Si - 0.3 ± 0.1 wt%

2.35 wt% ^{235}U UNENRICHED 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/mm³ (84% THEORETICAL DENSITY)

URANIUM ASSAY - 88.0 wt%

UO_2 - 825 g/ROD (AVERAGE)

FIGURE 3. DESCRIPTION OF FUEL RODS

TABLE I
WATER IMPURITIES

COMPONENT	CONCENTRATION g / m ³ (ppm)
Cl	≤5
NO ₃	0.02
Cr ⁺⁶	<0.01
Zn	16
Mn	<0.01
Pb	<0.005
F	0.18
Fe	24
Cu	<0.01
Cd	0.001
SO ₃	14.5
DISSOLVED SOLIDS	61 ± 3

FIGURE 4. DESCRIPTION OF STEEL WALLS

TABLE II
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	0.226 ± 0.004 0.452 ± 0.006

(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 B₄C-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.

neutron reflection. R. M. Westfall of the Oak Ridge National Laboratory determined this thickness to be about 175 mm (~ 7 inches) from calculations on an assembly representative of the experimental assemblies. Consequently, the measurements were performed with steel plate having a nominal thickness of seven inches (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 the manufacturer, these particles have the following size distribution:

<u>Particle Size</u> <u>(mm)</u>	<u>Wt% Particle Distribution</u>	
	<u>Boral</u>	<u>Boroflex</u>
> 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).

ASSEMBLIES WITHOUT NEUTRON ABSORBER PLATES

Each of the experiments without neutron absorber plates are 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 is shown graphically in Figure 5 for the near optimum moderated 20.32 mm lattice spacing and in Figure 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 about 10 mm of water between the walls and the fuel clusters.

The data for the 4.31 wt% ^{235}U enriched fuel is shown graphically in Figure 7 for the near optimum moderated 25.40 mm lattice spacing and in Figure 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 towards the fuel clusters. For the 25.40 mm lattice spacing this maximum effect occurs with about 10 mm of

TABLE III
EXPERIMENTAL DATA ON CLUSTERS OF 2.35 WT% ^{235}U ENRICHED UO_2 RODS
IN WATER WITH STEEL REFLECTING WALLS (a)

DISTANCE BETWEEN REFLECTING WALLS AND FUEL CLUSTERS (b) (mm)	20.32 mm SQUARE PITCH FUEL CLUSTERS (c)	CRITICAL SEPARATION BETWEEN FUEL CLUSTERS (d) (mm)	16.84 mm SQUARE PITCH FUEL CLUSTERS (c)	CRITICAL SEPARATION BETWEEN FUEL CLUSTERS (d) (mm)
0	3-19 x 16	106.5 $\pm$ 0.3	1-25 x 18 2-20 x 18	89.8 $\pm$ 0.1
6.60 $\pm$ 1.02	3-19 x 16	112.0 $\pm$ 0.3	1-25 x 18 2-20 x 18	95.8 $\pm$ 0.7
13.21 $\pm$ 0.76	3-19 x 16	112.0 $\pm$ 0.2	1-25 x 18 2-20 x 18	95.1 $\pm$ 0.2
16.84 $\pm$ 0.13	-	-	1-25 x 18 2-20 x 18	96.6 $\pm$ 0.8
23.44 $\pm$ 1.03	-	-	1-25 x 18 2-20 x 18	92.8 $\pm$ 0.3
26.16 $\pm$ 1.07	3-19 x 16	103.6 $\pm$ 0.2	-	-
30.05 $\pm$ 0.77	-	-	1-25 x 18 2-20 x 18	90.6 $\pm$ 0.2
39.12 $\pm$ 1.32	3-19 x 16	95.1 $\pm$ 0.5	1-25 x 18 2-20 x 18	85.4 $\pm$ 0.2
67.26 $\pm$ 1.27	-	-	1-25 x 18 2-20 x 18	76.7 $\pm$ 0.6
∞	3-19 x 16	83.1 $\pm$ 0.4 (e)	1-25 x 18 2-20 x 18	72.4 $\pm$ 0.3
∞	3-19 x 16	82.3 $\pm$ 0.4	1-25 x 18 2-20 x 18	71.9 $\pm$ 0.2 (e)

(a) ERROR LIMITS SHOWN ARE ONE STANDARD DEVIATION. REFLECTING WALLS ARE 178.5 $\pm$ 0.4 mm THICK

(b) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARY OF THE FUEL CLUSTERS AND THE REFLECTING WALLS

(c) NUMBER OF FUEL CLUSTERS, RODS LONG x RODS WIDE, ALIGNED IN A ROW

(d) PERPENDICULAR DISTANCE BETWEEN FUEL CLUSTERS, ROD SURFACE TO ROD SURFACE

(e) CRITICAL SEPARATIONS PREVIOUSLY REPORTED IN NUREG/CR -0796 OR NUREG/CR -1547 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 (a)

DISTANCE BETWEEN REFLECTING WALLS AND FUEL CLUSTERS (b) (mm)	25.40 mm SQUARE PITCH FUEL CLUSTERS (c)	CRITICAL SEPARATION BETWEEN FUEL CLUSTERS (d) (mm)	18.92 mm SQUARE PITCH FUEL CLUSTERS (c)	CRITICAL SEPARATION BETWEEN FUEL CLUSTERS (d) (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 (e)	3-12 x 16	129.8 ± 0.2
∞	-	-	3-12 x 16	127.5 ± 0.1 (e)

(a) ERROR LIMITS SHOWN ARE ONE STANDARD DEVIATION, REFLECTING WALLS ARE 178.5 ± 0.4 mm THICK

(b) PERPENDICULAR DISTANCE BETWEEN THE CELL BOUNDARY OF THE FUEL CLUSTERS AND THE REFLECTING WALLS

(c) NUMBER OF FUEL CLUSTERS, RODS LONG x RODS WIDE, ALIGNED IN A ROW

(d) PERPENDICULAR DISTANCE BETWEEN FUEL CLUSTERS, ROD SURFACE TO ROD SURFACE,

(e) CRITICAL SEPARATIONS PREVIOUSLY REPORTED FOR THESE ASSEMBLIES IN NUREG/CR - 0796 OR IN NUREG/CR - 1547

FIGURE 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

FIGURE 6. CRITICAL SEPARATION BETWEEN UNDER-MODERATED FUEL CLUSTERS OF 2.35 WT% ^{235}U ENRICHED UO_2 RODS IN WATER WITH STEEL REFLECTING WALLS AND FIXED NEUTRON ABSORBERS

FIGURE 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

FIGURE 8. CRITICAL SEPARATION BETWEEN UNDER-MODERATED FUEL CLUSTERS OF 4.31 WT% ^{235}U ENRICHED UO_2 RODS IN WATER WITH STEEL REFLECTING WALLS AND FIXED NEUTRON ABSORBERS

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 between fuel and reflecting walls, at which the maximum effect occurs, moved to about 15 mm (See Figure 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.⁽³⁾ The results of these previous measurements are shown with the steel wall results in Figure 5 and 7 to permit easily comparing the effects that these three types of biological shielding materials have on the critical separation between the fuel clusters. As can be seen in Figures 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 towards 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 about 20 mm from the fuel cluster for both the 2.35 wt% and the 4.31 wt% ^{235}U enriched fuel. As discussed earlier, the maximum critical separation occurs with only about 10 mm of water between the steel and these same fuel clusters. By comparing the curves in Figure 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 are described in Table V for the 2.35 wt% ^{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 summarized also 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 by 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.

The results of the experiments with the 2.35 wt% ^{235}U enriched fuel are shown graphically in Figure 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 Figure 8.

TABLE V
EXPERIMENTAL DATA ON CLUSTERS OF 2.35 WT% ²³⁵U ENRICHED UO₂ RODS IN WATER
REFLECTING WALLS AND FIXED NEUTRON ABSORBER PLATES (a)

NEUTRON ABSORBER (b) MATERIAL	THICKNESS (mm)	16.84 mm SQUARE PITCH FUEL CLUSTERS (c)	CRITICAL SEPARATION BETWEEN FUEL CLUSTERS (d) mm
NONE		1-25 x 18 2-20 x 18	95.1 ± 0.2
304-L STEEL	3.02 ± 0.13	1-25 x 18 2-20 x 18	82.8 ± 0.3
304-L STEEL WITH 1.1 WT. % B	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 (e)	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

(a) ERROR LIMITS ARE ONE STANDARD DEVIATION.

(b) ABSORBER PLATES, 302 mm WIDY BY 915 mm LONG, EACH CENTERED ON MIDDLE FUEL CLUSTER AT OUTER CELL BOUNDARY.

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

(d) PERPENDICULAR DISTANCE BETWEEN THE FUEL CLUSTERS, ROD SURFACE TO ROD SURFACE.

(e) INCLUDES 1.60 mm THICK PLEXIGLAS ON EITHER SIDE OF 2.26 ± 0.04 mm THICK BOROFLEX.

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 (a)

NEUTRON ABSORBER (b) MATERIAL	THICKNESS (mm)	18.92 mm SQUARE PITCH FUEL CLUSTERS (c)	CRITICAL SEPARATION BETWEEN FUEL CLUSTERS (d) mm
NONE	-	3-12 x 16	158.4 $\pm$ 0.2
304-L STEEL	3.02 $\pm$ 0.13	3-12 x 16	137.5 $\pm$ 0.6
304-L STEEL WITH 11.1 WT. % B	2.98 $\pm$ 0.06	3-12 x 16	98.3 $\pm$ 0.4
BORAL B	2.92 $\pm$ 0.13	3-12 x 16	83.0 $\pm$ 0.3
BOROFLEX	5.46 $\pm$ 0.18 (e)	3-12 x 16	83.7 $\pm$ 0.2
CADMIUM	0.61 $\pm$ 0.03	3-12 x 16	89.4 $\pm$ 0.6
COPPER	3.37 $\pm$ 0.08	3-12 x 16	134.7 $\pm$ 0.4
COPPER-CADMIUM	3.57 $\pm$ 0.08	3-12 x 16	105.7 $\pm$ 0.2

(a) ERROR LIMITS ARE ONE STANDARD DEVIATION.

(b) ABSORBER PLATES, 302 mm WIDY BY 915 mm LONG, EACH CENTERED ON MIDDLE FUEL CLUSTER AT OUTER CELL BOUNDARY.

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

(d) PERPENDICULAR DISTANCE BETWEEN THE FUEL CLUSTERS, ROD SURFACE TO ROD SURFACE

(e) INCLUDES 1.60 mm THICK PLEXIGLAS ON EITHER SIDE OF 2.26 $\pm$ 0.04 mm THICK BOROFLEX.

Measurements similar to those described in Tables V and VI, but without the reflecting walls, were reported on in NUREG/CR-1547.⁽⁴⁾ The results from some of these earlier experiments can be compared directly with these current experiments. Measurements were performed with the same neutron absorber plates in both the earlier and the current series of experiments; however, the geometries are identical in both cases for only the 4.31 wt% ^{235}U enriched assemblies. (This due partially to the size of some of the neutron absorber plates, partially to the amount of 2.35 wt% enriched fuel available, and partially to the earlier experiments being designed primarily to obtain data in a four cluster rectangular geometry). These comparable results are presented in Table VII. The data consistently indicates that the presence of the steel reflecting walls decreases the poisoning effect of the neutron absorber plates. As indicated in Table VII, this decrease was observed to be about 5% for the more effective absorber plates and only about 1% for the less effective plates.

TABLE VII
EFFECT OF STEEL REFLECTING WALLS ON THE EFFECTIVENESS
OF FIXED NEUTRON ABSORBER PLATES^(a)

4.31 wt% ²³⁵U ENRICHED UO₂ RODS IN WATER

NEUTRON ABSORBER ^(b)		18.92 mm SQUARE PITCH FUEL CLUSTERS ^(c)	CRITICAL SEPARATION ^(d)		CHANGE IN CRITICAL SEPARATION	
MATERIAL	THICKNESS (mm)		WITH WALLS (mm)	WITHOUT WALLS (mm)	WITH WALLS (%)	WITHOUT WALLS (%)
NONE	--	3-12 x 16	158.4 ± 0.2	122.7 ± 0.2	0	0
304-L STEEL	3.02 ± 0.13	3-12 x 16	137.5 ± 0.6	105.2 ± 0.2	-13.2	-14.3
304-L STEEL WITH 1.1 wt% B	2.98 ± 0.06	3-12 x 16	98.3 ± 0.4	72.3 ± 0.2	-38.0	-41.1
COPPER	3.37 ± 0.08	3-12 x 16	134.7 ± 0.4	103.6 ± 0.2	-15.0	-15.6
COPPER- CADMIUM	3.57 ± 0.08	3-12 x 16	105.7 ± 0.2	76.1 ± 0.2	-33.3	-38.0

(a) ERROR LIMITS ARE ONE STANDARD DEVIATION

(b) ABSORBER PLATES, 302 mm WIDE BY 915 mm LONG, EACH CENTERED ON MIDDLE FUEL CLUSTER AT OUTER CELL BOUNDARY

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

(d) PERPENDICULAR DISTANCE BETWEEN THE FUEL CLUSTERS, ROD SURFACE TO ROD SURFACE

CONCLUSIONS

As with both the depleted uranium and the lead reflecting walls reported on previously⁽³⁾, thick steel walls submerged in a water reflector are a better neutron reflector than water alone. It should be noted however, that thin sheets of steel next to fuel clusters submerged in water have a neutron poisoning effect on the system.⁽⁵⁾ 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 or depleted uranium in increasing the critical separation between fuel clusters, the effects of the steel reflecting walls are very similar to those observed previously⁽³⁾ with the depleted uranium. For either, the critical separation between the fuel clusters increased as the reflecting walls were moved towards the fuel clusters. This is true also for lead; however, in the steel and uranium cases this increase goes through a maximum. For the steel this maximum effect occurs with about 10 mm of water between the reflecting walls and the fuel; whereas, the maximum occurs at about 20 mm for the depleted uranium walls.

The data from these and previous⁽⁴⁾ experiments indicate the effectiveness of the neutron absorber plates to reduce the critical separation between fuel clusters is decreased slightly by the presence of the steel reflecting walls.

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. Available from Technical Information Files, Pacific Northwest Laboratory, PO Box 99, Richland, WA 99352.
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, USNRC Report, NUREG/CR-0073, 1978. Available from National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.
3. 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, USNRC Report, NUREG/CR-0796, 1979. Available from National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.*
4. 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, USNRC Report, NUREG/CR-1547, 1980. Available from National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Road, Springfield, VA 22161.*

5. R. C. Lloyd, E. D. Clayton, L. E. Hansen, and S. R. Bierman,
"Criticality of Plutonium Nitrate Solutions In Slab Geometry,"
Nuclear Technology, 18: 225-230, 1973. Available from American
Nuclear Society, 555 North Kensington Avenue, LaGrange Park, IL
60525.

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	Technical Information (5)
	Publishing Coordination (2)

NRC FORM 335 (7-77)		U.S. NUCLEAR REGULATORY COMMISSION BIBLIOGRAPHIC DATA SHEET		1. REPORT NUMBER (Assigned by DDC) NUREG/CR-1784 PNL-3602	
4. TITLE AND SUBTITLE (Add Volume No., if appropriate) Criticality Experiments With Subcritical Clusters of 2.35 Wt% and 4.31 Wt% ^{235}U Enriched UO_2 Rods in Water with Steel Reflecting Walls				2. (Leave blank)	
				3. RECIPIENT'S ACCESSION NO.	
7. AUTHOR(S) S.R. Bierman and E. D. Clayton				5. DATE REPORT COMPLETED MONTH: January YEAR: 1981	
9. PERFORMING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Pacific Northwest Laboratory Richland, WA 99352				DATE REPORT ISSUED MONTH: April YEAR: 1981	
				6. (Leave blank)	
				8. (Leave blank)	
12. SPONSORING ORGANIZATION NAME AND MAILING ADDRESS (Include Zip Code) Division of Safeguards, Fuel Cycle and Environmental Research Office of Nuclear Regulatory Research U.S. Nuclear Regulatory Commission Washington, DC 20555				10. PROJECT/TASK/WORK UNIT NO.	
				11. CONTRACT NO. NRC Fin. No. 82094	
13. TYPE OF REPORT			PERIOD COVERED (Inclusive dates)		
15. SUPPLEMENTARY NOTES				14. (Leave blank)	
16. ABSTRACT (200 words or less) <p>The results from the fifth in a series of criticality experiments, are presented in this paper. This fifth 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. This latest set of measurements are concerned with determining the effect that thick reactor grade steel reflecting walls adjacent to the fuel clusters have on the critical separation between the fuel clusters.</p>					
17. KEY WORDS AND DOCUMENT ANALYSIS			17a. DESCRIPTORS		
17b. IDENTIFIERS/OPEN-ENDED TERMS					
18. AVAILABILITY STATEMENT Unlimited			19. SECURITY CLASS (This report) Unclassified		21. NO. OF PAGES
			20. SECURITY CLASS (This page) Unclassified		22. PRICE \$