WATER-MODERATED RECTANGULAR CLUSTERS OF $U(4.31)O_2$ FUEL RODS (2.54-CM PITCH) SEPARATED BY STEEL, BORAL, COPPER, CADMIUM, ALUMINUM, OR ZIRCALOY-4 PLATES

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1.0 DETAILED DESCRIPTION

1.1 Overview of Experiment

A series of critical-approach experiments with clusters of 36-inch-long aluminum-clad $U(4.31)O_2$ fuel rods in a large water-filled tank was performed over the course of several years at the Critical Mass Laboratory at the Pacific Northwest Laboratories (PNL). Experiments included square-pitched lattice clusters with pitches of 2.54 cm or 1.892 cm. Some of these experiments were simply rod clusters in water (LEU-COMP-THERM-002 and LEU-COMP-THERM-004). Others added lead, depleted-uranium, or steel reflecting walls on two opposite sides of the cluster row (LEU-COMP-THERM-010). Some circular, triangular-pitched lattices, with pitches of 2.4, 1.8, or 1.6 cm, were used to measure the effect of gadolinium dissolved in the water (LEU-COMP-THERM-005).

This evaluation documents water-reflected experiments with 3 rectangular clusters of 2.54-cm-pitched rods. Two absorber plates separated the two outer clusters from the center one. The plates were stainless steel, borated stainless steel, Boral, copper, copper with 1% cadmium, cadmium, aluminum, or Zircaloy-4. A total of 27 experiments, performed in 1977, were evaluated.

The effect of the absorber plates is not large. The reactivity worths of the non-borated steel, copper without cadmium, aluminum, and Zircaloy-4 plates were calculated to be less than 0.85% of k_{eff}. Other plates were worth less than 2.5% of k_{eff}.

Because of the adequacy of the experimental data, all of these experiments are judged to be acceptable as benchmarks.

1.2 Description of Experimental Configuration

Information in this section comes from References 1 - 10, which are the original PNL reports of these experiments. References 11 - 15, logbooks, and conversations with experimenters provided supplementary information. Unless otherwise noted, data is from References 2 and 12. Details from other references are so noted.

1.2.1 Experiment Tank and Surroundings[a] **-** Experiments were performed in a 9.52-mm-thick, open, carbon-steel tank. (See Figures 1 and 2) Tank inside dimensions were 1.8 x 3 x 2.1 meters deep. The experiments were centered in the tank to within one-quarter inch. Nothing other than fuel rods, absorber plates, radiation detectors, and support structures (acrylic support plate and lattice plates, aluminum rod and angle supports, and control/safety-blade guides, all described in this section) was in the tank. Any control or safety rods or blades were withdrawn above the top water reflector.

The experiment tank was located in one corner of the Critical Mass Laboratory at the Pacific Northwest Laboratories, Hanford, Washington. The tank sat upon a concrete floor, which was at least 40.6 cm thick (Reference 11, p. 32). The concrete walls of the room were 5 feet thick. The concrete ceiling was 2 feet thick and approximately 20 feet high. The tank was located approximately four feet from the two closest corner walls.

[a] Tank dimensions were from Reference 2. Other information was from private communication, Sid Bierman, July, 1993.

Figure 1. Loading a Fuel Rod.

Figure 2. Experiment Tank, Lattice Plates for 3 Clusters, and Control/Safety Blades.

1.2.2 Fuel-Rod Support Plate - The bottoms of the fuel rods were supported by a 2.54-cm-thick acrylic support plate. The width and length of the support plate were approximately the width and length of the clusters. The plate was supported under its long edges by two 15.3 x 5.08 x 0.635-cm 6061-aluminum channels oriented so that the bottom of the plate was 15.3 cm above the bottom of the tank.[a]

1.2.3 Lattice Plates and Supports - The pitch of the fuel rods was maintained by two levels of 1.27-cm-thick acrylic (Plexiglas) lattice plates. Holes for the fuel rods were no more than 5 mils (0.0127 cm) larger than the rod diameter.[b]

The top lattice plates were ~66-78 cm above the fuel-rod support plate.[c] They were joined by half-inch-diameter vertical aluminum rods (83.9 cm long) to 5.08 x 5.08 x 0.635-cm aluminum angles,

[a] There may have been a separate support plate for each cluster for the 3-cluster experiments. (Private communication, Sid Bierman, August, 1993)

[b] Private communication, Sid Bierman, August, 1993.

[c] Sid Bierman estimated that the top lattice plate was about 6 inches below the top of the fuel (Private communication, August, 1993). Also this can be estimated from the photo in Reference 3, p. 3, which was obviously of the $U(4.31)O_2$ rods because the clusters were 8 rods wide.

which were attached at their ends to the walls of the tank. In one experiment with 2.35-wt.%-enriched fuel rods, these aluminum supports were doubled, with no effect on the critical separation between clusters (Reference 1, pp. 26 and 28). These experiments were not repeated with 4.31% enriched rods. However, the experimenters report, "Since the support structures are further from the fuel clusters in the experiments covered by this report, they would have even less of an effect on the data. Consequently, the measurements to determine the effect of the supports were not repeated for these current experiments." (Reference 2, p. 22)

The bottom lattice plates were raised above the support plate by putting 5- or 6-inch lengths of Tygon plastic tubing on 4 or 5 of the fuel rods under each bottom lattice plate.[a]

The use of shims was sometimes necessary[a] in order to accurately position the rod clusters and absorber plates. The required horizontal separation between bottom lattice plates or between lattice plates and the control/safety blade guides, was maintained by small Lucite or acrylic shims. The Lucite shim was approximately 1 inch thick.

1.2.4 Safety and Control Blade Guides - The aluminum control and safety blade guides were located between clusters. The blade guides, two for the control blade and two for the safety blade, extended from the bottom of the fuel-pin array to well above the water surface. Two slightly different sizes of guides were used at different times throughout the entire series of experiments.[a] The guides were 3.8 cm wide and were either 2.54 cm thick (Reference 3, p. 5) or 1.27 cm thick (Reference 4, p. 27), with a slot for the blades that was either 0.96 cm wide or 0.64 cm wide, respectively. The distance between the two guides for each blade could be adjusted, depending on the width of the blade.

During one experiment from a set of similar experiments using 2.35-wt.%-enriched UO_2 rods, the amount of aluminum of the control and safety blade guides was doubled. The results demonstrated "no change in the predicted critical separation between fuel-rod clusters" (Reference 1, pp. 13 and 28).

1.2.5 Radiation Detectors - The boron-lined proportional counters (usually three in number) were placed symmetrically around the experiments. The detectors were kept dry by being placed in aluminum tubes that extended above the top surface of the water. The elevation of the detectors varied, depending on the buoyancy of the tube holding the detector. The aluminum tubes were approximately 1.5 inches in diameter and were placed about 30 cm from the experimental assembly, always outside a 15-cm thickness of water.[b]

1.2.6 Water Reflector - The top water surface was always at least 15 cm above the top of the fuel region of the rods. (Reference 14, p. 132)[c] The bottom water reflector also was at least 15 centimeters thick, since the aluminum angle supporting the fuel-rod support plate above the bottom of the tank was 15.3-cm high. The longer side of the experiment was parallel to the longer side of

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[a] Private communication, Sid Bierman, August, 1993.

[b] Private communication, Sid Bierman, July, 1993.

[c] Confirmed by private communication, Sid Bierman, July, 1994.

the tank[a] so that the minimum reflector thickness in the horizontal direction for these experiments was about 70 centimeters.

Water temperatures were recorded in logbooks for approximately ten percent of all the experiments of the series reported in References 1-10, 12, and 14. Recorded temperatures ranged from 18 to 26°C. The logbook gave the water temperatures for five of the experiments evaluated here. They were 23°C (Cases 13 and 14) and 25°C (Cases 3, 4, and 24).

1.2.7 Neutron-Absorber Plates - The neutron-absorber plates were positioned between the clusters on either side of the middle cluster parallel to the interacting cluster surfaces. For each experiment they were at a fixed distance from the rod cell outer boundaries of the center cluster. Diagrams in the references show the plates centered horizontally with respect to the line of clusters, i.e., they extend on both sides by the same amount. The distance between absorber plate and center cluster was measured at several different horizontal positions to ensure that the plates were correctly positioned.[b]

The absorber plates were all 91.5 cm long and were 35.6 cm wide except for the two thinner sets of copper plates which were 30.6 cm wide. The plates were all wider than the rod clusters, which were 20.32 cm (8 rods) wide, but were only slightly longer than the nominal fuel-region length, which was 36 inches (91.44 cm). The absorber plates were positioned “to avoid a direct line of sight between rods of different clusters” (Reference 12, p. 142). An experimenter remembered that for some experiments a thick Lucite shim was used, probably beneath the absorber plate, so that the absorber plate, when in place atop the shim, would be directly opposite the fuel region.[a]

In some of these experiments the absorber plates replaced the safety and control blades. Absorber plates that replaced control and safety blades would be attached to an aluminum follower blade, ~¼ inch thick. When safety and control blades were used in this manner, acrylic or Lucite shims between the lattice plates and the control-blade guides held the blade guides in place. The control and safety blade guides could not, by themselves, be used for positioning since they were not fastened to anything below their attachment to the angles supporting the top lattice plates, in order to allow safety and control blades to fall easily. Absorber plates were held in place against blade guides or lattice plates by aluminum rods, ½ inch in diameter, ~1 inch long, cut to a wedge shape and pressed into place.[c]

<u>Steel Plates</u>. The 304L steel plates had thicknesses of 3.02 ± 0.13 mm and 4.85 ± 0.15 mm. The borated steel plates had a 2.98 ± 0.06-mm thickness; the critical separation between fuel-rod clusters was determined for two boron contents in the steel: 1.05 and 1.62 wt.% boron. The steel plates were 35.6 cm wide and 91.5 cm long.

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[a] Private communication, Sid Bierman, August, 1993.

[b] Private communication, Sid Bierman, June, 1998.

[c] Private communication, Sid Bierman, August, 1993.

Boral Plates. The Boral plates were 7.13 ± 0.11 mm thick, 35.6 cm wide,[a] and 91.5 cm long. The 7.13-mm thickness included 1.02-mm-thick cladding of Type 1100 aluminum on both sides of the B_4C-Al core material.

Copper Plates. Plates of copper and of copper containing 0.989 wt.% cadmium were used in the experiments. The copper plates without cadmium had thicknesses of 6.46 ± 0.08 mm and 3.37 ± 0.08 mm. The copper plates with cadmium were 3.57 ± 0.08 mm thick. The 6.46-mm-thick plates were 35.6 cm wide and 91.5 cm long. The thin (3.37- and 3.57-mm) copper plates were 30.6 cm wide and 91.5 cm long.

Cadmium Plates. The thicknesses of the cadmium plates were 0.291 ± 0.010 mm, 0.610 ± 0.025 mm, 0.901 ± 0.027 mm, and 2.006 ±0.051 mm. Thicknesses were measured with a micrometer at several places along the edges of the plates.[b] The plates were 35.6 cm wide and 91.5 cm long.

To maintain their stiffness and flatness, the cadmium sheets were probably sandwiched between thin Plexiglas sheets.[c] In later experiments (Reference 4, p. 30) cadmium was reported as mounted on 0.296-cm-thick Plexiglas, and 0.160-cm-thick Plexiglas was used on either side of thin Boroflex sheets.

Aluminum Plates. The thickness of the aluminum plates was 6.25 ± 0.01 mm. The plates were 35.6 cm wide and 91.5 cm long.

Zircalloy-4 Plates. The Zircaloy-4 plates were 6.52 ± 0.08 mm thick, 35.6 cm wide, and 91.5 cm long.

1.2.8 Fuel Rods - Fuel-rod dimensions are given in diagrams in References 3-10. Figure 3 is a reproduction of the diagram from Reference 10 (p. 2.3). UO_2 fuel pellets were taken from rods "originally fabricated for Core II of the N.S. Savannah…The fuel diameter (1.265 ± 0.003 cm) ... was checked repeatedly during the reloading operations and found to agree with that quoted in the document characterizing Core II of the N.S. Savannah." (Reference 10, p. 2.4)

Diagrams in some of the earlier references showed end plugs protruding from the ends of the rod beyond the aluminum cladding, with total rod length, including protruding plugs, of 96.52 cm. However, later references showed end plugs exactly filling the ends of the clad, which had a length of 96.52 cm.

One experimenter recalls that the experimenters carefully inserted rubber plugs in the bottoms of the rods, before filling, so that the rubber plug protruded approximately 1/16 inch uniformly for all rods.

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[a] Reference 2 gives the plate width as 365 mm. This is incorrect. The correct width is 356 mm. (Private communication, Sid Bierman, July, 1993.)

[b] Private communication, Sid Bierman, June, 1998.

[c] Private communication, Sid Bierman, August, 1993.

Some top end plugs protruded and some were recessed, depending on slight differences between thicknesses of UO_2 pellets. Differences in pellet thickness was also the reason for the reported maximum and minimum lengths of 92.71 cm and 91.44 cm for the fuel region. There were no problems with water leakage into the fuel region of the rods.[a]

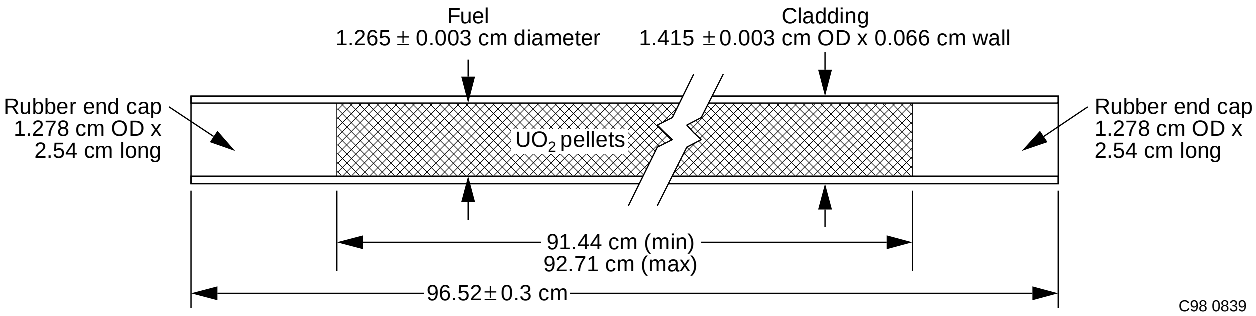

Figure 3. $U(4.31)O_2$ Fuel Rod.

Dimensions of the $U(4.31)O_2$ fuel rods are summarized in Table 1. To test the effects of small differences between rods, "experiments were repeated using alternate but identical (within the quality control applied during fabrication) fuel rods and different fuel loading arrangements on the approach to critical. ... the measurement data thus checked were reproduced to within a one-sigma limit of 0.3%" in most cases (Reference 2, p. 19). The standard deviations of a few reported critical cluster separations were greater than 0.3%.

Table 1. 4.31 Wt.% Enriched UO_2 Fuel-Rod Dimensions.

Component	Length (cm)	Diameter (cm)
UO_2 Fuel	91.44 - 92.71	1.265 ± 0.003
Rubber End Caps	2.54	1.278
Gap (not shown)	-	1.283 ± 0.003 OD
Clad (6061 Al)	96.52 ± 0.3	1.415 ± 0.003 OD (0.066 cm thick)

1.2.9 Source - A ^{252}Cf source of approximately 0.6 micrograms was placed near the center of the experimental assembly. The source was mounted in an open acrylic tube, 0.6 cm in diameter (Reference 8, pp 2.3 and 2.7) and two or three inches long.[b] During the triangular-pitched experiments, no measurable effect on critical size was detected with replacement-type reactivity worth measurements of the californium source (Reference 8, p. 3.7).

[a] Private communication, Sid Bierman, April, 1994.

[b] Private communication, Sid Bierman, August, 1993.

1.2.10 Experimental Method for Determining Critical Configuration[a] **-** The critical configuration was determined by measuring neutron-detector count rates (above background) produced by subcritical configurations and extrapolating to the critical condition. In particular, the averages of several (usually four, five, or six) 80-second counts from each of two or three detectors were recorded for each configuration. Generally, the most reactive configuration measured was "taken to within 99% of the critical condition" (Reference 12).

The experiments comprised three rectangular clusters of predetermined sizes with predetermined separation between the central cluster and the fixed neutron-absorber plates. The separation distance between clusters was varied. The variables plotted were [cluster separation]/[count rate] vs. [cluster separation] and [1]/[count rate] vs. [cluster separation]. At least two loadings close to critical were measured. The final result was the average predicted critical cluster separation distance.

Diagrams in the logbook indicated that cluster separation was varied by moving either a half row (4 rods) or a whole row (8 rods) from one end of an outer cluster to the other end of the same cluster. (The lattice plates were not moved.) Moving a half row on one outer cluster was said to be equivalent to a change in cluster separation of ¼-pitch length. Moving one half row on each of the two outer clusters toward the middle, or moving one whole row on one outer cluster, was said to be equivalent to ½-pitch separation change. (See LEU-COMP-THERM-001, Section 1.2.8, for an example of this method.)

1.2.11 Critical Cluster Dimensions and Separations - A typical arrangement of fuel clusters and the neutron-absorber material is shown in Figure 4.

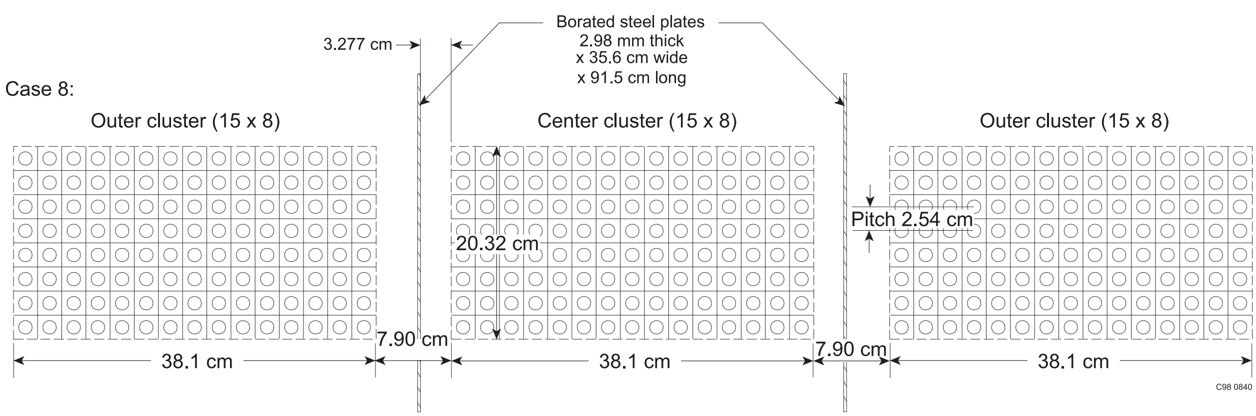

Figure 4. Typical Critical Configuration (Case 8, plan view).

[a] This information is from the logbooks, stored at the Los Alamos National Laboratory Archives.

Cluster sizes and separations for the 27 critical configurations are listed in Tables 2 through 7. Error limits are one standard deviation. Each configuration consisted of three clusters of fuel rods at 2.54-cm square pitch. All clusters are 8 rods wide and 15 rods long, arranged as shown in Figure 4. The separation of fuel clusters was the measured distances between the closest cell boundaries of rods of two adjacent clusters. (The cell boundary of each fuel rod is the square with side equal to the pitch centered on the axis of the fuel rod.) The distance to the absorber plate from the center cluster is the distance between the near surface of the plate and the cell boundaries of fuel rods of the center fuel cluster that are closest to the plate.

The critical separation of fuel clusters with no absorber plates was 106.2 mm (Case 4 of LEU-COMP-THERM-002).

Table 2. $U(4.31)O_2$ Fuel-Rod Cluster Critical Configurations with Steel Plates.

Case	Steel Plates			Separation of Fuel Clusters (mm)	Expt.
	Boron Content (wt.%)	Thickness (mm)	Distance to Center Fuel Cluster (mm)		
1	0	4.85 ± 0.15	2.45 ± 0.33	85.8 ± 0.2	014
2	0	4.85 ± 0.15	32.77 ± 0.32	96.5 ± 0.4	013
3	0	3.02 ± 0.13	4.28 ± 0.32	92.2 ± 0.1	008[(a)]
4	0	3.02 ± 0.13	32.77 ± 0.32	97.6 ± 0.3	007[(a)]
5	1.05	2.98 ± 0.06	4.32 ± 0.30	61.0 ± 0.1	010 R
6	1.05	2.98 ± 0.06	32.77 ± 0.32	80.8 ± 0.2	009
7	1.62	2.98 ± 0.05	4.32 ± 0.30	57.6 ± 0.2	012
8	1.62	2.98 ± 0.05	32.77 ± 0.32	79.0 ± 0.3	011

(a) Water temperature recorded in the logbook was 25°C.

Table 3. $U(4.31)O_2$ Fuel-Rod Cluster Critical Configuration with Boral Plates.

Case	Boral Plates		Separation of Fuel Clusters (mm)	Expt.
	Thickness (mm)[(a)]	Distance to Center Fuel Cluster (mm)		
9	7.13 ± 0.11	32.77 ± 0.32	67.2 ± 0.1	031

(a) Includes 1.02-mm-thick cladding of Type 1100 aluminum on either side of the B_4C-Al absorber material.

Table 4. $U(4.31)O_2$ Fuel-Rod Cluster Critical Configurations with Copper Plates.

Case	Copper Plates: Cd Content (wt.%)	Copper Plates: Thickness (mm)	Copper Plates: Distance to Center Fuel Cluster (mm)	Separation of Fuel Clusters (mm)	Expt.
10	0.0	6.46 ± 0.08	0.84 ± 0.30	81.5 ± 0.2	016
11	0.0	6.46 ± 0.08	32.77 ± 0.32	94.2 ± 0.2	015
12	0.0	3.37 ± 0.08	(a)	84.8 ± 0.4	018
13	0.0	3.37 ± 0.08	42.41 ± 0.18	96.4 ± 0.4	017[(b)]
14	0.989	3.57 ± 0.08	(a)	66.6 ± 0.6	020[(b)]
15	0.989	3.57 ± 0.08	42.41 ± 0.18	83.5 ± 0.5	019

(a) Plate surface nearest the center fuel cluster is 5.05 mm from the rods, which is 0.57 mm inside the cell boundary (References 2 and 12).

(b) Water temperature recorded in the logbook was 23°C.

Table 5. $U(4.31)O_2$ Fuel-Rod Cluster Critical Configurations with Cadmium Plates.

Case	Cadmium Plates: Thickness (mm)	Cadmium Plates: Distance to Center Fuel Cluster (mm)	Separation of Fuel Clusters (mm)	Expt.
16	0.291 ± 0.010	7.009[(a)] ± 0.29	59.3 ± 0.4	026
17	0.291 ± 0.010	32.77 ± 0.32	74.2 ± 0.2	025
18	0.610 ± 0.025	6.69 ± 0.29	59.6 ± 0.4	028
19	0.610 ± 0.025	32.77 ± 0.32	74.2 ± 0.2	027
20	0.901 ± 0.027	6.40 ± 0.29	58.7 ± 0.5	022
21	0.901 ± 0.027	32.77 ± 0.32	73.8 ± 0.2	021
22	2.006 ± 0.051	5.29 ± 0.29	56.8 ± 0.1	024
23	2.006 ± 0.051	32.77 ± 0.32	72.8 ± 0.3	023

(a) This is the value reported in both References 2 and 12, although the precision is not consistent with other entries in the table or with the uncertainty.

Table 6. $U(4.31)O_2$ Fuel-Rod Cluster Critical Configurations with Aluminum Plates.

Case	Aluminum Plates		Separation of Fuel Clusters (mm)	Expt.
	Thickness (mm)	Distance to Center Fuel Cluster (mm)		
24	6.25 ± 0.01	1.05 ± 0.29	107.2 ± 0.1	006[a]
25	6.25 ± 0.01	32.77 ± 0.32	107.7 ± 0.5	005

(a) Water temperature recorded in the logbook was 25°C.

Table 7. $U(4.31)O_2$ Fuel-Rod Cluster Critical Configurations with Zircaloy Plates.

Case	Zircaloy-4 Plates		Separation of Fuel Clusters (mm)	Expt.
	Thickness(mm)	Distance to Center Fuel Cluster (mm)		
26	6.52 ± 0.08	0.78 ± 0.30	109.2 ± 0.4	030
27	6.52 ± 0.08	32.77 ± 0.32	108.6 ± 0.4	029

1.3 Description of Material Data

1.3.1 Fuel Rod - UO_2 Fuel. **-** Over the course of performing the series of experiments, the experimenters improved their analyses of the fuel rods. In Reference 5, p. x, the experimenters state:

> 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. . . . the values quoted in this report should be considered the latest and, hopefully, the more correct values to use.

A similar statement is given in Reference 6 (p. xiii).

The latest reported values (Reference 10, p. 2.3) are assumed to be most accurate. In Reference 10, measurement methods are described. The experimenters state (Reference 10, p. 2.4):

> The uranium assay (1059.64 ± 4.80 g/rod) and the ^{235}U enrichment (4.306 ± 0.013%)…are the average of six assays and six spectrographic analyses made on fuel pellets chosen at random during the reloading. The oxide density (10.40 ± 0.06 g UO_2/cm^3) … is based on individual volume displacement measurements with 20 pellets selected at random during the reloading operations. The mass of UO_2 per rod (1203.38 ± 4.12 g) is the average mass of the 1865 rods of this type available for use in the experiments. … The rubber end cap density (1.321 g/cm^3) …is the result of a single mass-volume measurement with six end caps selected at random. The composition of the end caps is the result of four analyses on randomly selected end caps.

Uranium isotopic composition is summarized in Table 8.

Table 8. Isotopic Composition of Uranium in
4.31%-Enriched UO_2 Fuel Rods (Reference 10, p. 2.3).

Uranium Isotope	Wt.%
^{234}U	0.022 ± 0.002
^{235}U	4.306 ± 0.013
^{236}U	0.022 ± 0.002
^{238}U	95.650 ± 0.017
Total	100.000

Rubber end-cap data[a] and 6061-aluminum tubing (clad) data are given in Table 9. The 6061-aluminum data includes the measured density and the ASTM Standard chemical composition.[b]

[a] Reference 10, p. 2.3.

[b] Reference 10, p. A.2, and from *Alcoa Aluminum Handbook*, Aluminum Company of America, pp. 46-50, 1967.

Table 9. Rubber End-Cap and 6061-Aluminum Clad Data.

Element	Wt.%
Rubber End Cap (density - 1.321 g/cm^3)	
C	58.0 ± 1
H	6.5 ± 0.3
Ca	11.4 ± 1.8
S	1.7 ± 0.2
Si	0.3 ± 0.1
O	22.1 (balance)
6061 Aluminum (density - 2.69 g/cm^3)	
Si	0.40-0.80 (0.6 nominal)
Fe	0.7 (maximum)
Cu	0.15-0.40 (0.25 nominal)
Mn	0.15 (maximum)
Mg	0.8-1.2 (1.0 nominal)
Cr	0.04-0.35 (0.2 nominal)
Zn	0.25 (maximum)
Ti	0.15 (maximum)
Al	remainder (96.00-98.61)

1.3.2 Support Structures - Aluminum. Experiment support structures, including lattice plate supports and spacer rods, control/safety blade guides, and tubes housing the proportional counters, were 6061-aluminum alloy. The composition of 6061 aluminum is given in Table 9.

Acrylic. The acrylic fuel-rod support plates and lattice plates had a density of 1.185 g/cm^3 and were 8 wt.% hydrogen, 60 wt.% carbon, and 32 wt.% oxygen (References 4 and 14). Uncertainties and methods of determination were not given.

1.3.3 Absorber Plates - The neutron absorbers used in the experiments were steel, copper, Boral, cadmium, aluminum, and Zircaloy-4 plates. The measured chemical compositions from References 2 and 12 are given in Tables 10 - 15. According to Reference 2, "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."

Boron in boron absorbers was natural boron. The isotopic composition was not measured.[a]

Steel Plates. Three different types of 304L steel plates were used: without boron, with 1.1 wt.% boron, and with 1.6 wt.% boron. The reported density of the steel plate without boron is 7.930 g/cm^3. The densities of the steel plates with 1.1 and 1.6 wt.% boron are 7.900 and 7.770 g/cm^3, respectively. Chemical compositions of the three types of the steel plates are given in Table 10.

Table 10. Compositions of Steel Plates.

Element	304L Steel Plates		
	No Boron	1.1 wt.% Boron	1.6 wt.% Boron
B	-	1.05 ± 0.08	1.62 ± 0.10
Cr	18.56 ± 0.10	19.03 ± 0.10	19.60 ± 0.10
Cu	0.27 ± 0.05	0.28 ± 0.05	0.26 ± 0.05
Fe	68.24 ± 0.34	68.04 ± 0.34	66.40 ± 0.33
Mn	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
Ni	11.09 ± 0.06	9.53 ± 0.05	10.12 ± 0.05

Boral Plates. The reported density of the 5.09-mm-thick core of the Boral plates is 2.49 g/cm^3. The chemical composition of the B_4C-Al core is given in Table 11. The 1.02-mm-thick clad on both sides of the plates was Type 1100 aluminum.

Table 11. Composition of B_4C-Al Core of Boral Plate.[(a)]

Element	Wt.%	Element	Wt.%
Al	62.39 ± 2.8	Mn	0.05
B	28.70 ± 0.25	Na	0.02
C	7.97 ± 0.41	Ni	0.02
Cr	0.05	Si	0.20
Cu	0.09	S	0.03
Fe	0.33 ± 0.04	Zn	0.10
Mg	0.05	-	-

(a) This composition, as well as plate dimensions, clad, and density, is the same as Boral A absorber plates in later experiments (References 4 and 14).

[a] Private communication, Sid Bierman, July, 1993. Bierman said that if the ^{10}B fraction had been measured, it would have been reported in the reference. No ^{10}B values were reported for these experiments.

Copper Plates. Two different types of copper plates, one with and one without cadmium, were used. The reported densities were 8.910 g/cm^3 for plates with cadmium and 8.913 g/cm^3 for plates without cadmium. Chemical compositions of the copper plates are given in Table 12.

Table 12. Compositions of Copper Plates.

Element	Copper Plates	
	With Cd (Wt.%)	No Cd (Wt.%)
B	0.005	-
C	0.002	0.340
Cd	0.989 ± 0.003	-
Cu	98.685 ± 0.300	99.60 ± 0.14
Fe	0.020	0.004
Mg	-	0.002
Mn	0.009	-
Na	-	0.002
Ni	0.010	-
O	0.019	0.030
Si	0.004	0.020
Sn	0.250	-
S	-	0.002
Zn	0.007	-

Cadmium Plates. The reported density of the cadmium plates was 8.650 g/cm^3. Chemical composition of the plates was 99.7 ± 0.3 wt.% Cd and 0.3 wt.% Zn.

Aluminum Plates. The reported density of the 6061-aluminum plates was 2.692 g/cm^3. Chemical composition of the plates is given in Table 13.

Table 13. Composition of Type 6061-Aluminum Plates.

Element	Wt.%	Element	Wt.%
Al	97.15± 0.21	Mn	0.21[(a)]
Cr	0.21	Si	0.82[(a)]
Cu	0.12[(b)]	S	0.06
Fe	0.82[(a)]	Ti	0.61[(a)]

(a) Note that this value is greater than the maximum specified in the ASTM Standard, Table 9.
(b) This value is below the specified range in the ASTM Standard, Table 9.

Zircaloy-4 Plates. The reported density of the Zircaloy-4 plates is 6.32 g/cm^3. Chemical composition of the plates is given in Table 14.

Table 14. Composition of Zircaloy-4 Plates.

Element	Wt.%	Element	Wt.%
Zr	98.16 ± 0.35	Sn	1.50 ± 0.27
Fe	0.21 ± 0.03	Cr	0.13 ± 0.04

1.3.4 Water - The reported impurity constituents of the water moderator/reflector are given in Table 15 (Reference 2). The approximate average water temperature was 24°C, based on five values recorded in the logbook for experiments of this series.

Table 15. Water Impurities.

Component[(a)]	Concentration[(a)] (ppm)	Parameter[(b)]	Concentration[(b)] (ppm)
Cl	30.2 ± 5.8	Chloride	30.2
NO_3^-	0.42 ± 0.16	Nitrate (as NO_3-)	0.42
Cr^{+6}	<0.01	Chromium (total)	<0.01
Zn	0.26 ± 0.07	Zinc	0.26
Mn	<0.01	Manganese	<0.01
Pb	<0.005	Lead	<0.005
Fl	0.15 ± 0.04	Fluoride	0.15
Fe	<0.03	Iron	0.03
Cu	<0.01	Copper	<0.01
Cd	0.006 ± 0.001	Cadmium	0.006
SO_3	6.6 ± 0.04	Sulfates	0.66[(c)]
Dissolved Solids	137 ± 5	Total Dissolved Solids	137

(a) As listed in Reference 2.
(b) As listed in September 16, 1977, letter from Environmental Health Sciences, Richland, Washington, to B. M. Durst. Letter concluded that “all measured levels are within drinking water standards.”
(c) This entry included a handwritten “6.6” next to it.

1.3.7 Tank - The experiment tank was carbon steel. Density and composition were not reported.

1.4 Supplemental Experimental Measurements

No supplemental experimental measurements were reported.

2.0 EVALUATION OF EXPERIMENTAL DATA

Experiments were well documented and carefully performed. There were no significant omissions of data.

2.1 Fuel-Rod Data

The average length of the fuel region was not given. Rather, a maximum fuel length of 92.71 cm and a minimum fuel length of 91.44 cm were reported. Using the average of the reported maximum and minimum lengths (92.075 cm), the reported fuel diameter, and the reported average mass of UO_2 per rod does give the reported average UO_2 density of 10.40 g/cm^3. A sensitivity study, with mass of UO_2 per rod held constant over this range in fuel length, gave a maximum Δk_{eff} of 0.026%, as shown in Table 16.[a] Therefore uncertainty in the fuel length contributes a small uncertainty to the benchmark-model k_{eff} value.

Reported end-plug dimensions and density were for uncompressed plugs. A sensitivity study was performed with compressed plugs that exactly filled the clad on both ends of the centered fuel region. Compressing the plugs increased k_{eff} by 10^{-4}, a negligible effect.

The uncertainty in fuel diameter was ± 0.003 cm. Varying the fuel diameter by this amount, with a corresponding change in UO_2 density, gave a maximum k_{eff} of 0.021%. The maximum reported uncertainty in pitch was ± 0.003 inch (0.0076 cm)[b], which gave a Δk_{eff} of 0.103%.

Uncertainties were also reported in average mass of UO_2 per rod (± 4.12 g), in average mass of uranium per rod (± 4.80 g), and in enrichment (± 0.013 wt.%). Eight cases were calculated for all possible combinations of the extremes of these three variables. A decrease in ^{235}U wt.% was accompanied by an equal increase in ^{238}U wt.% in the calculational models. The highest calculated k_{eff} was for the minimum UO_2 mass, the maximum U mass, and the maximum enrichment. The calculated Δk_{eff}, compared to a model having the average amounts of these variables, was +0.083%. The lowest calculated k_{eff} was for maximum UO_2, minimum U, and minimum enrichment, with a Δk_{eff} of -0.147%. This last, worst-case result is included in the uncertainty in the benchmark-model k_{eff}.

Results, shown in Table 16, indicate that an uncertainty of ± 0.18% should be included in the benchmark-model k_{eff} to account for fuel-rod measurement uncertainties.

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[a] Sensitivity studies described in this section used ONEDANT models, with ENDF/B-IV 27-group cross sections, of a homogenized mixture representing an infinite slab of fuel rods with no absorber plates. The calculations were P_3, S_{16}, with a convergence criterion of 10^{-6}. (See sample input in Appendix C.)

[b] Reference 8, p. E.4, corrected standard deviation of hole-spacing measurements on bottom lattice plate.

Table 16. Sensitivity of k_{eff} to Uncertainties in Fuel-Rod Characterization.

Quantity (Amount of Change)	% k_{eff} (ONEDANT)[a]
Fuel Length (± 0.635 cm)	±0.026
Fuel Diameter (± 0.003 cm)	±0.021
Pitch (± 0.0076 cm)[b]	±0.103
Combination of Enrichment (± 0.013 wt.%), UO_2 Mass Per Rod (± 4.12 g), U Mass Per Rod (± 4.80 g)	±0.147
Combined Effect[c]	0.18

(a) 27-group ENDF/B-IV cross sections with homogenized lattice-cell fuel region (CSASIX); infinite slab geometry; sample input given in Appendix C.
(b) The largest standard deviation for sets of center-to-center spacing measurements for triangular-pitch lattice plates of Reference 8 (Appendix E) was 0.003 inch (0.0076 cm). Other references give the uncertainty in pitch as ± 0.001 cm or ± 0.005 cm. Therefore, the calculated uncertainty is conservative.
(c) Square root of sum of squares of individual effects.

2.2 <u>Water Reflector</u>

The minimum thickness of the top water reflector was 15 cm above the fuel region. Assuming the average fuel length of 92.075 cm centered within the 96.52-cm-long rod, the end-plug region is slightly less than 1 inch long (2.2225 cm). Therefore, the minimum water reflector thickness above the tops of the top plugs is 12.7775 cm.

ONEDANT (27-group, ENDF/B-IV) calculations were performed for an infinite-slab fuel region with a water reflector on both sides. The reflector thickness was varied from 15 to 30 centimeters. The effect on k_{eff} of the outermost 15 centimeters of water was less than 0.001%. Replacing the outermost 15 centimeters of water with 40 centimeters of full-density stainless steel or concrete gave similar results: the effect on k_{eff} was 0.002% or less.

These calculations indicate that a water reflector with a thickness of 15 centimeters may be considered as "effectively infinite" and the effects of materials beyond the top and bottom reflectors may be neglected. Therefore, the lack of data about material above the 15-cm-thick top water reflector and about detectors which were placed in the water reflector more than 15 centimeters away from the fuel rods does not affect the acceptability of these experiments.

2.3 Water Impurities

Water impurity sensitivity studies in Appendix C of LEU-COMP-THERM-002 indicate that only boron and gadolinium impurities significantly affect k_{eff}. No boron or gadolinium impurities were reported in References 2 and 12, which describe all of Cases 1 - 27. Therefore, the effect of water impurities is assumed to be negligible.

2.4 Temperature Data

Water temperatures were recorded in logbooks for approximately ten percent of all the experiments of this series. Measured temperatures ranged from 18°C to 26°C. ONEDANT (27-group ENDF/B-IV) calculations gave a change in k_{eff} of 0.072% between these two extremes of temperature for rods at a pitch of 2.54 cm without absorber plates. Therefore, an estimate of the uncertainty in k_{eff} due to the effect of uncertain temperature is half of this amount, namely 0.04%.

2.5 Cluster and Absorber-Plate Positions

Sensitivity studies described in this section used TWODANT models, with CSAS ENDF/B-IV 27-group cross sections. A homogeneous mixture was used to model fuel-rod clusters. The calculations were P_1, S_8, with a convergence criterion of 10^{-5}.

2.5.1 Cluster Separations - The measurement uncertainties in cluster separation (see Tables 2 through 7) vary from 0.01 cm to 0.06 cm. To calculate the effect on k_{eff}, cluster separations were reduced by the particular uncertainty for fourteen representative cases. Results indicate that the uncertainty in k_{eff} due to uncertainty in cluster separation is less than 0.011%. This value may be used as the k_{eff} uncertainty due to uncertainty in cluster separation.

2.5.2 Absorber Plate-Cluster Separations - The measurement uncertainties in the distance between the central fuel cluster and the absorber plates vary from 0.018 cm to 0.033 cm. To calculate the effect on k_{eff}, this distance was increased by the particular uncertainty for fourteen representative cases. Results indicate that the uncertainty in k_{eff} due to this uncertainty is less than 0.013%. This value may be used as the k_{eff} uncertainty due to uncertainty in separation between center cluster and absorber plates.

2.5.3 Vertical Position of Absorber Plates - According to Reference 12, absorber plates, which were ~ 0.1 cm longer than the nominal fuel-region length, were positioned "to avoid a direct line of sight between rods of different clusters." This would require raising the absorber plates by the length of the bottom plug (~2.2 cm) above the support plate. As mentioned in Section 1.2.7, an experimenter remembered that a shim was probably used for this purpose. However, this was not documented and is not certain. Therefore, for Case 7 with the borated steel plate (the plate with the largest calculated worth), the effect of raising absorber plates by the length of the bottom plug was calculated using KENO V.a with 44-group ENDF/B-V cross sections and with MCNP with continuous-energy ENDF/B-V cross sections. The effect on k_{eff} calculated by both codes was 0.078% ± 0.052%. This is included in the total uncertainty of the benchmark-model k_{eff}.

2.6 Absorber Plates

2.6.1 Absorber-Plate Composition - The maximum effects on k_{eff} of the absorber plates' composition uncertainties were calculated. Effects of maximum and minimum amounts of components were calculated. The greater difference from k_{eff} of the base case, which has average amounts of components, is given in Tables 17 through 24. The reactivity effects of replacing the absorber plates with water were also calculated to indicate the usefulness of these benchmarks for validating calculations of configurations that include these materials.

Steel Plates. For Case 1 of Table 2 the effects of maximum weight percents of iron and manganese in the non-borated steel plate were compared to effects of minimum weight percents. The difference from the base case is shown in Table 17. Similarly, for Case 5 effects of maximum and minimum weight percents of boron, iron, and manganese in the 1.1%-borated steel plate were individually calculated and compared to the base case. The effects of ±0.8 at.% variation in ^{10}B isotopic fraction in natural boron was also calculated. Results are shown in Table 18. Similar sensitivity calculations were performed for the 1.6%-borated steel plate (Case 7), and results are given in Table 19.

Table 17. Calculated Effects of Non-Borated Steel Plate Composition Uncertainties on k_{eff} (Case 1).

Description	Δk_{eff} (%)
Fe, 68.24 ± 0.34 wt.%	0.001
Mn, 1.58 ± 0.05 wt.%	0.001
Non-Borated Steel Plates Replaced with Water	0.687

Table 18. Calculated Effects of 1.1%-Borated Steel Plate Composition Uncertainties on k_{eff} (Case 5).

Description	Δk_{eff} (%)
B, 1.05 ± 0.08 wt.%	0.023
^{10}B, 19.9 ±0.8 at.%	0.013
Mn, 1.58 ± 0.05 wt.%	<0.001
Fe, 68.04 ± 0.34 wt.%	<0.001
1.1%-Borated Steel Plates Replaced with Water	2.164

Table 19. Calculated Effect of 1.6%-Borated Steel Plate Composition Uncertainties on k_{eff} (Case 7).

Description	Δk_{eff} (%)
B, 1.62 ± 0.10 wt.%	0.021
^{10}B, 19.9 ±0.8 at.%	0.014
Mn, 1.69 ± 0.05 wt.%	<0.001
Fe, 66.40 ± 0.33 wt.%	<0.001
1.6%-Borated Steel Plates Replaced with Water	2.427

Boral Plates. For Case 9 of Table 3, the maximum and minimum wt.%'s of boron and iron of the Boral plate were compared to the base case, as well as the maximum and minimum at.%'s of ^{10}B in boron, with results given in Table 20.

Table 20. Calculated Effects of Boral Plate Composition Uncertainties on k_{eff} (Case 9).

Description	Δk_{eff} (%)
B, 28.70 ± 0.25 wt.%	0.002
^{10}B, 19.9 ±0.8 at.%	0.007
Fe, 0.33 ± 0.04 wt.%	<0.001
Boral Plates Replaced with Water	1.805

Copper Plates. For Case 15 of Table 4 compositions with the maximum and minimum wt.% of cadmium of the copper plate with cadmium were compared to the base case, with result given in Table 21.

Table 21. Calculated Effect of Copper Plate Composition Uncertainties on k_{eff} (Case 15).

Description	Δk_{eff} (%)
Cd, 0.989 ± 0.003 wt.%	0.006
Copper Plates without Cd Replaced with Water (Case 10)	0.850
Copper Plates with Cd Replaced with Water (Case 15)	0.746

Cadmium Plates. The maximum and minimum wt.% Cd of the cadmium plates were compared for Case 16 of Table 5, with result given in Table 22. Effects of possible Plexiglas stiffener plates next to the cadmium were also calculated.

Table 22. Calculated Effects of Cadmium Plate Composition Uncertainties on k_{eff} (Case 16).

Description	Δk_{eff} (%)
Cd, 99.7 ± 0.3 wt.%	<0.001
0.296-cm-thick Plexiglas (one side)	0.005
0.16-cm-thick Plexiglas (both sides)	0.010
Cadmium Plates Replaced with Water	2.370

Aluminum Plates. The maximum and minimum wt.% Al in the aluminum plate were calculated, with result given in Table 23.

Table 23. Calculated Effect of Aluminum Plate Composition Uncertainties on k_{eff} (Case 24).

Description	Δk_{eff} (%)
Al, 97.15 ± 0.21 wt.%	0.007
Aluminum Plates Replaced with Water	0.004

Zircaloy-4 Plates. The maximum and minimum wt.% of zirconium and iron in the Zircaloy-4 plate were compared, with results given in Table 24.

Table 24. Calculated Effects of Zircaloy-4 Plate Composition Uncertainties on k_{eff} (Case 26).

Description	Δk_{eff} (%)
Zr, 98.16 ± 0.35 wt.%	0.011
Fe, 0.21 ± 0.03 wt.%	0.019
Zircaloy-4 Plates Replaced with Water	-0.015

Results indicate that the maximum uncertainty in k_{eff} due to uncertainty in composition of absorber plates is for the 1.1%-borated steel plates (Table 18). Combining the effects of uncertain boron gives an effect on k_{eff} of 0.026%. This maximum effect is included in the uncertainty of the benchmark-model k_{eff}.

2.6.2 Absorber Plate Thickness - The maximum effects of the uncertainties in absorber plate thickness on k_{eff} were calculated for approximately half of the cases. Results indicate that the uncertainty in k_{eff} due to uncertainty in absorber plate thickness is less than 0.013%. This is included in the uncertainty of the benchmark-model k_{eff}.

2.7 Conclusions of Acceptability

The effects of the non-borated steel, copper, aluminum, and Zircaloy-4 plates in these experiments were calculated to be small (<0.85% of k_{eff}). The effects of other plates were less than 2.5% of k_{eff}. Because the required experimental data and uncertainties were measured and recorded, and because the effects of uncertainties for all cases were calculated to be small, all cases are acceptable as benchmark experiments.

3.0 BENCHMARK SPECIFICATIONS

3.1 Description of Model

The calculational models consist of three rectangular clusters of square-pitched, aluminum-clad cylindrical fuel pins in water. The clusters are each 15 rods by 8 rods, arranged in a row with absorber plates between clusters.

Sensitivity studies were performed to justify simplifications of the benchmark model.

3.1.1 Lattice Plates - ONEDANT calculations were performed of an infinite slab of fuel pins (no absorber plates) with and without lattice plates present (using two fuel mixtures, one with acrylic moderator and one with water moderator) and reflected by 15 centimeters of water. The effect on k_{eff} of the lattice plates was 0.03%. This estimate of the effect of omitting the lattice plates is small and is included in the total k_{eff} uncertainty.

3.1.2 Bottom Reflector - The effects on k_{eff} of the one-inch-thick acrylic support plate and of the carbon-steel[a] tank 17.84 cm below an infinite slab of the fuel rods (without absorber plates) were calculated using ONEDANT. Results are shown in Table 25. As expected, the carbon-steel tank had practically no effect on k_{eff}, while the acrylic support plate had a small measurable effect (0.02% for one support plate). Therefore, the acrylic support plate is retained in the benchmark model. Because the aluminum channels supporting the acrylic plate are at the edges of the clusters, their effect is judged to be negligible and they are omitted from the model. As discussed in Section 2.2, concrete or stainless steel beyond 15 centimeters of water reflector have a negligible effect on k_{eff}. Therefore, the model of the bottom reflector is 2.54 cm of acrylic followed by 15.3 cm of water.

Table 25. Effect of Reflector Materials on k_{eff}.[(a)]

Reflector			k_{eff} (%)
Inner 2.54 cm	Middle 15.3 cm	Outer 0.952 cm	
acrylic	water	carbon steel	-
acrylic	water	water	+0.001
water	water	water	-0.04

(a) ONEDANT infinite slab of fuel pins with reflector materials on both sides. (CSAS 27-group ENDF/B-IV cross sections and homogeneous fuel region mixture created by XSDRNPM)

[a] 1 wt.% Mn, 0.9 wt.% C, and the remainder Fe (Robert C. Weast, ed., *CRC Handbook of Chemistry and Physics, 68th Edition*, CRC Press, 1987, p. E-114).

3.2 Dimensions

Fuel-rod dimensions are shown in Figure 5. The rod has an outer diameter of 1.415 cm and is 96.52 cm long. The UO_2 fuel region has a diameter of 1.265 cm and is 92.075 cm long. The clad is 0.066 cm thick. Therefore, the gap between UO_2 and clad is 0.009 cm thick with an outer radius of 0.6415 cm. The compressed rubber end plugs are 2.2225 cm long with a radius of 0.6415 cm, to fit exactly within the ends of the fuel rod.

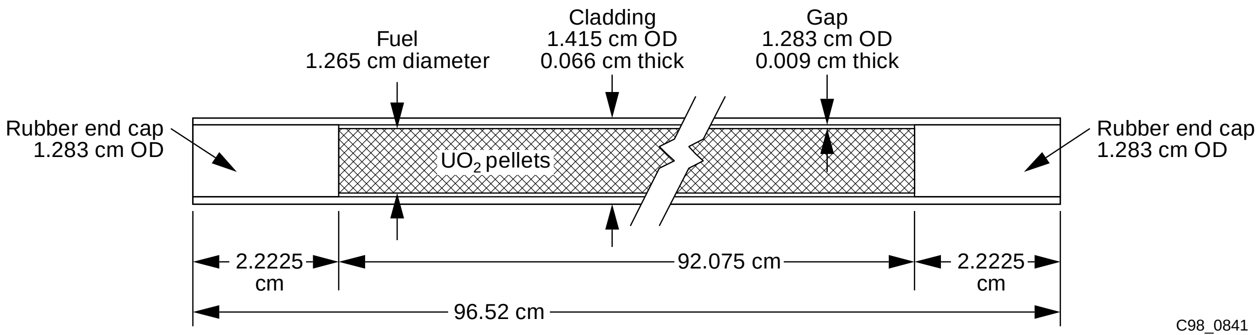

Figure 5. Fuel-Rod Model.

Each configuration comprises three rectangular clusters, 15 rods long by 8 rods wide at 2.54-cm pitch, and two absorber plates in water. The clusters are arranged in a line with absorber plates between them, as shown in Figure 6. Dimensions are given in Table 26. Separation of clusters, $\mathbf{S_c}$, is the distance between closest fuel-rod cell boundaries of adjacent clusters. The distance from the plate to the center cluster, $\mathbf{S_p}$, is the distance between the near surface of the plate and the outer cell boundary of the center fuel cluster.

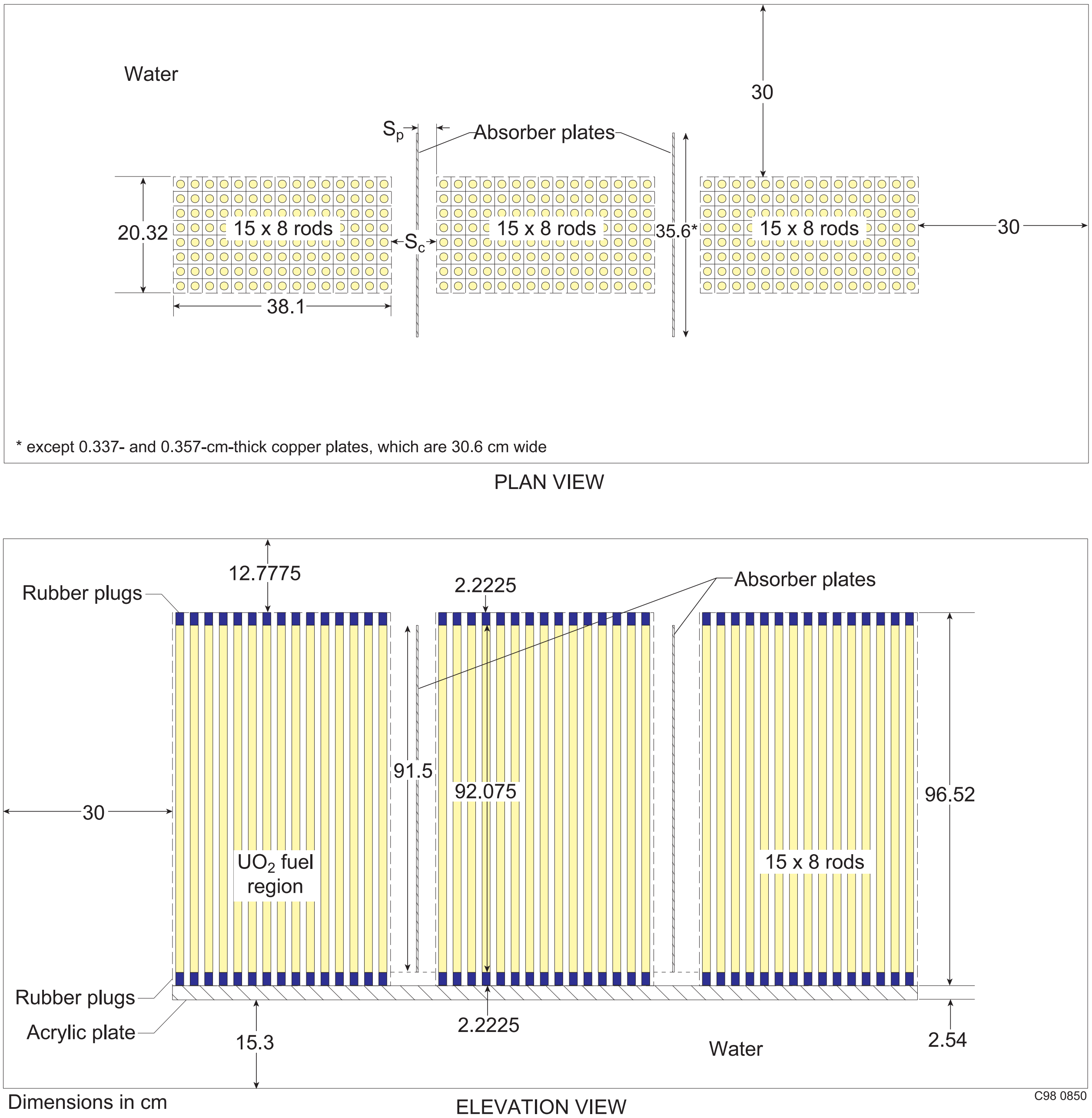

Figure 6. Benchmark Model.

Absorber plates are 35.6 cm wide, except the thin copper plates, which are 30.6 cm wide, as noted in Table 26. All absorber plates are 91.5 cm long. The plates are parallel to the interacting faces of adjacent clusters, and are centered horizontally with respect to the cluster faces. The bottom edge of the plates is at the same level as the bottom of the fuel region in the fuel rods.

The bottom reflector is a single 2.54-cm-thick acrylic plate, which extends horizontally to the outermost cell-boundary edges of the clusters, followed by 15.3 cm of water. The top reflector is

12.7775 cm of water above the tops of the fuel rods. The four side water reflectors are 30 cm thick, measured from the cluster outer cell boundaries.

Table 26. Critical Configurations.

Case	Type of Plate	Plate Thickness (cm)	Distance from Plate to Center Cluster, $\mathbf{S_p}$ (cm)	Separation of Clusters, $\mathbf{S_c}$ (cm)
1	Steel (no B)	0.485	0.245	8.58
2	Steel (no B)	0.485	3.277	9.65
3	Steel (no B)	0.302	0.428	9.22
4	Steel (no B)	0.302	3.277	9.76
5	Steel, 1.1% B	0.298	0.432	6.10
6	Steel, 1.1% B	0.298	3.277	8.08
7	Steel, 1.6% B	0.298	0.432	5.76
8	Steel, 1.6% B	0.298	3.277	7.90
9	Boral	0.713[a]	3.277	6.72
10	Copper (no Cd)	0.646	0.084	8.15
11	Copper (no Cd)	0.646	3.277	9.42
12	Copper (no Cd)	0.337[b]	-0.0575[c]	8.48
13	Copper (no Cd)	0.337[b]	4.241	9.64
14	Copper, 1% Cd	0.357[b]	-0.0575[c]	6.66
15	Copper, 1% Cd	0.357[b]	4.241	8.35
16	Cadmium	0.0291	0.7009	5.93
17	Cadmium	0.0291	3.277	7.42
18	Cadmium	0.061	0.669	5.96
19	Cadmium	0.061	3.277	7.42
20	Cadmium	0.0901	0.64	5.87
21	Cadmium	0.0901	3.277	7.38
22	Cadmium	0.2006	0.529	5.68
23	Cadmium	0.2006	3.277	7.28
24	Aluminum	0.625	0.105	10.72
25	Aluminum	0.625	3.277	10.77
26	Zircaloy-4	0.652	0.078	10.92
27	Zircaloy-4	0.652	3.277	10.86

(a) Includes 0.102-cm-thick cladding of Type 1100 aluminum on both sides of the B_4C-Al material, which is 0.509 cm thick.
(b) Plates are 30.6 cm wide, rather than 35.6 cm wide.
(c) Plates are inside the outer cell boundaries of the center fuel cluster.

3.3 Material Data

3.3.1 Fuel Rods - The fuel region consists of 1203.38 g of UO_2. The mass of uranium in each rod is 1059.64 g. The isotopic composition of the uranium is 0.022 wt.% ^{234}U, 4.306 wt.% ^{235}U, 0.022 wt.% ^{236}U, and 95.650 wt.% ^{238}U. Fuel rods have 6061-aluminum clad and compressed rubber end plugs of density 1.498 g/cm^3.[a] Atom densities are given in Table 27.

Table 27. Fuel-Rod Atom Densities.

Material	Isotope	Atom Density (barn-cm)$^{-1}$
U(4.306)O_2 Fuel	^{234}U	5.1835×10^{-6}
	^{235}U	1.0102×10^{-3}
	^{236}U	5.1395×10^{-6}
	^{238}U	2.2157×10^{-2}
	O	4.6753×10^{-2}
6061-Aluminum Clad (2.69 g/cm^3)	Al	5.8433×10^{-2}
	Cr	6.2310×10^{-5}
	Cu	6.3731×10^{-5}
	Mg	6.6651×10^{-4}
	Mn	2.2115×10^{-5}
	Ti	2.5375×10^{-5}
	Zn	3.0967×10^{-5}
	Si	3.4607×10^{-4}
	Fe	1.0152×10^{-4}
Rubber End Plug (1.498 g/cm^3)	C	4.3562×10^{-2}
	H	5.8178×10^{-2}
	Ca	2.5660×10^{-3}
	S	4.7820×10^{-4}
	Si	9.6360×10^{-5}
	O	1.2461×10^{-2}

3.3.2 Absorber Plates - Steel, Boral, copper, cadmium, aluminum, and Zircaloy-4 atom densities are given in Tables 28 - 31. Boron is assumed to be 19.9 at.% ^{10}B and 80.1 at.% ^{11}B.[b]

[a] This density is more than the reported density of the plugs in Table 9 because of the compression of the plugs.

[b] *Nuclides and Isotopes, Fourteenth Edition*, General Electric Company, 1989.

Table 28. Steel Absorber-Plate Atom Densities.

Material	Isotope	Wt.%	Atom Density (barn-cm)$^{-1}$
304L Steel without B (7.93 g/cm^3)	Cr	18.56	1.7046×10^{-2}
	Cu	0.27	2.0291×10^{-4}
	Fe	68.24	5.8353×10^{-2}
	Mn	1.58	1.3734×10^{-3}
	Mo	0.26	1.2942×10^{-4}
	Ni	11.09	9.0238×10^{-3}
304L Steel with 1.1 wt.% B (7.9 g/cm^3)	^{10}B	1.05 wt.% boron, 19.9 at.% ^{10}B	9.1950×10^{-4}
	^{11}B	1.05 wt.% boron, 80.1 at.% ^{11}B	3.7011×10^{-3}
	Cr	19.03	1.7412×10^{-2}
	Cu	0.28	2.0963×10^{-4}
	Fe	68.04	5.7961×10^{-2}
	Mn	1.58	1.3682×10^{-3}
	Mo	0.49	2.4298×10^{-4}
	Ni	9.53	7.7251×10^{-3}
304L Steel with 1.6 wt.% B (7.77 g/cm^3)	^{10}B	1.62 wt.% boron, 19.9 at.% ^{10}B	1.3953×10^{-3}
	^{11}B	1.62 wt.% boron, 80.1 at.% ^{11}B	5.6163×10^{-3}
	Cr	19.6	1.7638×10^{-2}
	Cu	0.26	1.9145×10^{-4}
	Fe	66.4	5.5634×10^{-2}
	Mn	1.69	1.4394×10^{-3}
	Mo	0.31	1.5119×10^{-4}
	Ni	10.12	8.0684×10^{-3}

Table 29. Boral Absorber-Plate Atom Densities.

Material	Isotope	Wt.%	Atom Density
B_4C-Al[(a)] (2.49 g/cm^3)	Al	62.39	3.4673×10^{-2}
	^{10}B	28.7 wt.% boron, 19.9 at.% ^{10}B	7.9217×10^{-3}
	^{11}B	28.7 wt.% boron, 80.1 at.% ^{11}B	3.1886×10^{-2}
	C	7.97	9.9501×10^{-3}
	Cr	0.05	1.4419×10^{-5}
	Cu	0.09	2.1237×10^{-5}
	Fe	0.33	8.8606×10^{-5}
	Mg	0.05	3.0848×10^{-5}
	Mn	0.05	1.3647×10^{-5}
	Na	0.02	1.3045×10^{-5}
	Ni	0.02	5.1099×10^{-6}
	Si	0.2	1.0678×10^{-4}
	S	0.03	1.4027×10^{-5}
	Zn	0.1	2.2932×10^{-5}
1100 Aluminum[(b)] (2.70 g/cm^3)	Al	99.0	5.9660×10^{-2}
	Cu	0.12	3.0705×10^{-5}
	Mn	0.025	7.3991×10^{-6}
	Zn	0.05	1.2433×10^{-5}
	Si	0.4025	2.3302×10^{-4}
	Fe	0.4025	1.1719×10^{-4}

(a) middle 0.509-cm thickness of plate
(b) 0.102-cm-thick clad on both sides of B_4C-Al

Table 30. Copper Absorber-Plate Atom Densities.

Material	Isotope	Wt.%	Atom Density
Copper without Cd (8.913 g/cm^3)	C	0.34	1.5194×10^{-3}
	Cu	99.6	8.4128×10^{-2}
	Fe	0.004	3.8444×10^{-6}
	Mg	0.002	4.4168×10^{-6}
	Na	0.002	4.6695×10^{-6}
	O	0.03	1.0064×10^{-4}
	Si	0.02	3.8223×10^{-5}
	S	0.002	3.3474×10^{-6}
Copper with Cd (8.910 g/cm^3)	^{10}B	0.005 wt.% boron, 19.9 at.% ^{10}B	4.9384×10^{-6}
	^{11}B	0.005 wt.% boron, 80.1 at.% ^{11}B	1.9878×10^{-5}
	C	0.002	8.9346×10^{-6}
	Cd	0.989	4.7208×10^{-4}
	Cu	98.685	8.3328×10^{-2}
	Fe	0.02	1.9216×10^{-5}
	Mn	0.009	8.7901×10^{-6}
	Ni	0.01	9.1424×10^{-6}
	O	0.019	6.3720×10^{-5}
	Si	0.004	7.6419×10^{-6}
	Sn	0.25	1.1300×10^{-4}
	Zn	0.007	5.7440×10^{-6}

Table 31. Cadmium, Aluminum, and Zircaloy-4 Absorber-Plate Atom Densities.

Material	Isotope	Wt.%	Atom Density (barn-cm)$^{-1}$
Cadmium (8.65 g/cm^3)	Cd	99.7	4.6201×10^{-2}
	Zn	0.3	2.3899×10^{-4}
Aluminum (2.692 g/cm^3)	Al	97.15	5.8371×10^{-2}
	Cr	0.21	6.5475×10^{-5}
	Cu	0.12	3.0614×10^{-5}
	Fe	0.82	2.3803×10^{-4}
	Mn	0.21	6.1968×10^{-5}
	Si	0.82	4.7332×10^{-4}
	S	0.06	3.0330×10^{-5}
	Ti	0.61	2.0654×10^{-4}
Zircaloy-4 (6.32 g/cm^3)	Zr	98.16	4.0953×10^{-2}
	Fe	0.21	1.4311×10^{-4}
	Sn	1.5	4.8092×10^{-4}
	Cr	0.13	9.5156×10^{-5}

3.3.3 Moderator-Reflector - The acrylic support plate has a density of 1.185 g/cm^3 and a composition of 8 wt.% hydrogen, 60 wt.% carbon, and 32 wt.% oxygen. The moderator-reflector is water at a temperature of 24°C, which corresponds to a density of 0.997297 g/cm^3.[a] Atom densities are given in Table 32.

Table 32. Moderator-Reflector Atom Densities.

Material	Isotope	Atom Density (barn-cm)$^{-1}$
Water	H	6.6675×10^{-2}
	O	3.3338×10^{-2}
Acrylic	H	5.6642×10^{-2}
	C	3.5648×10^{-2}
	O	1.4273×10^{-2}

[a] Calculated from fifth-degree density equation as a function of temperature, Robert C. Weast, ed., *CRC Handbook of Chemistry and Physics, 70th Edition*, p. F-5.

3.4 Temperature Data

Temperature data for the individual experiments were not published. Logbook records give water temperatures of 23 – 25°C for five experiments of this series. Water density for a temperature of 24°C is used in the models.

3.5 Experimental and Benchmark-Model k_{eff}

The reported configurations were extrapolations to critical configurations. Therefore the experimental k_{eff} was 1.000.

Experimental uncertainties (Section 2) and simplifying the model by omitting the two lattice plates (Section 3.1.1) contribute to the estimated uncertainty in the benchmark-model k_{eff}. The included uncertainties are listed in Table 33.

Table 33. Uncertainty in Benchmark-Model k_{eff}.

Measurement Uncertainty or Model Simplification	Δk_{eff}
Fuel-Rod Characterization	0.0018
Temperature	0.0004
Cluster Separation	0.0001
Distance from Absorber Plate to Central Fuel Cluster	0.0001
Absorber-Plate Vertical Position	0.0008
Absorber-Plate Composition	0.0003
Absorber-Plate Thickness	0.0001
No Lattice Plates	0.0003
Total Uncertainty in k_{eff}[a]	0.0021

(a) Square root of sum of squares of individual Δk_{eff}'s.

Therefore the benchmark-model k_{eff} is 1.0000 ± 0.0021.

4.0 RESULTS OF SAMPLE CALCULATIONS

Results of calculations representing the twenty-seven critical configurations are presented in Table 34. Code versions and modeling options are discussed briefly in paragraphs preceding the input listings in Appendix A.

Table 34. Sample Calculation Results (United States).[(a)]

Code (Cross Section Set) → Case ↓	KENO (44-Group ENDF/B-V)	MCNP (Continuous Energy ENDF/B-V)
1	0.9966 ± 0.0018	0.9963 ± 0.0020
2	0.9970 ± 0.0020	0.9976 ± 0.0019
3	0.9922 ± 0.0021	0.9959 ± 0.0020
4	0.9980 ± 0.0021	0.9985 ± 0.0019
5	0.9959 ± 0.0018	0.9964 ± 0.0019
6	0.9967 ± 0.0017	0.9957 ± 0.0019
7	0.9986 ± 0.0020	0.9963 ± 0.0016
8	0.9987 ± 0.0019	0.9961 ± 0.0017
9	0.9949 ± 0.0020	0.9982 ± 0.0021
10	0.9957 ± 0.0019	0.9967 ± 0.0017
11	0.9946 ± 0.0018	0.9972 ± 0.0020
12	0.9989 ± 0.0019	0.9992 ± 0.0017
13	0.9964 ± 0.0018	0.9979 ± 0.0019
14	0.9947 ± 0.0019	0.9988 ± 0.0016[(b)]
15	0.9954 ± 0.0018	0.9989 ± 0.0018
16	0.9999 ± 0.0018	0.9971 ± 0.0019
17	0.9934 ± 0.0018	0.9989 ± 0.0021
18	0.9964 ± 0.0017	0.9954 ± 0.0018
19	0.9933 ± 0.0019	0.9991 ± 0.0019
20	0.9973 ± 0.0017	0.9985 ± 0.0021
21	0.9995 ± 0.0018	0.9963 ± 0.0017
22	0.9952 ± 0.0021	0.9968 ± 0.0017
23	0.9978 ± 0.0019	1.0006 ± 0.0020
24	0.9946 ± 0.0020	0.9971 ± 0.0016
25	0.9962 ± 0.0018	0.9956 ± 0.0020
26	0.9984 ± 0.0019	0.9974 ± 0.0019
27	0.9945 ± 0.0017	0.9966 ± 0.0018

(a) Because ENDF/B-V cross sections for Zn were not available, Zn was replaced by Cu in the calculations.

(b) Sn in copper plate was omitted because cross sections were not available.

5.0 REFERENCES

1. S. R. Bierman, E. D. Clayton, B. M. Durst, "Critical Separation Between Subcritical Clusters of 2.35 Wt% ^{235}U Enriched UO_2 Rods in Water with Fixed Neutron Poisons," PNL-2438, Batelle Pacific Northwest Laboratories, Richland, Washington, October 1977.

2. S. R. Bierman, B. M. Durst, E. D. Clayton, "Critical Separation Between Subcritical Clusters of 4.29 Wt% ^{235}U Enriched UO_2 Rods in Water with Fixed Neutron Poisons," NUREG/CR-0073, Batelle Pacific Northwest Laboratories, Richland, Washington, May 1978.

3. S. R. Bierman, B. M. Durst, E. D. Clayton, "Criticality Experiments with Subcritical Clusters of 2.35 Wt% and 4.29 Wt% ^{235}U Enriched UO_2 Rods in Water with Uranium or Lead Reflecting Walls, Near Optimum Water-to-Fuel Volume Ratio," NUREG/CR-0796, Vol. 1, PNL-2827, Batelle Pacific Northwest Laboratories, Richland, Washington, April 1979.

4. S. R. Bierman, 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, PNL-3314, Batelle Pacific Northwest Laboratories, Richland, Washington, July 1980.

5. S. R. Bierman, E. D. Clayton, "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," NUREG/CR-1784, PNL-3602, Batelle Pacific Northwest Laboratories, Richland, Washington, April 1981.

6. S. R. Bierman, B. M. Durst, E. D. Clayton, "Criticality 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, Undermoderated Water-to-Fuel Volume Ratio of 1.6," NUREG/CR-0796, PNL-3926, Vol. 2, Batelle Pacific Northwest Laboratories, Richland, Washington, December 1981.

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8. S. R. Bierman, E. S. Murphy, E. D. Clayton, R. T. Keay, "Criticality Experiments with Low Enriched UO_2 Fuel Rods in Water Containing Dissolved Gadolinium," PNL-4976, Batelle Pacific Northwest Laboratories, Richland, Washington, February 1984.

9. S. R. Bierman, "Criticality Experiments to Provide Benchmark Data on Neutron Flux Traps," PNL-6205, UC-714, Batelle Pacific Northwest Laboratories, Richland, Washington, June 1988.

10. S. R. Bierman, Criticality Experiments with Neutron Flux Traps Containing Voids," PNL-7167, TTC-0969, UC-722, Batelle Pacific Northwest Laboratories, Richland, Washington, April 1990.

11. B. M. Durst, S. R. Bierman, E. D. Clayton, J. F. Mincey, R. T. Primm III, "Summary of Experimental Data for Critical Arrays of Water Moderated Fast Test Reactor Fuel," PNL-3313, ORNL/Sub-81/97731/1, Batelle Pacific Northwest Laboratories, Richland, Washington, May 1981.

12. S. R. Bierman, B. M. Durst, E. D. Clayton, "Critical Separation between Subcritical Clusters of Low Enriched UO_2 Rods in Water with Fixed Neutron Poisons," Nuc. Technol., Vol. **42**, pp. 237-249, March 1979.

13. R. I. Smith and G. J. Konzek, principal investigators, "Clean Critical Experiment Benchmarks for Plutonium Recycle in LWR's," NP-196, Volumes 1 and 2, Battelle Pacific Northwest Laboratories, Richland, Washington, April, 1976, and September 1978.

14. S. R. Bierman and E. D. Clayton, "Criticality Experiments with Subcritical Clusters of 2.35 and 4.31 wt% ^{235}U-Enriched UO_2 Rods in Water with Steel Reflecting Walls," Nuc. Technol., Vol. **54**, August 1981.

15. S. R. Bierman, B. M. Durst, and E. D. Clayton, "Criticality Experiments with Subcritical Clusters of Low Enriched UO_2 Rods in Water with Uranium or Lead Reflecting Walls," Nuc. Technol., Vol. **47**, January 1980.

APPENDIX A: TYPICAL INPUT LISTINGS

A.1 KENO Input Listings

The version of KENO V.a used was SCALE 4.3 with CSAS 44-group ENDF/B-V cross sections, last updated 5/14/96, provided by the Radiation Safety Information Computational Center.

KENO V.a was run using 110 active generations of 1500 neutrons each, after skipping 50 generations. The small amounts of zinc were replaced by copper, due to unavailability of Zn cross sections.

KENO Input Listing for Case 7 of Table 34.

```
=CSAS25

f407p THREE 15X8 CLUSTERS, 2.54  CM PITCH, 5.76   CM SEPARATION
44GROUPNDF5 LATTICECELL
' U(4.306)02
U-234  1 0  5.1835-6 295 END
U-235  1 0  1.0102-3 295 END
U-236  1 0  5.1395-6 295 END
U-238  1 0  2.2157-2 295 END
O  1 0  4.6753-2 295 END
' water
H  2 0  6.6675-2 295 END
O  2 0  3.3338-2 295 END
' 6061 Al (clad)
AL  3 0  5.8433-2 295 END
CR  3 0  6.2310-5 295 END
CU  3 0  6.3731-5 295 END
MG  3 0  6.6651-4 295 END
MN  3 0  2.2115-5 295 END
TI  3 0  2.5375-5 295 END
'       (Zn replaced by Cu)
CU  3 0  3.0967-5 295 END
SI  3 0  3.4607-4 295 END
FE  3 0  1.0152-4 295 END
'  rubber end plug
C   4 0  4.3562-2 295 END
H   4 0  5.8178-2 295 END
CA  4 0  2.5660-3 295 END
S   4 0  4.7820-4 295 END
SI  4 0  9.6360-5 295 END
O   4 0  1.2461-2 295 END
' acrylic
H   5 0  5.6642-2 295 END
C   5 0  3.5648-2 295 END
O   5 0  1.4273-2 295 END
' SS plate
B-10 6 0 1.3953-3 295 END
B-11 6 0 5.6163-3 295 END
CR  6 0  1.7638-2 295 END
CU  6 0  1.9145-4 295 END
FE  6 0  5.5634-2 295 END
MN  6 0  1.4394-3 295 END
MO  6 0  1.5119-4 295 END
NI  6 0  8.0684-3 295 END
END COMP
SQUAREPITCH 2.540 1.265 1 2 1.415 3 1.283 0 END
k407p  THREE 15X8 CLUSTERS, 2.540 CM PITCH, 5.76  CM SEPARATION
READ PARA TME=200 GEN=160 NPG=1500 NSK=50 NUB=YES XS1=YES RUN=YES
END PARA
READ GEOM
UNIT 1
 COM=* FUEL PIN *
 CYLINDER  1 1  0.6325 92.075 0.0
 CYLINDER  0 1  0.6415 92.075 0.0
 CYLINDER  4 1  0.6415 94.2975 -2.2225
 CYLINDER  3 1  0.7075 94.2975 -2.2225
 CUBOID  2 1  4P1.27 94.2975 -2.2225
UNIT 2
 COM=* ARRAY OF FUEL PINS *
 ARRAY 1 0 0 -2.2225
 REPLICATE 5 1  2R0.0 2R0.0 0.0 2.54  1
 REPLICATE 2 1 0.0 0.0 7.64 7.64 0.0 0.0 1
UNIT 3
 COM=* WATER BETWEEN CLUSTERS 5.03  cm  *
 CUBOID  2 1  5.03   0 27.96  -7.64  94.2975 -2.2225
 CUBOID  5 1  5.03   0 27.96  -7.64  94.2975 -4.7625
```

KENO Input Listing for Case 7 of Table 34 (cont’d).

```
UNIT 4
 COM=* SS POISON PLATE BETWEEN CLUSTERS, 0.298CM WIDE *
 CUBOID  6 1  0.298 0.0 27.96 -7.64   91.5      0.0
 CUBOID  2 1  0.298 0.0 27.96 -7.64   94.2975 -2.2225
 CUBOID  5 1  0.298 0.0 27.96 -7.64   94.2975 -4.7625
UNIT 5
 COM=* WATER BETWEEN CLUSTERS, 0.432CM WIDE *
 CUBOID  2 1  0.432 0.0 27.96 -7.64   94.2975 -2.2225
 CUBOID  5 1  0.432 0.0 27.96 -7.64   94.2975 -4.7625
GLOBAL
UNIT 6
 COM=* CLUSTERS WITH WATER BETWEEN *
 ARRAY 2 0 0 -2.2225
 REPLICATE 2 1  2R30.5  2R22.86 12.7775 15.3  1
END GEOM
READ ARRAY  ARA=1 NUX=15 NUY=8  FILL F1 END FILL
          ARA=2 NUX=9 NUY=1
          FILL  2 3 4 5 2 5 4 3 2
               END FILL
END ARRAY
READ PLOT
  XUL=-4 YUL=34 ZUL=20 XLR=97 YLR=-4
  ZLR=20  UAX=1  VDN=-1 NAX=120 NCH=' *~ctla~' END
END PLOT
END DATA
END
```

A.2 MCNP Input Listings

MCNP4 was used. MCNP k_{eff} calculations used 110 generations of 1500 neutrons each after skipping 50 generations. The small amounts of zinc were replaced by copper, due to unavailability of Zn cross sections. ENDF/B-V cross sections for Sn were also unavailable. Sn in absorber plates was omitted (Case 14) or was represented by endl85 cross sections.

MCNP Input Listing for Case 7 of Table 34.

```
LCT9C7 - 3 15X8 clusters of U(4.31)O2 rods, ss w 1.6%B plates, plate high
1    1 .06993042   -1 7 -8  u=1 imp:n=1 $ uo2 fuel
2    0   -2 1 7 -8  u=1 imp:n=1 $ gap
3    3 .0597517   -12 2  u=1 imp:n=1 $ clad
4    4 .1173416   -2 8 u=1 imp:n=1 $ rubber end plug (top)
5    4 .1173416   -2 -7 u=1 imp:n=1 $ rubber end plug (bottom)
6    2 .1000126     12 u=1 imp:n=1 $ water
7    0  -4 3 -6 5  imp:n=1 lat=1 u=2 fill=1  $ lattice of fuel rods
8    0  -10 11 -20 19 -9 23 fill=2 imp:n=1  $ first rod cluster
9    0  -14 15 -20 19 -9 23 fill=2(43.86  0 0) imp:n=1  $ second rod cluster ***
10    0  -16 17 -20 19 -9 23 fill=2(87.72  0 0) imp:n=1  $ third rod cluster ***
11    2 .1000126     10 -15 -20 19 -9 23 #14  imp:n=1 $ water between clusters
12    2 .1000126     14 -17 -20 19 -9 23 #15  imp:n=1 $ water between clusters
13    5 .106563  19 -20 11 -16 -23 29  imp:n=1  $ acrylic support plate
14    6 .09013387   43 -44 41 -42  7 -47  imp:n=1  $ SS plate
15    6 .09013387   45 -46 41 -42 7 -47  imp:n=1  $ SS plate
16    2 .1000126    (-11:16:20:-19:9:-29) -24 25 -26 27 -28 35
               #14 #15             imp:n=1 $ water
17    0  24:-25:26:-27:28:-35  imp:n=0

1    c/z 1.27 1.27 .6325  $ fuel cylinder
2    c/z 1.27 1.27 .6415  $ clad inner surface
3    px  0.0  $ fuel rod cell boundary
4    px  2.54  $ fuel rod cell boundary
5    py  0.0  $ fuel rod cell boundary
6    py  2.54  $ fuel rod cell boundary
7    pz  0.0  $ bottom of fuel
8    pz  92.075  $ top of fuel
9    pz  94.2975  $ top of clad
10    px  38.0999  $ farthest edge of first cluster
11    px  .0001  $ closest edge of first cluster
12    c/z 1.27 1.27 .7075  $ clad outer surface
14    px  81.9599  $ farthest edge of second cluster  ***
15    px  43.8601  $ closest edge of second cluster  ***
16    px  125.8199 $ farthest edge of third cluster  ***
17    px  87.7201  $ closest edge of third cluster  ***
19    py  0.00001  $ sides of clusters
20    py  20.31999 $ sides of clusters
23    pz  -2.2225  $ bottom of fuel rod
24    px  155.82     $ side of water reflector    ***
25    px  -30   $ side of water reflector
26    py  50.32  $ side of water reflector
27    py  -30  $ side of water reflector
28    pz  107.075  $ top of water
29    pz  -4.7625  $ bottom of acrylic support plate
35    pz  -20.0625  $ bottom of water
41    py  -7.64     $ SS plate   **
42    py  27.96     $ SS plate   **
43    px  43.13     $ SS plate   ***
44    px  43.428    $ SS plate   ***
45    px  82.392    $ SS plate   ***
46    px  82.69     $ SS plate   ***
```

MCNP Input Listing for Case 7 of Table 34 (cont'd).

```
47    pz  91.5   $ SS plate

kcode  2500 1 10 810 50000
sdef  x=d1 y=d2 z=d3 cel=d4
si1   0 138
sp1   0 1
si2   0 31
sp2   0 1
si3   0 93
sp3   0 1
si4   l 8 9 10
sp4   v
print
c
c     MATERIALS FOR U(4.306)O2 RODS
c
c     m1 is UO2 fuel
m1    92234.50c 5.1835e-6 92235.50c 1.0102e-3
      92236.50c 5.1395e-6 92238.50c 2.2157e-2
      8016.50c  4.6753e-2
c     m2 is water
m2    8016.50c 3.3338e-2  1001.50c 6.6675e-2
mt2   lwtr.01t
c     m3 is 6061 Al (clad)
m3    13027.50c  5.8433e-2  24000.50c  6.2310e-5
      29000.50c  6.3731e-5  12000.50c  6.6651e-4
      25055.50c  2.2115e-5  22000.50c  2.5375e-5
c     Zn replaced by Cu, below
      29000.50c  3.0967e-5  14000.50c  3.4607e-4
      26000.50c  1.0152e-4
c     m4 is rubber (end plugs)
m4    6000.50c   4.3562-2    1001.50c 5.8178e-2
      20000.50c  2.5660e-3  16032.50c 4.7820e-4
      14000.50c  9.6360e-5   8016.50c  1.2461e-2
mt4   poly.01t
c     m5 is acrylic (support plate)
m5    1001.50c 5.6642e-2  6000.50c 3.5648e-2
      8016.50c 1.4273e-2
mt5   poly.01t
c     m6 is SS plate with 1.6% B (absorber plate)
m6    5010.50c 1.3953e-3 5011.50c 5.6163e-3
      24000.50c  1.7638e-2  29000.50c  1.9145e-4
      26000.50c  5.5634e-2  25055.50c  1.4394e-3
      42000.50c  1.5119e-4  28000.50c  8.0684e-3
```

A.3 ONEDANT/TWODANT Input Listings

CSASIX, ONEDANT and TWODANT input listings for sensitivity studies are provided in Appendix C.

APPENDIX B: LOGBOOKS

Logbooks are stored at the Los Alamos National Laboratory Archives under the original experiment number. Logbooks for the experiments were listed on the July 16, 1993, inventory for the shipment from Hanford to Los Alamos as being in Box 6. These 2.54-cm-pitch experiments are numbered SSC (Simulated Shipping Cask) 4.3-000-005 to -031 dated 7/28/77 to 9/15/77.

APPENDIX C: SAMPLE CSASIX, ONEDANT, AND TWODANT INPUTS FOR SENSITIVITY STUDIES USING HOMOGENIZED FUEL-ROD REGION

CSASIX and TWODANT

```
=CSASIX
c4ss1 CASE 1  THREE 15x8  CLUSTERS,
27GROUPNDF4 LATTICECELL
' U(4.31)02
U-234  1 0  5.1835-6 295 END
U-235  1 0  1.0102-3 295 END
U-236  1 0  5.1395-6 295 END
U-238  1 0  2.2157-2 295 END
O  1 0  4.6753-2 295 END
' water
H  2 0  6.6706-2 295 END
O  2 0  3.3353-2 295 END
' 6061 Al (clad)
AL  3 0  5.8433-2 295 END
CR  3 0  6.2310-5 295 END
CU  3 0  6.3731-5 295 END
MG  3 0  6.6651-4 295 END
MN  3 0  2.2115-5 295 END
TI  3 0  2.5375-5 295 END
'       (Zn replaced by Cu)
CU  3 0  3.0967-5 295 END
SI  3 0  3.4607-4 295 END
FE  3 0  1.0152-4 295 END
' SS plate
CR  4 0  1.7046-2 295 END
CU  4 0  2.0291-4 295 END
FE  4 0  5.8353-2 295 END
MN  4 0  1.3734-3 295 END
MO  4 0  1.2942-4 295 END
NI  4 0  9.0238-3 295 END
' water
H  5 0  6.6706-2 295 END
O  5 0  3.3353-2 295 END
END COMP
SQUAREPITCH 2.54  1.265  1 2 1.415 3 1.283 0  END
MORE DATA EPS=1.-7 PTC=1.-7 END MORE
END


    1     0     0
da41, 4.31 wt% 3 15 x 8clusters, 8.58 cm separation,

/      SS plates
/  Block 1
igeom=6 ngroup=27 isn=8 niso=6 mt=6 nzone=6 im=6 it=173 jm=5
jt=134  maxscm=560000 maxlcm=4500000 t

/  Block 2
xmesh=0 19.05 19.295 19.78 27.63 65.73 96.23
xints= 36 2 3 16 76 40
ymesh=0.0 22.86  30.5 50.82  58.46  81.32
yints= 30 16 42 16  30
zones=6r5; 2r5 4 3r5; 6 5 4 5 6 5;
     2r5 4 3r5; 6r5  t

/ Block 3
 lib=xs27.p3
 chivec=.021 .188 .215 .125 .166 .180 .090 .014 .001 18z
 maxord=3 ihm=42 iht=3 ihs=16 ititl=1 ifido=2 i2lp1=1   t

/ Block 4
 matls=isos  assign=matls   t
```

```
/ Block 5
 ievt=1  isct=1 ith=0 ibl=1 ibr=0 ibt=0 ibb=0
 epsi=0.00001 iitm=60 influx=0 oitm=40 bhgt=109.06  t

/ Block 6
 edoutf=3  pted=1 zned=0  t
```

CSASIX and ONEDANT

```
=CSASIX
GENERATE 27-GRP LIB FOR PNL FUEL PINS IN WATER
27GROUPNDF4 LATTICECELL
U-234 1 0 5.21951-6 295 END
U-235 1 0 1.01724-3 295 END
U-236 1 0 5.17519-6 295 END
U-238 1 0 2.23108-2 295 END
O 1 0 4.70776-2 295 END
H 2 0 6.67619-2 295 END
O 2 0 3.33809-2 295 END
AL 3 0 5.8433-2 295 END
CR 3 0 6.2310-5 295 END
CU 3 0 6.3731-5 295 END
MG 3 0 6.6651-4 295 END
MN 3 0 2.2115-5 295 END
TI 3 0 2.5375-5 295 END
AL 4 0 2.53336-3 295 END
CR 4 0 2.70145-6 295 END
CU 4 0 2.76306-6 295 END
MG 4 0 2.88965-5 295 END
MN 4 0 9.58796-7 295 END
TI 4 0 1.10013-6 295 END
C 4 0 7.63823-3 295 END
H 4 0 6.06879-2 295 END
CA 4 0 4.49928-4 295 END
S 4 0 8.38481-5 295 END
O 4 0 2.74185-2 295 END
SI 4 0 1.68960-5 295 END
H 5 0 6.67619-2 295 END
O 5 0 3.33809-2 295 END
END            COMP
SQUAREPITCH 2.54 1.265 1 2 1.415 3 1.283 0 END
END


 1 0 0
SLAB OF U(4.31)O2 FUEL PINS IN WATER, 15 CM WATER REFL, 91.44 CM LENGTH
 / Block 1
 igeom=slab ngroup=27 isn=16 niso=6 mt=6 nzone=6 im=5  it=129 t


 / Block 2
 xmesh= 0 44 45.72 48.26 50 63.26
 xints= 68 8 13 10 30  zones= 6 6 4 5 5 t


 / Block 3
 lib=xs27.p3
 chivec= .021 .188 .215 .125 .166 .180 .090 .014 .001 18z
 maxord=3 ihm=42 iht=3 ihs=16 ititl=1 ifido=2 i2lp1=1 t


 / Block 4
 matls=isos assign=matls t


 / Block 5
 ievt=1 isct=3 ibl=1 ibr=0 epsi=.000001 t


 / Block 6
 pted=1 zned=0 edoutf=3 t
```