NEA/NSC/DOC(95)03/IV
Volume IV

LEU-COMP-THERM-016

WATER-MODERATED RECTANGULAR CLUSTERS OF U(2.35)O_2 FUEL RODS (2.032-CM PITCH) SEPARATED BY STEEL, BORAL, COPPER, CADMIUM, ALUMINUM, OR ZIRCALOY-4 PLATES

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ACKNOWLEDGMENTS

The authors wish to thank three of the experimenters, Sid Bierman, Duane Clayton, and Michael Durst, who provided valuable additional information about how the experiments were conducted. They would also like to thank Roger Meade and Linda Sandoval of the Los Alamos National Laboratory Archives, who assisted in finding stored logbooks.

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IDENTIFICATION NUMBER: LEU-COMP-THERM-016 SPECTRA

KEY WORDS: absorber, acceptable, aluminum, boral, borated stainless steel, cadmium, compound, copper, fuel rods, low-enriched, plates, PNL, poison, stainless steel, thermal, ^{235}U, uranium, uranium dioxide, water-moderated, Zircaloy-4

1.0 DETAILED DESCRIPTION

1.1 Overview of Experiment

A series of critical approach experiments with clusters of 36-inch-long aluminum-clad U(2.35)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 2.032 cm or 1.684 cm. Some of these experiments were simply rod clusters in water (LEU-COMP-THERM-001, -003). Others added lead, depleted-uranium, or steel reflecting walls on two opposite sides of the cluster row (LEU-COMP-THERM-017). Some circular, triangular-pitched lattices, with pitches of 1.598 cm or 1.895 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 2.032-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 32 experiments, performed in early 1977, were evaluated.

The reactivity worths of the non-borated steel, copper without cadmium, aluminum, and Zircaloy-4 plates were calculated to be less than 1.1% of k_{eff}. Therefore these experiments are not recommended to validate calculations of these particular materials. However, 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. Primary references are 1 and 12. Details from specific references are so noted.

1.2.1 Experiment Tank and Surroundings[a] **-** Experiments were performed in a 0.952-cm-thick, open, carbon-steel tank (see Figures 1 and 2). Tank inside dimensions were 1.8 x 3.0 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 and lattice plates, aluminum rod and angle supports, and control/safety-blade guides, all described below) 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 sits upon a concrete floor, which is at least 40.6 cm thick (Reference 11, p. 32). The concrete walls of the room are 5 feet thick. The concrete ceiling is 2 feet thick and approximately 20 feet high. The tank is located approximately four feet from the two closest corner walls.

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 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.[b]

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.[c]

The top lattice plates were approximately 77 cm[d] above the fuel-rod support plate. They were joined by half-inch-diameter rods to 5.08 x 5.08 x 0.635 cm aluminum angles, which were attached at their ends to the walls of the tank. In one experiment, these aluminum supports were doubled, with no effect on the critical separation between clusters (Reference 1, pp. 26 and 28). 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.[d]

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[a] Tank dimensions were from References 1 - 10. Other information was from private communication, Sid Bierman, July, 1993.

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

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

[d] Reference 4, pp. 11 and 20. Also estimated from figures in Reference 1, pp. 4 and 6. Sid Bierman also estimated that the top lattice plate was about 6 inches below the top of the fuel (Private communication, August, 1993).

Figure 1. Loading a Fuel Rod.

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

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.

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

During one experiment from this set of experiments, 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.[a]

1.2.6 Water Reflector - The top water surface was always at least 15 centimeters above the top of the fuel region of the rods. (Reference 14, p. 132)[b] 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 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 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 temperature as 19.5 or 19.6°C for at least eight of the experiments of this particular series of 3-cluster experiments at this pitch. Three (experiments 013, 014, and 015) were experiments without absorber plates, reported in LEU-COMP-THERM-001. Three others (experiments 006, 010, and 016) were absorber-plate experiments (Cases 13, 16, and 30).

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 surfaces. For each experiment they were at a fixed distance from the outer-cell boundaries of the rods of the center cluster. The distance between absorber plate and center cluster was measured at several different horizontal positions to ensure that the plates were correctly positioned.[c] Each plate was slightly longer and wider than the rod clusters involved, and was positioned “to avoid a direct line of sight between rods of different clusters” (Reference 12, p 142).

In some of these experiments, specifically those in Reference 1, the absorber plates replaced the safety and control blades. The logbook described experiment 006 (Case 16) as *¼” Cu CR & SR Between A-B-C units positioned either side of “B”,* and indicated that the final count rates were for the *In-In* position of the control and safety 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

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

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

[c] Private communication, Sid Bierman, June, 1998. Sid Bierman said that the smaller uncertainty of the distance for closer spacings might have been because the smaller spacing was measured differently, perhaps with a more accurate micrometer or a piece of aluminum machined to a precise length. Such a piece of aluminum was used to horizontally position the lattice plates accurately, with holes of one directly above holes of the other.

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.[a]

Steel Plates. The 304L steel plates had thicknesses of 2.98 ± 0.06 mm, 3.02 ± 0.13 mm, and 4.85 ± 0.15 mm (References 1 and 12). At the 2.98-mm thickness, the critical separation between fuel-rod clusters was determined for three boron contents in the steel: 0.0, 1.05, and 1.62 wt.% boron. The steel plates were 35.6 cm wide and 91.5 cm long.

Boral Plates. The boral plates were 7.13 ± 0.11 mm thick, 35.6 cm wide, and 91.5 cm long. The 7.13-mm thickness included 1.02-mm-thick cladding of Type 1100 aluminum on either side of the B_4C-Al core material (Reference 12).

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 others were 30.6 cm wide and 91.5 cm long. The narrower width necessitated reduction of the width of the clusters from 16 to 15 rods in order to block the direct line of sight between clusters.

Cadmium Plates. The thicknesses of the cadmium plates were 0.291 ± 0.010 mm, 0.610 ± 0.025 mm, and 0.901 ± 0.027 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.[a] 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.

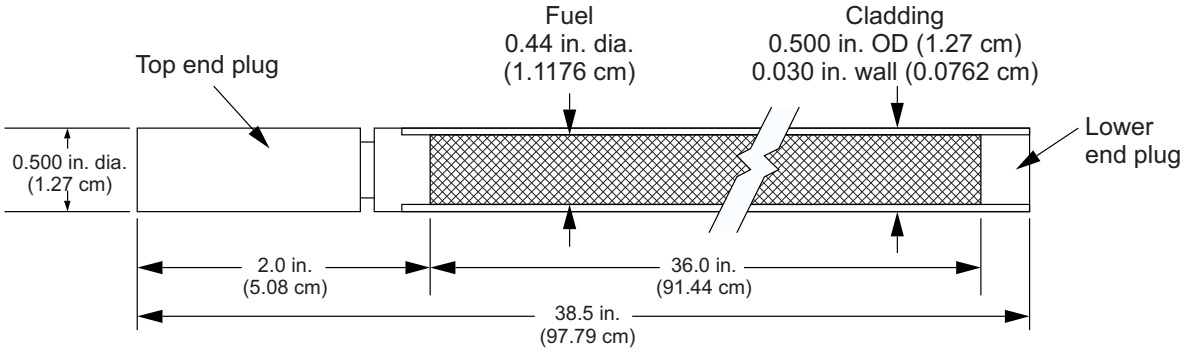
1.2.8 Fuel Rods - Fuel-rod dimensions are given in diagrams in References 1, 3-6, and 8. These diagrams are the same as Figure 3, which is a reproduction of an annotated diagram from Reference 13 (Vol 1, p. 29). Reference 13 is cited by Reference 8, p. 2.7, as the source of fuel-rod data.

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

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

Fuel specifications: 2.35% enriched UO_2

Fuel rods
1. Rod dimensions



2. Cladding: 6061 Aluminum tubing seal welded with a lower end plug of 5052-H32 Aluminum and a top plug of 1100 Aluminum.
3. Total weight of loaded fuel rods: 917 g (average)

Fuel loading
1. Fuel mixture vibrationally compacted.
2. 825 g of UO_2 powdered/rod, 726 g of U/rod, 17.08 g of U-235/rod.
3. Enrichment = 2.35 ± 0.05 w/o U-235.
4. Fuel density = 9.20 g/cm (84% theoretical density).

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Figure 3. U(2.35)O_2 Fuel Rod.

Dimensions of the U(2.35)O_2 fuel rods are summarized in Table 1. The total rod length is 97.79 cm. The clad length is an approximation from measuring Figure B-1 in Reference 13 (Vol 1, p. 29). The clad envelops the lower end plug, fuel, and ~0.48 cm of the top end plug. Dimensions of the notch shown in the top end plug are not known. When the fuel rods were fabricated, end plugs were pushed in (or on) for a tight fit, then were cut off; so the lengths of the plugs are only approximate.[a]

Table 1. 2.35-Wt.%-Enriched UO_2 Fuel-Rod Dimensions.

Component	Length (cm)	Diameter (cm)
UO_2 fuel	91.44	1.1176
Top end plug(1100 Al)	5.08	1.27
Lower end plug (5052-H32 Al)	1.27	1.1176
Clad (6061 Al)	~93.19	1.270 OD (0.0762 cm thick)

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

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, p 2.3) and two or three inches long.[a] 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, pp. 3.6 and 3.7).

1.2.10 Experimental Method for Determining Critical Configuration[b] **-** 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). For 12 experiments with these rods at this pitch, the logbook gives the ratio of the extrapolated critical separation to the smallest experimental (subcritical) separation. Most of these ratios were greater than 0.93. The lowest ratio was 0.65 for experiment number 011, which is not listed in the published data.

These 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.[c]

To vary the cluster separation, fuel rods were moved from one side of the cluster to the other side in half-row or whole-row increments, so that the average rod worth of the addition was approximately equal to the average rod worth of an entire row. The lattice plates were not moved. (See LEU-COMP-THERM-001, Section 1.2.8, for an example of this method.)

1.2.11 Critical Cluster Dimensions and Separations - Typical arrangements of fuel clusters and the neutron-absorber material are shown in Figures 4 and 5.

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

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

[c] Plots of both [separation]/[count rate] vs. [separation] and 1/[count rate] vs. [separation]) were used because one tended to overestimate the critical parameter variation and the other to underestimate it. The lower prediction was used in applying the operational safety rule that no more than 85% of the difference between latest configuration and predicted critical configuration could be implemented. As criticality was approached, both curves tended to predict the same critical configuration. (Private communication, Duane Clayton, August, 1993.)

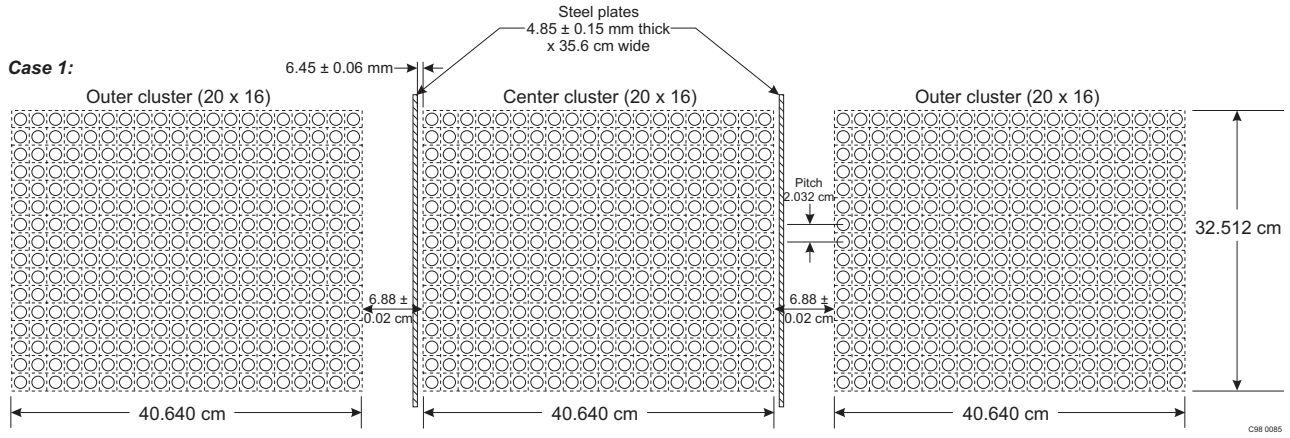

Figure 4. Critical Configuration of Case 1.

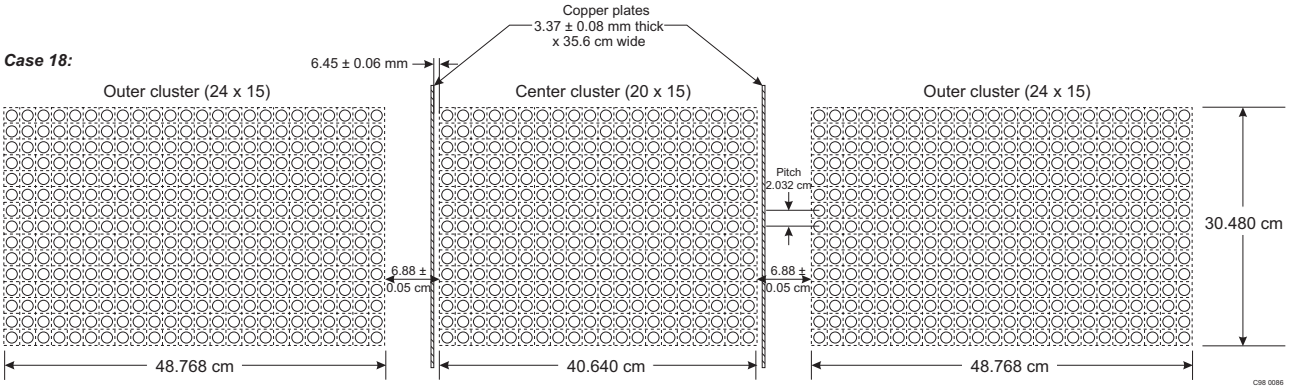

Figure 5. Critical Configuration of Case 18.

Cluster sizes and separations (References 1 and 12) for the 32 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 2.032-cm square pitch. Cluster dimensions are given in rods: the first dimension is along the direction of cluster placement; the second dimension is the width of facing sides, as shown in Figures 4 and 5. Cluster separations are 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.

Table 2. $U(2.35)O_2$ Fuel-Rod Cluster Critical Configurations with Steel Plates.

Case No.	Cluster Dimensions (number of rods)	Steel Plates			Separation of Fuel Clusters (mm)	Exp. No.
		Boron Content (wt.%)	Thickness (mm)	Distance to Center Fuel Cluster (mm)		
1	20 x 16	0	4.85 ± 0.15	6.45 ± 0.06	68.8 ± 0.2	028
2	20 x 16	0	4.85 ± 0.15	27.32 ± 0.50	76.4 ± 0.4	005
3	20 x 16	0	4.85 ± 0.15	40.42 ± 0.70	75.1 ± 0.3	029
4	20 x 16	0	3.02 ± 0.13	6.45 ± 0.06	74.2 ± 0.2	027
5	20 x 16	0	3.02 ± 0.13	40.42 ± 0.70	77.6 ± 0.3	026
6	20 x 17	0	3.02 ± 0.13	6.45 ± 0.06	104.4 ± 0.3	034
7	20 x 17	0	3.02 ± 0.13	40.42 ± 0.70	114.7 ± 0.3	035
8	20 x 17	1.05	2.98 ± 0.06	6.45 ± 0.06	75.6 ± 0.2	032
9	20 x 17	1.05	2.98 ± 0.06	40.42 ± 0.70	96.2 ± 0.3	033
10	20 x 17	1.62	2.98 ± 0.05	6.45 ± 0.06	73.6 ± 0.3	038
11	20 x 17	1.62	2.98 ± 0.05	40.42 ± 0.70	95.2 ± 0.3	039

Table 3. $U(2.35)O_2$ Fuel-Rod Cluster Critical Configurations with Boral Plates.

Case No.	Cluster Dimensions (number of rods)	Boral Plates		Separation of Fuel Clusters (mm)	Exp. No.
		Thickness (mm)[a]	Distance to Center Fuel Cluster (mm)		
12	20 x 17	7.13 ± 0.11	6.45 ± 0.06	63.3[b] ± 0.5	020, 023
13	20 x 17	7.13 ± 0.11	44.42 ± 0.60[c]	90.3 ± 0.5	016[d]
14	20 x 16 (center) 22 x 16 (two outer)	7.13 ± 0.11	6.45 ± 0.06	50.5 ± 0.3	017

(a) Includes 1.02-mm-thick cladding of Type 1100 aluminum on either side of the B_4C-Al absorber material.
(b) Average of two experiments with results 63.4 ± 0.2 and 63.2 ± 0.5. The uncertainty is from Reference 1. Reference 12 gives this uncertainty as 0.2 mm.
(c) This uncertainty is from Reference 1. Reference 12 gives this uncertainty as 0.06 mm.
(d) Water temperature recorded in logbook as 19.5°C.

Table 4. $U(2.35)O_2$ Fuel-Rod Cluster Critical Configurations with Copper Plates.

Case No.	Cluster Dimensions (number of rods) (X x Y)	Copper Plates			Separation of Fuel Clusters (mm)	Exp. No.
		Cd Content (wt.%)	Thickness (mm)	Distance to Center Fuel Cluster (mm)		
15	20 x 16	0.0	6.46 ± 0.08	6.45 ± 0.06	66.2 ± 0.2	031
16	20 x 16	0.0	6.46 ± 0.08	27.32 ± 0.50	77.2 ± 0.6	006[(a)]
17	20 x 16	0.0	6.46 ± 0.08	44.42 ± 0.60	75.1 ± 0.2	012
18	20 x 15 (center) 24 x 15 (two outer)	0.0	3.37 ± 0.08	6.45 ± 0.06	68.8 ± 0.5	043
19	20 x 15 (center) 24 x 15 (two outer)	0.0	3.37 ± 0.08	40.42 ± 0.70	70.0 ± 0.4	044
20	20 x 15 (center) 24 x 15 (two outer)	0.989	3.57 ± 0.08	6.45 ± 0.06	51.5 ± 0.6	041

(a) Water temperature recorded in logbook as 19.5°C; room temperature recorded as 19.7°C.

Table 5. $U(2.35)O_2$ Fuel-Rod Cluster Critical Configurations with Cadmium Plates.

Case No.	Cluster Dimensions (number of rods)	Cadmium Plates		Separation of Fuel Clusters (mm)	Exp. No.
		Thickness (mm)	Distance to Center Fuel Cluster (mm)		
21	20 x 17	0.610 ± 0.025	6.45 ± 0.06	67.4 ± 0.6	036
22	20 x 17	0.610 ± 0.025	14.82 ± 0.70	76.0 ± 0.2	054
23	20 x 17	0.610 ± 0.025	40.42 ± 0.70	93.7 ± 0.3	037
24	20 x 17	0.291 ± 0.010	14.82 ± 0.70	77.8 ± 1.0	050
25	20 x 17	0.291 ± 0.010	40.42 ± 0.70	94.0 ± 0.3	051
26	20 x 17	0.901 ± 0.027	14.82 ± 0.70	75.4 ± 0.3	052
27	20 x 17	0.901 ± 0.027	40.42 ± 0.70	93.9 ± 0.3	053

Table 6. $U(2.35)O_2$ Fuel-Rod Cluster Critical Configurations with Aluminum Plates.

Case No.	Cluster Dimensions (number of rods)	Aluminum Plates		Separation of Fuel Clusters (mm)	Exp. No.
		Thickness (mm)	Distance to Center Fuel Cluster (mm)		
28	20 x 16	6.25 ± 0.01	6.45 ± 0.06	86.7 ± 0.3	024
29	20 x 16	6.25 ± 0.01	40.42 ± 0.7	87.8 ± 0.3	048
30	20 x 16	6.25 ± 0.01	44.42 ± 0.60	88.3 ± 0.3	010[(a)]

(a) Water temperature recorded in logbook as 19.5°C.

Table 7. $U(2.35)O_2$ Fuel-Rod Cluster Critical Configurations with Zircaloy Plates.

Case No.	Cluster Dimensions (number of rods)	Zircaloy-4 Plates		Separation of Fuel Clusters (mm)	Exp. No.
		Thickness(mm)	Distance to Center Fuel Cluster (mm)		
31	20 x 16	6.52 ± 0.08	6.45 ± 0.06	87.9 ± 0.3	046
32	20 x 16	6.52 ± 0.08	40.42 ± 0.70	87.8 ± 0.4	047

1.3 Description of Material Data

1.3.1 Fuel Rod - UO_2 Fuel. Figure 3 (from Reference 13, Vol. 1, p. 29) and results of a fuel-rod sample analysis (Reference 13, Vol. 2, p. 3) are the bases for the fuel material characterization. As also stated in Reference 1, a fuel rod contains 825 g of UO_2 powder, 726 g of 2.35 wt.% enriched uranium, and 17.08 g of ^{235}U, at an oxide density of 9.20 g/cm^3.[a] The isotopic content of the uranium is given in Table 8.

Table 8. Isotopic Composition of Uranium in 2.35% Enriched UO_2 Fuel Rods. (Reference 8, p. 2.8)

Uranium Isotope	Wt.%[(a)]
^{234}U	0.0137 ± 0.0003
^{235}U	2.350 ± 0.003
^{236}U	0.0171 ± 0.0003
^{238}U	97.62 ± 0.003

(a) Values are originally from Reference 13, Vol 2, p. 3. Uncertainties are 1σ. (Note that the total of weight percents is 100.008.)

Aluminum Alloys. Aluminum components of the fuel rods are the top (longer) end plug of 1100 aluminum, the lower end plug of 5052 aluminum, and the clad of 6061 aluminum. Measured densities and ASTM Standard chemical compositions of these three types of aluminum are given in Table 9.[b] The ASTM Standard for these three aluminum alloys includes limits on impurities to maximums of 0.05 wt.% each and 0.15 wt.% total.

[a] These values are not self-consistent. See discussion in Section 2.1.

[b] ASTM Standard, from Reference 8, pp. A.2-A.4, and from *Alcoa Aluminum Handbook*, Aluminum Company of America, 1967, pp. 46-50.

1.3.2 Support Structures - Aluminum. Experiment support structures, including lattice plate supports and spacer rods, control/safety blade guides, tubes housing the proportional counters, and sleeves for gadolinium control rods, were 6061 aluminum alloy.

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 chemical compositions from References 1 and 12 are given in Tables 10 - 15. According to Reference 1, "Error limits where shown are one standard deviation based on multiple chemical analyses. Error limits not shown for minor impurities. Impurities distribution based on spark source mass spectrographic analyses and represent best estimate of maximum concentration for each element present in significant quantity."

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

[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.

Table 9. Measured Densities and Standard Compositions of Aluminum Alloys.

Element	Wt.%
1100 Aluminum (density - 2.70 g/cm^3)	
Si, Fe	1.0 (combined maximum)
Cu	0.05-0.20 (0.12 nominal)
Mn	0.05 (maximum)
Zn	0.10 (maximum)
Al	99.00 (minimum)
5052 Aluminum (density - 2.69 g/cm^3)	
Si, Fe	0.45 (combined maximum)
Cu	0.10 (maximum)
Mn	0.10 (maximum)
Mg	2.2-2.8 (2.5 nominal)
Cr	0.15-0.35 (0.25 nominal)
Zn	0.10 (maximum)
Al	remainder (96.10-97.65)
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)

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).

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 Plate.

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 - Laboratory analyses of the water in the tank were done at the beginning and near the end of the experiments. The reported average impurity concentrations are given in Table 15 (Reference 1). The approximate average water temperature was 19.5°C, based on six values recorded in the logbook for experiments of this series. Three of the six are Cases 13, 16, and 30, as noted in footnotes to Tables 3, 4, and 6. This corresponds to a density of 0.998306 g/cm^3.[a]

Table 15. Water Impurities.

Component	Concentration (ppm)
Cl	26.2 ± 5.4
NO_3^-	0.24 ± 0.12
Cr^{+6}	<0.028
Zn	0.35 ± 0.05
Mn	<0.55
Pb	<0.015
F	0.21 ± 0.02
Fe	<0.06
Cu	<0.06
Cd	0.004 ± 0.001
SO_3	6.7 ± 0.4

1.3.7 Tank - The experiment tank was carbon steel, which is approximately 1 wt.% Mn, 0.9 wt.% C, and the remainder 98.1 wt.% Fe.[b] Density and composition were not reported.

1.4 Supplemental Experimental Measurements

No supplemental experimental measurements were reported.

[a] Calculated from fifth-degree density equation as a function of temperature, Robert C. Weast, ed., *CRC Handbook of Chemistry and Physics, 68th Edition*, p. F-5.

[b] Robert C. Weast, ed., *CRC Handbook of Chemistry and Physics, 68th Edition*, CRC Press, 1987, p. E-114.

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

UO_2. Some uncertainty exists in the characterization of the fuel rods. Dimensions and masses are stated in the source document (Reference 13, Vol. 1, p. 29) with no mention of measurement techniques or uncertainties. The 3σ-uncertainty in enrichment is stated as 0.01 wt.% without further discussion (Reference 13, Vol. 2, p. 3).

As mentioned in Section 1.3.1, quantities characterizing the fuel are not self-consistent. Table 16 gives the mass of ^{235}U derived in different ways from the given quantities. The highest and lowest uranium masses represent a difference of less than 0.2% (727.22 g vs. 726 g).

Table 16. Mass of ^{235}U Per Fuel Rod Derived from Different Reported Sets of Quantities.

Reported Quantities	Derived ^{235}U Mass (g)
^{235}U mass[(a)]	17.08
Mass of U (726 g)[(b)] and 2.35 wt.% ^{235}U	17.0610
Mass of UO_2 (825 g)[(c)] and 2.07 wt.% ^{235}U in UO_2 [(d)]	17.0775[(e)]
UO_2 density (9.20 g/cm^3)[(c)], volume of fuel[(f)], and 2.07 wt.% ^{235}U in UO_2 [(d)]	17.0827
Mass of UO_2 (825 g)[(c)], 2.35 wt.% ^{235}U, and 2-to-1 ratio of O atoms to U atoms in UO_2	17.0896
Total rod mass (917 g)[(a)], volume[(f)] and density of aluminum, and 2.07 wt.% ^{235}U in UO_2 [(d)]	17.0775

(a) Given only in Reference 1.
(b) Given in References 1 and 8.
(c) Given in all reports on experiments with 2.35 wt.% enriched rods. (References 1, 3-6, and 8.)
(d) Reference 13, Vol. 2, p. 3.
(e) This mass and the given wt.%'s of the uranium isotopes result in a formula for uranium dioxide of $UO_{2.012}$. This is within the typical range for UO_2 powders of $UO_{2.005}$ and $UO_{2.129}$.[a]
(f) Calculated from reported dimensions.

[a] C. R. Tipton, Jr., ed., *Reactor Handbook, Second Edition*, Interscience Publishers, Inc., N.Y., vol. I, p. 292.

An experimenter recommended that mass of the UO_2 powder be used as the basic quantity for characterizing the fuel, rather than grams of U per rod, average weight of the rod, or reported fuel density.[a] Therefore to determine benchmark atom densities of the fuel, the reported masses of UO_2 (825 g) and of ^{235}U (17.08 g), with uranium enrichment of 2.35% and the reported fuel-region dimensions were used.

Aluminum Alloys. In order to test the sensitivity of the critical configurations to the small amounts of alloying substances in the aluminum, four cases were calculated with ONEDANT of a near-critical, cylindrical, water-reflected lattice of rods at pitch 2.032 cm. Each case used only one of the three aluminum alloys or pure aluminum for clad. Results are given in Table 17. The greatest difference is 0.17%, between pure aluminum clad and 6061 aluminum clad. Therefore, to more accurately represent the fuel rods for this benchmark, the specified aluminum alloys with nominal amounts of all constituents are included.

Table 17. Calculated Effects of Different Aluminum Claddings.[(a)]

Clad Material	Δk_{eff} (%)[(b)]
6061 aluminum[(c)]	-
1100 aluminum[(c)]	0.04
5052 aluminum[(c)]	0.12
aluminum[(d)]	0.17

(a) Clad thickness was increased by 28% to include the amount of aluminum in the endplugs.
(b) Homogenized fuel-rod mixture, SCALE 27-group ENDF/B-IV cross sections created by CSASIX.
(c) Minimum amounts of aluminum and maximum amounts of other components (see Table 9).
(d) Density is the nominal ^{27}Al density in 6061 aluminum alloy (97.325 wt.% of 2.69 g/cm^3).

The magnitudes of other uncertainties in fuel-rod data are taken as half the value of the least significant digit, when the uncertainty is not given. The effects on k_{eff} of the uncertainties in enrichment, fuel diameter, fuel length, clad thickness, pitch, and uranium mass for a near-critical configuration are summarized in Table 18. Effects were calculated with ONEDANT and CSAS ENDF/B-IV 27-group cross sections using an infinite-slab homogeneous mixture representing the fuel rods. The calculations were P_3, S_{16}, with a convergence criterion of 10^{-6}. The last two entries in Table 18 are the calculated results from two models that contain a combination of individual changes. Results indicate that effects on k_{eff} due to uncertainties in fuel-rod characterization and pitch could be as great as 0.31%. Note that this is for the case of all rods having all changes that affect k_{eff} positively, which is unlikely. However, an uncertainty of ± 0.31% due to uncertainties in fuel-rod characterization may be included in the benchmark-model k_{eff}.

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

Table 18. Sensitivity of k_{eff} to Uncertainties in Fuel-Rod Characterization.

Quantity (Amount of Change)	% Δk_{eff} (ONEDANT)[a]	
	Increase in the Quantity	Decrease in the Quantity
Enrichment (± 0.01 wt.%[b])	+0.10	-0.09
Fuel Diameter (± 0.0127 cm)	+0.10	-0.08
Fuel Length (± 0.127 cm)	-0.07	0.00
Clad Diameter (± 0.00127 cm)	-0.00	+0.01
Pitch (± 0.0076 cm[c])	-0.14	+0.21
Random Pitch (±0.0127 cm/√ 300[d])	-0.01	+0.02
Uranium Mass (-0.81 g and +0.41 g)	+0.03	+0.01
Simultaneously make all above changes that individually increase k_{eff}	Δk_{eff} = +0.31%	
Simultaneously make all above changes that individually decrease k_{eff}	Δk_{eff} = -0.30%	

(a) 27-group ENDF/B-IV cross sections with homogenized lattice-cell fuel region (CSASIX); sample input given in Appendix C.
(b) 3σ uncertainty (Reference 13, Vol. 2, p. 3)
(c) 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). References 7 (p. 2) and 8 (p. 36) give the uncertainty in pitch as ± 0.005 cm. References 9 (p. 3.2) and 10 (Appendix D) give the uncertainty in pitch as ± 0.001 cm. Therefore, the calculated uncertainty is conservative.
(d) Difference between fuel-rod OD and diameter of holes in lattice plates, divided by the square root of the minimum number of rods per cluster.

2.2 Water Reflector

2.2.1 Top Reflector Thickness - The minimum thickness of the top water reflector is 15 cm above the fuel region. Since the top end plug is 2 inches (5.08 cm) long, the minimum water reflector thickness above the rods is 9.92 cm.

Calculations were performed for an infinite-slab fuel region with a water reflector on both sides. ONEDANT and CSAS 27-group ENDF/B-IV cross sections, with a lattice-cell fuel region homogenized by XSDRNPM, were used. 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 0.002%.

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 less than 0.004%. This value is included in the k_{eff} uncertainty.

These calculations indicate that a top water reflector with a thickness of 15 centimeters may be considered as "effectively infinite" and materials beyond the top and bottom reflectors may be neglected. Therefore, lack of data about material above the 15-cm-thick top water reflector does not affect the acceptability of these experiments as benchmark critical experiments.

2.2.2 Side Water Reflector Thickness - Additionally ONEDANT was used to determine the effect of radial-reflector thickness for a near-critical, cylindrical, XSDRN-homogenized array of pins. The difference in k_{eff} between a 15-cm-thick side reflector and a 30-cm-thick side reflector is less than 0.001%. Replacing the outermost 15 cm of the 30-cm-thick water with 20% stainless steel in water affects k_{eff} by less than 0.002%. Therefore, lack of specifications about detectors, which were placed in the water reflector more than 15 cm away from the clusters, does not affect acceptability of these experiments.

2.3 Water Impurities

Water impurity sensitivity studies described in Appendix C of LEU-COMP-THERM-001 indicate that only gadolinium and boron impurities significantly affect k_{eff}. No gadolinium or boron impurity is reported for these configurations. The effects on k_{eff} of impurities in the water listed in Table 15 for a near-critical cylindrical cluster of $U(2.35)O_2$ fuel pins, were calculated using ONEDANT. The combined effect of the impurities is less than 0.004% of k_{eff}. This effect of impurities is included in the k_{eff} uncertainty.

2.4 Temperature Data

Eight of the 3-cluster experiments with these rods at this pitch were noted in the logbook with water temperature of 19.5 or 19.6°C. Therefore the average temperature of 19.5°C is assumed for these experiments. Water temperatures were recorded in logbooks for approximately ten percent of all the experiments reported in References 1 - 10, 12, and 14. Measured temperatures ranged from 18°C to 26°C, indicating a larger range of uncertainty. ONEDANT calculations with CSAS ENDF/B-IV 27-group cross sections, for an infinite slab of fuel pins reflected on both sides by 15 cm of water were run with temperatures specified for cross section processing and water atom densities appropriately modified. The results gave a change in k_{eff} of 0.01% between these two extremes of temperature. Therefore, an estimate of the uncertainty in k_{eff} due to the effects of temperature is 0.008%, representing the 6.5°C maximum deviation from the benchmark temperature.

2.5 Cluster and Absorber Plate Separations

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 0.02 cm to 0.1 cm. To calculate the effect on k_{eff}, cluster separations were reduced by the particular uncertainty for eighteen representative cases. The effect of the uncertainty was ≤0.001% for all cases except two with aluminum and Zircaloy-4 plates, where the effect was 0.015%. 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 distance between the central fuel cluster and the absorber plates vary from 0.01 cm to 0.07 cm. To calculate the effect on k_{eff}, cluster separations were increased by the particular uncertainty for twenty-four representative cases. Calculated effects were ≤0.001% except for the 0.07-cm separation uncertainty for cadmium plates, which gave a calculated effect of 0.002%. This value may be used as the k_{eff} uncertainty due to uncertainty in separation between center cluster and absorber plates.

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 (average amounts of components) is given in Tables 19 through 26. 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 Cases 1 and 7 of Table 2 the effects of maximum weight percents of iron and manganese in the non-borated steel plate were individually compared to effects of minimum weight percents. The difference from the base case is shown in Table 19. Similarly, for Case 8 effects of maximum and minimum weight percents of boron, iron, and manganese in the 1.1-wt.% borated steel plate were individually calculated and compared to the base case. The variation in ^{10}B isotopic fraction in natural boron from 0.191 to 0.203 was also calculated. Results are shown in Table 20. Similar sensitivity calculations were performed for the 1.6-wt.% borated steel plate (Case 10), and results are given in Table 21.

Table 19. Calculated Effect of Non-Borated Steel Plate Composition Uncertainties on k_{eff}.

Case	Description	Δk_{eff} (%)
1 (Three 20x16 Clusters)	Fe (68.24) ± 0.34 (wt.%)	0.002
	Mn (1.58) ± 0.05 (wt.%)	0.001
	Non-Borated Steel Plates Replaced with Water	0.890
7 (Three 20x17 Clusters)	Fe (68.24) ± 0.34 (wt.%)	<0.001
	Mn (1.58) ± 0.05 (wt.%)	<0.001
	Non-Borated Steel Plates Replaced with Water	0.156

Table 20. Calculated Effect of 1.1-wt.% Borated Steel Plate Composition Uncertainties on k_{eff} (Case 8).

Description	Δk_{eff} (%)
B (1.05) ± 0.08 (wt.%)	0.017
^{10}B (19.9) +0.4, -0.8 (at.%)	0.009
Mn (1.58) ± 0.05 (wt.%)	<0.001
Fe (68.04) ± 0.34 (wt.%)	<0.001
1.1-wt.% Borated Steel Plates Replaced with Water	1.715

Table 21. Calculated Effect of 1.6-wt.% Borated Steel Plate Composition Uncertainties on k_{eff} (Case 10).

Description	Δk_{eff} (%)
B (1.62) ± 0.10 (wt.%)	0.014
^{10}B (19.9) +0.4, -0.8 (at.%)	0.009
Mn (1.69) ± 0.05 (wt.%)	<0.001
Fe (66.40) ± 0.33 (wt.%)	<0.001
1.1-wt.% Borated Steel Plates Replaced with Water	1.874

Boral Plates. For Case 12 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 22.

Table 22. Calculated Effect of Boral Plate Composition Uncertainties on k_{eff} (Case 12).

Description	Δk_{eff} (%)
B (28.70) ± 0.25 (wt.%)	0.002
^{10}B (19.9) +0.4, -0.8 (at.%)	0.007
Fe (0.33) ± 0.04 (wt.%)	<0.001
Boral Plates Replaced with Water	2.665

Copper Plates. For Case 20 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 results given in Table 23.

Table 23. Calculated Effect of Copper Plate Composition Uncertainties on k_{eff} (Case 20).

Description	Δk_{eff} (%)
Cd (0.989) ± 0.003 (wt.%)	0.001
Copper Plates without Cd Replaced with Water (Case 15)	1.061
Copper Plates with Cd Replaced with Water (Case 20)	1.680

Cadmium Plates. The maximum and minimum wt.% Cd of the cadmium plate were compared for Case 21 of Table 5, with results given in Table 24. Effects of Plexiglas stiffener plates next to the cadmium were also calculated.

Table 24. Calculated Effect of Cadmium Plate Composition Uncertainties on k_{eff} (Case 21).

Description	Δk_{eff} (%)
Cd (99.7) ± 0.3 (wt.%)	<0.001
0.296-cm-thick Plexiglas (one side)	<0.001
0.16-cm-thick Plexiglas (both sides)	0.001
Cadmium Plates Replaced with Water	2.213

Aluminum Plates. The maximum and minimum wt.% Al in the aluminum plate were calculated, with results given in Table 25.

Table 25. Calculated Effect of Aluminum Plate Composition Uncertainties on k_{eff} (Case 28).

Description	Δk_{eff} (%)
Al (97.15) ± 0.21 (wt.%)	0.001
Aluminum Plates Replaced with Water	-0.089

Zircaloy-4 Plates. The maximum and minimum wt.% of zirconium and iron in the Zircaloy-4 plate were compared, with results given in Table 26.

Table 26. Calculated Effect of Zircaloy-4 Plate Composition Uncertainties on k_{eff} (Case 31).

Description	Δk_{eff} (%)
Zr (98.16) ± 0.35 (wt.%)	<0.001
Fe (0.21) ± 0.03 (wt.%)	0.001
Zircaloy-4 Plates Replaced with Water	-0.216

Results indicate that the uncertainty in k_{eff} due to uncertainty in composition of absorber plates is less than 0.019% Δk_{eff}. 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 0.002% Δk_{eff}. This can be included in the uncertainty of the benchmark-model k_{eff}.

2.7 Conclusions of Acceptability

Because the effects of the non-borated steel, copper without cadmium, aluminum, and Zircaloy-4 plates in these experiments with water were calculated to be small (<1.1% of k_{eff}), the cases that include these plates (Cases 1-7, 15-19, and 28-32) are not considered as good tests of the ability of code packages to correctly calculate these materials. But 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 square-pitched, aluminum-clad cylindrical fuel pins in water in three rectangular clusters arranged in a row with absorber plates between clusters. Several sensitivity studies were performed to justify simplifications of the benchmark model.

3.1.1 Water Impurities - The calculated effect on k_{eff} of impurities in the water is less than 0.004% (Section 2.3). This effect of impurities is included in the total k_{eff} uncertainty. Impurities are not included in the benchmark model.

3.1.2 Lattice Plates - The acrylic lattice plates are omitted from the benchmark model. A ONEDANT sensitivity study of a slab of homogenized fuel pins reflected by 15 cm of water with two lattice plates placed ~30 cm above and below the centers of the pins gave a calculated effect on k_{eff} of the two lattice plates of 0.02%. This is included in the uncertainty of the benchmark-model k_{eff}.

3.1.3 Reflector - The model of the bottom reflector is 2.54 cm of acrylic followed by 15.3 cm of water. The effects on k_{eff} of the one-inch-thick acrylic support plate directly beneath the fuel rods and the carbon steel tank 17.84 cm below the fuel rods were calculated using a ONEDANT slab model with CSAS ENDF/B-IV 27-group cross sections and a homogeneous fuel region. Results are shown in Table 27. The conclusions are that the carbon steel tank has no effect and the acrylic support plate has a small effect (0.06%). Therefore the support plate is retained in the benchmark model and the tank wall is omitted.

Table 27. Calculated Effect of Bottom Reflector Materials on k_{eff}.

Reflector			Δk_{eff} (%)
Inner 2.54 cm	Middle 15.3 cm	Outer 0.952 cm	
acrylic	water	carbon steel	-
acrylic	water	water	+0.00
water	water	water	-0.05

Because of the negligible effect of materials beyond the water reflector region (Section 2.2), nothing outside the water reflector is included in the benchmark model.

3.2 Dimensions

Fuel-rod dimensions, as modeled, are shown in Figure 6. The entire rod has a diameter of 1.27 cm and is 97.79 cm long. The UO_2 fuel region has a diameter of 1.1176 cm and is 91.44 cm long. The clad is 0.0762 cm thick and 93.19 cm long. The clad surrounds the fuel, the lower end plug, and 0.48 cm of the top end plug. There is no gap between the clad and fuel or end plugs. The top end plug is 5.08 cm long. The lower end plug is 1.27 cm long.

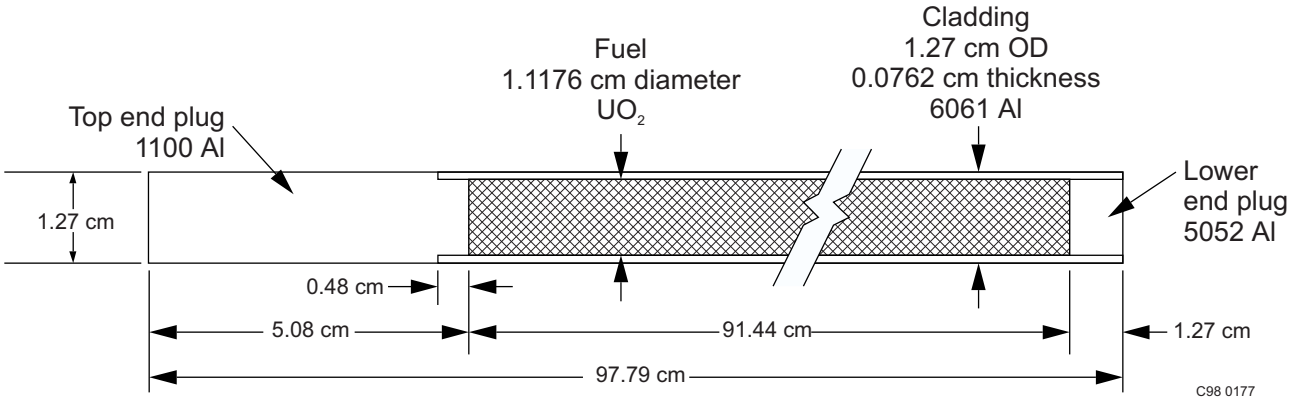

Figure 6. Model of Fuel Rod.

The fuel rods are arranged in rectangular clusters at a square pitch of 2.032 cm. Each configuration includes 3 clusters and 2 absorber plates as shown in Figures 4 and 5. The plates are between clusters at a fixed distance from the middle rod cluster, are parallel to the interacting faces of adjacent clusters, and are centered horizontally with respect to the cluster faces. They extend downward to the acrylic plate that supports the fuel rods. All absorber plates are 91.5 cm long.

The bottom reflector is a single 2.54-cm-thick acrylic plate followed by 15.3 cm of water. The acrylic plate extends horizontally to the outermost cell-boundary edges of the clusters. The four side reflectors are 30-cm-thick water. The top reflector is 9.92 cm of water above the top plugs of the fuel rods.

Cluster and absorber-plate dimensions are given in Tables 28 through 33. Cluster dimensions are given as rods along the direction of cluster placement followed by the width of all three clusters, in rods. Separation of clusters is the distance between closest fuel-rod cell boundaries of adjacent clusters. The distance from the plate to the center cluster is the distance between the near surface of the plate and the outer cell boundary of the center fuel cluster.

Table 28. Critical Configurations with Steel Plates.

Case	Cluster Dimensions (rods)	Separation of Clusters (cm)	Boron Content of Plate (wt.%)	Plate Thickness (cm)	Distance from Plate to Center Cluster (cm)	Width of Plate (cm)
1	20 x 16	6.88	0	0.485	0.645	35.6
2	20 x 16	7.64	0	0.485	2.732	35.6
3	20 x 16	7.51	0	0.485	4.042	35.6
4	20 x 16	7.42	0	0.302	0.645	35.6
5	20 x 16	7.76	0	0.302	4.042	35.6
6	20 x 17	10.44	0	0.302	0.645	35.6
7	20 x 17	11.47	0	0.302	4.042	35.6
8	20 x 17	7.56	1.05	0.298	0.645	35.6
9	20 x 17	9.62	1.05	0.298	4.042	35.6
10	20 x 17	7.36	1.62	0.298	0.645	35.6
11	20 x 17	9.52	1.62	0.298	4.042	35.6

Table 29. Critical Configurations with Boral Plates.

Case	Cluster Dimensions (rods)	Separation of Clusters (cm)	Plate Thickness (cm)[(a)]	Distance from Plate to Center Cluster (cm)	Width of Plate (cm)
12	20 x 17	6.33	0.713	0.645	35.6
13	20 x 17	9.03	0.713	4.442	35.6
14	20 x 16 (center) 22 x 16 (two outer)	5.05	0.713	0.645	35.6

(a) Includes 0.102-cm-thick cladding of Type 1100 aluminum on either side of the B_4C-Al material, which is 0.509 cm thick.

Table 30. Critical Configurations with Copper Plates.

Case	Cluster Dimensions (rods)	Separation of Clusters (cm)	Cd Content (wt.%)	Plate Thickness (cm)	Distance from Plates to Center Cluster (cm)	Width of Plate (cm)
15	20 x 16	6.62	0.0	0.646	0.645	35.6
16	20 x 16	7.72	0.0	0.646	2.732	35.6
17	20 x 16	7.51	0.0	0.646	4.442	35.6
18	20 x 15 (center) 24 x 15 (two outer)	6.88	0.0	0.337	0.645	30.6
19	20 x 15 (center) 24 x 15 (two outer)	7.0	0.0	0.337	4.042	30.6
20	20 x 15 (center) 24 x 15 (two outer)	5.15	0.989	0.357	0.645	30.6

Table 31. Cluster Critical Configurations with Cadmium Plates.

Case	Cluster Dimensions (rods)	Separation of Clusters (cm)	Plate Thickness (cm)	Distance from Plate to Center Cluster (cm)	Width of Plate (cm)
21	20 x 17	6.74	0.061	0.645	35.6
22	20 x 17	7.6	0.061	1.482	35.6
23	20 x 17	9.37	0.061	4.042	35.6
24	20 x 17	7.78	0.0291	1.482	35.6
25	20 x 17	9.4	0.0291	4.042	35.6
26	20 x 17	7.54	0.0901	1.482	35.6
27	20 x 17	9.39	0.0901	4.042	35.6

Table 32. Critical Configurations with Aluminum Plates.

Case	Cluster Dimensions (rods)	Separation of Clusters (cm)	Plate Thickness (cm)	Distance from Plate to Center Cluster (cm)	Width of Plate (cm)
28	20 x 16	8.67	0.625	0.645	35.6
29	20 x 16	8.78	0.625	4.042	35.6
30	20 x 16	8.83	0.625	4.442	35.6

Table 33. Cluster Critical Configurations with Zircaloy-4 Plates.

Case	Cluster Dimensions (rods)	Separation of Fuel Clusters (cm)	Plate Thickness (cm)	Distance from Plate to Center Fuel Cluster (cm)	Width of Plate (cm)
31	20 x 16	8.79	0.652	0.645	35.6
32	20 x 16	8.78	0.652	4.042	35.6

3.3 Material Data

3.3.1 Fuel Rods - The fuel region, as shown in Figure 6, consists of 825 g of UO_2. The mass of ^{235}U in each rod is 17.08 g. The isotopic composition of the uranium is 0.0137 wt.% ^{234}U, 2.35 wt.% ^{235}U, 0.0171 wt.% ^{236}U, and balance (97.6192 wt.%) ^{238}U.

Fuel rods have 6061 aluminum clad, with a 5052 aluminum lower end plug and a 1100 aluminum top end plug, as shown in Figure 6. Aluminum clad and end-plug weight percents and fuel-rod atom densities are given in Table 34. Weight percents are the approximate average values (see Table 9).

Table 34. Fuel-Rod Atom Densities.

Material	Isotope	Wt.%	Atom Density (barn-cm)$^{-1}$
UO_2 Fuel	^{234}U		2.8563×10^{-6}
	^{235}U		4.8785×10^{-4}
	^{236}U		3.5348×10^{-6}
	^{238}U		2.0009×10^{-2}
	O		4.1202×10^{-2}
1100 Aluminum (top end plug; 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}
5052 Aluminum (lower end plug; 2.69 g/cm^3)	Al	96.65	5.8028×10^{-2}
	Cr	0.25	7.7888×10^{-5}
	Cu	0.05	1.2746×10^{-5}
	Mg	2.5	1.6663×10^{-3}
	Mn	0.05	1.4743×10^{-5}
	Zn	0.05	1.2387×10^{-5}
	Si	0.225	1.2978×10^{-4}
	Fe	0.225	6.5265×10^{-5}
6061 Aluminum (clad; 2.69 g/cm^3)	Al	97.325	5.8433×10^{-2}
	Cr	0.2	6.2310×10^{-5}
	Cu	0.25	6.3731×10^{-5}
	Mg	1.0	6.6651×10^{-4}
	Mn	0.075	2.2115×10^{-5}
	Ti	0.075	2.5375×10^{-5}
	Zn	0.125	3.0967×10^{-5}
	Si	0.6	3.4607×10^{-4}
	Fe	0.35	1.0152×10^{-4}

3.3.2 Absorber Plates – Steel, boral, copper, cadmium, aluminum, and Zircaloy-4 atom densities are given in Tables 35 - 37. Boron is assumed to be 19.9 at.% ^{10}B and 80.1 at.% ^{11}B.[a]

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

Table 35. 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 x 10^{-2}
	Cu	0.27	2.0291 x 10^{-4}
	Fe	68.24	5.8353 x 10^{-2}
	Mn	1.58	1.3734 x 10^{-3}
	Mo	0.26	1.2942 x 10^{-4}
	Ni	11.09	9.0238 x 10^{-3}
304L Steel with 1.1 wt.% B (7.9 g/cm^3)	^{10}B	1.05 x 0.18431	9.1950 x 10^{-4}
	^{11}B	1.05 x 0.81569	3.7011 x 10^{-3}
	Cr	19.03	1.7412 x 10^{-2}
	Cu	0.28	2.0963 x 10^{-4}
	Fe	68.04	5.7961 x 10^{-2}
	Mn	1.58	1.3682 x 10^{-3}
	Mo	0.49	2.4298 x 10^{-4}
	Ni	9.53	7.7251 x 10^{-3}
304L Steel with 1.6 wt.% B (7.77 g/cm^3)	^{10}B	1.62 x 0.18431	1.3953 x 10^{-3}
	^{11}B	1.62 x 0.81569	5.6163 x 10^{-3}
	Cr	19.6	1.7638 x 10^{-2}
	Cu	0.26	1.9145 x 10^{-4}
	Fe	66.4	5.5634 x 10^{-2}
	Mn	1.69	1.4394 x 10^{-3}
	Mo	0.31	1.5119 x 10^{-4}
	Ni	10.12	8.0684 x 10^{-3}

Table 36. Boral and Copper Absorber-Plate Atom Densities.

Material	Isotope	Wt.%	Atom Density
Boral[(a)] (2.49 g/ cm^3)	Al	62.39	3.4673×10^{-2}
	^{10}B	28.7 x 0.18431	7.9217×10^{-3}
	^{11}B	28.7 x 0.81569	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}
Copper with Cd (8.910 g/ cm^3)	^{10}B	0.005 x 0.18431	4.9384×10^{-6}
	^{11}B	0.005 x 0.81569	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}
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}

(a) See Table 34 for atom densities of the type 1100 aluminum clad of the boral plates.

Table 37. Cadmium, Aluminum, and Zircaloy-4 Absorber-Plate Atom Densities.

Material	Isotope	Wt.%	Atom Density $(barn\text{-}cm)^{-1}$
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 19.5°C (density $0.998306\ g/cm^3$). Atom densities are given in Table 38.

Table 38. Moderator-Reflector Atom Densities.

Material	Isotope	Atom Density $(barn\text{-}cm)^{-1}$
Water	H	6.6743×10^{-2}
	O	3.3371×10^{-2}
Acrylic	H	5.6642×10^{-2}
	C	3.5648×10^{-2}
	O	1.4273×10^{-2}

3.4 Temperature Data

Temperature data for the individual experiments were not published. Logbook records give water temperatures of 19.5 or 19.6°C for eight experiments of this series with these rods at this pitch. Water density for a temperature of 19.5°C was 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.

Some model simplifications (no aluminum support structures; nothing beyond the water reflector, no measurement devices in the water, no notch in the top end plug) were judged to have negligible effect on k_{eff}. However, experimental uncertainties (Section 2) and simplifying the model by omitting the two lattice plates and water impurities (Section 3.1) contribute to the estimated uncertainty in the benchmark-model k_{eff}. The included uncertainties are listed in Table 39.

Table 39. Uncertainty in Benchmark-Model k_{eff}.

Measurement Uncertainty or Model Simplification	Δk_{eff}
Fuel-Rod Characterization	0.0031
Surroundings	0.00004
Impurities in Water	0.00004
Temperature	0.00008
Cluster Separation	0.0002
Distance from Absorber Plate to Central Fuel Cluster	0.00002
Absorber Plate Thickness	0.00002
Absorber Plate Composition	0.0002
No Lattice Plates	0.0002
Total Uncertainty in k_{eff}[(a)]	0.0031

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

Therefore the benchmark-model k_{eff}, for all cases, is 1.0000 ± 0.0031.

4.0 RESULTS OF SAMPLE CALCULATIONS

Results of calculations representing the thirty-two critical configurations are presented in Table 40. Code versions and modeling options are discussed briefly in paragraphs preceding the input listings in Appendix A.

Approximately two thirds of the results are below the range of k_{eff} that includes the estimated uncertainty. KENO with CSAS 27-group ENDF/B-IV cross sections slightly underpredicts k_{eff}. MCNP with ENDF/B-V continuous cross sections also slightly underpredicts k_{eff}.

Note that for Cases 1-7, 15-19, and 28-32, the absorber plates (non-borated steel, copper without cadmium, aluminum, or Zircaloy-4) have only a small effect on k_{eff} (see Tables 18, 22, 24, and 25). Therefore, these benchmarks are not recommended for the purpose of validating calculations of these materials.

Table 40. Sample Calculation Results (United States).

Code(Cross Section Set) → Case ↓	KENO (27-Group ENDF/B-IV)	KENO (44-Group ENDF/B-V)	MCNP (Continuous Energy ENDF/B-V)
1	0.9914 ± 0.0016	0.9961 ± 0.0017	0.9982 ± 0.0014
2	0.9934 ± 0.0015	0.9949 ± 0.0018	0.9967 ± 0.0014
3	0.9927 ± 0.0015	0.9981 ± 0.0018	0.9942 ± 0.0016
4	0.9927 ± 0.0015	0.9954 ± 0.0016	0.9960 ± 0.0018
5	0.9916 ± 0.0014	0.9949 ± 0.0017	0.9923 ± 0.0018
6	0.9893 ± 0.0016	0.9946 ± 0.0016	0.9943 ± 0.0015
7	0.9901 ± 0.0015	0.9933 ± 0.0016	0.9963 ± 0.0016
8	0.9946 ± 0.0015	0.9936 ± 0.0016	0.9990 ± 0.0016
9	0.9940 ± 0.0016	0.9991 ± 0.0015	0.9950 ± 0.0015
10	0.9923 ± 0.0014	0.9938 ± 0.0019	0.9969 ± 0.0015
11	0.9922 ± 0.0017	0.9963 ± 0.0017	0.9954 ± 0.0015
12	0.9918 ± 0.0018	0.9958 ± 0.0016	0.9931 ± 0.0017
13	0.9894 ± 0.0016	0.9956 ± 0.0015	0.9992 ± 0.0015
14	0.9932 ± 0.0016	0.9970 ± 0.0017	1.0006 ± 0.0015

Table 40 Sample Calculation Results (United States) (continued).

Code(Cross Section Set) → Case ↓	KENO (27-Group ENDF/B-IV)	KENO (44-Group ENDF/B-V)	MCNP (Continuous Energy ENDF/B-V)
15	0.9874 ± 0.0017	0.9956 ± 0.0014	0.9935± 0.0017
16	0.9869 ± 0.0015	0.9944 ± 0.0015	0.9932 ± 0.0019
17	0.9934 ± 0.0016	0.9911 ± 0.0015	0.9970 ± 0.0015
18	0.9903 ± 0.0015	0.9967 ± 0.0016	0.9953 ± 0.0017
19	0.9932± 0.0017	0.9988 ± 0.0015	0.9986 ± 0.0015
20	0.9920 ± 0.0015	1.0006 ± 0.0020	0.9993 ± 0.0015
21	0.9973 ± 0.0016	0.9968 ± 0.0018	0.9949 ± 0.0015
22	0.9927 ± 0.0016	0.9935 ± 0.0015	0.9961 ± 0.0015
23	0.9899 ± 0.0019	0.9936 ± 0.0016	0.9966 ± 0.0017
24	0.9912 ± 0.0016	0.9921 ± 0.0017	0.9913 ± 0.0016
25	0.9929 ± 0.0016	0.9937 ± 0.0019	0.9965 ± 0.0018
26	0.9917 ± 0.0014	0.9973 ± 0.0016	0.9974 ± 0.0016
27	0.9888 ± 0.0015	0.9952 ± 0.0018	0.9949 ± 0.0016
28	0.9932 ± 0.0018	0.9943 ± 0.0014	0.9965 ± 0.0017
29	0.9911 ± 0.0017	0.9995 ± 0.0015	0.9957 ± 0.0017
30	0.9931 ± 0.0016	0.9979 ± 0.0018	0.9970 ± 0.0016
31	0.9911 ± 0.0016	0.9969 ± 0.0018	0.9972 ± 0.0017
32	0.9946 ± 0.0017	0.9987 ± 0.0016	0.9943 ± 0.0016

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.

7. B. M. Durst, S. R. Bierman, E. D. Clayton, "Critical Experiments with 4.31 Wt% ^{235}U Enriched UO_2 Rods in Highly Borated Water Lattices," NUREG/CR-2709, PNL-4267, Batelle Pacific Northwest Laboratories, Richland, Washington, August 1982.

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 (SCALE 4.0, creation date 07/20/92, for KENO V.a with CSAS 27-group ENDF/B-IV cross sections, SCALE 4.3, creation date 12/23/97, for KENO V.a with CSAS 44-group ENDF/B-V cross sections) provided by the Radiation Shielding Information Center.

KENO V.a was run using 110 active generations of 1500 neutrons each, after skipping 50 generations.

KENO V.a Input Listing for Case 1 of Table 40 (27-Energy Group SCALE Cross Sections)

```
=CSAS25
k201p CASE 1  THREE 20X16 CLUSTERS, 6.88 CM SEPARATION
27GROUPNDF4 LATTICECELL
' U(2.35)02
U-234  1 0  2.8563-6 295 END
U-235  1 0  4.8785-4 295 END
U-236  1 0  3.5348-6 295 END
U-238  1 0  2.0009-2 295 END
O  1 0  4.1202-2 295 END
' water
H  2 0  6.6743-2 295 END
O  2 0  3.3371-2 295 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
'  1100 Al (top end plug)
AL  4 0  5.9660-2 295 END
CU  4 0  3.0705-5 295 END
MN  4 0  7.3991-6 295 END
'       (Zn replaced by Cu)
CU  4 0  1.2433-5 295 END
SI  4 0  2.3302-4 295 END
FE  4 0  1.1719-4 295 END
' 5052 Al (lower end plug)
AL  5 0  5.8028-2 295 END
CR  5 0  7.7888-5 295 END
CU  5 0  1.2746-5 295 END
MG  5 0  1.6663-3 295 END
MN  5 0  1.4743-5 295 END
'       (Zn replaced by Cu)
CU  5 0  1.2387-5 295 END
SI  5 0  1.2978-4 295 END
FE  5 0  6.5265-5 295 END
' acrylic
H   6 0  5.6642-2 295 END
C   6 0  3.5648-2 295 END
O   6 0  1.4273-2 295 END
' water
H  7 0  6.6743-2 295 END
O  7 0  3.3371-2 295 END
' SS plate
CR  8 0  1.7046-2 295 END
CU  8 0  2.0291-4 295 END
FE  8 0  5.8353-2 295 END
MN  8 0  1.3734-3 295 END
MO  8 0  1.2942-4 295 END
NI  8 0  9.0238-3 295 END
END COMP
SQUAREPITCH 2.032 1.1176 1 2 1.27 3 END
k201p  CASE 1  THREE 20X16 CLUSTERS, 6.88 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  0.5588 91.44 0.0
```

KENO V.a Input Listing for Case 1 of Table 40 (27-Energy Group SCALE Cross Sections) (cont'd)

```
 CYLINDER  4 1  0.5588 91.92 0.0
 CYLINDER  5 1  0.5588 91.92 -1.27
 CYLINDER  3 1  0.635  91.92 -1.27
 CYLINDER  4 1  0.635  96.52 -1.27
 CUBOID  2 1  4P1.016 96.52 -1.27
UNIT 2
 COM=* 20X16 ARRAY OF FUEL PINS *
 ARRAY 1 3R0
 REPLICATE 6 1 5R0.0 2.54 1
 REPLICATE 7 1  0.0 0.0 1.544 1.544 0.0 0.0  1
UNIT 3
 COM=* WATER BETWEEN CLUSTERS, 5.75 CM WIDE *
 CUBOID  7 1  5.75  0.0  34.056 -1.544 96.52 -1.27
 CUBOID  6 1  5.75  0.0  34.056 -1.544 96.52 -3.81
UNIT 4
 COM=* SS POISON PLATE BETWEEN CLUSTERS, 0.485CM WIDE *
 CUBOID  8 1  0.485 0.0 34.056 -1.544 90.23 -1.27
 CUBOID  7 1  0.485 0.0 34.056 -1.544 96.52 -1.27
 CUBOID  6 1  0.485 0.0 34.056 -1.544 96.52 -3.81
UNIT 5
 COM=* WATER BETWEEN CLUSTERS, 0.645CM WIDE *
 CUBOID  7 1  0.645 0.0 34.056 -1.544 96.52 -1.27
 CUBOID  6 1  0.645 0.0 34.056 -1.544 96.52 -3.81
GLOBAL
UNIT 6
 COM=* ARRAY OF 3 CLUSTERS, 1 IN. ACRYLIC BELOW, WATER REFLECTOR *
 ARRAY 2 3R0
 REPLICATE 7 1  2R30.0 2R28.456 9.92 15.3  1
END GEOM
READ ARRAY  ARA=1 NUX=20 NUY=16  FILL F1 END FILL
         ARA=2 NUX=9  FILL 2 3 4 5  2 5 4 3 2 END FILL
END ARRAY
READ PLOT
  XUL=0.0 YUL=40. ZUL=10 XLR=155.0 YLR=-5.0
  ZLR=10  UAX=1  VDN=-1 NAX=130  NCH=' 12*45678' END
END PLOT
END DATA
END
```

KENO V.a Input Listing for Case 12 of Table 40 (27-Energy Group SCALE Cross Sections)

```
=CSAS25
k213p CASE 13 THREE 20X17 CLUSTERS, 6.32 CM SEPARATION
27GROUPNDF4 LATTICECELL
' U(2.35)02
U-234  1 0  2.8563-6 295 END
U-235  1 0  4.8785-4 295 END
U-236  1 0  3.5348-6 295 END
U-238  1 0  2.0009-2 295 END
O  1 0  4.1202-2 295 END
' water
H  2 0  6.6743-2 295 END
O  2 0  3.3371-2 295 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
'  1100 Al (top end plug)
AL  4 0  5.9660-2 295 END
CU  4 0  3.0705-5 295 END
MN  4 0  7.3991-6 295 END
'       (Zn replaced by Cu)
CU  4 0  1.2433-5 295 END
SI  4 0  2.3302-4 295 END
FE  4 0  1.1719-4 295 END
' 5052 Al (lower end plug)
AL  5 0  5.8028-2 295 END
CR  5 0  7.7888-5 295 END
CU  5 0  1.2746-5 295 END
MG  5 0  1.6663-3 295 END
MN  5 0  1.4743-5 295 END
'       (Zn replaced by Cu)
CU  5 0  1.2387-5 295 END
SI  5 0  1.2978-4 295 END
FE  5 0  6.5265-5 295 END
' acrylic
H   6 0  5.6642-2 295 END
C   6 0  3.5648-2 295 END
O   6 0  1.4273-2 295 END
' water
H  7 0  6.6743-2 295 END
O  7 0  3.3371-2 295 END
' Boral plate
B-10 8 0 7.9217-3 295 END
B-11 8 0 3.1886-2 295 END
AL  8 0  3.7222-2 295 END
C   8 0  9.9501-3 295 END
CR  8 0  1.4419-5 295 END
CU  8 0  4.0394-5 295 END
FE  8 0  1.6172-4 295 END
MG  8 0  3.0848-5 295 END
MN  8 0  1.8263-5 295 END
NA  8 0  1.3045-5 295 END
NI  8 0  5.1099-6 295 END
SI  8 0  2.5216-4 295 END
S  8 0  1.4027-5 295 END
'  8    (Zn replaced by Cu)
CU  8 0  3.0689-5 295 END
END COMP
```

KENO V.a Input Listing for Case 12 of Table 40 (27-Energy Group SCALE Cross Sections) (cont'd)

```
SQUAREPITCH 2.032 1.1176 1 2 1.27 3 END
k213p  CASE 13 THREE 20X17 CLUSTERS, 6.32 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  0.5588 91.44 0.0
 CYLINDER  4 1  0.5588 91.92 0.0
 CYLINDER  5 1  0.5588 91.92 -1.27
 CYLINDER  3 1  0.635  91.92 -1.27
 CYLINDER  4 1  0.635  96.52 -1.27
 CUBOID  2 1  4P1.016 96.52 -1.27
UNIT 2
 COM=* 20X17 ARRAY OF FUEL PINS *
 ARRAY 1 3R0
 REPLICATE 6 1  5R0.0 2.54  1
 REPLICATE 7 1  0.0 0.0 0.528 0.528 0.0 0.0  1
UNIT 3
 COM=* WATER BETWEEN CLUSTERS,4.962 CM WIDE *
 CUBOID  7 1  4.972 0.0  35.072 -0.528 96.52 -1.27
 CUBOID  6 1  4.972 0.0  35.072 -0.528 96.52 -3.81
UNIT 4
 COM=* Cd POISON PLATE BETWEEN CLUSTERS,0.0901CM WIDE *
 CUBOID  4 1 0.102  0.0 35.072 -0.528 90.23 -1.27
 CUBOID  8 1 0.611  0.0 35.072 -0.528 90.23 -1.27
 CUBOID  4 1 0.713  0.0 35.072 -0.528 90.23 -1.27
 CUBOID  7 1 0.713  0.0 35.072 -0.528 96.52 -1.27
 CUBOID  6 1 0.713  0.0 35.072 -0.528 96.52 -3.81
UNIT 5
 COM=* WATER BETWEEN CLUSTERS, 0.645 CM WIDE *
 CUBOID  7 1  0.645 0.0 35.072 -0.528 96.52 -1.27
 CUBOID  6 1  0.645 0.0 35.072 -0.528 96.52 -3.81
GLOBAL
UNIT 6
 COM=* ARRAY OF 3 CLUSTERS, 1 IN. ACRYLIC BELOW, WATER REFLECTOR *
 ARRAY 2 3R0
 REPLICATE 7 1  2R30.0 2R29.472 9.92 15.3  1
END GEOM
READ ARRAY  ARA=1 NUX=20 NUY=17  FILL F1 END FILL
         ARA=2 NUX=9  FILL 2 3 4 5  2 5 4 3 2 END FILL
END ARRAY
READ PLOT
  XUL=0.0 YUL=40. ZUL=10 XLR=155.0 YLR=-5.0
  ZLR=10  UAX=1  VDN=-1 NAX=130  NCH=' 12*45678' END
END PLOT
END DATA
END
```

KENO V.a Input Listing for Case 18 of Table 40 (27-Energy-Group SCALE Cross Sections)

```
=CSAS25
k222p CASE 22  2 24X15, 1 20x15 CLUSTERS, 6.88 CM SEPARATION
27GROUPNDF4 LATTICECELL
' U(2.35)02
U-234  1 0  2.8563-6 295 END
U-235  1 0  4.8785-4 295 END
U-236  1 0  3.5348-6 295 END
U-238  1 0  2.0009-2 295 END
O  1 0  4.1202-2 295 END
' water
H  2 0  6.6743-2 295 END
O  2 0  3.3371-2 295 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
'  1100 Al (top end plug)
AL  4 0  5.9660-2 295 END
CU  4 0  3.0705-5 295 END
MN  4 0  7.3991-6 295 END
'       (Zn replaced by Cu)
CU  4 0  1.2433-5 295 END
SI  4 0  2.3302-4 295 END
FE  4 0  1.1719-4 295 END
' 5052 Al (lower end plug)
AL  5 0  5.8028-2 295 END
CR  5 0  7.7888-5 295 END
CU  5 0  1.2746-5 295 END
MG  5 0  1.6663-3 295 END
MN  5 0  1.4743-5 295 END
'       (Zn replaced by Cu)
CU  5 0  1.2387-5 295 END
SI  5 0  1.2978-4 295 END
FE  5 0  6.5265-5 295 END
' acrylic
H   6 0  5.6642-2 295 END
C   6 0  3.5648-2 295 END
O   6 0  1.4273-2 295 END
' water
H  7 0  6.6743-2 295 END
O  7 0  3.3371-2 295 END
' CU plate w/o Cd
C   8 0  1.5194-3 295 END
CU  8 0  8.4128-2 295 END
FE  8 0  3.8444-6 295 END
MG  8 0  4.4168-6 295 END
NA  8 0  4.6695-6 295 END
O   8 0  1.0064-4 295 END
SI  8 0  3.8223-5 295 END
S   8 0  3.3474-6 295 END
END COMP
SQUAREPITCH 2.032 1.1176 1 2 1.27 3 END
k222p  CASE 22  2 24x15, 1 20X15 CLUSTERS, 6.88  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 *
```

KENO V.a Input Listing for Case 18 of Table 40 (27-Energy-Group SCALE Cross Sections) (cont'd)

```
 CYLINDER  1 1  0.5588 91.44 0.0
 CYLINDER  4 1  0.5588 91.92 0.0
 CYLINDER  5 1  0.5588 91.92 -1.27
 CYLINDER  3 1  0.635  91.92 -1.27
 CYLINDER  4 1  0.635  96.52 -1.27
 CUBOID  2 1  4P1.016 96.52 -1.27
UNIT 2
 COM=* 24X15 ARRAY OF FUEL PINS *
 ARRAY 1 3R0
 REPLICATE 6 1  5R0.0 2.54  1
 REPLICATE 7 1  0.0 0.0 0.060 0.060 0.0 0.0  1
UNIT 3
 COM=* 20X15 ARRAY OF FUEL PINS *
 ARRAY 2 3R0
 REPLICATE 6 1  5R0.0 2.54  1
 REPLICATE 7 1  0.0 0.0 0.060 0.060 0.0 0.0  1
UNIT 4
 COM=* WATER BETWEEN CLUSTERS, 5.898 CM WIDE *
 CUBOID  7 1  5.898  0.0  30.540 -0.060 96.52 -1.27
 CUBOID  6 1  5.898  0.0  30.540 -0.060 96.52 -3.81
UNIT 5
 COM=* SS POISON PLATE BETWEEN CLUSTERS, 0.337CM WIDE *
 CUBOID  8 1  0.337 0.0 30.540 -0.060 90.23 -1.27
 CUBOID  7 1  0.337 0.0 30.540 -0.060 96.52 -1.27
 CUBOID  6 1  0.337 0.0 30.540 -0.060 96.52 -3.81
UNIT 6
 COM=* WATER BETWEEN CLUSTERS, 0.645 CM WIDE *
 CUBOID  7 1  0.645 0.0 30.540 -0.060 96.52 -1.27
 CUBOID  6 1  0.645 0.0 30.540 -0.060 96.52 -3.81
GLOBAL
UNIT 7
 COM=* ARRAY OF 3 CLUSTERS, 1 IN. ACRYLIC BELOW, WATER REFLECTOR *
 ARRAY 3 3R0
 REPLICATE 7 1  2R30.0 2R29.940 9.92 15.3  1
END GEOM
READ ARRAY  ARA=1 NUX=24 NUY=15  FILL F1 END FILL
          ARA=2 NUX=20 NUY=15  FILL F1 END FILL
          ARA=3 NUX=9  FILL 2 4 5 6  3 6 5 4 2 END FILL
END ARRAY
READ PLOT
  XUL=0.0 YUL=40. ZUL=10 XLR=155.0 YLR=-5.0
  ZLR=10  UAX=1  VDN=-1 NAX=130  NCH=' 12*45678' END
END PLOT
END DATA
END
```

KENO V.a Input Listing for Case 1 of Table 40 (44-Energy-Group SCALE Cross Sections)

```
=CSAS25
f201p CASE 1  THREE 20X16 CLUSTERS, 6.88 CM SEPARATION
44GROUPNDF5 LATTICECELL
' U(2.35)02
U-234  1 0  2.8563-6 295 END
U-235  1 0  4.8785-4 295 END
U-236  1 0  3.5348-6 295 END
U-238  1 0  2.0009-2 295 END
O  1 0  4.1202-2 295 END
' water
H  2 0  6.6743-2 295 END
O  2 0  3.3371-2 295 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
'  1100 Al (top end plug)
AL  4 0  5.9660-2 295 END
CU  4 0  3.0705-5 295 END
MN  4 0  7.3991-6 295 END
'       (Zn replaced by Cu)
CU  4 0  1.2433-5 295 END
SI  4 0  2.3302-4 295 END
FE  4 0  1.1719-4 295 END
' 5052 Al (lower end plug)
AL  5 0  5.8028-2 295 END
CR  5 0  7.7888-5 295 END
CU  5 0  1.2746-5 295 END
MG  5 0  1.6663-3 295 END
MN  5 0  1.4743-5 295 END
'       (Zn replaced by Cu)
CU  5 0  1.2387-5 295 END
SI  5 0  1.2978-4 295 END
FE  5 0  6.5265-5 295 END
' acrylic
H   6 0  5.6642-2 295 END
C   6 0  3.5648-2 295 END
O   6 0  1.4273-2 295 END
' water
H  7 0  6.6743-2 295 END
O  7 0  3.3371-2 295 END
' SS plate
CR  8 0  1.7046-2 295 END
CU  8 0  2.0291-4 295 END
FE  8 0  5.8353-2 295 END
MN  8 0  1.3734-3 295 END
MO  8 0  1.2942-4 295 END
NI  8 0  9.0238-3 295 END
END COMP
SQUAREPITCH 2.032 1.1176 1 2 1.27 3 END
k201p  CASE 1  THREE 20X16 CLUSTERS, 6.88 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  0.5588 91.44 0.0
 CYLINDER  4 1  0.5588 91.92 0.0
```

KENO V.a Input Listing for Case 1 of Table 40 (44-Energy-Group SCALE Cross Sections) (cont'd)

```
 CYLINDER  5 1  0.5588 91.92 -1.27
 CYLINDER  3 1  0.635  91.92 -1.27
 CYLINDER  4 1  0.635  96.52 -1.27
 CUBOID  2 1  4P1.016 96.52 -1.27
UNIT 2
 COM=* 20X16 ARRAY OF FUEL PINS *
 ARRAY 1 3R0
 REPLICATE 6 1 5R0.0 2.54 1
 REPLICATE 7 1  0.0 0.0 1.544 1.544 0.0 0.0  1
UNIT 3
 COM=* WATER BETWEEN CLUSTERS, 5.75 CM WIDE *
 CUBOID  7 1  5.75  0.0  34.056 -1.544 96.52 -1.27
 CUBOID  6 1  5.75  0.0  34.056 -1.544 96.52 -3.81
UNIT 4
 COM=* SS POISON PLATE BETWEEN CLUSTERS, 0.485CM WIDE *
 CUBOID  8 1  0.485 0.0 34.056 -1.544 90.23 -1.27
 CUBOID  7 1  0.485 0.0 34.056 -1.544 96.52 -1.27
 CUBOID  6 1  0.485 0.0 34.056 -1.544 96.52 -3.81
UNIT 5
 COM=* WATER BETWEEN CLUSTERS, 0.645CM WIDE *
 CUBOID  7 1  0.645 0.0 34.056 -1.544 96.52 -1.27
 CUBOID  6 1  0.645 0.0 34.056 -1.544 96.52 -3.81
GLOBAL
UNIT 6
 COM=* ARRAY OF 3 CLUSTERS, 1 IN. ACRYLIC BELOW, WATER REFLECTOR *
 ARRAY 2 3R0
 REPLICATE 7 1  2R30.0 2R28.456 9.92 15.3  1
END GEOM
READ ARRAY  ARA=1 NUX=20 NUY=16  FILL F1 END FILL
          ARA=2 NUX=9  FILL 2 3 4 5  2 5 4 3 2 END FILL
END ARRAY
READ PLOT
  XUL=0.0 YUL=40. ZUL=10 XLR=155.0 YLR=-5.0
  ZLR=10  UAX=1  VDN=-1 NAX=130  NCH=' 12*45678' END
END PLOT
END DATA
END
```

KENO V.a Input Listing for Case 12 of Table 40 (44-Energy-Group SCALE Cross Sections)

```
=CSAS25
f213p CASE 13 THREE 20X17 CLUSTERS, 6.32 CM SEPARATION
44GROUPNDF5 LATTICECELL
' U(2.35)02
U-234  1 0  2.8563-6 295 END
U-235  1 0  4.8785-4 295 END
U-236  1 0  3.5348-6 295 END
U-238  1 0  2.0009-2 295 END
O  1 0  4.1202-2 295 END
' water
H  2 0  6.6743-2 295 END
O  2 0  3.3371-2 295 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
'  1100 Al (top end plug)
AL  4 0  5.9660-2 295 END
CU  4 0  3.0705-5 295 END
MN  4 0  7.3991-6 295 END
'       (Zn replaced by Cu)
CU  4 0  1.2433-5 295 END
SI  4 0  2.3302-4 295 END
FE  4 0  1.1719-4 295 END
' 5052 Al (lower end plug)
AL  5 0  5.8028-2 295 END
CR  5 0  7.7888-5 295 END
CU  5 0  1.2746-5 295 END
MG  5 0  1.6663-3 295 END
MN  5 0  1.4743-5 295 END
'       (Zn replaced by Cu)
CU  5 0  1.2387-5 295 END
SI  5 0  1.2978-4 295 END
FE  5 0  6.5265-5 295 END
' acrylic
H   6 0  5.6642-2 295 END
C   6 0  3.5648-2 295 END
O   6 0  1.4273-2 295 END
' water
H  7 0  6.6743-2 295 END
O  7 0  3.3371-2 295 END
' Boral plate
B-10 8 0 7.9217-3 295 END
B-11 8 0 3.1886-2 295 END
AL  8 0  3.7222-2 295 END
C   8 0  9.9501-3 295 END
CR  8 0  1.4419-5 295 END
CU  8 0  4.0394-5 295 END
FE  8 0  1.6172-4 295 END
MG  8 0  3.0848-5 295 END
MN  8 0  1.8263-5 295 END
NA  8 0  1.3045-5 295 END
NI  8 0  5.1099-6 295 END
SI  8 0  2.5216-4 295 END
S  8 0  1.4027-5 295 END
'  8    (Zn replaced by Cu)
CU  8 0  3.0689-5 295 END
END COMP
```

KENO V.a Input Listing for Case 12 of Table 40 (44-Energy-Group SCALE Cross Sections) (cont'd)

```
SQUAREPITCH 2.032 1.1176 1 2 1.27 3 END
k213p  CASE 13 THREE 20X17 CLUSTERS, 6.32 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  0.5588 91.44 0.0
 CYLINDER  4 1  0.5588 91.92 0.0
 CYLINDER  5 1  0.5588 91.92 -1.27
 CYLINDER  3 1  0.635  91.92 -1.27
 CYLINDER  4 1  0.635  96.52 -1.27
 CUBOID  2 1  4P1.016 96.52 -1.27
UNIT 2
 COM=* 20X17 ARRAY OF FUEL PINS *
 ARRAY 1 3R0
 REPLICATE 6 1  5R0.0 2.54  1
 REPLICATE 7 1  0.0 0.0 0.528 0.528 0.0 0.0  1
UNIT 3
 COM=* WATER BETWEEN CLUSTERS,4.962 CM WIDE *
 CUBOID  7 1  4.972 0.0  35.072 -0.528 96.52 -1.27
 CUBOID  6 1  4.972 0.0  35.072 -0.528 96.52 -3.81
UNIT 4
 COM=* Cd POISON PLATE BETWEEN CLUSTERS,0.0901CM WIDE *
 CUBOID  4 1 0.102  0.0 35.072 -0.528 90.23 -1.27
 CUBOID  8 1 0.611  0.0 35.072 -0.528 90.23 -1.27
 CUBOID  4 1 0.713  0.0 35.072 -0.528 90.23 -1.27
 CUBOID  7 1 0.713  0.0 35.072 -0.528 96.52 -1.27
 CUBOID  6 1 0.713  0.0 35.072 -0.528 96.52 -3.81
UNIT 5
 COM=* WATER BETWEEN CLUSTERS, 0.645 CM WIDE *
 CUBOID  7 1  0.645 0.0 35.072 -0.528 96.52 -1.27
 CUBOID  6 1  0.645 0.0 35.072 -0.528 96.52 -3.81
GLOBAL
UNIT 6
 COM=* ARRAY OF 3 CLUSTERS, 1 IN. ACRYLIC BELOW, WATER REFLECTOR *
 ARRAY 2 3R0
 REPLICATE 7 1  2R30.0 2R29.472 9.92 15.3  1
END GEOM
READ ARRAY  ARA=1 NUX=20 NUY=17  FILL F1 END FILL
          ARA=2 NUX=9  FILL 2 3 4 5  2 5 4 3 2 END FILL
END ARRAY
READ PLOT
  XUL=0.0 YUL=40. ZUL=10 XLR=155.0 YLR=-5.0
  ZLR=10  UAX=1  VDN=-1 NAX=130  NCH=' 12*45678' END
END PLOT
END DATA
END
```

KENO V.a Input Listing for Case 18 of Table 40 (44-Energy-Group SCALE Cross Sections)

```
=CSAS25
f222p CASE 22  2 24X15, 1 20x15 CLUSTERS, 6.88 CM SEPARATION
44GROUPNDF5 LATTICECELL
' U(2.35)02
U-234  1 0  2.8563-6 295 END
U-235  1 0  4.8785-4 295 END
U-236  1 0  3.5348-6 295 END
U-238  1 0  2.0009-2 295 END
O  1 0  4.1202-2 295 END
' water
H  2 0  6.6743-2 295 END
O  2 0  3.3371-2 295 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
'  1100 Al (top end plug)
AL  4 0  5.9660-2 295 END
CU  4 0  3.0705-5 295 END
MN  4 0  7.3991-6 295 END
'       (Zn replaced by Cu)
CU  4 0  1.2433-5 295 END
SI  4 0  2.3302-4 295 END
FE  4 0  1.1719-4 295 END
' 5052 Al (lower end plug)
AL  5 0  5.8028-2 295 END
CR  5 0  7.7888-5 295 END
CU  5 0  1.2746-5 295 END
MG  5 0  1.6663-3 295 END
MN  5 0  1.4743-5 295 END
'       (Zn replaced by Cu)
CU  5 0  1.2387-5 295 END
SI  5 0  1.2978-4 295 END
FE  5 0  6.5265-5 295 END
' acrylic
H   6 0  5.6642-2 295 END
C   6 0  3.5648-2 295 END
O   6 0  1.4273-2 295 END
' water
H  7 0  6.6743-2 295 END
O  7 0  3.3371-2 295 END
' CU plate w/o Cd
C   8 0  1.5194-3 295 END
CU  8 0  8.4128-2 295 END
FE  8 0  3.8444-6 295 END
MG  8 0  4.4168-6 295 END
NA  8 0  4.6695-6 295 END
O   8 0  1.0064-4 295 END
SI  8 0  3.8223-5 295 END
S   8 0  3.3474-6 295 END
END COMP
SQUAREPITCH 2.032 1.1176 1 2 1.27 3 END
k222p  CASE 22  2 24x15, 1 20X15 CLUSTERS, 6.88  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 *
```

KENO V.a Input Listing for Case 18 of Table 40 (44-Energy-Group SCALE Cross Sections) (cont'd)

```
 CYLINDER  1 1  0.5588 91.44 0.0
 CYLINDER  4 1  0.5588 91.92 0.0
 CYLINDER  5 1  0.5588 91.92 -1.27
 CYLINDER  3 1  0.635  91.92 -1.27
 CYLINDER  4 1  0.635  96.52 -1.27
 CUBOID  2 1  4P1.016 96.52 -1.27
UNIT 2
 COM=* 24X15 ARRAY OF FUEL PINS *
 ARRAY 1 3R0
 REPLICATE 6 1  5R0.0 2.54  1
 REPLICATE 7 1  0.0 0.0 0.060 0.060 0.0 0.0  1
UNIT 3
 COM=* 20X15 ARRAY OF FUEL PINS *
 ARRAY 2 3R0
 REPLICATE 6 1  5R0.0 2.54  1
 REPLICATE 7 1  0.0 0.0 0.060 0.060 0.0 0.0  1
UNIT 4
 COM=* WATER BETWEEN CLUSTERS, 5.898 CM WIDE *
 CUBOID  7 1  5.898  0.0  30.540 -0.060 96.52 -1.27
 CUBOID  6 1  5.898  0.0  30.540 -0.060 96.52 -3.81
UNIT 5
 COM=* SS POISON PLATE BETWEEN CLUSTERS, 0.337CM WIDE *
 CUBOID  8 1  0.337 0.0 30.540 -0.060 90.23 -1.27
 CUBOID  7 1  0.337 0.0 30.540 -0.060 96.52 -1.27
 CUBOID  6 1  0.337 0.0 30.540 -0.060 96.52 -3.81
UNIT 6
 COM=* WATER BETWEEN CLUSTERS, 0.645 CM WIDE *
 CUBOID  7 1  0.645 0.0 30.540 -0.060 96.52 -1.27
 CUBOID  6 1  0.645 0.0 30.540 -0.060 96.52 -3.81
GLOBAL
UNIT 7
 COM=* ARRAY OF 3 CLUSTERS, 1 IN. ACRYLIC BELOW, WATER REFLECTOR *
 ARRAY 3 3R0
 REPLICATE 7 1  2R30.0 2R29.940 9.92 15.3  1
END GEOM
READ ARRAY  ARA=1 NUX=24 NUY=15  FILL F1 END FILL
          ARA=2 NUX=20 NUY=15  FILL F1 END FILL
          ARA=3 NUX=9  FILL 2 4 5 6  3 6 5 4 2 END FILL
END ARRAY
READ PLOT
  XUL=0.0 YUL=40. ZUL=10 XLR=155.0 YLR=-5.0
  ZLR=10  UAX=1  VDN=-1 NAX=130  NCH=' 12*45678' 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.

MCNP Input Listing for Case 1 of Table 40

```
message:      outp=m201p.o  runtpe=m201p.r  srctp=m201p.s

m201p  THREE 20X16 CLUSTERS OF U(2.35)O2 RODS, 6.88 CM SEPR, PITCH 2.032 CM
1    1 .06170524 -1 7 -8 u=1 imp:n=1 $ uo2 fuel
2    3 .0597516   1 -2 -9 u=1 imp:n=1 $ clad
3    4 .06006075  -1 8 -9 u=1 imp:n=1 $ top end plug (lower piece)
4    4 .06006075  -2 9 u=1 imp:n=1 $ top end plug (top piece)
5    5 .06000711  -1 -7 u=1 imp:n=1 $ lower end plug
6    2 .100116  2 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 21 -22 23 fill=2 imp:n=1  $ first rod cluster
9    0 -13 12 -20 21 -22 23 fill=2(47.52 0 0) imp:n=1  $ second rod cluster
10   0 -15 14 -20 21 -22 23 fill=2(95.04 0 0) imp:n=1  $ third rod cluster
11   7 .08612853 33 -34 31 -32 23 -37  imp:n=1  $ SS plate
12   7 .08612853 35 -36 31 -32 23 -37  imp:n=1  $ SS plate
13   6 .106563  -23 29 -15 11 -20 21 imp:n=1  $ acrylic support plate
14   2 .100116  -12 10 -20 21  -22 23 #11  imp:n=1  $ water between clusters
15   2 .100116  -14 13 -20 21  -22 23 #12  imp:n=1  $ water between clusters
16   2 .100116 (-11:15:20:-21:22:-29)
          #11 #12 -24 25 -26 27 -28 30 imp:n=1 $ water
17   0  24:-25:26:-27:28:-30  imp:n=0

1    c/z 1.016 1.016 .5588  $ fuel cylinder
2    c/z 1.016 1.016 .635  $ clad cylinder
3    px  0.0  $ fuel rod cell boundary
4    px  2.032  $ fuel rod cell boundary
5    py  0.0  $ fuel rod cell boundary
6    py  2.032  $ fuel rod cell boundary
7    pz  0.0  $ bottom of fuel
8    pz  91.44  $ top of fuel
9    pz  91.92  $ top of clad
10   px  40.6399  $ farthest edge of closest cluster
11   px  .0001  $ closest edge of closest cluster
12   px  47.5201  $ closest edge of center cluster **
13   px  88.1599  $ farthest edge of center cluster
14   px  95.0401  $ closest edge of farthest cluster **
15   px  135.6799  $ farthest end of clusters
20   py  32.5119  $ sides of clusters
21   py  .0001  $ sides of clusters
22   pz  96.52  $ top of fuel rod
23   pz  -1.27  $ bottom of fuel rod
24   px  165.68   $ side of water reflector
25   px  -30.0   $ side of water reflector
26   py  62.512  $ side of water reflector
27   py  -30.0   $ side of water reflector
28   pz  106.44  $ top of water
29   pz  -3.81  $ bottom of acrylic support plate
30   pz  -19.11  $ bottom of water
c    plates
31   py  -1.544  $ plate bottom
32   py  34.056  $ plate top
33   px  46.39   $ 1st plate
34   px  46.875  $ 1st plate
35   px  88.805  $ 2st plate
36   px  89.29   $ 2st plate
37   pz  90.23   $ plate top

kcode  1500 1 50 160 50000
c    kcode  100 1 1 5 50000
sdef  x=d1 y=d2 z=d3 cel=d4
si1   0 150
sp1   0 1
si2   0 100
```

MCNP Input Listing for Case 1 of Table 40 (cont'd)

```
sp2   0 1
si3   0 100
sp3   0 1
si4   l 8 9 10
sp4   v
print
c     m1 is UO2 fuel
m1    92234.50c 2.8563e-6 92235.50c 4.8785e-4
      92236.50c 3.5348e-6 92238.50c 2.0009e-2
      8016.50c  4.1202e-2
c     m2 is water
m2    8016.50c 3.3371e-2  1001.50c 6.6743e-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 1100 aluminum (top end plug)
m4    13027.50c  5.9660e-2  29000.50c  3.0705e-5
      25055.50c  7.3991e-6
c       Zn replaced by Cu, below
      29000.50c  1.2433e-5  14000.50c  2.3302e-4
      26000.50c  1.1719e-4
c     m5 is 5052 aluminum (lower end plug)
m5    13027.50c  5.8028e-2  24000.50c  7.7888e-5
      29000.50c  1.2746e-5  12000.50c  1.6663e-3
      25055.50c  1.4743e-5
c       Zn replaced by Cu, below
      29000.50c  1.2387e-5  14000.50c  1.2978e-4
      26000.50c  6.5265e-5
c     m6 is acrylic (support plate)
m6    1001.50c 5.6642e-2  6000.50c 3.5648e-2
      8016.50c 1.4273e-2
mt6   poly.01t
c     m7 is SS plate
m7    24000.50c  1.7046e-2  29000.50c  2.0291e-4
      26000.50c  5.8353e-2  25055.50c  1.3734e-3
      42000.50c  1.2942e-4  28000.50c  9.0238e-3
```

MCNP Input Listing for Case 12 of Table 40

```
message:      outp=m213p.o  runtpe=m213p.r  srctp=m213p.s

m213p  THREE 20X17 CLUSTERS OF U(2.35)O2 RODS, 7.54 CM SEPR, PITCH 2.032 CM
c     Boral Plates
1     1 .06170524 -1 7 -8 u=1 imp:n=1 $ uo2 fuel
2     3 .0597516   1 -2 -9 u=1 imp:n=1 $ clad
3     4 .06006075  -1 8 -9 u=1 imp:n=1 $ top end plug (lower piece)
4     4 .06006075  -2 9 u=1 imp:n=1 $ top end plug (top piece)
5     5 .06000711  -1 -7 u=1 imp:n=1 $ lower end plug
6     2 .100116  2 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 21 -22 23 fill=2 imp:n=1  $ first rod cluster
9     0 -13 12 -20 21 -22 23 fill=2(46.97  0 0) imp:n=1  $ second rod cluster
10    0 -15 14 -20 21 -22 23 fill=2(93.94  0 0) imp:n=1  $ third rod cluster
11    4 .06006075 33 -34 31 -32 23 -37  imp:n=1  $ Boral-al
12    7 .08756048 34 -35 31 -32 23 -37  imp:n=1  $ Boral
13    4 .06006075 35 -36 31 -32 23 -37  imp:n=1  $ Boral-al
14    4 .06006075 43 -44 31 -32 23 -37  imp:n=1  $ Boral-al
15    7 .08756048 44 -45 31 -32 23 -37  imp:n=1  $ Boral
16    4 .06006075 45 -46 31 -32 23 -37  imp:n=1  $ Boral-al
17    6 .106563  -23 29 -15 11 -20 21 imp:n=1  $ acrylic support plate
18    2 .100116  -12 10 -20 21  -22 23 #11 #12 #13  imp:n=1  $ water between clusters
19    2 .100116  -14 13 -20 21  -22 23 #14 #15 #16  imp:n=1  $ water between clusters
20    2 .100116 (-11:15:20:-21:22:-29)
            #11 #12 #13 #14 #15 #16 -24 25 -26 27 -28 30 imp:n=1 $ water
21    0  24:-25:26:-27:28:-30  imp:n=0

1     c/z 1.016 1.016 .5588  $ fuel cylinder
2     c/z 1.016 1.016 .635  $ clad cylinder
3     px  0.0  $ fuel rod cell boundary
4     px  2.032  $ fuel rod cell boundary
5     py  0.0  $ fuel rod cell boundary
6     py  2.032  $ fuel rod cell boundary
7     pz  0.0  $ bottom of fuel
8     pz  91.44  $ top of fuel
9     pz  91.92  $ top of clad
10    px  40.6399  $ farthest edge of closest cluster
11    px  .0001  $ closest edge of closest cluster
12    px  46.9701  $ closest edge of center cluster **
13    px  87.6099  $ farthest edge of center cluster
14    px  93.9401 $ closest edge of farthest cluster **
15    px  134.5799  $ farthest end of clusters
20    py  34.5439  $ sides of clusters
21    py  .0001  $ sides of clusters
22    pz  96.52  $ top of fuel rod
23    pz  -1.27  $ bottom of fuel rod
24    px  164.58   $ side of water reflector
25    px  -30.0   $ side of water reflector
26    py  64.544  $ side of water reflector
27    py  -30.0   $ side of water reflector
28    pz  106.44  $ top of water
29    pz  -3.81  $ bottom of acrylic support plate
30    pz  -19.11  $ bottom of water
c     plates
31    py  -0.528  $ plate bottom
32    py  35.072  $ plate top
33    px  45.612 $ 1st plate-
34    px  45.714  $ 1st plate-al
35    px  46.223  $ 2st plate-boral
36    px  46.325  $ 2st plate-al
37    pz  90.23   $ plate top
43    px  88.255 $ 1st plate-
```

MCNP Input Listing for Case 12 of Table 40 (cont'd)

```
44    px  88.357  $ 1st plate-al
45    px  88.866  $ 2st plate-boral
46    px  88.968  $ 2st plate-al

kcode  1500 1 50 160 50000
c     kcode  100 1 1 5 50000
sdef  x=d1 y=d2 z=d3 cel=d4
si1   0 150
sp1   0 1
si2   0 100
sp2   0 1
si3   0 100
sp3   0 1
si4   l 8 9 10
sp4   v
print
c     m1 is UO2 fuel
m1    92234.50c 2.8563e-6 92235.50c 4.8785e-4
      92236.50c 3.5348e-6 92238.50c 2.0009e-2
      8016.50c  4.1202e-2
c     m2 is water
m2    8016.50c 3.3371e-2  1001.50c 6.6743e-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 1100 aluminum (top end plug)
m4    13027.50c  5.9660e-2  29000.50c  3.0705e-5
      25055.50c  7.3991e-6
c       Zn replaced by Cu, below
      29000.50c  1.2433e-5  14000.50c  2.3302e-4
      26000.50c  1.1719e-4
c     m5 is 5052 aluminum (lower end plug)
m5    13027.50c  5.8028e-2  24000.50c  7.7888e-5
      29000.50c  1.2746e-5  12000.50c  1.6663e-3
      25055.50c  1.4743e-5
c       Zn replaced by Cu, below
      29000.50c  1.2387e-5  14000.50c  1.2978e-4
      26000.50c  6.5265e-5
c     m6 is acrylic (support plate)
m6    1001.50c 5.6642e-2  6000.50c 3.5648e-2
      8016.50c 1.4273e-2
mt6   poly.01t
c     m7 is Boral Plate- Core
m7    5010.50c  7.9217-3   5011.50c  3.1886-2
      6000.50c  9.9501-3   13027.50c 3.7222-2
      24000.50c 1.4419-5   29000.50c 4.0394-5
      26000.50c 1.6172-4   12000.50c 3.0848-5
      25055.50c 1.8263-5   11023.50c 1.3045-5
      28000.50c 5.1099-6   14000.50c 2.5216-4
      16032.50c 1.4027-5   29000.50c 3.0689-5
```

MCNP Input Listing for Case 18 of Table 40

```
message:      outp=m222p.o  runtpe=m222p.r  srctp=m222p.s

m222p  THREE 24X15 CLUSTERS OF U(2.35)O2 RODS, 6.88 CM SEPR, PITCH 2.032 CM
1    1 .06170524 -1 7 -8 u=1 imp:n=1 $ uo2 fuel
2    3 .0597516   1 -2 -9 u=1 imp:n=1 $ clad
3    4 .06006075  -1 8 -9 u=1 imp:n=1 $ top end plug (lower piece)
4    4 .06006075  -2 9 u=1 imp:n=1 $ top end plug (top piece)
5    5 .06000711  -1 -7 u=1 imp:n=1 $ lower end plug
6    2 .100116  2 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 21 -22 23 fill=2 imp:n=1  $ first rod cluster
9    0 -13 12 -20 21 -22 23 fill=2(55.648 0 0) imp:n=1  $ second rod cluster
10   0 -15 14 -20 21 -22 23 fill=2(103.168 0 0) imp:n=1  $ third rod cluster
11   7 .0858025  33 -34 31 -32 23 -37  imp:n=1  $ Cu plate
12   7 .0858025  35 -36 31 -32 23 -37  imp:n=1  $ Cu plate
13   6 .106563  -23 29 -15 11 -20 21 imp:n=1  $ acrylic support plate
14   2 .100116  -12 10 -20 21  -22 23 #11  imp:n=1  $ water between clusters
15   2 .100116  -14 13 -20 21  -22 23 #12  imp:n=1  $ water between clusters
16   2 .100116 (-11:15:20:-21:22:-29)
          #11 #12 -24 25 -26 27 -28 30 imp:n=1 $ water
17   0  24:-25:26:-27:28:-30  imp:n=0

1    c/z 1.016 1.016 .5588  $ fuel cylinder
2    c/z 1.016 1.016 .635  $ clad cylinder
3    px  0.0  $ fuel rod cell boundary
4    px  2.032  $ fuel rod cell boundary
5    py  0.0  $ fuel rod cell boundary
6    py  2.032  $ fuel rod cell boundary
7    pz  0.0  $ bottom of fuel
8    pz  91.44  $ top of fuel
9    pz  91.92  $ top of clad
10   px  48.7679  $ farthest edge of closest cluster
11   px  .0001  $ closest edge of closest cluster
12   px  55.6481  $ closest edge of center cluster **
13   px  96.2879  $ farthest edge of center cluster
14   px  103.1681 $ closest edge of farthest cluster **
15   px  151.9359  $ farthest end of clusters
20   py  30.4799  $ sides of clusters
21   py  .0001  $ sides of clusters
22   pz  96.52  $ top of fuel rod
23   pz  -1.27  $ bottom of fuel rod
24   px  181.936  $ side of water reflector
25   px  -30.0   $ side of water reflector
26   py  60.480  $ side of water reflector
27   py  -30.0   $ side of water reflector
28   pz  106.44  $ top of water
29   pz  -3.81  $ bottom of acrylic support plate
30   pz  -19.11  $ bottom of water
c    plates
31   py  -0.06   $ plate bottom
32   py  30.54   $ plate top
33   px  54.666  $ 1st plate
34   px  55.003  $ 1st plate
35   px  96.933  $ 2st plate
36   px  97.27   $ 2st plate
37   pz  90.23   $ plate top

kcode  1500 1 50 160 50000
c    kcode  100 1 1 5 50000
sdef  x=d1 y=d2 z=d3 cel=d4
si1   0 180
sp1   0 1
si2   0 100
```

MCNP Input Listing for Case 18 of Table 40 (cont'd)

```
sp2   0 1
si3   0 100
sp3   0 1
si4   l 8 9 10
sp4   v
print
c     m1 is UO2 fuel
m1    92234.50c 2.8563e-6 92235.50c 4.8785e-4
      92236.50c 3.5348e-6 92238.50c 2.0009e-2
      8016.50c  4.1202e-2
c     m2 is water
m2    8016.50c 3.3371e-2  1001.50c 6.6743e-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 1100 aluminum (top end plug)
m4    13027.50c  5.9660e-2  29000.50c  3.0705e-5
      25055.50c  7.3991e-6
c       Zn replaced by Cu, below
      29000.50c  1.2433e-5  14000.50c  2.3302e-4
      26000.50c  1.1719e-4
c     m5 is 5052 aluminum (lower end plug)
m5    13027.50c  5.8028e-2  24000.50c  7.7888e-5
      29000.50c  1.2746e-5  12000.50c  1.6663e-3
      25055.50c  1.4743e-5
c       Zn replaced by Cu, below
      29000.50c  1.2387e-5  14000.50c  1.2978e-4
      26000.50c  6.5265e-5
c     m6 is acrylic (support plate)
m6    1001.50c 5.6642e-2  6000.50c 3.5648e-2
      8016.50c 1.4273e-2
mt6   poly.01t
c     m7 is Cu plate w/o Cd
m7    6000.50c   1.5194e-3  29000.50c  8.4128e-2
      26000.50c  3.8444e-6  12000.50c  4.4168e-6
      11023.50c  4.6695e-6   8016.50c  1.0064e-4
      14000.50c  3.8223e-5  16032.50c  3.3474e-6
```

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 11. These 2.032-cm-pitch experiments are numbered SSC (Simulated Shipping Cask) 2.35-000-001 to -054 dated 1/11/77 to 6/7/77. (The first group was erroneously listed as SSC-413-000-001 to 026 in Box 11.)

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

```
=CSASIX
GENERATE 27-GRP LIB FOR 2.35 WT% UO2 PNL FUEL PINS IN WATER
27GROUPNDF4 LATTICECELL
U-234  1 0  2.85626-6 291 END
U-235  1 0  4.87852-4 291 END
U-236  1 0  3.53484-6 291 END
U-238  1 0  2.00094-2 291 END
O  1 0  4.12021-2 291 END
H  2 0  6.67619-2 291 END
O  2 0  3.33809-2 291 END
Al  3 0  6.01507-2 291 END
H  4 0  6.67619-2 291 END
O  4 0  3.33809-2 291 END
END COMP
SQUAREPITCH 2.032 1.1176 1 2 1.27 3 END
END


1     0     0
SLAB OF U(2.35)O2 FUEL PINS IN WATER, BASE CASE
/  Block 1
igeom=slab ngroup=27 isn=16 niso=5 mt=5 nzone=5 im=4 it=251  T

/  Block 2
xmesh= 0 44.72 45.72 46.72 60.72
xints= 179    8     8     56
zones=   5    5     4      4 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=0 zned=1  T
```

```
=CSASIX
98fc1 CASE 1  THREE 20X16 CLUSTERS, 6.88 CM SEPARATION
27GROUPNDF4 LATTICECELL
' U(2.35)O2
U-234  1 0  2.8563-6 295 END
U-235  1 0  4.8785-4 295 END
U-236  1 0  3.5348-6 295 END
U-238  1 0  2.0009-2 295 END
O  1 0  4.1202-2 295 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
'  1100 Al (top end plug)
AL  4 0  5.9660-2 295 END
CU  4 0  3.0705-5 295 END
MN  4 0  7.3991-6 295 END
'       (Zn replaced by Cu)
CU  4 0  1.2433-5 295 END
SI  4 0  2.3302-4 295 END
FE  4 0  1.1719-4 295 END
' 5052 Al (lower end plug)
AL  5 0  5.8028-2 295 END
CR  5 0  7.7888-5 295 END
CU  5 0  1.2746-5 295 END
MG  5 0  1.6663-3 295 END
MN  5 0  1.4743-5 295 END
'       (Zn replaced by Cu)
CU  5 0  1.2387-5 295 END
SI  5 0  1.2978-4 295 END
FE  5 0  6.5265-5 295 END
' acrylic
H   6 0  5.6642-2 295 END
C   6 0  3.5648-2 295 END
O   6 0  1.4273-2 295 END
' water
H  7 0  6.6706-2 295 END
O  7 0  3.3353-2 295 END
' SS plate
CR  8 0  1.7046-2 295 END
CU  8 0  2.0291-4 295 END
FE  8 0  5.8353-2 295 END
MN  8 0  1.3734-3 295 END
MO  8 0  1.2942-4 295 END
NI  8 0  9.0238-3 295 END
END COMP
SQUAREPITCH 2.032 1.1176 1 2 1.27 3 END
MORE DATA EPS=1.-7 PTC=1.-7 END MORE
END


   1    0    0
```

```
98f1, 2.35 wt% 3 20x16 clusters, 6.88 cm separation,
/      SS plates
/  Block 1
igeom=6 ngroup=27 isn=8 niso=9 mt=9 nzone=9 im=6 it=177 jm=5
jt=134  maxscm=560000 maxlcm=4500000 t

/  Block 2
xmesh=0 20.32 20.965 21.450 27.2 67.84 98.34
xints= 40 2 3 12 80 40
ymesh=0.0 28.956 30.5 63.012 64.556 93.512
yints= 30 4 66 4  30
zones=6r7; 2r7 8 3r7; 9 7 8 7 9 7;
      2r7 8 3r7; 6r7  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=110.33  t

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