Criticality Experiments with Mixed Plutonium and Uranium Nitrate Solution at a Plutonium Fraction of 0.4 in Slab Geometry

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MIX-SOL-THERM-005

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CRITICALITY EXPERIMENTS WITH MIXED PLUTONIUM AND URANIUM NITRATE SOLUTION AT A PLUTONIUM FRACTION OF 0.4 IN SLAB GEOMETRY

IDENTIFICATION NUMBER: MIX-SOL-THERM-005

KEY WORDS: acceptable, bare, critical experiment, homogeneous solution, slab, moderated, plutonium, plutonium nitrate, solution, thermal, water-reflected, uranium, uranyl nitrate

1.0 DETAILED DESCRIPTION

1.1 Overview of Experiment

R. C. Lloyd of PNL has completed and published a series of critical experiments with mixed plutonium-uranium nitrate solutions (Reference 1). This series of critical experiments was part of an extensive program jointly sponsored by the U. S. Department of Energy (DOE) and the Power Reactor and Nuclear Fuel Development Corporation (PNC) of Japan and was carried out in the mid-1980's. The experiments evaluated here (published as Report PNL-6327) were performed with mixed plutonium-uranium nitrate solution in a variable thickness slab tank with two 106.7 cm square sides and a width that could be varied from 7.6 to 22.8 cm. The objective of these experiments was to obtain experimental data to permit the validation of computer codes for criticality calculations and of cross-section data to minimize the uncertainties inherent therein, so that facility safety, efficiency, and reliability could be enhanced. The concentrations of the solution were about 105, 293, and 435 g(Pu+U)/liter with a ratio of plutonium to total heavy metal (plutonium plus uranium) of about 0.40 for all eight experiments. Four measurements were made with a water reflector, and four with no reflector.

Following the publication of the initial PNL reports, considerable effort was devoted to an extensive reevaluation of this series of experiments by a collaboration of researchers from ORNL, PNL, and PNC (Reference 2). Their work resulted in a more accurate description of the "as built" hardware configuration and the materials specifications. For the evaluations in this report, the data published in Reference 2 by Smolen et al. is selected to supersede the original PNL report.

Eight experiments have been evaluated and seven (063, 064, 071, 072, 074, 075, and 076) provide benchmark criticality data. Experiment 073 could not achieve criticality within vessel height limitations.

1.2 Description of the Experimental Configuration

1.2.1 Room - The solution system is located in the critical assembly room at PNL, which is 10.67 meters square and has a ceiling height of 6.4 meters. Three side walls are composed of 1.52 meters-thick-concrete; the south wall is 0.91-meters-thick. Both the concrete ceiling and floor are 0.61 meters thick.

1.2.2 Bellows Assembly - The all stainless steel (Type 304L) slab tank holding the fissile solution is composed of two square sides each connected to four accordion-like sides joined to each other through a 2.54 cm spacer. (The spacer in the middle of the expandable side can be seen in Figure 3.) Because of these expandable sides, the width of the solution tank can be continuously varied from 7.6 to 22.8 cm in the north-south direction. The average height and width of the square faces of the slab solution tank were 106.7 cm, measured from halfway between the peaks and troughs of the pleats in the expandable sides. Each of the four corners of the square faces was rounded on a 14.4 cm radius. A photograph of the bellows assembly is shown in Figure 1. The thickness of the steel forming the pleats is 0.079 cm; the distance from a pleat trough to a pleat peak is 5.08 cm for a slab thickness of 15.2 cm. Each expandable side bellows assembly contains a total of 10 peaks and 8 troughs; the peaks and troughs correspond to the outermost and innermost extent of the bellows, respectively. The square end plates of the bellows are 0.159 cm thick and are prevented from bulging by an attached egg-crate style support grid. The open grid has a square pitch spacing of 10.6 cm, a depth of 11.43 cm, and is constructed of 0.3175 cm stainless steel plates. The support grid maintains the position of the side to within a tolerance of 0.025 cm as the tank is filled. Schematic diagrams of this vessel system are shown in Figures 2 and 3.

1.2.3 Reflector Tank - The bellows assembly was housed in a cuboidal 304L stainless steel tank that could be filled to form a water reflector. The inside dimensions of the tank are 68.6 cm in the north-south direction, 142.2 cm in the east-west direction and 143.5 cm high. The plates on the north and south sides are 0.635 cm thick; the others, including the bottom, are 0.476 cm thick. The bellows is raised 18.4 cm from the bottom of the reflector tank (measured from the midpoint of the bellows pleat). There is an equal space of 17.75 cm between the bellows and both the east and west sides of the reflector tank (measured from the midpoint of the bellows pleat). The north-south spacing of the bellows within the reflector tank is variable, depending on the particular experiment, from 25.6 cm to 33.2 cm on the south side, and 20.2 cm to 27.8 cm on the north side, for slab thicknesses of 22.8 cm (maximum extent) to 7.6 cm (minimum extent), respectively. The bottom of the reflector tank is situated 100.6 cm above the concrete floor.

1.2.4 Containment Hood - The bellows and reflector tank system is additionally enclosed in a containment hood composed of 0.635-cm-thick stainless steel plates and 0.95-cm-thick Plexiglas viewing windows. The east-west extent of the hood is 278.522 cm, the north-south extent of the hood is 243.84 cm. The north-west corner of the hood is located 183 cm from the north wall of the room and 152 cm from the west wall. Within the hood the broad faces of the reflector tank are situated 34.3 cm from the south hood wall and 138.4 cm from the north hood wall. The narrow faces of the reflector tank are situated 24.6 cm from the west hood wall and 109.5 cm from the east hood wall. The hood extends from the floor to ~100 cm below the ceiling^(a). A photograph of the containment hood is shown in Figure 4. A 2.5 cm thick open steel grate catwalk placed 230 cm above the floor was mounted on the inside perimeter of the hood. The grate did not cover the slab tank and was predominately open space.

^(a)No specification was listed for the height of the containment hood. The estimated height used in this model was based on the photograph in Figure 4.

Figure 1. Photograph of the Slab Tank System (Reference 1, p. 2.11)

Figure 2. Schematic of Variable Thickness Slab Tank (Reference 2, p. 309).

Figure 4. Photograph of the Containment Hood (Reference 2, p. 310)

1.2.5 Critical Measurements - The critical heights for the experiments in this evaluation were determined using the critical approach method (Reference 3). Neutron flux measurements were made with three independent boron-lined proportional counters located at separate positions as the height of the solution was incrementally increased. A plot of solution height over count rate plotted as a function of solution height produces a straight line that extrapolates to zero at delayed critical. The uncertainty in the critical height was estimated to be ± 1.6 mm.

The solution slab thickness for each experiment, the measured critical heights, and the temperatures of the reflector water, where applicable, are listed in Table 1. For the water-reflected experiments, the water level was even with the top of the slab tank (the midpoint of the upper bellows pleat). The empty reflector tank remained in place during the bare experiments.

Table 1. Slab Thickness and Critical Heights.

Experiment ID number	Reflector (Temperature °C)	Slab Thickness (cm)	Critical Height (cm) ^(a)
063	bare	19.81	54.70
064	water ^(b) (17.3)	13.97	80.14
071	water ^(b) (22.1)	13.97	47.44
072	water ^(b) (22.7)	12.70	67.16
074	bare	18.03	70.13
075	bare	19.05	85.38
076	water ^(b) (21.7)	13.46	74.19

(a) measured from the midpoint of the bottom pleats

(b) Water height is 106.7 cm, measured from the midpoint of the bottom pleats of the slab tank.

1.3 Description of the Material Data

The solution was characterized by measuring the concentration of plutonium and uranium, the density of the solution, and the molarity of the free nitric acid. No data exists for the temperature of the fissile solution during the actual experiments, although temperatures for the fissile solution storage tank and the containment hood were reported. The estimated temperature range was from about 17 °C to 30 °C. The values of the solution parameters are given in Table 2.

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Table 2. Solution Parameters. ^(a)

Experiment Number	Plutonium Concentration [g/l]	Uranium Concentration [g/l]	Solution Density ^(b) [g/ml]	Free Nitric Acid [M]
063	41.06	62.89	1.1725	0.61
064	41.90	63.36	1.1752	0.61
071	118.87	173.48	1.4633	1.03
072	118.87	173.48	1.4633	1.03
074	119.04	174.01	1.4637	1.04
075	172.77	262.81	1.6703	1.24
076	172.68	262.94	1.6699	1.24

(a) The PNL-estimated uncertainties were: plutonium or uranium concentration $\pm 0.2\%$, solution density $\pm 0.0003 \text{ g/cm}^3$, and free nitric acid $\pm 0.04 \text{ M}$.

(b) Measured at 23 °C.

The ^{241}Am concentration was measured in 30 chemical analyses spaced over a four year period. Since the ^{241}Am concentration depends on the radioactive decay of ^{241}Pu , the ^{241}Am concentration should be a smooth time-dependent function. Smolen, et al. (Reference 2, p.310) performed a linear regression analysis on the concentration data and developed an analytic expression for the relative ^{241}Am concentration as a function of time for all of the experiments studied here. The relative concentration is given in terms of $\text{mg } ^{241}\text{Am}$ per g Pu and is given by:

$$^{241}\text{Am} = 4.950 + 5.921 \times 10^{-4} \times t \quad (1)$$

where t is the time in days from January 1, 1985 that the experiment in question was run, and this is listed in Table 3. The predicted ^{241}Am concentrations in $\mu\text{g } ^{241}\text{Am}$ per ml for all experiments dealt with in this report are also given in Table 3.

Table 3. Run Dates for Experiments and Corresponding Time in Days from January 1, 1985, and Concentration Values for Americium-241.

Experiment Number	Sample Number	Run Date	t (days)	$^{241}\text{Am}^{(a)}$ ($\mu\text{g/ml}$)
063	1153	2-04-86	399	212.95
064	1154	2-10-86	405	217.45
071	1166	3-13-86	436	619.09
072	1166	3-14-86	437	619.16
074	1167	3-18-86	441	620.33
075	1170	4-22-86	476	903.90
076	1171	4-23-86	477	903.54

(a) The concentration values are given to five significant figures to avoid roundoff problems when attempting to reproduce the number densities for ^{241}Am in Tables 16-22.

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The data for the isotopic values for the plutonium and uranium of the experiments were reevaluated by Smolen, et al. (Reference 2, p. 310 and Table V, p. 313). Using their results, the isotopic composition for Pu and U is shown in Tables 4 and 5 in wt.%. All experiments evaluated in this report have the same isotopic values.

Table 4. Isotopic Analyses Values of Pu for All Experiments.

^{238}Pu Wt.%	^{239}Pu Wt.%	^{240}Pu Wt.%	^{241}Pu Wt.%	^{242}Pu Wt.%
0.029 ± 0.001	91.118 ± 0.02	8.310 ± 0.02	0.450 ± 0.004	0.093 ± 0.002

Table 5. Isotopic Analyses Values of U for All Experiments.

^{238}U Wt.%	^{236}U Wt.%	^{235}U Wt.%	^{234}U Wt.%
99.406 ± 0.004	0.023 ± 0.001	0.564 ± 0.005	0.007 ± 0.001

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Selected data of impurity concentrations were also reevaluated and averaged for experiments coming from the same parent solution by Smolen, et al. (Reference 2, Table VII). By averaging the appropriate impurity measurements obtained from the Inductively Coupled Plasma (ICP) Atomic Emission Spectroscopy method the uncertainty in impurity concentration can be reduced to ± 25 percent. The averaged impurity concentrations, in μg impurity per g Pu, for all impurities measured are listed in Table 6. Impurities were measured by Spark Source Mass Spectroscopy, with an estimated factor-of-3 uncertainty, unless otherwise noted in Table 6.

Table 6. Analysis of Impurities.

Element	Impurity Concentration ($\mu\text{g/g}$ Pu)	Element	Impurity Concentration ($\mu\text{g/g}$ Pu)	Element	Impurity Concentration ($\mu\text{g/g}$ Pu)
Al	950 ^(a)	Fe	2935 ^(a)	Nd	20
B	49 ^(b)	Gd	11	Ni	542 ^(a)
Ba	46	K	94	Rh	75
Ca	598 ^(a)	La	5	Ru	27
Cd	57 ^(a)	Li	3	Si	556
Ce	46	Mg	154	Sr	2
Cr	746 ^(a)	Mn	148 ^(a)	Ti	225 ^(a)
Cu	163	Mo	10	Zn	48
Dy	7	Na	470	Zr	45

^(a) $\pm 25\%$; measured by ICP method (Reference 2)

^(b) $\pm 70\%$ (Reference 2)

The density and composition of stainless steel 304L is given in Table 7.

Table 7. Density^(a) and Composition^(b) for Stainless Steel 304L.

Element	Wt. %
Stainless Steel 304L (density = 8.02 g/ml)	
C	0.03 Max
Mn	2.0 Max
P	0.045 Max
S	0.03 Max
Si	1.00 Max
Cr	18.00 - 20.00
Ni	8.00 - 10.00
Fe	66.895 - 74.00

(a) R.C. Weast, et al., page D-186, *Handbook of Chemistry and Physics*; 70th Edition, CRC Press, Inc. (1989)

(b) Ibid., page F-135. The minimum Fe value results from subtracting the maximum composition of all other elements from 100%, and the maximum Fe value results from subtracting the minimum composition (or zero) of all other elements.

2.0 EVALUATION OF PUBLISHED DATA

The experiments are documented in extreme detail and are presented in a well organized format. All relevant data are included in the report (Reference 1). Engineering drawings were provided in PNL-5768 (Lloyd 1986) (Reference 4) for the slab tank system. These drawings contain design dimensions used for fabrication of the hardware; they agree quite well with those actually measured by Smolen et al. (References 2 and 5).

The density and composition of the concrete chosen for the models of the walls, floor and ceiling are listed in Table 8. No actual description of the structural room concrete composition was supplied in the PNL report. The composition chosen is the same concrete composition and density specified in Reference 1 for a companion experiment in which an annular concrete collar was used to shroud a small cylindrical reaction vessel (MIX-SOL-THERM-004).

Table 8. Density^(a) and Composition^(b) for Concrete.

Element	Wt. %
Concrete	(density = 2.33 g/ml)
O	51.91
Si	23.10
Ca	12.00
Al	4.79
Fe	3.37
Na	1.43
H	1.05
Mg	0.92
K	0.72
S	0.38
Ti	0.33

(a) Corrected density as given on page 306 in Reference 2.

(b) Composition as given in Table F.3, page F.3 in Reference 1.

All of the ONEDANT calculations referred to in this section were performed using SCALE 27-group ENDF/B-IV cross sections, with S_{48} angular quadrature, and with inner loop convergence parameter equal to 10^{-6} .

2.1 Measurement Uncertainties

The PNL documentation (Reference 1) and Smolen, et. al. (Reference 2) identify seven sources of experimental uncertainty accompanied by estimated magnitudes. They are listed in Tables 9 and 10.

Table 9. Effects on k_{eff} Due to Some PNL-Estimated Experimental Uncertainties (Reference 1)

Solution Parameter Varied	PNL-Estimated Uncertainty	Experiment		
		064 Δk_{eff}	071 Δk_{eff}	076 Δk_{eff}
Pu concentration	$\pm 0.2\%$	0.0002	0.0003	0.0005
U concentration	$\pm 0.2\%$	0.0004	0.0005	0.0006
Density	$\pm 0.0003 \text{ g/cm}^3$	0.0003	0.0003	0.0001
Free Acid	$\pm 0.04 \text{ M}$	0.0014	0.0011	0.0013

Geometric Parameter Varied	PNL-Estimated Uncertainty	$\Delta k_{eff}^{(a)}$	$\sigma \Delta k_{eff}^{(b)}$
Critical Slab Thickness	$\pm 0.5 \text{ mm}$	0.0002	± 0.0001
Critical Slab Height	$\pm 1.6 \text{ mm}$	0.0005	± 0.0001

(a) Common for all experiments

(b) The uncertainty in Δk_{eff} is due to the subtraction of two Monte Carlo k_{eff} values each of which is uncertain.

There were essentially three different solution densities used in the experimental investigation; see Table 2. The water-reflected experiments were chosen as reference systems to investigate the effects of each of these uncertainties because they are essentially fully water reflected and so it is not necessary to include external reflector objects. The effect of the experimental uncertainty in the first four parameters was estimated by constructing an analog of experiments 064, 071, and 076 with spherical symmetry and performing ONEDANT calculations.

To estimate the effect of the experimental uncertainty in the critical slab height for these experiments, MCNP calculations were performed with the solution at the measured critical height and at the critical height $\pm 8 \text{ mm}$. To estimate the effect of the experimental uncertainty in the critical slab thickness for these experiments, MCNP calculations were performed with the solution thickness at the measured critical thickness and at the critical thickness $\pm 2.5 \text{ mm}$. The three data points for each experiment were then used to determine the slope of the k_{eff} versus critical dimension curve. The changes in reactivity for the corresponding six sources of experimental uncertainty are listed in Table 9.

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The experimenters make particular note of the fact that the "free acid" analysis had previously been prone to error. The analyses of the solution data samples used in this experiment were performed using the method developed by J. L. Ryan^a, and they indicate that this "significantly" reduced the uncertainties in this crucial measurement. The nitrate concentration was not specified, however. It is recognized that an independent measurement of the nitrate concentration would enhance the accuracy of the solution assay.

Errors associated with uncertainties in the concrete composition of the floor, walls, and ceiling of the room are were evaluated by comparisons made using MCNP with two other standard concrete mixtures, "KENO Regular" mix and "Los Alamos MCNP" mix^b. The effects are inconsequential.

Table 10. Effects on k_{eff} Due to Differing Concrete Mixtures

Concrete Mix Used to Compare Effects	Δk_{eff}	$\sigma \Delta k_{eff}$
KENO Regular	0.0005	± 0.0011
Los Alamos MCNP	0.0003	± 0.0011

The effects on k_{eff} due to the uncertainties on solution temperature are given in Table 11. Following Smolen, et. al. (Reference 2), the solution temperature was assumed to be 23 °C for all experiments, the temperature at which density measurements were made. The effect of the experimental uncertainty in the solution temperature was estimated by using the spherical analog of experiments 064, 071, and 076 mentioned above and performing ONEDANT calculations.

The water temperature of the reflector in the water reflected experiments was taken as the value measured during the experiments. The uncertainty in k_{eff} due to the uncertainty in the water-reflector temperature is expected to be very small, and therefore was not calculated.

Table 11. Temperature Effects on k_{eff} Due to Some Estimated Experimental Uncertainties by Smolen, et. al. (Reference 2) on the Water Reflected Experiments.

Parameter Varied	Estimated Uncertainty (Reference 2)	Experiment		
		064 Δk_{eff}	071 Δk_{eff}	076 Δk_{eff}
Solution Temperature ^(a)	± 7 °C	0.0018	0.0018	0.0016

- (a) Smolen, et. al. determined, based on empirical density data for Pu and U solutions, that the Pu + U solution concentrations would decrease by 0.34% due to an increase in solution temperature of +7 °C. Therefore, the concentration of each solution element was decreased by 0.34% in determining Δk_{eff} .

^a J. L. Ryan et al., *Preparation of Acid Standards for and Determination of Free Acid in Concentrated Plutonium-Uranium Solutions*, **Analytical Chemistry**, 57:1423-1427 (1985)

^b C. D. Harmon, II et al., *Criticality Calculations with MCNP: A Primer*, LA-12827-M Manual, C-4, (1994)

The experimental standard deviations, σ , of the solution-height zero intercept from the least squares fits to experimental data are given in Table 12 (Reference 1, Figures C-1 through C-14 in Appendix C.). The critical height is also reproduced from Table 1. The value of σ for Experiment 075 is about two times larger than the next largest σ . Nothing was said in the PNL report regarding the increased size of σ for this experiment, and there is nothing unusual appearing in the least squares plot shown in Figure C.13 to suggest an explanation.

Table 12. Standard Deviations of Critical Heights.

Experiment ID number	Critical Height (cm)	σ (mm)
063	54.70	0.26
064	80.14	0.24
071	47.44	0.22
072	67.16	0.49
074	70.13	0.50
075	85.38	1.23
076	74.19	0.19

Table 12 shows that all of the standard deviations from the least squares fits to the experimental data are less than the experimental uncertainty of ± 1.6 mm reported in Table 9.

3.0 BENCHMARK SPECIFICATIONS

3.1 Description of Model

The pleated bellows assembly used for the variable-width slab tank is difficult, if not impossible, to accurately model with many common code/cross-section packages. To allow use of less sophisticated geometry capabilities of many modeling codes, a simplification of the bellows assembly was developed. In order to justify the simple model, an exact model of one of the slab tank configurations was prepared for input into MCNP (see Appendix B) and the results were compared to those represented by the simple model. The aim of this exercise was to generate a rectangular cuboid model for the reaction vessel that would neutronically represent the bellows. The largest obstacle was finding an appropriate thickness for the flat surface approximation needed to replace the four non-orthogonally pleated sides of the tank (see Figure 5.). This process was achieved through a sensitivity study described later in this section.

Figure 5. Model Simplification of the Bellows

For water-reflected cases additional simplifications were made to the benchmark model. Previous benchmark evaluations were reported for the small and large cylinders and the annular cylinders using the same solution system in the critical assembly room at PNL (MIX-SOL-THERM-001, MIX-SOL-THERM-002, and MIX-SOL-THERM-004). All three of the previous benchmark calculations involving small and large cylinders as well as annular cylinders indicated that for the water-reflected experiments, simpler benchmark models could be developed from the more complex version of the model of the actual experiment. For these cases, it was not necessary to include the details of the room and equipment in the room outside of the reflector material, since few neutrons escape from the water and return into the fissile material. For this evaluation we were able to eliminate the containment hood, floor and walls from the water reflected cases.

Two simplified benchmark models were developed for these experiments:

- (1) Water reflected cases: Only the cuboidal representation of the slab tank, reinforcing egg-crate support grid, water, and reflector tank faces are included.
- (2) Bare cases: In addition, the containment hood, floor, ceiling, and walls are included.

Reaction Vessel

The benchmark model for the fuel solution slab consists of a cuboid with square sides 106.7 cm in height and width. The width of the slab of solution (inner width of the slab tank) varied from one experiment to the other and is listed in Table 13 below. The distances from the solution's square surfaces to the inner reflector tank walls are also given in Table 13.

Table 13. Solution Slab Placement Within the Reflector Tank and Slab Width.

Experiment ID Number	Distance of Fuel Surface from Inner North Reflector-Tank Wall (cm)	Distance of Fuel Surface from Inner South Reflector-Tank Wall (cm)	Slab Fuel Width (cm)
063	21.695	27.095	19.81
064	24.615	30.015	13.97
071	24.615	30.015	13.97
072	25.250	30.650	12.70
074	22.585	27.985	18.03
075	22.075	27.475	19.05
076	24.870	30.270	13.46

The benchmark model for the slab tank reaction vessel consists of a stainless steel cuboid with square sides 106.7 cm in height and width. These square end plates are 0.159 cm thick. The square faces of the tank are reinforced by an egg-crate style support grid. The grid has a square pitch spacing of 10.6 cm, a depth of 11.43 cm, and is constructed of 0.3175-cm stainless steel. The thickness of the slab tank plates that replace the pleated sides of the bellows assembly (as determined by a sensitivity study) is 0.316 cm. Using this thickness for the replacement plates, the outside height and width of the reaction vessel is 107.332 cm.

Reflector Tank

The cuboidal reaction vessel is located inside a cuboidal 304L stainless steel reflector tank that contains water to form a water reflector. The inside dimensions of the tank are 68.6 cm in the north-south direction, 142.2 cm in the east-west direction and 143.5 cm high. The north and south sides of the tank are 0.635 cm thick; the other sides and bottom are 0.476 cm thick. The outside bottom of the reaction vessel is 18.084 cm above the inside bottom of the reflector tank and there is a space of 17.434 cm between the side replacing the bellows and the east and west sides of the reflector tank. The north-south spacing of the vessel within the reflector tank is variable (see Table 13) depending on the particular experiment. The bottom of the reflector tank is 100.6 cm above the floor.

Containment Hood (pertains to bare experiments only)

The reaction vessel and reflector tank system is additionally enclosed in a containment hood. In the benchmark model, the hood is composed of 0.635-cm-thick stainless steel plates. The east-west extent of the hood is 278.522 cm, the north-south extent of the hood is 243.84 cm. The north-west corner of the hood is located 183 cm from the north wall and 152 cm from the west wall. Within the hood the broad faces of the reflector tank are situated 34.3 cm from the south hood wall and 138.4 cm from the north hood wall. The narrow faces of the reflector tank are situated 24.6 cm from the west hood wall and 109.5 cm from the east hood wall. The hood extends from the floor to 100 cm below the ceiling. (The Plexiglas windows are not included in the benchmark model.)

Room (pertains to bare experiments only)

The solution system is located in a room which is 10.67 meters square and has a ceiling height of 6.4 meters. Three of the side walls are composed of 1.52-meters-thick concrete; the south wall is 0.91 meters thick. The concrete ceiling and floor are each 0.61 meters thick. Since no description of the structural concrete composition was supplied in the report, the same composition was used for the walls, floor, and ceiling as was provided for the concrete reflectors used in other previous experiments.

Figures 6 through 10 are plan and elevation views of the benchmark geometry, used for both the bare and water-reflected experiments.

Figure 7. Plan View of a Bare-Experiment Benchmark Geometry Showing the Room, Containment hood, Reflector Tank, Reaction Vessel, and Reinforcing Grid.

Figure 8. Plan View of a Bare-Experiment Benchmark Geometry Detailing the Containment Hood, Reflector Tank, Reaction Vessel, and Reinforcing Grid.

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Figure 10. Elevation View of the Benchmark Geometry for Both the Bare and Water-Reflected Experiments, Detailing the Reflector Tank, and Reinforcing Grid of the Reaction Vessel.

Sensitivity Studies:**Corner Rounding**

An unresolved issue both in the PNL and Smolen's reports was the effect, if any, of the rounded corners of the experimental slab vessel. Each of the four corners of the steel bellows is rounded on a 14.4 cm radius. The missing volume represents 1.6% of the total volume with square corners. Sensitivity studies were performed to investigate this issue. Two simple geometries were created with just a bare volume of fuel in both round-cornered cuboid and square-cornered cuboid configurations with the same dimensions as the slab tank, as shown in Figure 11. Each configuration was used in a MCNP calculation for both water-reflected and bare environments. The calculated differences in reactivity, shown in Table 14, were very small; the water-reflected cases were almost identical.

Figure 11. Slab Tank Corner Rounding

Table 14. Changes in k_{eff} Due to Corner Rounding

Reflector Type	Δk_{eff}	$\sigma \Delta k_{\text{eff}}$
Water Reflected	0.00008	± 0.00056
Bare	0.00072	± 0.00056

Bellows to Planar Surface Transformation

The edges of the experimental vessel consisted of a flexible bellows that could expand and contract to effect a variable-width slab tank. Modeling the non-orthogonal pleats of the bellows are beyond the capability of many modeling codes. Thus an appropriate approximation was sought using a flat planar surface at the midpoint of the pleats. Since there is as much volume above and below the midpoints of the pleats, the volume of the solution is conserved.

The thickness of the equivalent plane side plate is not apparent. The actual pleats are fabricated from 0.079 cm stainless steel. Since they are folded several times it is intuitively obvious that the effective thickness is larger than 0.079 cm. To resolve this issue an exact MCNP model (see Appendix B) of the pleated bellows was constructed and the results of the k_{eff} calculations were compared to a flat plate simulation. A sensitivity study was performed in units of 0.079 cm to determine the thickness of the plate that most closely matched the exact calculation. The results are presented in Table 15.

Table 15. Changes in k_{eff} Due to Plate Thickness (in units of 0.079 cm)

Thickness Multiplier	Δk_{eff}	$\sigma \Delta k_{\text{eff}}$
1 x 0.079	0.00082	± 0.00118
2 x 0.079	0.00077	± 0.00117
3 x 0.079	0.00106	± 0.00118
4 x 0.079	0.00028	± 0.00114
5 x 0.079	0.00038	± 0.00120
6 x 0.079	0.00078	± 0.00114
8 x 0.079	0.00128	± 0.00115

For all reasonable values of thickness (2 to 6 x .079) the effect on k_{eff} due to the choice of flat plate approximation is statistically insignificant. We chose a value of 4 which did show a slight minimum in the difference in k_{eff} . Thus the plate thickness chosen is $4 \times 0.079 = 0.316$ cm. This choice is consistent with conserving the total mass of the pleated assembly for typical configurations.

Containment Hood Modeling

No detailed information was provided for the geometry of the containment hood other than its perimeter dimensions and the thickness of the Plexiglas and stainless steel plates used in the construction. The hood is outside of the reflector tank and outside of the egg-crate support grid of the slab tank and thus should have small effect on an experiment. Sensitivity studies were run to determine whether the selection of materials made a difference in the k_{eff} value. Calculations were run with all Plexiglas, all stainless steel, and a homogenized mixture of both. The results are shown in Table 16. No significant difference was observed. A calculation run with no hood (voided material) did show a slight effect. For the sake of simplicity, stainless steel was chosen for the benchmark model.

Table 16. Changes in k_{eff} Due to Hood Material Other Than 304L Stainless Steel

Hood Material	Δk_{eff}	$\sigma \Delta k_{\text{eff}}$
Plexiglas	0.00007	± 0.00086
Homogenized Plexiglas and SS304L	0.00009	± 0.00090
Void	0.00050	± 0.00088

The steel grate catwalk inside the hood was not directly above the reflector tank and was predominantly open space. Therefore, it was not included in the model. Similarly, the top of the hood is sufficiently far enough above the reaction vessel that uncertainties in its height are inconsequential.

Modeling Specification Uncertainties

The calculational uncertainties due to the three aforementioned benchmark model simplifications (0.00072, 0.00114, and 0.00090) combine in quadrature to give an additional k_{eff} uncertainty of ± 0.00162 .

3.2 Dimensions

Reaction Vessel

The benchmark model for the slab tank reaction vessel consists of a stainless steel cuboid with two square sides with inside dimensions of 106.7 cm in height and depth. These square sides are 0.159 cm thick. The remaining four flat walls of the cuboid, replacing the bellows assembly, are 0.316 cm thick. The width of the tank varied from one experiment to another and is listed in Table 13. The square sides of the tank are reinforced by an egg-crate style support grid. The grid has a square pitch spacing of 10.6 cm, a depth of 11.43 cm, and is constructed of 0.3175 cm stainless steel, except for the four outside plates which are 0.667 cm thick. The solution thickness and critical heights are listed in Table 17.

Table 17. Slab Thickness and Critical Heights.

Experiment ID number	Slab Thickness (cm)	Critical Height (cm)
063	19.81	54.70
064	13.97	80.14
071	13.97	47.44
072	12.70	67.16
074	18.03	70.13
075	19.05	85.38
076	13.46	74.19

Reflector Tank

The cuboidal reaction vessel is located inside a cuboidal 304L stainless steel tank. The inside dimensions of the tank are 68.6 cm in the north-south direction, 142.2 cm in the east-west direction and 143.5 cm high. The north and south sides are 0.635 cm thick; the other two sides and the bottom are 0.476 cm thick. The outside bottom of the reaction vessel is 18.084 cm above the inside bottom of the reflector tank and has spaces of 17.434 cm between the plates replacing the bellows and the east and west sides of the reflector tank. The north-south spacing of the vessel within the reflector tank is variable depending on the particular experiment. Spacings are listed in Table 13. The bottom of the reflector tank is 100.6 cm above the concrete floor.

For the water-reflected experiments, the reflector tank contains water with a depth of 122.56 cm.

Containment Hood (pertains to bare experiments only)

The reaction vessel and reflector tank system are additionally enclosed in a cuboidal containment hood composed of 0.635-cm-thick stainless steel plate. The east-west extent of the hood is 278.522 cm; the north-south extent of the hood is 243.84 cm. The north-west corner of the hood is located 183 cm from the north wall and 152 cm from the west wall. Within the hood the broad faces of the reflector tank are

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situated 34.3 cm from the south hood wall and 138.4 cm from the north hood wall. The narrow faces of the reflector tank are situated 24.6 cm from the west hood wall and 109.5 cm from the east hood wall. The hood extends from the floor to 100 cm below the ceiling.

Room (pertains to bare experiments only)

The solution system is located in a room which is 10.67 meters square and has a ceiling height of 6.4 meters. Three side walls are composed of 1.52-meters-thick concrete; the south wall is 0.91 meters thick. The concrete ceiling and floor are each 0.61 meters thick.

3.3 Material Data

By definition a molar solution is a gram molecular weight dissolved in enough water to make 1 liter of solution. The density of the free acid in g/cm³ is obtained by multiplying the measured molarity by the molecular weight of the acid and dividing by 1000.

In this analysis, the concentrations of Pu and U are measured quantities. To obtain the densities for Pu(NO₃)₄ and UO₂(NO₃)₂, the Pu and U concentrations are multiplied by the ratio of the molecular weight of the nitrate to the atomic weight of the metal.

In a similar way the measured contaminants, assumed to be in solution as nitrates, are scaled by the ratio of the molecular weights of their nitrates to their atomic weights. The form of the nitrate for each impurity can depend on the molarity of the acid solution. That information was not available for most of the impurity nitrates; in those cases the stable nitrate from the list in the "Handbook of Chemistry and Physics"^a was assumed. The forms used for this report were Al(NO₃)₃, B(NO₃)₃, Ba(NO₃)₂, Ca(NO₃)₂, Cd(NO₃)₂, Ce(NO₃)₃, Cr(NO₃)₃, Cu(NO₃)₂, Dy(NO₃)₃, Fe(NO₃)₂, Gd(NO₃)₃, K(NO₃)₁, La(NO₃)₃, Li(NO₃)₁, Mg(NO₃)₂, Mn(NO₃)₂, Mo(NO₃)₃, Na(NO₃)₁, Nd(NO₃)₃, Ni(NO₃)₂, Rh(NO₃)₃, Ru(NO₃)₃, Si(NO₃)₄, Sr(NO₃)₂, Ti(NO₃)₃, Zn(NO₃)₂, Zr(NO₃)₄. Concentrations were determined from the values given in Table 6. Errors resulting from using the wrong nitrate form for an impurity will be very small since the impurity concentrations are, in general, also relatively small. In fact including all impurities by assuming they have the form (Metal Ion)(NO₃)₂ gives a difference in k_{eff} of about 0.002.

The density of water in a solution is obtained by adjusting the measured solution density, ρ_{solution} , of the solution for acid and nitrates:

$$\rho_{\text{water}} = \rho_{\text{solution}} - \rho_{\text{acid}} - \rho_{\text{Pu(NO}_3)_4} - \rho_{\text{UO}_2(\text{NO}_3)_2} - \rho^{241}\text{AmO}_2(\text{NO}_3)_2 - \rho_{\text{contaminants}}$$

The concentration of hydrogen, oxygen and nitrogen can then be determined by adding the known concentrations of the appropriate components in the water, acid (HNO₃), and all nitrates. Several of the solution impurity concentrations were large enough (²⁴¹Am, Fe) or were strong enough neutron absorbers (¹⁰B, Cd) to be included explicitly in the benchmark model. (The concentration-times-absorption cutoff value used was arbitrary.) The strong neutron absorbers Gd and ⁶Li were also included for completeness.

^a R.C. Weast, et al., pages B-68 through B-146, *Handbook of Chemistry and Physics*; 70th Edition, CRC Press, Inc. (1989)

3.3.1 Solution.

The number densities of each solution for all the slab tank experiments are given in Tables 18-24. The number densities for the solution explicitly includes ^{241}Am and the neutron absorbers, boron, cadmium, iron, gadolinium, and lithium, in the contaminants. The isotopic abundance for ^{10}B is chosen to be 19.9% and that for ^6Li is chosen to be 7.5%^a. The density of the nitrates of all the contaminants listed in Table 6 lowers the density of the water in the solution and contributes some extra nitrogen and oxygen. The hydrogen, nitrogen, and oxygen contributed from all sources, including that due to all contaminants, is included in Tables 18-24.

Table 18. Solution Atom Densities for Experiment 063.

Isotope/Element	Atom Density [(b-cm) ⁻¹]
H	6.3508×10^{-02}
N	1.1117×10^{-03}
O	3.5225×10^{-02}
^{238}Pu	3.0123×10^{-08}
^{239}Pu	9.4249×10^{-05}
^{240}Pu	8.5597×10^{-06}
^{241}Pu	4.6159×10^{-07}
^{242}Pu	9.5001×10^{-08}
^{234}U	1.1328×10^{-08}
^{235}U	9.0878×10^{-07}
^{236}U	3.6903×10^{-08}
^{238}U	1.5815×10^{-04}
^{241}Am	5.3199×10^{-07}
^{10}B	2.2301×10^{-08}
Cd	1.2538×10^{-08}
Fe	1.2995×10^{-06}
Gd	1.7297×10^{-09}
^6Li	8.0152×10^{-10}

^a R.C. Weast, et al., page B-228, *Handbook of Chemistry and Physics*: 70th Edition, CRC Press, Inc. (1989)

Table 19. Solution Atom Densities for Experiment 064.

Isotope/Element	Atom Density [(b-cm) ⁻¹]
H	6.3520 x 10 ⁻⁰²
N	1.1228 x 10 ⁻⁰³
O	3.5266 x 10 ⁻⁰²
²³⁸ Pu	3.0739 x 10 ⁻⁰⁸
²³⁹ Pu	9.6178 x 10 ⁻⁰⁵
²⁴⁰ Pu	8.7348 x 10 ⁻⁰⁶
²⁴¹ Pu	4.7104 x 10 ⁻⁰⁷
²⁴² Pu	9.6945 x 10 ⁻⁰⁸
²³⁴ U	1.1412 x 10 ⁻⁰⁸
²³⁵ U	9.1557 x 10 ⁻⁰⁷
²³⁶ U	3.7179 x 10 ⁻⁰⁸
²³⁸ U	1.5933 x 10 ⁻⁰⁴
²⁴¹ Am	5.4324 x 10 ⁻⁰⁷
¹⁰ B	2.2758 x 10 ⁻⁰⁸
Cd	1.2795 x 10 ⁻⁰⁸
Fe	1.3261 x 10 ⁻⁰⁶
Gd	1.7650 x 10 ⁻⁰⁹
⁶ Li	8.1792 x 10 ⁻¹⁰

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Table 20. Solution Atom Densities for Experiment 071

Isotope/Element	Atom Density [(b-cm) ⁻¹]
H	5.8360×10^{-02}
N	2.7318×10^{-03}
O	3.7946×10^{-02}
²³⁸ Pu	8.7207×10^{-08}
²³⁹ Pu	2.7285×10^{-04}
²⁴⁰ Pu	2.4781×10^{-05}
²⁴¹ Pu	1.3363×10^{-06}
²⁴² Pu	2.7503×10^{-07}
²³⁴ U	3.1247×10^{-08}
²³⁵ U	2.5068×10^{-06}
²³⁶ U	1.0180×10^{-07}
²³⁸ U	4.3625×10^{-04}
²⁴¹ Am	1.5466×10^{-06}
¹⁰ B	6.4563×10^{-08}
Cd	3.6298×10^{-08}
Fe	3.7621×10^{-06}
Gd	5.0074×10^{-09}
⁶ Li	2.3204×10^{-09}

Table 21. Solution Atom Densities for Experiment 072

Isotope/Element	Atom Density [(b-cm) ⁻¹]
H	5.8360 x 10 ⁻⁰²
N	2.7318 x 10 ⁻⁰³
O	3.7946 x 10 ⁻⁰²
²³⁸ Pu	8.7207 x 10 ⁻⁰⁸
²³⁹ Pu	2.7285 x 10 ⁻⁰⁴
²⁴⁰ Pu	2.4781 x 10 ⁻⁰⁵
²⁴¹ Pu	1.3363 x 10 ⁻⁰⁶
²⁴² Pu	2.7503 x 10 ⁻⁰⁷
²³⁴ U	3.1247 x 10 ⁻⁰⁸
²³⁵ U	2.5068 x 10 ⁻⁰⁶
²³⁶ U	1.0180 x 10 ⁻⁰⁷
²³⁸ U	4.3625 x 10 ⁻⁰⁴
²⁴¹ Am	1.5468 x 10 ⁻⁰⁶
¹⁰ B	6.4563 x 10 ⁻⁰⁸
Cd	3.6298 x 10 ⁻⁰⁸
Fe	3.7621 x 10 ⁻⁰⁶
Gd	5.0074 x 10 ⁻⁰⁹
⁶ Li	2.3204 x 10 ⁻⁰⁹

Table 22. Solution Atom Densities for Experiment 074

Isotope/Element	Atom Density [(b-cm) ⁻¹]
H	5.8269×10^{-02}
N	2.7423×10^{-03}
O	3.7932×10^{-02}
²³⁸ Pu	8.7332×10^{-08}
²³⁹ Pu	2.7325×10^{-04}
²⁴⁰ Pu	2.4816×10^{-05}
²⁴¹ Pu	1.3382×10^{-06}
²⁴² Pu	2.7542×10^{-07}
²³⁴ U	3.1342×10^{-08}
²³⁵ U	2.5145×10^{-06}
²³⁶ U	1.0211×10^{-07}
²³⁸ U	4.3759×10^{-04}
²⁴¹ Am	1.5497×10^{-06}
¹⁰ B	6.4655×10^{-08}
Cd	3.6350×10^{-08}
Fe	3.7674×10^{-06}
Gd	5.0146×10^{-09}
⁶ Li	2.3237×10^{-09}

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Table 23. Solution Atom Densities for Experiment 075

Isotope/Element	Atom Density [(b-cm) ⁻¹]
H	5.4050×10^{-02}
N	3.8698×10^{-03}
O	3.9595×10^{-02}
²³⁸ Pu	1.2675×10^{-07}
²³⁹ Pu	3.9658×10^{-04}
²⁴⁰ Pu	3.6017×10^{-05}
²⁴¹ Pu	1.9423×10^{-06}
²⁴² Pu	3.9974×10^{-07}
²³⁴ U	4.7336×10^{-08}
²³⁵ U	3.7977×10^{-06}
²³⁶ U	1.5421×10^{-07}
²³⁸ U	6.6090×10^{-04}
²⁴¹ Am	2.2581×10^{-06}
¹⁰ B	9.3838×10^{-08}
Cd	5.2757×10^{-08}
Fe	5.4679×10^{-06}
Gd	7.2780×10^{-09}
⁶ Li	3.3726×10^{-09}

Table 24. Solution Atom Densities for Experiment 076

Isotope/Element	Atom Density [(b-cm) ⁻¹]
H	5.4021 x 10 ⁻⁰²
N	3.8695 x 10 ⁻⁰³
O	3.9581 x 10 ⁻⁰²
²³⁸ Pu	1.2668 x 10 ⁻⁰⁷
²³⁹ Pu	3.9637 x 10 ⁻⁰⁴
²⁴⁰ Pu	3.5998 x 10 ⁻⁰⁵
²⁴¹ Pu	1.9413 x 10 ⁻⁰⁶
²⁴² Pu	3.9953 x 10 ⁻⁰⁷
²³⁴ U	4.7360 x 10 ⁻⁰⁸
²³⁵ U	3.7996 x 10 ⁻⁰⁶
²³⁶ U	1.5429 x 10 ⁻⁰⁷
²³⁸ U	6.6122 x 10 ⁻⁰⁴
²⁴¹ Am	2.2572 x 10 ⁻⁰⁶
¹⁰ B	9.3789 x 10 ⁻⁰⁸
Cd	5.2729 x 10 ⁻⁰⁸
Fe	5.4651 x 10 ⁻⁰⁶
Gd	7.2742 x 10 ⁻⁰⁹
⁶ Li	3.3708 x 10 ⁻⁰⁹

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3.3.2 Water

The published water temperatures are listed in Table 25 below. The water density and hydrogen and oxygen number densities for the water reflector are also given in the table.

Table 25. Temperature, Density, and Atom Number Densities for Water Reflector.

Experiment Number	Temperature [°C]	Density ^(a) [g/ml]	Hydrogen Atom Density [(b-cm) ⁻¹]	Oxygen Atom Density [(b-cm) ⁻¹]
063	(b)			
064	17.2	0.99876	6.6773×10^{-2}	3.3387×10^{-2}
071	22.1	0.99775	6.6705×10^{-2}	3.3353×10^{-2}
072	22.7	0.99760	6.6695×10^{-2}	3.3348×10^{-2}
074	(b)			
075	(b)			
076	21.7	0.99784	6.6711×10^{-2}	3.3356×10^{-2}

(a) Interpolations of Table 1-36, *Handbook of Tables for Applied Engineering Science*; page 67, R.E. Bolz Editor, The Chemical Rubber Publishing Company. (1970)

(b) Water reflector was not used

3.3.3 Stainless Steel

The density for stainless steel 304L is given in Table 7. Possible atomic weight percents for stainless steel 304L are also given in Table 7. Since the atomic weight percents are given as maximums or as ranges there is a large variety of atomic number densities possible. In order to select a specific set of values that might be representative of the composition of stainless steel 304L as used in nuclear criticality calculations, the atomic weight percents for stainless steel 304L were chosen from previously accepted standard handbook data. The element weight percents the atomic number densities are given in Table 26.

Table 26. Number densities for stainless steel 304L.

Element	Wt. % ^(a)	Atom Density ^(a) [(b-cm) ⁻¹]
Fe	70.97	6.1376×10^{-2}
Cr	19.00	1.7648×10^{-2}
Ni	10.00	8.2292×10^{-3}
C	0.03	1.2063×10^{-4}

(a) R. H. Perry and C. H. Chilton, page 23-29, *Chemical Engineers' Handbook*; 5th Edition, McGraw-Hill Book Co. (1973)

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3.3.4 Concrete

The corresponding number densities using the atomic weight fractions from Table 8 for concrete are given in Table 27. These atom densities are used for room floor, ceiling, and walls.

Table 27. Composition of Concrete Used for Room Floor, Ceiling, and Walls.

Element	Atom Density (atom/[b-cm])
O	4.5525×10^{-2}
Si	1.1541×10^{-2}
Ca	4.2012×10^{-3}
Al	2.4910×10^{-3}
Fe	8.4670×10^{-4}
Na	8.7278×10^{-4}
H	1.4617×10^{-2}
Mg	5.3112×10^{-4}
K	2.5839×10^{-4}
S	1.6628×10^{-4}
Ti	9.6702×10^{-5}

3.4 Temperature Data

No data exists for the temperature of the fissile solution during the actual experiments. The estimated temperature range was from about 17 °C to 30 °C. Since the systems were never taken to full critical, it is assumed that little fission heating took place. Thus room temperature cross-sections should be adequate. Following Smolen, et. al. (Reference 2), the fissile solution temperature is taken to be 23 °C for all experiments. The temperature of the water reflector varied several degrees throughout the set of experiments. Table 28 shows the variation of the measured reflector temperatures for the four water-reflected experiments. The water temperature of the reflector in the water-reflected experiments was taken as the value shown in Table 28.

Table 28. Variation of Reflector Temperatures.

Experiment ID number	Reflector Temperature °C
064	17.2
071	22.1
072	22.7
076	21.7

3.5 Experimental and Benchmark k_{eff}

All experiments were extrapolated to criticality by the inverse multiplication method, thus the experimental and benchmark k_{eff} are 1.000.

The uncertainty in the benchmark k_{eff} for the bare and water-reflected experiments is estimated by taking the square root of the sum of the squares of the values for the uncertainties listed in Tables 9, 10, and 11 in Section 2.1 combined with the Δk_{eff} of 0.00162 due to the modeling simplifications. These combined uncertainties yield an uncertainty in the benchmark k_{eff} for both the bare and water-reflected experiments of ± 0.0030 or ± 0.0031 . Therefore, the benchmark-model k_{eff} is 1.000 ± 0.0031 .

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4.0 RESULTS OF SAMPLE CALCULATIONS

All calculated k_{eff} values and standard deviations are reported in Table 29

Table 29. Calculated results.

Experiment Number	$k_{\text{eff}} \pm \sigma$ KENO (16 gp Hansen Roach)	$k_{\text{eff}} \pm \sigma$ KENO (27 gp ENDF/B-IV)	$k_{\text{eff}} \pm \sigma$ MCNP (ENDF/B-V)
063	0.9991 ± 0.0004	1.0029 ± 0.0004	1.0015 ± 0.0008
064	1.0048 ± 0.0015	1.0053 ± 0.0015	1.0034 ± 0.0007
071	1.0109 ± 0.0014	1.0102 ± 0.0015	1.0019 ± 0.0008
072	1.0121 ± 0.0015	1.0068 ± 0.0016	1.0000 ± 0.0008
074	0.9997 ± 0.0004	0.9979 ± 0.0004	0.9934 ± 0.0009
075	1.0058 ± 0.0004	0.9972 ± 0.0004	0.9902 ± 0.0008
076	1.0160 ± 0.0015	1.0039 ± 0.0016	0.9990 ± 0.0008

Three of the KENO 16-group Hansen Roach calculations and one of the 27-group calculations are more than one percent high with the remainder lying in the region between plus and minus one percent of 1.0000. The MCNP with ENDF/B-V cross sections and the other KENO 27-group results with ENDF/B-IV cross sections all lie in the region between plus and minus one percent of 1.0000.

5.0 REFERENCES

1. R. C. Lloyd, *Criticality Experiments with Mixed Plutonium and Uranium Nitrate Solution at a Plutonium Fraction of 0.4 in Slab and Cylindrical Geometry*, PNL-6327 Battelle Pacific Northwest Laboratories, Richland, Washington, April 1988.
2. G. R. Smolen, R.C. Lloyd, and H. Funabashi, *Criticality Data and Validation Studies of Plutonium-Uranium Nitrate Solutions in Cylindrical and Slab Geometry*, Nuclear Technology, **107**: pp. 304-325, 1994
3. E. D. Clayton, *Neutron Source Multiplication Method*, in Proceedings Workshop on Subcriticality Reactivity Measurements, (G. A. Whan Ed.), University of New Mexico, Albuquerque, New Mexico, August 1985.
4. R. C. Lloyd, *Criticality Experiments with Mixed Plutonium and Uranium Nitrate Solution at a Plutonium Fraction of 0.5 in Slab and Cylindrical Geometry*, PNL-5768 Battelle Pacific Northwest Laboratories, Richland, Washington, December 1986.
5. G. R. Smolen, R.C. Lloyd, and H. Funabashi, *Criticality Data and Validation Studies of Plutonium-Uranium Nitrate Solutions in Annular Geometry*, Nuclear Technology, **107**: pp. 326-339, 1994

APPENDIX A: TYPICAL INPUT LISTINGS

A.1 KENO V.a Input Listings

Hansen-Roach Cross Sections

For the bare experiments, KENO V.a with 16-energy-group Hansen-Roach cross sections was run using 4800 active generations with 1000 neutrons per generation, resulting in 4,800,000 neutron histories. For the water reflected experiments, 300 active generations with 1000 neutrons per generation were run, resulting in 300,000 neutron histories. Nine generations were skipped before averaging for all calculations. Phosphorous cross sections are not available for 16-energy-group Hansen-Roach and so do not appear in carbon steel material. The gadolinium and lithium cross sections were also not included for the fissile solution.

The σ_p value for each experiment was calculated using the Hopper-Reiner method^a. The actual σ_p used is to linearly apportion the cross sections between the two closest available Hansen-Roach library values.

27-Group ENDF/B-IV Cross Sections

For the bare experiments, KENO V.a with the SCALE-4 27-energy-group cross sections was run using 4800 active generations with 1000 neutrons per generation, resulting in 4,800,000 neutron histories. For the water reflected experiments, 300 active generations with 1000 neutrons per generation were run, resulting in 300,000 neutron histories. Nine generations were skipped before averaging for all calculations.

In the calculations the thickness of the plates making up the egg-crate grids was entered as 0.3174 cm due to significant-figure rounding. The specified benchmark value is 0.3175 cm. This small discrepancy is not expected to affect k_{eff} .

^a C. M. Hopper and J-P Renier, *Expanded and Applied Sixteen-Neutron-Energy-Group Cross-Section Library*, Transactions American Nuclear Society, 61, 186 (June 1990).

Sample KENO V.a Input Listing (Hansen-Roach Cross Sections)

Bare Experiments

```
=keno5
6327 (23) exp.063, slab tank, refl. walls, hood walls, room walls r23b63
read param tme=1200 lib=41 gen=4809 npg=1000 nsk=9 run=yes plt=yes
      lng=1000000 end param
read mixt eps=0.011 sct=1
  mix=1
1102  6.3508-2
7100  1.1117-3
8100  3.5225-2
94803 3.0123-8
94912 5.1248-5
94913 4.3001-5
94014 3.3944-6
94015 5.1653-6
94100 4.6159-7
94200 9.5001-8
92400 1.1328-8
92512 9.0878-7
92600 3.6903-8
92850 1.0450-4
92851 5.3647-5
5100  1.1207-7
48100 1.2538-8
26100 1.2995-6
  mix=2
26100 6.1376-2
24100 1.7648-2
28100 8.2292-3
  6100 1.2063-4
  mix=3
1102  1.4617-2
8100  4.5525-2
13100 2.4910-3
16100 1.6628-4
26100 8.4670-4
19100 2.5839-4
12100 5.3112-4
11100 8.7278-4
14100 1.1541-2
22100 9.6702-5
20100 4.2012-3
end mixt
read geom
unit 1
com='bellows with fuel - bottom'
cuboid 1 1 53.35 -53.35 2p9.905 1.35 -53.35
cuboid 0 1 53.35 -53.35 2p9.905 50.81 -53.35
cuboid 2 1 53.666 -53.666 2p10.064 50.81 -53.666
unit 2
com='bellows - top'
cuboid 0 1 53.35 -53.35 2p9.905 53.35 50.81
cuboid 2 1 53.666 -53.666 2p10.064 53.666 50.81
unit 3
com='full egg crate block'
cuboid 0 1 2p5.1413 2p5.715 2p5.1413
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```

cuboid 2 1 2p5.3      2p5.715  2p5.3
unit 4
com='part-full egg crate block, bottom'
cuboid 0 1 2p5.1413  2p5.715   3.11 -5.1413
cuboid 2 1 2p5.3      2p5.715   3.11 -5.3
unit 5
com='part-full egg crate block, top'
cuboid 0 1 2p5.1413  2p5.715   5.1413 3.11
cuboid 2 1 2p5.3      2p5.715   5.3   3.11
unit 6
com='egg crate unit - bottom'
array 1  -53.  0.0  -53.
replicate 2 1 2R0.666 2R0.0   0.0 0.666 1
unit 7
com='egg crate unit - top'
array 2  -53.  0.0  50.81
replicate 2 1 2R0.666 2R0.0   0.666 0.0 1
unit 8
com='slab tank accordian with egg crate units - bottom'
array 3  -53.666 -21.494 -53.666
unit 9
com='slab tank accordian with egg crate units - top'
array 4  -53.666 -21.494 50.81
unit 10
com='slab tank in reflector tank in hood within room - bottom'
cuboid 0 1 2p53.6661  2p21.4941  50.8101 -53.6661
hole 8  0.0  0.0  0.0
cuboid 0 1 2p71.1      31.6  -37.0      50.8101 -71.75
cuboid 2 1 2p71.576    32.235 -37.635    50.8101 -72.226
cuboid 0 1 181.076 -96.176 170.635 -71.935 50.8101 -172.165
cuboid 2 1 181.711 -96.811 171.27 -72.57 50.8101 -172.8
cuboid 0 1 818.189 -248.811 354.27 -712.73 50.8101 -172.826
cuboid 3 1 970.189 -400.811 506.27 -803.73 50.8101 -233.826
unit 11
com='slab tank in reflector tank in hood within room - top'
cuboid 0 1 2p53.6661  2p21.4941  53.6661 50.8099
hole 9  0.0  0.0  0.0
cuboid 0 1 2p71.1      31.6  -37.0      71.75 50.8099
cuboid 2 1 2p71.576    32.235 -37.635    71.75 50.8099
cuboid 0 1 181.076 -96.176 170.635 -71.935 365.904 50.8099
cuboid 2 1 181.711 -96.811 171.27 -72.57 366.539 50.8099
cuboid 0 1 818.189 -248.811 354.27 -712.73 466.539 50.8099
cuboid 3 1 970.189 -400.811 506.27 -803.73 527.539 50.8099
global unit 12
com='slab tank in reflector tank in hood within room'
array 5  -400.811 -803.73 -234.461
end geom
read array
com='array 1 is egg crate unit - bottom'
ara=1 nux=10 nuy=1 nuz=10 fill 90r3 10r4 end fill
com='array 2 is egg crate unit - top'
ara=2 nux=10 nuy=1 nuz=1 fill f5 end fill
com='array 3 is slab tank accordian with egg crate units - bottom'
ara=3 nux=1 nuy=3 nuz=1 fill 6 1 6 end fill
com='array 4 is slab tank accordian with egg crate units - top'
ara=4 nux=1 nuy=3 nuz=1 fill 7 2 7 end fill
com='array 5 is slab tank room - top and bottom'
ara=5 nux=1 nuy=1 nuz=2 fill 10 11 end fill
end array
read plot

```


MIX-SOL-THERM-005

```

ttl='x-y plane through the slab tank at z=0.'
xul=-55. yul=55. zul=0. xlr=55. ylr=-55. zlr=0.
uax=1. vdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the bellows wall at y=-10.'
xul=-55. yul=-10. zul=55. xlr=55. ylr=-10. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the bellows wall at y=10.'
xul=-55. yul=10. zul=55. xlr=55. ylr=10. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate block at y=-20.'
xul=-6. yul=-20. zul=6. xlr=6. ylr=-20. zlr=-6.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate block at y=20.'
xul=-6. yul=20. zul=6. xlr=6. ylr=20. zlr=-6.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate block at y=-20.'
xul=-55. yul=-20. zul=-41. xlr=-41. ylr=-20. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate block at y=20.'
xul=41. yul=20. zul=55. xlr=55. ylr=20. zlr=41.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate at y=-20.'
xul=-55. yul=-20. zul=55. xlr=55. ylr=-20. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate at y=20.'
xul=-55. yul=20. zul=55. xlr=55. ylr=20. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='y-z plane through the slab tank at x=0'
xul=0. yul=-35. zul=61.7 xlr=0. ylr=35. zlr=-61.7
vax=1. wdn=-1. nax=130 ndn=20 nch='.fscw' plt=yes end
end plot
end data
end

```

MIX-SOL-THERM-005

Water Reflected Experiments

```

=keno5
6327 (24) exp.064, slab tank, refl. walls r24a64
read param tme=1200 lib=41 gen=309 npg=1000 nsk=9 run=yes plt=yes
      lng=1000000 end param
read mixt eps=0.011 sct=1
  mix=1
1102  6.3520-2
7100  1.1228-3
8100  3.5266-2
94803 3.0739-8
94912 5.5063-5
94913 4.1114-5
94014 3.7405-6
94015 4.9944-6
94100 4.7104-7
94200 9.6945-8
92400 1.1412-8
92512 9.1557-7
92600 3.7179-8
92850 1.1021-4
92851 4.9127-5
5100  1.1436-7
48100 1.2795-8
26100 1.3261-6
  mix=2
26100 6.1376-2
24100 1.7648-2
28100 8.2292-3
  6100 1.2063-4
  mix=3
1102  6.6773-2
8100  3.3387-2
end mixt
read geom
unit 1
com='bellows with fuel - bottom'
cuboid 1 1 53.35 -53.35 2p6.985 26.79 -53.35
cuboid 0 1 53.35 -53.35 2p6.985 50.81 -53.35
cuboid 2 1 53.666 -53.666 2p7.144 50.81 -53.666
unit 2
com='bellows - top'
cuboid 0 1 53.35 -53.35 2p6.985 53.35 50.81
cuboid 2 1 53.666 -53.666 2p7.144 53.666 50.81
unit 3
com='full egg crate block'
cuboid 3 1 2p5.1413 2p5.715 2p5.1413
cuboid 2 1 2p5.3 2p5.715 2p5.3
unit 4
com='part-full egg crate block, bottom'
cuboid 3 1 2p5.1413 2p5.715 3.11 -5.1413
cuboid 2 1 2p5.3 2p5.715 3.11 -5.3
unit 5
com='part-full egg crate block, top'
cuboid 0 1 2p5.1413 2p5.715 5.1413 3.11
cuboid 2 1 2p5.3 2p5.715 5.3 3.11

```

MIX-SOL-THERM-005

```

unit 6
com='egg crate unit - bottom'
array 1 -53. 0.0 -53.
replicate 2 1 2R0.666 2R0.0 0.0 0.666 1
unit 7
com='egg crate unit - top'
array 2 -53. 0.0 50.81
replicate 2 1 2R0.666 2R0.0 0.666 0.0 1
unit 8
com='slab tank accordian with egg crate units - bottom'
array 3 -53.666 -18.574 -53.666
unit 9
com='slab tank accordian with egg crate units - top'
array 4 -53.666 -18.574 50.81
unit 10
com='slab tank in reflector tank in hood within room - bottom'
cuboid 0 1 2p53.6661 2p18.5741 50.8101 -53.6661
hole 8 0.0 0.0 0.0
cuboid 3 1 2p71.1 31.6 -37.0 50.8101 -71.75
cuboid 2 1 2p71.576 32.235 -37.635 50.8101 -72.226
unit 11
com='slab tank in reflector tank in hood within room - top'
cuboid 0 1 2p53.6661 2p18.5741 53.6661 50.8099
hole 9 0.0 0.0 0.0
cuboid 0 1 2p71.1 31.6 -37.0 71.75 50.8099
cuboid 2 1 2p71.576 32.235 -37.635 71.75 50.8099
global unit 12
com='slab tank in reflector tank in hood within room'
array 5 -71.576 -37.635 -72.226
end geom
read array
com='array 1 is egg crate unit - bottom'
ara=1 nux=10 nuy=1 nuz=10 fill 90r3 10r4 end fill
com='array 2 is egg crate unit - top'
ara=2 nux=10 nuy=1 nuz=1 fill f5 end fill
com='array 3 is slab tank accordian with egg crate units - bottom'
ara=3 nux=1 nuy=3 nuz=1 fill 6 1 6 end fill
com='array 4 is slab tank accordian with egg crate units - top'
ara=4 nux=1 nuy=3 nuz=1 fill 7 2 7 end fill
com='array 5 is slab tank room - top and bottom'
ara=5 nux=1 nuy=1 nuz=2 fill 10 11 end fill
end array
read plot
ttl='x-y plane through the slab tank at z=0.'
xul=-55. yul=55. zul=0. xlr=55. ylr=-55. zlr=0.
uax=1. vdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the bellows wall at y=-10.'
xul=-55. yul=-10. zul=55. xlr=55. ylr=-10. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the bellows wall at y=10.'
xul=-55. yul=10. zul=55. xlr=55. ylr=10. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate block at y=-20.'
xul=-6. yul=-20. zul=6. xlr=6. ylr=-20. zlr=-6.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate block at y=20.'
xul=-6. yul=20. zul=6. xlr=6. ylr=20. zlr=-6.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate block at y=-20.'
xul=-55. yul=-20. zul=-41. xlr=-41. ylr=-20. zlr=-55.

```

MIX-SOL-THERM-005

```
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate block at y=20.'
xul=41. yul=20. zul=55. xlr=55. ylr=20. zlr=41.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate at y=-20.'
xul=-55. yul=-20. zul=55. xlr=55. ylr=-20. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate at y=20.'
xul=-55. yul=20. zul=55. xlr=55. ylr=20. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='y-z plane through the slab tank at x=0'
xul=0. yul=-35. zul=61.7 xlr=0. ylr=35. zlr=-61.7
vax=1. wdn=-1. nax=130 ndn=20 nch='.fscw' plt=yes end
end plot
end data
end
```

Sample KENO V.a Input Listing (27-energy-group SCALE-4)

Bare Experiments

```
=csas25
6327 (23) exp.063, slab tank, refl. tank, hood walls, room walls c23b63
27groupndf4 infhommedium
h      1 0. 6.3508E-02 end
n      1 0. 1.1117E-03 end
o      1 0. 3.5225E-02 end
pu-238 1 0. 3.0123E-08 end
pu-239 1 0. 9.4249E-05 end
pu-240 1 0. 8.5597E-06 end
pu-241 1 0. 4.6159E-07 end
pu-242 1 0. 9.5001E-08 end
u-234  1 0. 1.1328E-08 end
u-235  1 0. 9.0878E-07 end
u-236  1 0. 3.6903E-08 end
u-238  1 0. 1.5815E-04 end
am-241 1 0. 5.3199E-07 end
b-10   1 0. 2.2301E-08 end
cd      1 0. 1.2538E-08 end
fe      1 0. 1.2995E-06 end
gd      1 0. 1.7297E-09 end
li-6   1 0. 8.0152E-10 end
fe      2 0. 6.1376E-02 end
cr      2 0. 1.7648E-02 end
ni      2 0. 8.2292E-03 end
c       2 0. 1.2063e-04 end
h       3 0. 1.4617E-02 end
o       3 0. 4.5525E-02 end
na      3 0. 8.7278E-04 end
mg      3 0. 5.3112E-04 end
al      3 0. 2.4910E-03 end
si      3 0. 1.1541E-02 end
s       3 0. 1.6628E-04 end
k       3 0. 2.5839E-04 end
ca      3 0. 4.2012E-03 end
ti      3 0. 9.6702E-05 end
fe      3 0. 8.4670E-04 end
end comp
6327 (23) exp.063, slab tank, refl. tank, hood walls, room walls b23163
read param tme=3000 gen=4809 npg=1000 nsk=9 run=yes plt=yes end param
read mixt eps=0.011 end mixt
read geom
unit 1
com='bellows with fuel - bottom'
cuboid 1 1 53.35 -53.35 2p9.905 1.35 -53.35
cuboid 0 1 53.35 -53.35 2p9.905 50.81 -53.35
cuboid 2 1 53.666 -53.666 2p10.064 50.81 -53.666
unit 2
com='bellows - top'
cuboid 0 1 53.35 -53.35 2p9.905 53.35 50.81
cuboid 2 1 53.666 -53.666 2p10.064 53.666 50.81
unit 3
com='full egg crate block'
cuboid 0 1 2p5.1413 2p5.715 2p5.1413
cuboid 2 1 2p5.3 2p5.715 2p5.3
```

MIX-SOL-THERM-005

```

unit 4
com='part-full egg crate block, bottom'
cuboid 0 1 2p5.1413 2p5.715 3.11 -5.1413
cuboid 2 1 2p5.3 2p5.715 3.11 -5.3
unit 5
com='part-full egg crate block, top'
cuboid 0 1 2p5.1413 2p5.715 5.1413 3.11
cuboid 2 1 2p5.3 2p5.715 5.3 3.11
unit 6
com='egg crate unit - bottom'
array 1 -53. 0.0 -53.
replicate 2 1 2R0.666 2R0.0 0.0 0.666 1
unit 7
com='egg crate unit - top'
array 2 -53. 0.0 50.81
replicate 2 1 2R0.666 2R0.0 0.666 0.0 1
unit 8
com='slab tank accordian with egg crate units - bottom'
array 3 -53.666 -21.494 -53.666
unit 9
com='slab tank accordian with egg crate units - top'
array 4 -53.666 -21.494 50.81
unit 10
com='slab tank in reflector tank in hood within room - bottom'
cuboid 0 1 2p53.6661 2p21.4941 50.8101 -53.6661
hole 8 0.0 0.0 0.0
cuboid 0 1 2p71.1 31.6 -37.0 50.8101 -71.75
cuboid 2 1 2p71.576 32.235 -37.635 50.8101 -72.226
cuboid 0 1 181.076 -96.176 170.635 -71.935 50.8101 -172.165
cuboid 2 1 181.711 -96.811 171.27 -72.57 50.8101 -172.8
cuboid 0 1 818.189 -248.811 354.27 -712.73 50.8101 -172.826
cuboid 3 1 970.189 -400.811 506.27 -803.73 50.8101 -233.826
unit 11
com='slab tank in reflector tank in hood within room - top'
cuboid 0 1 2p53.6661 2p21.4941 53.6661 50.8099
hole 9 0.0 0.0 0.0
cuboid 0 1 2p71.1 31.6 -37.0 71.75 50.8099
cuboid 2 1 2p71.576 32.235 -37.635 71.75 50.8099
cuboid 0 1 181.076 -96.176 170.635 -71.935 365.904 50.8099
cuboid 2 1 181.711 -96.811 171.27 -72.57 366.539 50.8099
cuboid 0 1 818.189 -248.811 354.27 -712.73 466.539 50.8099
cuboid 3 1 970.189 -400.811 506.27 -803.73 527.539 50.8099
global unit 12
com='slab tank in reflector tank in hood within room'
array 5 -400.811 -803.73 -234.461
end geom
read array
com='array 1 is egg crate unit - bottom'
ara=1 nux=10 nuy=1 nuz=10 fill 90r3 10r4 end fill
com='array 2 is egg crate unit - top'
ara=2 nux=10 nuy=1 nuz=1 fill f5 end fill
com='array 3 is slab tank accordian with egg crate units - bottom'
ara=3 nux=1 nuy=3 nuz=1 fill 6 1 6 end fill
com='array 4 is slab tank accordian with egg crate units - top'
ara=4 nux=1 nuy=3 nuz=1 fill 7 2 7 end fill
com='array 5 is slab tank room - top and bottom'
ara=5 nux=1 nuy=1 nuz=2 fill 10 11 end fill
end array
read plot
ttl='x-y plane through the slab tank at z=0.'

```

MIX-SOL-THERM-005

```
xul=-55. yul=55. zul=0. xlr=55. ylr=-55. zlr=0.
uax=1. vdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the bellows wall at y=-10.'
xul=-55. yul=-10. zul=55. xlr=55. ylr=-10. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the bellows wall at y=10.'
xul=-55. yul=10. zul=55. xlr=55. ylr=10. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate block at y=-20.'
xul=-6. yul=-20. zul=6. xlr=6. ylr=-20. zlr=-6.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate block at y=20.'
xul=-6. yul=20. zul=6. xlr=6. ylr=20. zlr=-6.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate block at y=-20.'
xul=-55. yul=-20. zul=-41. xlr=-41. ylr=-20. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate block at y=20.'
xul=41. yul=20. zul=55. xlr=55. ylr=20. zlr=41.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate at y=-20.'
xul=-55. yul=-20. zul=55. xlr=55. ylr=-20. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the egg-crate at y=20.'
xul=-55. yul=20. zul=55. xlr=55. ylr=20. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='y-z plane through the slab tank at x=0'
xul=0. yul=-35. zul=61.7 xlr=0. ylr=35. zlr=-61.7
vax=1. wdn=-1. nax=130 ndn=20 nch='.fscw' plt=yes end
end plot
end data
end
```

Water Reflected Experiments

```
=csas25
6327 (24) exp.064, slab tank, refl. tank
27groupndf4 infhommedium
h      1 0. 6.3520E-02 end
n      1 0. 1.1228E-03 end
o      1 0. 3.5266E-02 end
pu-238 1 0. 3.0739E-08 end
pu-239 1 0. 9.6178E-05 end
pu-240 1 0. 8.7348E-06 end
pu-241 1 0. 4.7104E-07 end
pu-242 1 0. 9.6945E-08 end
u-234  1 0. 1.1412E-08 end
u-235  1 0. 9.1557E-07 end
u-236  1 0. 3.7179E-08 end
u-238  1 0. 1.5933E-04 end
am-241 1 0. 5.4324E-07 end
b-10   1 0. 2.2758E-08 end
cd      1 0. 1.2795E-08 end
fe      1 0. 1.3261E-06 end
gd      1 0. 1.7650E-09 end
li-6   1 0. 8.1792E-10 end
fe      2 0. 6.1376E-02 end
cr      2 0. 1.7648E-02 end
ni      2 0. 8.2292E-03 end
c       2 0. 1.2063e-04 end
h       3 0. 1.4617E-02 end
o       3 0. 4.5525E-02 end
na      3 0. 8.7278E-04 end
mg      3 0. 5.3112E-04 end
al      3 0. 2.4910E-03 end
si      3 0. 1.1541E-02 end
s       3 0. 1.6628E-04 end
k       3 0. 2.5839E-04 end
ca      3 0. 4.2012E-03 end
ti      3 0. 9.6702E-05 end
fe      3 0. 8.4670E-04 end
h       4 0. 6.6773E-02 end
o       4 0. 3.3387E-02 end
end comp
6327 (24) exp.064, slab tank, refl. tank
read param tme=3000 gen=309 npg=1000 nsk=9 run=yes plt=yes end param
read mixt eps=0.011 end mixt
read geom
unit 1
com='bellows with fuel - bottom'
cuboid 1 1 53.35 -53.35 2p6.985 26.79 -53.35
cuboid 0 1 53.35 -53.35 2p6.985 50.81 -53.35
cuboid 2 1 53.666 -53.666 2p7.144 50.81 -53.666
unit 2
com='bellows - top'
cuboid 0 1 53.35 -53.35 2p6.985 53.35 50.81
cuboid 2 1 53.666 -53.666 2p7.144 53.666 50.81
unit 3
com='full egg crate block'
cuboid 4 1 2p5.1413 2p5.715 2p5.1413
cuboid 2 1 2p5.3 2p5.715 2p5.3
```


MIX-SOL-THERM-005

```

unit 4
com='part-full egg crate block, bottom'
cuboid 4 1 2p5.1413 2p5.715 3.11 -5.1413
cuboid 2 1 2p5.3 2p5.715 3.11 -5.3
unit 5
com='part-full egg crate block, top'
cuboid 0 1 2p5.1413 2p5.715 5.1413 3.11
cuboid 2 1 2p5.3 2p5.715 5.3 3.11
unit 6
com='egg crate unit - bottom'
array 1 -53. 0.0 -53.
replicate 2 1 2R0.666 2R0.0 0.0 0.666 1
unit 7
com='egg crate unit - top'
array 2 -53. 0.0 50.81
replicate 2 1 2R0.666 2R0.0 0.666 0.0 1
unit 8
com='slab tank accordian with egg crate units - bottom'
array 3 -53.666 -18.574 -53.666
unit 9
com='slab tank accordian with egg crate units - top'
array 4 -53.666 -18.574 50.81
unit 10
com='slab tank in reflector tank in hood within room - bottom'
cuboid 0 1 2p53.6661 2p18.5741 50.8101 -53.6661
hole 8 0.0 0.0 0.0
cuboid 4 1 2p71.1 31.6 -37.0 50.8101 -71.75
cuboid 2 1 2p71.576 32.235 -37.635 50.8101 -72.226
unit 11
com='slab tank in reflector tank in hood within room - top'
cuboid 0 1 2p53.6661 2p18.5741 53.6661 50.8099
hole 9 0.0 0.0 0.0
cuboid 0 1 2p71.1 31.6 -37.0 71.75 50.8099
cuboid 2 1 2p71.576 32.235 -37.635 71.75 50.8099
global unit 12
com='slab tank in reflector tank in hood within room'
array 5 -71.576 -37.635 -72.226
end geom
read array
com='array 1 is egg crate unit - bottom'
ara=1 nux=10 nuy=1 nuz=10 fill 90r3 10r4 end fill
com='array 2 is egg crate unit - top'
ara=2 nux=10 nuy=1 nuz=1 fill f5 end fill
com='array 3 is slab tank accordian with egg crate units - bottom'
ara=3 nux=1 nuy=3 nuz=1 fill 6 1 6 end fill
com='array 4 is slab tank accordian with egg crate units - top'
ara=4 nux=1 nuy=3 nuz=1 fill 7 2 7 end fill
com='array 5 is slab tank room - top and bottom'
ara=5 nux=1 nuy=1 nuz=2 fill 10 11 end fill
end array
read plot
ttl='x-y plane through the slab tank at z=0.'
xul=-55. yul=55. zul=0. xlr=55. ylr=-55. zlr=0.
uax=1. vdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the bellows wall at y=-10.'
xul=-55. yul=-10. zul=55. xlr=55. ylr=-10. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end
ttl='x-z plane through the bellows wall at y=10.'
xul=-55. yul=10. zul=55. xlr=55. ylr=10. zlr=-55.
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end

```

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```
ttl='x-z plane through the egg-crate block at y=-20.'  
xul=-6. yul=-20. zul=6. xlr=6. ylr=-20. zlr=-6.  
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end  
ttl='x-z plane through the egg-crate block at y=20.'  
xul=-6. yul=20. zul=6. xlr=6. ylr=20. zlr=-6.  
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end  
ttl='x-z plane through the egg-crate block at y=-20.'  
xul=-55. yul=-20. zul=-41. xlr=-41. ylr=-20. zlr=-55.  
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end  
ttl='x-z plane through the egg-crate block at y=20.'  
xul=41. yul=20. zul=55. xlr=55. ylr=20. zlr=41.  
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end  
ttl='x-z plane through the egg-crate at y=-20.'  
xul=-55. yul=-20. zul=55. xlr=55. ylr=-20. zlr=-55.  
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end  
ttl='x-z plane through the egg-crate at y=20.'  
xul=-55. yul=20. zul=55. xlr=55. ylr=20. zlr=-55.  
uax=1. wdn=-1. nax=74 nch='.fscw' plt=yes end  
ttl='y-z plane through the slab tank at x=0'  
xul=0. yul=-35. zul=61.7 xlr=0. ylr=35. zlr=-61.7  
vax=1. wdn=-1. nax=130 ndn=20 nch='.fscw' plt=yes end  
end plot  
end data  
end
```

A.2 MCNP Input Listings

MCNP version 4a was run with the ENDF/B-V cross section library for all materials except for natural gadolinium for which the cross sections were extracted from the ENDL-85 library. MCNP was run for 440 generations of 3000 neutrons per generation. Forty generations were skipped before averaging, so the results are an average of 1,200,000 neutron histories.

Because of number rounding of the individual cells, and the increase in exterior dimensions necessitated by the model simplification process, an additional 0.5087cm of stainless steel is added to the top and bottom, and east and west perimeter of the egg-crate assembly to match the exterior surfaces of the slab tank.

Sample MCNP Input Listing (ENDF/B-V cross section library)

MCNP4a was run using 440 generations with 3000 neutrons per generation. Forty generations were skipped before averaging, so the results are an average of 1,200,000 neutron histories.

Bare Experiments

```
PNL EXP-063   Vertical bellows slab geometry   simplified
c
c   Bare system.  Room return from hood and walls included in model.
c
c   *****
c   **               ....cell descriptions....               **
c   *****
c
c
c   MAIN FUEL SECTION
10   9   8.7374E-02   (41 -42 45 -44 47 -46) (-41:42:-52:53:-50:51)
      imp:n=1   $ very approximate SS fuel tank narrow edges
11   1   1.0011E-01   (41 -42 52 -53 50 -30) imp:n=1 $ rectangular fuel column
12   0           (41 -42 52 -53 -51 30) imp:n=1 $ void above fuel
c
c
60   9 8.7374E-02   42 -71 45 -44 47 -46  imp:n=1 $ right SS end plate
61   9 8.7374E-02   70 -41 45 -44 47 -46  imp:n=1 $ left SS end plate
c
c
c   SQUARE LATTICE STAINLESS STEEL SUPPORT GRID
c
70   9   8.7374E-02   (-500:502:504:-506:76:-71)
      ( 47 -46 -44 45 -76 71) imp:n=1 $ steel walls of right grid holding box
71   9   8.7374E-02   (-500:502:504:-506:-75:70)
      ( 47 -46 -44 45 -70 75) imp:n=1 $ steel walls of left grid holding box
c
100  0 500 -502 -504 506 -76 71 fill=5 imp:n=1 $inner right holding box to be filled
200  0 500 -502 -504 506 -70 75 fill=5 imp:n=1 $inner left holding box to be filled
c
c
c
101  0 -301 302 -305 306 lat=1 u=5  imp:n=1 trcl=(5.3 0 5.3)
      fill= -5:4 -5:4 0:0 20 89r 30 9r $ repeated unit cell with upper layer partly
filled
102  0           -401 402 -405 406           u=20  imp:n=1  $ innermost unit cell
103  9   8.7374E-02   (401:-402:405:-406)           u=20  imp:n=1  $ unbounded outside of unit
cell
104  0           (-401 402 -405 406) 304 u=30  imp:n=1  $ void innermost unit cell
105  0           (-401 402 -405 406) -304 u=30  imp:n=1  $ innermost unit cell
106  9   8.7374E-02   (401:-402:405:-406)           u=30  imp:n=1  $ unbounded outside of unit
cell
c
c
c
c
c
90   0   ((-75:76:-47:46:-45:44))
```

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```

(100 -102 -103 105 -115 113)) -29 imp:n=1 $ void outside completed bellows
91 0 ( (-75:76:-47:46:-45:44)
(100 -102 -103 105 -115 113)) 29 imp:n=1 $ void outside completed bellows
c
c RECTANGULAR WATER MODERATOR TANK, HOOD and WALLS
c
900 9 8.7374E-02 (-100:102:103:-105:115:-113)
(101 -102 -104 106 -116 114) imp:n=1 $ steel skin of water tank
c
901 0 (-101:102:104:-106:116:-114)
(-200 202 -204 206 -210 208) imp:n=1 $ air outside reflector
902 9 8.7374E-02 (200:-202:204:-206:210:-208)
(-201 203 -205 207 -211 209) imp:n=1 $ SS containment hood
903 0 (201:-203:205:-207:211:-209)
(-220 222 -224 226 -230 228) imp:n=1 $ air outside hood
904 40 8.1147E-02 (220:-222:224:-226:230:-228)
(-221 223 -225 227 -231 229) imp:n=1 $ concrete walls
c
999 0 (221:-223:225:-227:231:-229) imp:n=0 $ out of the problem
c
c *****
c ** ....surface equations.... **
c *****
c
c
c
c
29 pz 50.81 $ ***** unused water level in reflector tank *****
30 pz 1.35 $ ***** fuel level relative to origin *****
c ***** measured from bottom of fuel column *****
c
c
c
c
41 py -9.905 $ large SS fuel box
42 py 9.905
44 px 53.666 $ using 4 x 0.079 walls
45 px -53.666
46 pz 53.666
47 pz -53.666
c
50 pz -53.35 $ flat plate approx of bellows. bottom of fuel
51 pz 53.35 $ flat plate approx of bellows. top of fuel
52 px -53.35 $ flat plate approx of bellows. left of fuel
53 px 53.35 $ flat plate approx of bellows. right of fuel
c
c
70 py -10.064 $ rightmost steel edge (.159 thick end plate)
71 py 10.064 $ leftmost steel edge
c
c
75 py -21.494 $ rightmost grid support edge (11.43 thick)
76 py 21.494 $ leftmost grid support edge
c
c
c SQUARE LATTICE SUPPORT GRID
c
301 px 5.3 $ outside dimensions of the individual grid sections
302 px -5.3
305 pz 5.3

```

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306 pz -5.3
c
304 pz 3.11 \$ water level in uppermost support grids
c
401 px 5.1413 \$ inside dimensions of the individual grid sections
402 px -5.1413
405 pz 5.1413
406 pz -5.1413
c
500 pz -52.999 \$ inside dimensions of the egg-crate grid holding box
502 pz 52.999
504 px 52.999
506 px -52.999
c
c RECTANGULAR REFLECTOR TANK FACES
c
100 pz -71.75 \$ inside bottom surface of water tank
101 pz -72.226 \$ outside bottom surface of water tank
102 pz 71.75 \$ top of water tank / no lid
c
103 px 71.1 \$ east inside face of water tank
104 px 71.576 \$ east outside face of water tank
105 px -71.1 \$ west inside face of water tank
106 px -71.576 \$ west outside face of water tank
c
113 py -37 \$ south inside face of water tank
114 py -37.635 \$ south outside face of water tank
115 py 31.6 \$ north inside face of water tank
116 py 32.235 \$ north outside face of water tank
c
c CONTAINMENT HOOD TANK FACES
c
200 pz 365.904 \$ inside top surface of containment hood
201 pz 366.539 \$ outside top surface of containment hood
202 pz -172.165 \$ inside bottom surface of containment hood
203 pz -172.8 \$ outside bottom surface of containment hood
c
204 px 181.076 \$ east inside face of containment hood
205 px 181.711 \$ east outside face of containment hood
206 px -96.176 \$ west inside face of containment hood
207 px -96.811 \$ west outside face of containment hood
c
208 py -71.935 \$ south inside face of containment hood
209 py -72.570 \$ south outside face of containment hood
210 py 170.635 \$ north inside face of containment hood
211 py 171.270 \$ north outside face of containment hood
c
c CONCRETE ROOM WALL FACES
c
220 pz 466.5390 \$ inside top surface of concrete roof
221 pz 527.539 \$ outside top surface of concrete roof
222 pz -172.826 \$ inside bottom surface of concrete floor
223 pz -233.826 \$ outside bottom surface of concrete floor
c
224 px 818.189 \$ east inside face of concrete wall
225 px 970.189 \$ east outside face of concrete wall
226 px -248.811 \$ west inside face of concrete wall
227 px -400.811 \$ west outside face of concrete wall
c
228 py -712.73 \$ south inside face of concrete wall

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```

229 py -803.73 $ south outside face of concrete wall
230 py 354.27 $ north inside face of concrete wall
231 py 506.27 $ north outside face of concrete wall
c

c
c *****
c ** ....execution parameters.... **
c
c *****
c
kcode 3000 1.0 40 440
totnu
vol no
c
c
c
c *****
c ** ....neutron source initiation .... **
c *****
c
ksrc 1 1 1 1 1 -20 1 1 20
c
c *****
c ** .... material specifications ... **
c *****
c
c
c
m1 1001.50c 6.3508E-02 7014.50c 1.1117E-03 8016.50c 3.5225E-02
94238.50c 3.0123E-08 94239.55c 9.4249E-05 94240.50c 8.5597E-06
94241.50c 4.6159E-07 94242.50c 9.5001E-08 92234.50c 1.1328E-08
92235.50c 9.0878E-07 92236.50c 3.6903E-08 92238.50c 1.5815E-04
95241.50c 5.3199E-07 5010.50c 2.2301E-08 48000.50c 1.2538E-08
26000.50c 1.2995E-06 64000.35c 1.7297E-09 3006.50c 8.0152E-10
$ Pu/U fuel solution in bellows
c
m9 26000.50c 6.1376E-02 24000.50c 1.7648E-02
28000.50c 8.2292E-03 6012.50c 1.2063E-04 $ Stainless Steel 304
c
m40 1001.50c 1.4617E-02 8016.50c 4.5525E-02 11023.50c 8.7278E-04
12000.50c 5.3112E-04 13027.50c 2.4910E-03 14000.50c 1.1541E-02
16032.50c 1.6628E-04 19000.50c 2.5839E-04 20000.50c 4.2012E-03
22000.50c 9.6702E-05 26000.50c 8.4670E-04 $ Concrete pnl-6327
c
mt1 lwtr.01t $ S(alpha,beta)s
mt40 lwtr.01t

```

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Water Reflected Experiments

PNL EXP-064 Vertical bellows slab geometry simplified

C

C

C

C

C

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C

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C

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**cell descriptions..... **

MAIN FUEL SECTION

10 9 8.7374E-02 (41 -42 45 -44 47 -46) (-41:42:-52:53:-50:51)
imp:n=1 \$ very approximate SS fuel tank edges
11 1 1.0018E-01 (41 -42 52 -53 50 -30) imp:n=1 \$ rectangular fuel column
12 0 (41 -42 52 -53 -51 30) imp:n=1 \$ void above fuel

60 9 8.7374E-02 42 -71 45 -44 47 -46 imp:n=1 \$ right SS end plate
61 9 8.7374E-02 70 -41 45 -44 47 -46 imp:n=1 \$ left SS end plate

SQUARE LATTICE STAINLESS STEEL SUPPORT GRID

70 9 8.7374E-02 (-500:502:504:-506:76:-71)
(47 -46 -44 45 -76 71) imp:n=1 \$ steel walls of right grid holding box
71 9 8.7374E-02 (-500:502:504:-506:-75:70)
(47 -46 -44 45 -70 75) imp:n=1 \$ steel walls of left grid holding box

100 0 500 -502 -504 506 -76 71 fill=5 imp:n=1 \$inner right holding box to be filled
200 0 500 -502 -504 506 -70 75 fill=5 imp:n=1 \$inner left holding box to be filled

101 0 -301 302 -305 306 lat=1 u=5 imp:n=1 trcl=(5.3 0 5.3)
fill= -5:4 -5:4 0:0 20 89r 30 9r \$ repeated unit cell with upper layer partly
filled

102 10 1.0016e-01 -401 402 -405 406 u=20 imp:n=1 \$ innermost unit cell
103 9 8.7374E-02 (401:-402:405:-406) u=20 imp:n=1 \$ unbounded outside of unit
cell
104 0 (-401 402 -405 406) 304 u=30 imp:n=1 \$ void innermost unit cell
105 10 1.0016e-01 (-401 402 -405 406) -304 u=30 imp:n=1 \$ innermost unit cell
106 9 8.7374E-02 (401:-402:405:-406) u=30 imp:n=1 \$ unbounded outside of unit
cell

90 10 1.0016e-01 ((-75:76:-47:46:-45:44)
(100 -102 -103 105 -115 113)) -29 imp:n=1 \$ water outside completed bellows
91 0 ((-75:76:-47:46:-45:44)
(100 -102 -103 105 -115 113)) 29 imp:n=1 \$ void outside completed bellows

RECTANGULAR WATER MODERATOR TANK

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```

900      9 8.7374E-02 (-100:102:103:-105:115:-113)
      (101 -102 -104 106 -116 114)      imp:n=1 $ steel skin of water tank
c
999      0 (-101:102:104:-106:-114:116)      imp:n=0 $ out of this world
c
c
c      *****
c      **                      ....surface equations....      **
c      *****
c
c
c
c
c
c
c
29      pz  50.81      $ *****      water level in reflector tank      *****
30      pz  26.79      $ *****      fuel level relative to origin      *****
c                      *****      measured from bottom of fuel column      *****
c
c
c
41      py  -6.985      $ large SS fuel box
42      py   6.985
44      px  53.666      $ using 4 x 0.079 walls
45      px -53.666
46      pz  53.666
47      pz -53.666
c
50      pz -53.35      $ flat plate approx of bellows. bottom of fuel
51      pz  53.35      $ flat plate approx of bellows. top of fuel
52      px -53.35      $ flat plate approx of bellows. left of fuel
53      px  53.35      $ flat plate approx of bellows. right of fuel
c
c
70      py  -7.144      $ rightmost steel edge (.159 thick end plate)
71      py   7.144      $ leftmost steel edge
c
c
75      py -18.574      $ rightmost grid support edge (11.43 thick)
76      py  18.574      $ leftmost grid support edge
c
c
c      SQUARE LATTICE SUPPORT GRID
c
301      px  5.3      $ outside dimensions of the grid sections
302      px -5.3
305      pz  5.3
306      pz -5.3
c
304      pz  3.1      $ water level in uppermost support grids
c
401      px  5.1413      $ inside dimensions of the grid sections
402      px -5.1413
405      pz  5.1413
406      pz -5.1413
c
500      pz -52.999      $ inside dimensions of the grid holding box
502      pz  52.999
504      px  52.999
506      px -52.999
c
c      RECTANGULAR REFLECTOR TANK FACES
c

```

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```

100 pz -71.75 $ inside bottom surface of water tank
101 pz -72.226 $ outside bottom surface of water tank
102 pz 71.75 $ top of water tank / no lid
c
103 px 71.1 $ east inside face of water tank
104 px 71.576 $ east outside face of water tank
105 px -71.1 $ west inside face of water tank
106 px -71.576 $ west outside face of water tank
c
113 py -37 $ south inside face of water tank
114 py -37.635 $ south outside face of water tank
115 py 31.6 $ north inside face of water tank
116 py 32.235 $ north outside face of water tank
c

c
c *****
c ** ....execution parameters.... **
c
c *****
c
kcode 3000 1.0 40 440
totnu
vol no
c
c
c *****
c ** ....neutron source initiation .... **
c *****
c
ksrc 1 1 -1 1 1 -20 1 1 20
c
c *****
c ** .... material specifications ... **
c *****
c
c
c
m1 1001.50c 6.3520E-02 7014.50c 1.1228E-03 8016.50c 3.5266E-02
94238.50c 3.0739E-08 94239.55c 9.6178E-05 94240.50c 8.7348E-06
94241.50c 4.7104E-07 94242.50c 9.6945E-08 92234.50c 1.1412E-08
92235.50c 9.1557E-07 92236.50c 3.7179E-08 92238.50c 1.5933E-04
95241.50c 5.4324E-07 5010.50c 2.2758E-08 48000.50c 1.2795E-08
26000.50c 1.3261E-06 64000.35c 1.7650E-09 3006.50c 8.1792E-10
$ Pu/U fuel solution in bellows
c
m9 26000.50c 6.1376E-02 24000.50c 1.7648E-02
28000.50c 8.2292E-03 6012.50c 1.2063E-04 $ Stainless Steel 304
c
c
m10 1001.50c 6.6773E-02 8016.50c 3.3387E-02 $ 17.2 deg water
c
mt1 lwtr.01t $ S(alpha,beta)s
mt10 lwtr.01t

```

APPENDIX B: DETAILED MODEL

This detailed model was constructed to verify the adequacy of the simplified benchmark model and for use in the sensitivity study to determine the appropriate thickness of the flat plates that would replace the pleats.

MCNP4a was run using 440 generations with 3000 neutrons per generation. Forty generations were skipped before averaging, so the results are an average of 1,200,000 neutron histories.

Figure 12. Detailed Model of the Reaction Vessel with Pleated Bellows Assembly

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MCNP Input listing of Detailed Model

```

PNL EXP-064   Vertical bellows slab geometry
C
C
C
C *****
C **          ....cell descriptions....          **
C *****
C
C
C   MAIN FUEL IN BELLOWS IN TWO PLEATED ARRAYS
C
1  1 1.0018E-01 (-1 -2 -11 -12 22) -30 u=1 imp:n=1 $ r main fuel slab
2  1 1.0018E-01 (-5 -6 -15 -16 -22) -30 u=1 imp:n=1 $ l main fuel slab
3  0 (-1 -2 -11 -12 22) 30 u=1 imp:n=1 $ r void above fuel slab
4  0 (-5 -6 -15 -16 -22) 30 u=1 imp:n=1 $ l void above fuel slab
C
5  9 8.7374E-02 (-3 -4 -13 -14 22)
      (1 :2 :11 :12 :-22) u=1 imp:n=1 $ r SS bellows skin
6  9 8.7374E-02 (-7 -8 -17 -18 -22)
      (5 :6 :15 :16 :22) u=1 imp:n=1 $ l SS bellows skin
C
7  10 1.0016e-01 ( (3 :4 :13 :14 :-22) (7 :8 :17 :18 :22) ) -29,
      u=1 imp:n=1 $ array element fuel cell below water line
17  0 ( (3 :4 :13 :14 :-22) (7 :8 :17 :18 :22) ) 29
      u=1 imp:n=1 $ array element fuel cell above water line
C
8  0 -33 31 -35 34 -37 36 fill=1 u=2 lat=1 imp:n=1 $ unit cell holding box
C
C
9  0 (43 -41 45 -44 47 -46) fill=2 imp:n=1 $ r main fuel array holding box
10 0 (53 -51 45 -44 47 -46) fill=2 imp:n=1 $ l main fuel array holding box
C
C
C   CENTER THINNER REGION OF THE SLAB TANK
C
20 1 1.0018E-01 (51 -52 61 -62 65 -66) -30 imp:n=1 $ thin fuel near center
21 0 (51 -52 61 -62 65 -66) 30 imp:n=1 $ thin void near center
22 9 8.7374E-02 (51 -52 47 -46 45 -44) (-51 :52 :-61 :62 :-65 :66) imp:n=1
C
40 1 1.0018E-01 (42 -43 61 -62 65 -66) -30 imp:n=1 $ thin fuel near center
41 0 (42 -43 61 -62 65 -66) 30 imp:n=1 $ thin void near center
42 9 8.7374E-02 (42 -43 47 -46 45 -44) (-42 :43 :-61 :62 :-65 :66) imp:n=1
C
50 1 1.0018E-01 (52 -42 61 -62 65 -66) -30 imp:n=1 $ fuel in central region
51 0 (52 -42 61 -62 65 -66) 30 imp:n=1 $ void in central region
52 9 8.7374E-02 (52 -42 60 -63 64 -67)
      (-52:42:-61:62:-65:66) imp:n=1 $ center region SS tank
C
C
C
53 10 1.0016e-01 ((52 -42 47 -46 45 -44)
      (-52:42:-60:63:-64:67)) -29 imp:n=1 $ water outside
54 0 ((52 -42 47 -46 45 -44)
      (-52:42:-60:63:-64:67)) 29 imp:n=1 $ void outside
C

```

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```

60  9 8.7374E-02  41 -70 45 -44 47 -46  imp:n=1 $ right SS end plate
61  9 8.7374E-02  71 -53 45 -44 47 -46  imp:n=1 $ left SS end plate
c
c
c
c  SQUARE LATTICE STAINLESS STEEL SUPPORT GRID
c
70  9 8.7374E-02  (-500:502:504:-506:75:-70)
      ( 47 -46 -44 45 -75 70) imp:n=1 $ steel walls of right grid holding box
71  9 8.7374E-02  (-500:502:504:-506:-76:71)
      ( 47 -46 -44 45 -71 76) imp:n=1 $ steel walls of left grid holding box
c
100 0 500 -502 -504 506 -75 70 fill=5 imp:n=1 $inner right holding box to be filled
200 0 500 -502 -504 506 -71 76 fill=5 imp:n=1 $inner left holding box to be filled
c
c
c
101 0 -301 302 -305 306 lat=1 u=5 imp:n=1 trcl=(5.3 0 5.3)
      fill= -5:4 -5:4 0:0 20 89r 30 9r $ repeated unit cell with upper layer partly
filled
102 10 1.0016e-01 -401 402 -405 406 u=20 imp:n=1 $ innermost unit cell
103 9 8.7374E-02 (401:-402:405:-406) u=20 imp:n=1 $ unbounded outside of unit
cell
104 0 (-401 402 -405 406) 304 u=30 imp:n=1 $ void innermost unit cell
105 10 1.0016e-01 (-401 402 -405 406) -304 u=30 imp:n=1 $ innermost unit cell
106 9 8.7374E-02 (401:-402:405:-406) u=30 imp:n=1 $ unbounded outside of unit
cell
c
c
c
c
c
90 10 1.0016e-01 ((-76:75:-47:46:-45:44)
      (100 -102 -103 105 -113 115)) -29 imp:n=1 $ water outside completed bellows
91 0 (-76:75:-47:46:-45:44)
      (100 -102 -103 105 -113 115)) 29 imp:n=1 $ void outside completed bellows
c
c  RECTANGULAR WATER MODERATOR TANK
c
900 9 8.7374E-02 (-100:102:103:-105:113:-115)
      (101 -102 -104 106 -114 116) imp:n=1 $ steel skin of water tank
c
999 0 (-101:102:104:-106:114:-116) imp:n=0 $ out of this world

c
c *****
c ** ....surface equations.... **
c *****
c
c
c  SPECIFY ONE PLEAT OF THE BELLWS TO BE REPEATED
c
1  p -52.7654 0 52.7654 -52.7654 .6944 47.6744 52.7654 0 52.7654 $ r wedge top
of bellows
2  p -52.7654 0 -52.7654 -52.7654 .6944 -47.6744 52.7654 0 -52.7654 $ r wedge
bottom of bellows
c
3  p -53.35 0 53.35 -53.35 .6944 48.2589 53.35 0 53.35 $ r wedge top of
SS

```

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4      p  -53.35 0 -53.35  -53.35 .6944  -48.2589  53.35 0 -53.35  $ r wedge bot of
SS
c
c
5      p  -52.7654 0 52.7654  -52.7654 -.6944  47.6744  52.7654 0 52.7654  $ l wedge top
of bellows
6      p  -52.7654 0 -52.7654  -52.7654 -.6944  -47.6744  52.7654 0 -52.7654  $ l wedge
bottom of bellows
c
7      p  -53.35 0 53.35  -53.35 -.6944  48.2589  53.35 0 53.35  $ l wedge top
of SS
8      p  -53.35 0 -53.35  -53.35 -.6944  -48.2589  53.35 0 -53.35  $ l wedge bot
of SS
c
11     p  52.7654 0 -52.7654  47.6744 .6944  -52.7654  52.7654 0 52.7654  $ r wedge side
of bellows
12     p  -52.7654 0 -52.7654  -47.6744 .6944  -52.7654 -52.7654 0 52.7654  $ r wedge side
of bellows
c
c
13     p  53.35 0 -53.35  48.2589 .6944  -53.35  53.35 0 53.35  $ r wedge side of SS
14     p  -53.35 0 -53.35  -48.2589 .6944  -53.35  -53.35 0 53.35  $ r wedge side of SS
c
c
15     p  52.7654 0 -52.7654  47.6744 -.6944  -52.7654  52.7654 0 52.7654  $ l wedge side
of bellows
16     p  -52.7654 0 -52.7654  -47.6744 -.6944  -52.7654 -52.7654 0 52.7654  $ l wedge side
of bellows
c
17     p  53.35 0 -53.35  48.2589 -.6944  -53.35  53.35 0 53.35  $ r wedge side
of SS
18     p  -53.35 0 -53.35  -48.2589 -.6944  -53.35  -53.35 0 53.35  $ l wedge side
of SS
c
c
22     py  0  $ middle plane of each bellows section
c
c
c
29     pz  50.81  $ ***** water level in the reflector tank *****
c                      ***** half way up the top pleat *****
30     pz  29.9201  $ ***** fuel level relative to origin *****
c                      ***** measured from half way up the bottom pleat *****
c
31     py  .69440001  $holding box for unit cells
33     py  -.69440001
34     px  53.350001
35     px  -53.350001
36     pz  53.350001
37     pz  -53.350001
c
41     py  6.985  $right large array holding box
42     py  1.271  $ (.159 SS sheet)
43     py  1.43
44     px  53.35
45     px  -53.35
46     pz  53.35
47     pz  -53.35
c
51     py  -1.43  $left large array holding box

```

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```

52  py  -1.271  $ (.159 SS sheet)
53  py  -6.985
c
60  pz  -50.85  $ central band
61  pz  -50.691 $ (.159 SS sheet)
62  pz   50.691
63  pz   50.85
c
64  px  -50.85  $ central band
65  px  -50.691 $ (.159 SS sheet)
66  px   50.691
67  px   50.85
c
70  py   7.144  $ rightmost steel edge (.159 thick end plate)
71  py  -7.144  $ leftmost steel edge
c
c
75  py  18.574  $ rightmost grid support edge (11.43 thick)
76  py -18.574  $ leftmost grid support edge
c
c
c    SQUARE LATTICE SUPPORT GRID
c
301 px  5.3      $ outside dimensions of the grid sections
302 px -5.3
305 pz  5.3
306 pz -5.3
c
304 pz  3.11     $ water level in uppermost support grids
c
401 px  5.1413   $ inside dimensions of the grid sections
402 px -5.1413
405 pz  5.1413
406 pz -5.1413
c
500 pz -52.999   $ inside dimensions of the grid holding box
502 pz  52.999
504 px  52.999
506 px -52.999
c
c    RECTANGULAR REFLECTOR TANK FACES
c
100 pz -71.75    $ inside bottom surface of water tank
101 pz -72.226   $ outside bottom surface of water tank
102 pz  71.75    $ top of water tank / no lid
c
103 px  71.1     $ east inside face of water tank
104 px  71.576   $ east outside face of water tank
105 px -71.1     $ west inside face of water tank
106 px -71.576   $ west outside face of water tank
c
113 py  37       $ south inside face of water tank
114 py  37.635   $ south outside face of water tank
115 py -31.6     $ north inside face of water tank
116 py -32.235   $ north outside face of water tank
c
c
c *****
c **          ....execution parameters....          **
c

```

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```

c
c *****
c
c kcode 3000 1.0 40 440
c totnu
c vol no
c
c
c
c *****
c ** ....neutron source initiation .... **
c *****
c
c ksrc 1 1 1 1 1 -20 1 1 20
c
c *****
c ** .... material specifications ... **
c *****
c
c
c m1 1001.50c 6.3520E-02 7014.50c 1.1228E-03 8016.50c 3.5266E-02
94238.50c 3.0739E-08 94239.55c 9.6178E-05 94240.50c 8.7348E-06
94241.50c 4.7104E-07 94242.50c 9.6945E-08 92234.50c 1.1412E-08
92235.50c 9.1557E-07 92236.50c 3.7179E-08 92238.50c 1.5933E-04
95241.50c 5.4324E-07 5010.50c 2.2758E-08 48000.50c 1.2795E-08
26000.50c 1.3261E-06 64000.35c 1.7650E-09 3006.50c 8.1792E-10
$ Pu/U fuel solution in bellows
c
c m9 26000.50c 6.1376E-02 24000.50c 1.7648E-02
28000.50c 8.2292E-03 6012.50c 1.2063E-04 $ Stainless Steel 304
c
c
c m10 1001.50c 6.6773E-02 8016.50c 3.3387E-02 $ 17.2 deg water
c
c mt1 lwtr.01t $ S(alpha,beta)s
c mt10 lwtr.01t

```


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