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Critical Configuration and Physics Measurements for Graphite Reflected Assemblies of U(93.15)O_2 Fuel Rods (1.506-CM Pitch)

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1.0 DETAILED DESCRIPTION

A series of critical experiments were completed in 1962-1965 at Oak Ridge National Laboratory's Critical Experiments Facility in support of the Medium-Power Reactor Experiments (MPRE) program. In the late 1950's efforts were made to study "power plants for the production of electrical power in space vehicles." The MPRE program was a part of those efforts and studied the feasibility of a stainless steel system, boiling potassium 1 MW(t), or about 140 kW(e), reactor. The program was carried out in [fiscal years] 1964, 1965, and 1966. A summary of the program's effort was compiled in 1967.[a] The delayed critical experiments were a mockup of a small, potassium-cooled space power reactor for validation of reactor calculations and reactor physics methods.

Initial experiments, performed in November and December of 1962, consisted of a core of 253 unmoderated stainless steel tubes, each containing 26 UO_2 fuel pellets, surrounded by a graphite reflector. Measurements were made to determine critical reflector arrangements, fission-rate distributions, and cadmium ratio distributions. Subsequent experiments used beryllium reflectors and also measured the reactivity for various materials placed in the core. "The [assemblies were built] on [a] vertical assembly machine so that the movable part was the core and bottom reflector." The first experiment in the series was evaluated in HEU-COMP-FAST-001. It had the 253 fuel tubes packed tightly into a 22.87 cm outside diameter (OD) core tank (see References 1 and 2). The second experiment in the series, performed in early 1963, which is studied in this evaluation, had the 253 fuel tubes at a 1.506-cm triangular lattice in a 25.96 cm OD core tank and graphite reflectors on all sides. The experiment has been determined to represent an acceptable benchmark experiment. It should, however, be noted that this experiment and HEU-COMP-FAST-001 are very similar and are thus correlated.

Information for this evaluation was compiled from published reports on all three parts of the experimental series (see References 1 through 5) and the experimental logbook [b] as well as from communication with the experimenter, John T. Mihalczo.

1.1 Overview of Experiment

Upon completion of part one of the three part experimental series, the core was reassembled with a 1.506-cm pitch for part two. Grid plates, spacer tubes, and fuel clips were used to maintain the fuel tube spacing. The amount of graphite reflector was varied to obtain the critical configurations. For the initial trials, a Pu-Be source (#563) was placed at the side of the reflector. During the final approaches to

[a] A.P. Fraas, "Summary of the MPRE Design and Development Program," ORNL-4048, Oak Ridge National Laboratory (1967).

[b] Radiation Safety Information Computation Center (RSICC), The ORNL Critical Experiments Logbooks, Book 75r, http://rsicc.ornl.gov/RelatedLinks.aspx?t=criticallist, logbook page 10-60 (PDF page 3-43).

critical, the source was mounted in one of the 1.27-cm radial holes in the reflector. If all radial holes in the graphite radial reflector were ever all filled, the source was adjacent to the outside of the radial reflector. The source was withdrawn into a shield for the final critical measurements and had negligible reflection contribution to keff.[a] The core tank was raised stepwise into the reflector as each configuration was tested.

The uncertainty in both mass and size measurements was "one in the last significant digit given.[b]"

1.2 Description of Experimental Configuration

The assemblies were built on a vertical assembly machine in the east experimental cell of the Oak Ridge Critical Experiments Facility (ORCEF). Safety mechanisms of the device and facility are discussed in the facility safety review. The machine was located such that the center of the core was 3.67 m from the 1.5-m-thick west wall, 3.9 m from the 0.6-m-thick north wall, and 2.8 m above the concrete floor in the 10.7×10.7-m-square 9.1-m-tall room (see Reference 2). Figure 1-1 is a photograph of the vertical assembly machine.

[a] Personal email communication with J.T. Mihalczo, September 29, 2011.
[b] Personal email communication with J. T. Mihalczo, May 23, 2011.

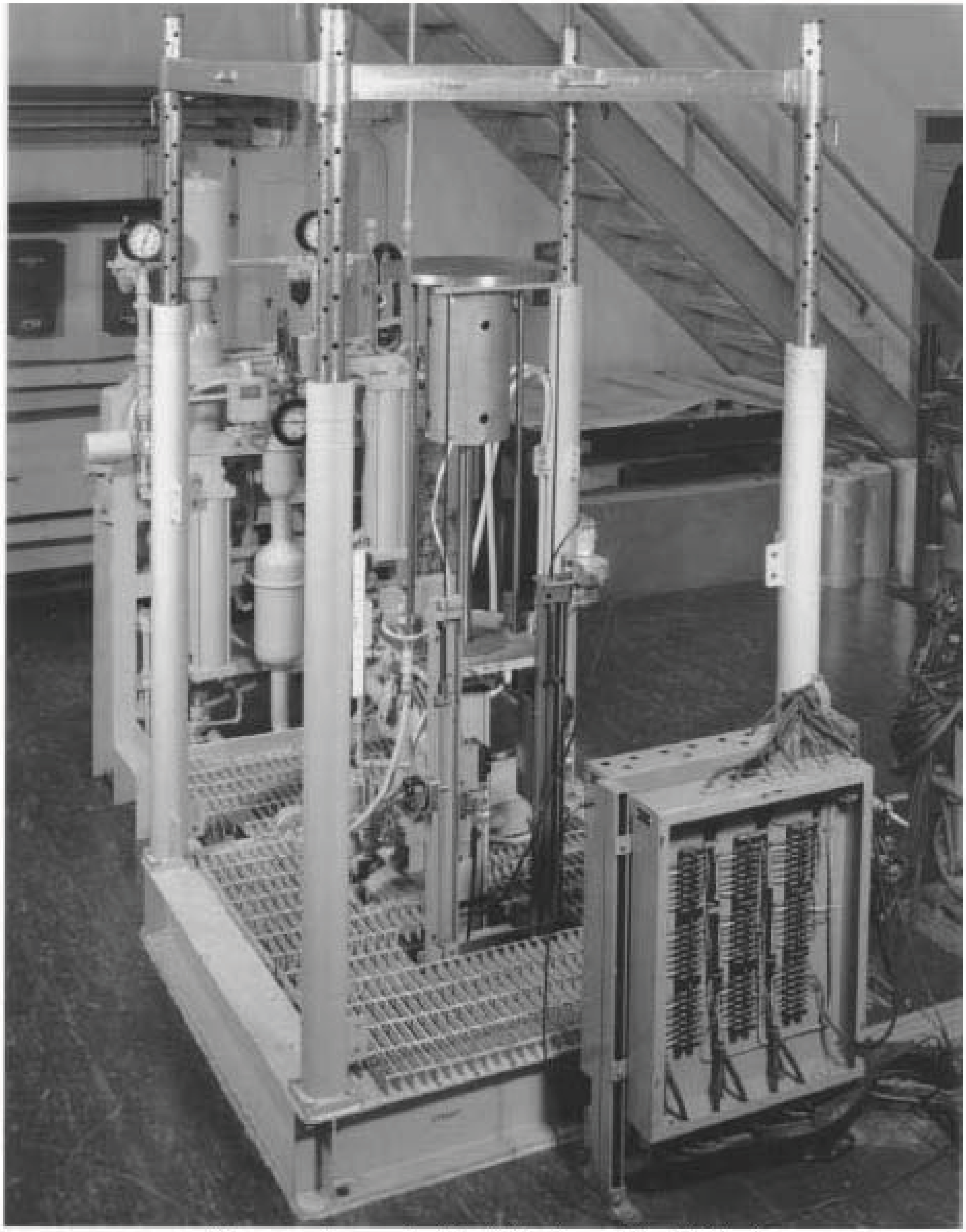

Figure 1-1. Photograph of the Vertical Assembly Machine.[a]

[a] *Safety Review of the Oak Ridge Critical Experiments Facility*, Union Carbide Nuclear Corporation, Oak Ridge National Laboratory (1962).

The top and side reflectors were on an iron table mounted from the four poles of the vertical assembly machine. The bottom reflector and the core were placed on the moveable portion of the table and raised into the side reflector such that the core came into contact with the top reflector or within 0.001 inches of it and usually lifted it ~0.001 inches.[a] A displacement gauge was placed on top of the graphite to determine when the core was in the up position and in contact with the top reflector.[b] In addition, the core and graphite bottom reflector were supported on a Type 1100 Aluminum cylinder and disc, which was attached to the Type 304 Stainless Steel moveable platform of the vertical assembly machine. Figure 1-2 shows the arrangement of the core and the reflectors on the vertical assembly machine for part one of the experimental series with the close packed core. In the experiment evaluated in this evaluation, the bottom reflector was in the core tank while the bottom of the fuel pins were directly in contact with the bottom reflector (see Figure 1-3).

[a] Personal email communication with J.T. Mihalczo on May 23 and September 19, 2011. This gauge was also used to insure that the core did not lift the top and side reflector as it was being inserted.
[b] RSICC Logbook 75r, p. 41.

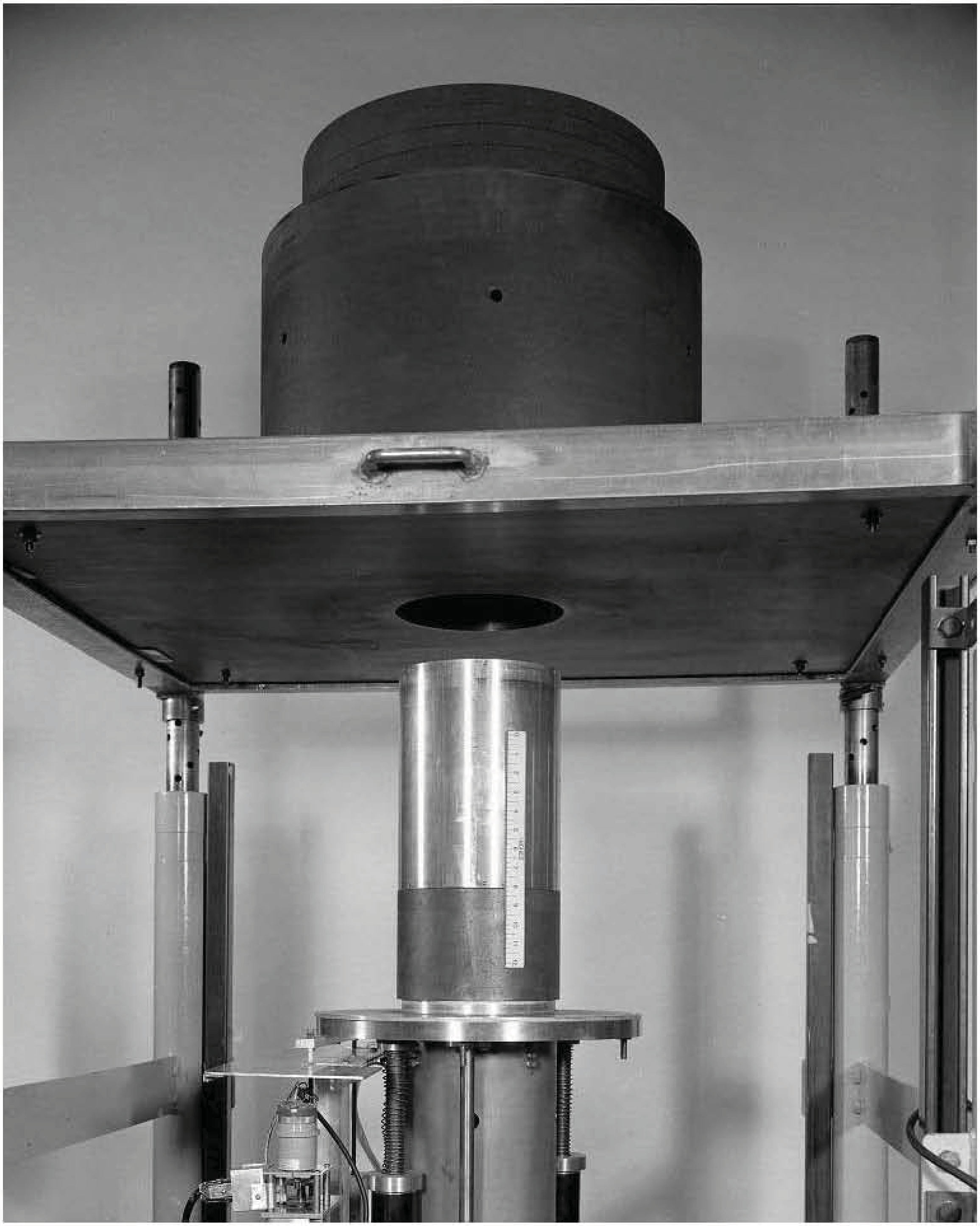

Figure 1-2. Core and Reflector Placement for the Vertical Assembly Machine for Part One of the Experimental Series.[a,b]

[a] ORNL Photograph 39302.
[b] This photograph shows part one of the experimental series, which had close packed fuel pins, but also shows the general arrangement of the core and reflectors on the vertical assembly machine for the evaluated experiment.

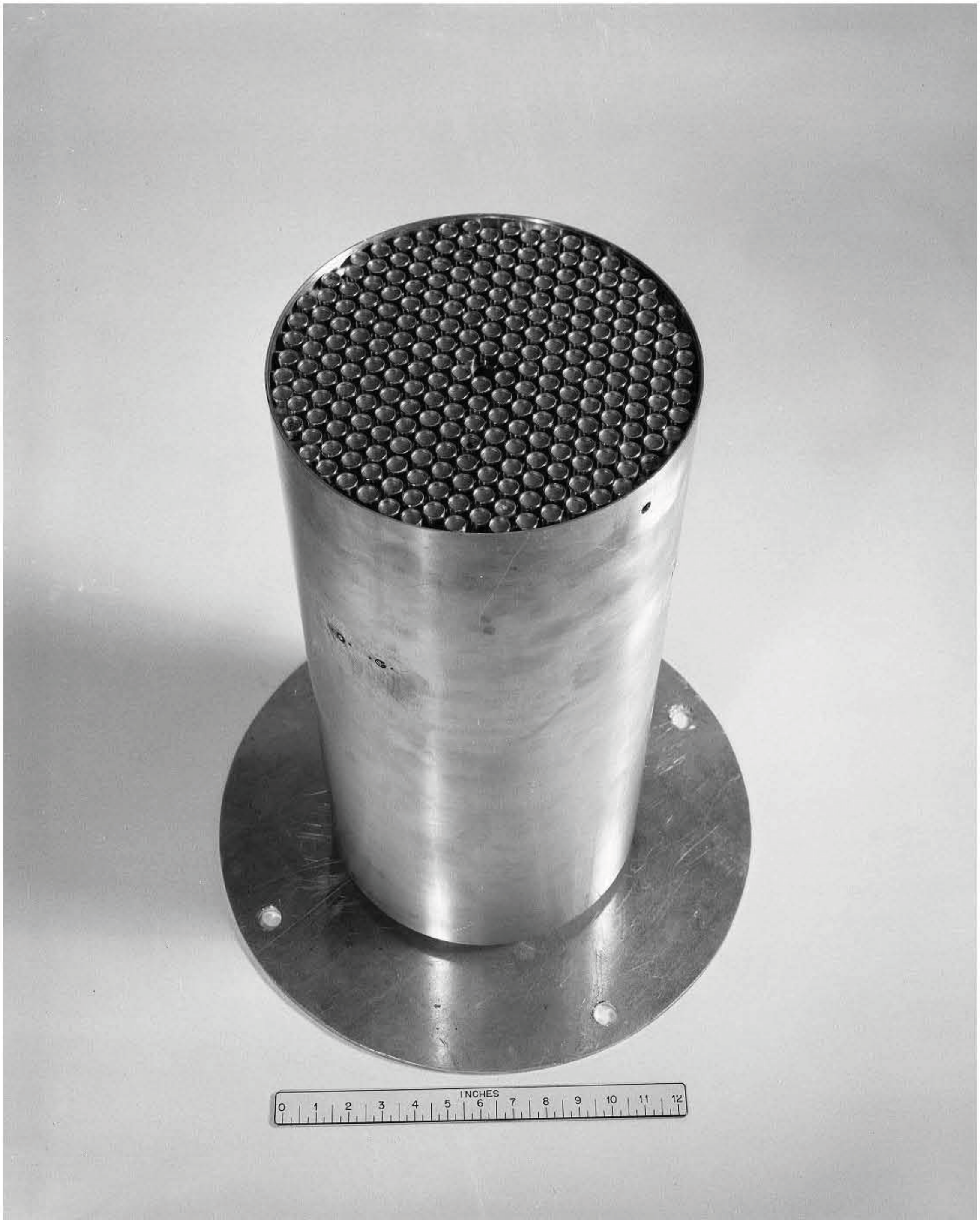

Figure 1-3. Core, Core Tank and Aluminum Support Plate.[a]
(bottom reflector is in the core tank)

[a] ORNL Photograph 39522.

1.2.1 The Fuel

The critical core assembly consisted of 253 1.27 cm-outside-diameter[a] fuel tubes in a Type 1100 Aluminum cylindrical core tank with the center fuel tube removed thus only 252 fuel tubes remained (see Figure 1-3). Pellets were packed into Type 347 Stainless Steel tubes and held in place by end caps. The tubes were made of standard commercially available tubing.[b] The end caps created small wells at the top and bottom of the fuel tubes as can be seen in Figure 1-4.[c] Dimensions and a photograph of the fuel pellets and tubes as taken from References 1 and 4 can be found in Tables 1-1 and 1-2 and in Figure 1-4.

Table 1-1. Fuel Pellet Dimensions
(see References 1, 2, and 4).

Number of Pellets per Tube	26	
UO_2 Density	9.71	g/cm^3
UO_2 Mass per Tube	295.8	g
Pellet Diameter	1.141	cm
Length of One Pellet	1.145	cm
Length of 26 Pellets	29.88	cm[(a)]

(a) This length "includes 0.110 cm of void or ~0.0044 cm of void between each pellet." (see Reference 2)

Table 1-2. Fuel Tube Dimensions
(see References 1, 2, and 4).

Length	30.48	cm
Outside Diameter	1.27	cm
Wall Thickness	0.051	cm
Weight with End Caps	45.37	g[(a)]
Weight of One End Cap	0.64	g

(a) Compared to values in the logbook this weight is too low by the weight of one end cap. (see HEU-COMP-FAST-001)

The mass of the fuel tube given in Table 1-2 is the mass of the tube and one end cap, not two end caps. Using logbook data, the fuel tube and end cap mass can be calculated as being 44.729 and 0.64107 g, respectively (see HEU-COMP-FAST-001).

[a] References 1and 2 only give two significant digits, but according to the experimenter, the diameter was measured to three significant digits (September 19, 2011). A value of 1.27-cm, as reported in References 1, 2, and 4, has been used in this evaluation.
[b] Personal email communication with J.T. Mihalczo, June 28, 2012.
[c] Personal email communication with J. T. Mihalczo, May 23, 2011

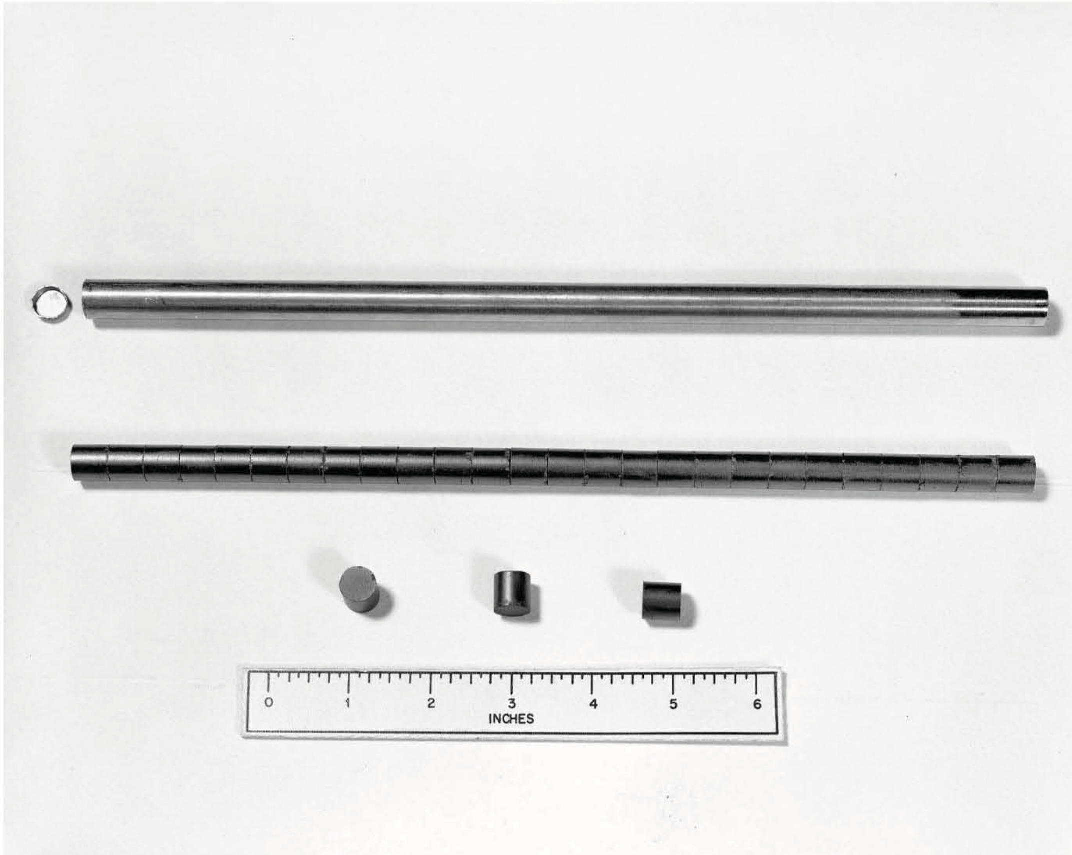

Figure 1-4. Stainless Steel Tube (with one end cap removed) and the Fuel Pellets.[a,b]

1.2.2 The Core

The center-to-center spacing between fuel pins was 1.506 cm. The fuel pins, less the center fuel tube, which was removed in the critical configuration, were in a Type 1100 Aluminum, 25.96-cm-OD tank. Twelve of the fuel tubes at the periphery of the core were moved in until they were nearly in contact with adjacent fuel rods in order to reduce the size of the core. This can be seen in a photograph of the grid plate (see Figure 1-5). Fuel tubes were held in place within the core tank using grid plates, grid plate spacer tubes, shims, and fuel tube clips. Two grid plates were used; one was adjacent to the top of the bottom reflector in the core tank, while the other was held up using the grid plate spacer tubes. The grid plate spacer tubes were 90 degrees apart and "fit into a recess on the inner sides of the grid plates.[c]" The fuel tube clips "snapped around and fit on more than half way around each of the 2 fuel tubes whose spacing they were maintaining.[d]" According to the experimenter, aluminum shims were used in this experiment and the fuel tube clips were only used in the next experiment during reactivity effect measurements. [e] No dimensions for the aluminum shims were given in Reference 3, Reference 4, or the logbook. The dimensions of the core tank, grid plates, spacer tubes, and fuel clips are given in Table 1-3. The fuel arranged in the core tank can be seen in Figure 1-3.

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[a] "The edges of the pellets were chipped during their removal from the tube preparatory to this photograph." (see Reference 1).
[b] ORNL Photograph 39309.
[c] Personal email communication with J.T. Mihalczo, December 17, 2011.
[d] Personal email communication with J.T. Mihalczo, December 17, 2011.
[e] Personal email communication with J.T. Mihalczo, December 17, 2011.

The core and bottom reflector were raised into the side reflectors until the top of the core came into contact with the top reflector or within 0.001 inches of it and usually lifted it ~0.001 inches.[a] A displacement gauge was placed on top of the graphite to determine when the core was in the up position and in contact with the top reflector.[b]

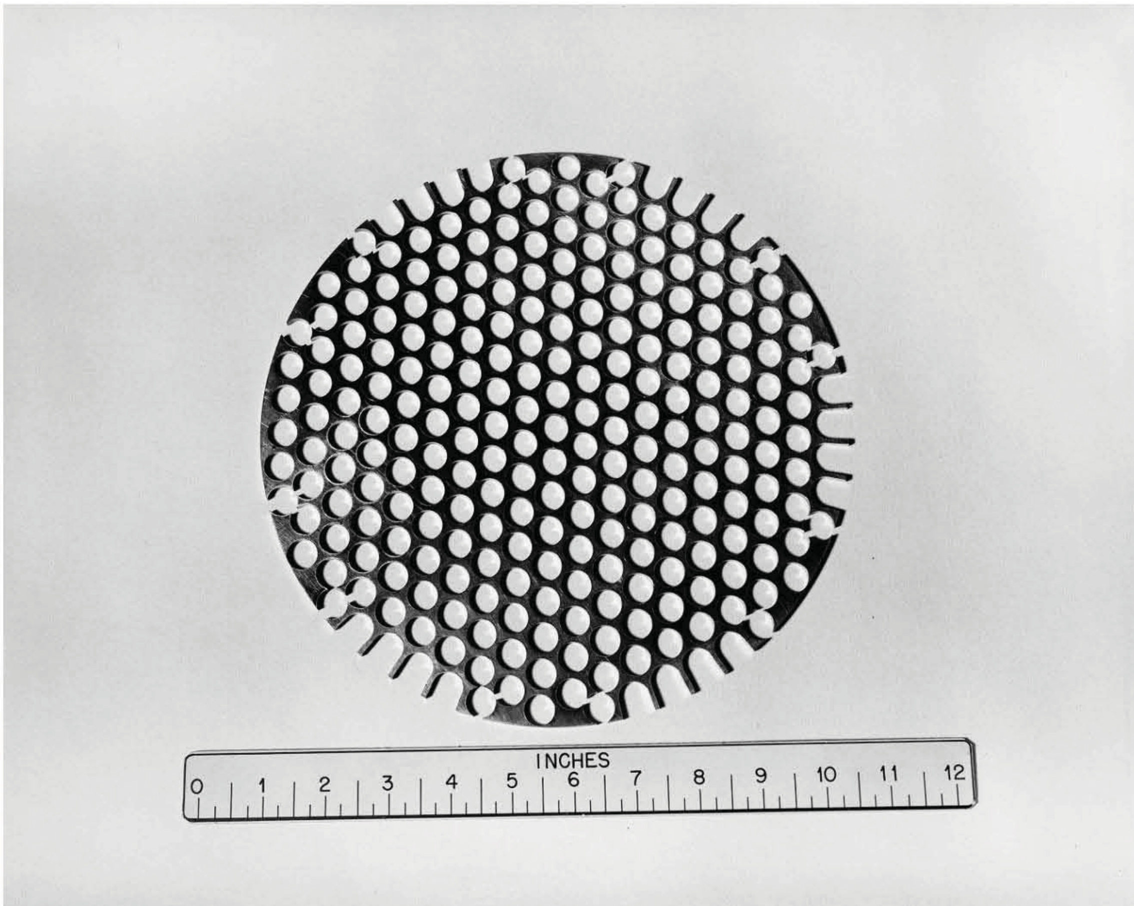

Figure 1-5. Grid Plate.[c]

[a] Personal email communication with J.T. Mihalczo, May 23 and September 19, 2011. This displacement gauge was also used to insure that the core did not lift the top and side reflector as it was being inserted.
[b] RSICC Logbook 75r, p. 41.
[c] ORNL Photograph 39521.

Table 1-3. Core Dimensions (see References 3 and 4).

Core Tank (Open Top)	
Material	Type 1100 Aluminum
Side Wall Thickness (cm)	0.254
Bottom Thickness (cm)	0.364
Outside Diameter (cm)	25.96
Outside Length (cm)	54.04
Mass (kg)	3.387
Grid Plates (2)	
Material	Type 1100 Aluminum
Thickness (cm)	0.317
Mass (g)	139 (each)
Grid Plate Spacer Tubes (4)	
Material	Type 347 Stainless Steel
Outside Diameter (cm)	1.37
Wall Thickness (cm)	0.076
Length (cm)	27.94
Weight (g)	37.5 (each)
Fuel Tube Clips[a]	
Material	Type 1100 Aluminum
Mass (g)	2.3 (each)

(a) These clips were at the core midplane to hold outer fuel elements in position. According to the experimenter these clips were not used for the critical configuration but only during reactivity effect measurements.

1.2.3 The Reflectors

The core was reflected by Type ATL Graphite. The assembly sat on core support plates and a reflector support table that provided additional reflection. The dimensions of the reflectors are given in Table 1-4 and shown in Figure 1-6.

Table 1-4. Reflector Dimensions (see References 3 and 4).

Side Reflector -Graphite (Type ATL)		
Height (cm)	Lower Section	46.63
	Upper Section	7.63
Thickness (cm)	Lower Section	27.90
	Upper Section	25.53
Inside Diameter (cm)	Lower Section	26.13
	Upper Section	26.14
Mass (kg)	Lower Section	388.6
	Upper Section	55.0
Top Reflector Graphite (Type ATL)		
Thickness (cm)	Lower Section	15.25
	Upper Section	8.36
Diameter (cm)	Lower Section	76.2
	Upper Section	50.8
Mass (kg)	Lower Section	124.1
	Upper Section	28.5
Bottom Reflector -Graphite (Type ATL)		
Thickness (cm)		22.86
Diameter (cm)		25.42
Mass (kg)		19.21
Additional Bottom Reflector		
Bottom of Core Tank- Aluminum Type (1100)		
Thickness (cm)		0.364
Diameter (cm)		25.96
Mass (kg)		0.504
Core Support Plates		
Aluminum (type 1100)		
Thickness (cm)	Lower Section	0.63
	Upper Section	1.94
Diameter (cm)	Lower Section	45.72
	Upper Section	21.60
Mass (kg)	Lower Section	2.787
	Upper Section	1.920
Stainless Steel (Type 304)		
Thickness (cm)		2.38
Diameter (cm)		45.72
Mass (kg)		31.2[a]
Reflector Support Plate -Iron		
Thickness (cm)		1.27
Outside Dimensions (cm)		121.9 × 121.9
Inside Diameter (cm)		26.67
Mass (kg)		136.7

(a) The mass given in Reference 3 was 7.76 kg and was incorrect. The correct mass was 31.2 kg as given in Reference 4.

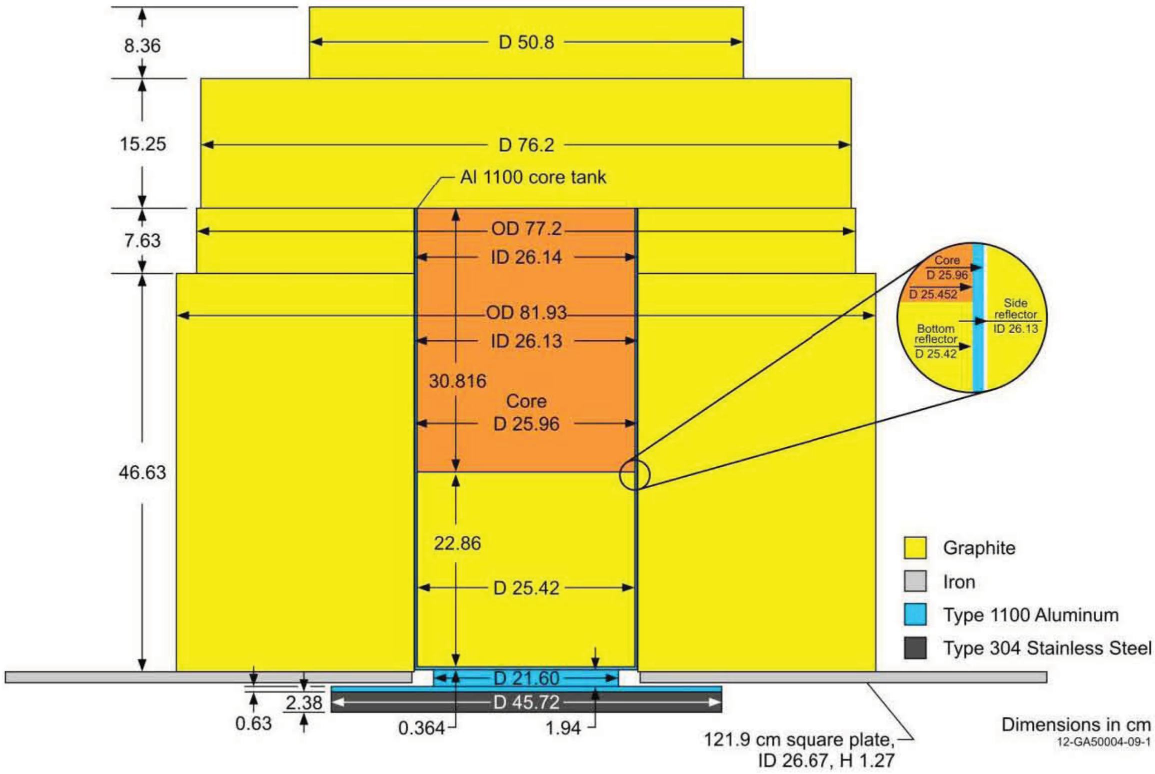

Figure 1-6. Reactor-Core Assembly (redrawn from Reference 3).

The mass of the stainless steel core support plate was incorrectly published in References 1 and 3. The correct mass of 31.2 kg was given in Reference 4.

Each section of reflector was one solid mass. Six equally spaced radial holes, 1.27 cm in diameter, were located 7.63 cm below the midplane of the core through the side reflector to allow for physics measurements. Five of the six radial holes, along with a hole of the same size at the midline of the top reflectors, were plugged using graphite plugs. Plugs were in place when reflector masses were measured. The published reports give the diameter of the graphite plugs as 0.95-cm, but the logbook gives a diameter of 0.437 inches or 1.110 cm. The experimenter has stated that the diameter given in the logbook should be used.[a]

1.2.4 Reactivity of the Final Configuration

The final-near-critical configuration had a reactivity of -1 ¢. The effective delayed neutron fraction, β_{eff}, for the system was 0.0068. (This β_{eff} value is an approximation made by the experimenter.)[b]

1.3 Description of Material Data

Impurity analyses for the uranium oxide and the graphite and an isotopic analysis for the uranium were performed and reported in Reference 1 (see Sections 1.3.1 and 1.3.2). The fuel tubes and grid plate spacer tubes were made of Type 347 Stainless Steel; the core tank, grid plates, and fuel tube clips were made of Type 1100 Aluminum; and the vertical assembly machine support structures were made of Type 1100 Aluminum, Type 304 Stainless Steel, and iron (see Reference 3). According to the experimenter,

[a] RSICC Lobgook 75r, p. 40, Personal communication with J.T. Mihalczo, October 2, 2011.
[b] Personal email communication with J. T. Mihalczo, May 23, 2011, August 19, 2011, and November 14, 2011.

the iron table that supported the top and radial reflectors was typical normal low carbon steel.[a] The compositions for these materials were not given. The type of aluminum and/or composition of the aluminum shims was not given in either the references or the logbook.

The core was reported to contain a ^{235}U mass of 61.15 kg, a UO_2 mass of 74.54 kg, and a stainless steel mass of 11.43 kg[b] (see Reference 3).

1.3.1 Fuel Composition

The basic fuel units were pellets of UO_2 with a density of 9.71 g/cm^3. The pellets were pressed and sintered at the Oak Ridge Y-12 Plant (see Reference 2). An impurity analysis is provided in Table 1-5, and the uranium isotopic distribution is given in Table 1-6. The uncertainty in the isotopic distribution was ±0.005 wt.% for ^{234}U, ^{235}U, and ^{236}U.[c]

Table 1-5. Mass Spectrographic Analysis of Uranium Oxide (see References 1 and 4).[(a)]

Silver, Ag	<	40	ppm[(b)]
Beryllium, Be	<	0.3	ppm
Chromium, Cr		6 to 40	ppm
Lithium, Li	<	1.5	ppm
Nickel, Ni	<	25	ppm
Tin, Sn		5 to 25	ppm
Aluminum, Al		3 to 30	ppm
Calcium, Ca		50	ppm
Copper, Cu		3 to 35	ppm
Magnesium, Mg	<	12	ppm
Phosphorous, P	<	100	ppm
Boron, B	<	1	ppm
Iron, Fe		10 to 250	ppm
Manganese, Mn	<	8	ppm
Barium, Ba	<	10	ppm
Potassium, K	<	50	ppm
Sodium, Na	<	10	ppm
Silicon, Si		10 to 50	ppm

(a) Reference 1 reports these as results of spectrochemical analysis.
(b) These were measured by weight.

[a] Personal email communication with J.T. Mihalczo, May 23, 2011.
[b] The UO_2 mass is based off of a fuel mass of 295.8 g per tube and disregards fuel impurities. The total stainless steel mass is incorrect due to the incorrect fuel tube mass given in Table 1-2.
[c] According to J.T. Mihalczo (personal email communication, August 19, 2011), the uncertainty in the isotopic values was the same as those given in HEU-MET-FAST-051. This report gives the isotopic uncertainties as stated.

Table 1-6. Uranium Isotopic Composition (wt.%) (see References 1, 2, and 4).

^{234}U	1.01
^{235}U	93.15
^{236}U	0.47
^{238}U	5.37

1.3.2 Graphite

The reflectors were all Type ATL Graphite. A spectrochemical analysis of the graphite was performed and the results are given in Table 1-7.

Table 1-7. Spectrochemical Analyses of Type ATL Graphite (see Reference 1).

Element	ppm[(a)]	Element	ppm[(a)]
Aluminum, Al	270	Magnesium, Mg	1
Barium, Ba	22	Manganese, Mn	1
Boron, B	< 1	Molybdenum, Mo	5
Calcium, Ca	820	Sodium, Na	3
Cobalt, Co	3	Nickel, Ni	27
Chromium, Cr	16	Silicon, Si	54
Copper, Cu	1	Strontium, Sr	5
Iron, Fe	3940	Titanium, Ti	54
Potassium, K	5	Vanadium, V	220
Lithium, Li	2	Yttrium, Y	11
Lutetium, Lu	1	Ytterbium, Yb	3

(a) These were measured by weight.

1.4 Temperature

The temperature of the experiment was 72°F (22°C).[a]

1.5 Supplemental Experimental Measurements

Worth measurements, relative axial and radial fission rate distribution measurements, and radial cadmium ratio measurements were performed on the critical configuration. These measurements are preserved and evaluated in SCCA-FUND-EXP-002.[b]

[a] Personal email communication with J. T. Mihalczo, May 23, 2011.
[b] International Handbook of Evaluated Reactor Physics Benchmark Experiments, NEA/NSC/DOC(2006)1, OECD-NEA, Paris (2013).

2.0 EVALUATION OF EXPERIMENTAL DATA

The critical configuration was evaluated using Monte Carlo N-Particle (MCNP) versions 5-1.60[a] and ENDF/B-VII.0[b] neutron cross section libraries. Unless stated otherwise, the simple or detailed benchmark models, as described in Section 3, were used for the uncertainty analyses. The effect of the uncertainty in all measured parameters was found individually by increasing and decreasing the specified value by a given amount; the Δk_{eff} for that uncertainty was found by taking one half of the difference between the k_{eff} values for the upper and lower perturbed models. The magnitude of most perturbations was increased from the 1σ uncertainties in order to obtain statistically significant results. The ratio of the perturbation to the 1σ uncertainty for the parameter was used as a "scaling factor" to convert the calculated Δk_{eff} to a 1σ uncertainty in k_{eff}. All models were calculated such that the statistical uncertainty, σ_{MC}, was no more than ±0.00006, although most models had a σ_{MC} of 0.00002. An uncertainty was considered to have a negligible effect (NEG) when the magnitude of the 1σ Δk_{eff} was ≤0.00010.

2.1 Evaluation of Critical Measurement

The final-near-critical configuration had a reactivity of -1¢. The experimenter estimated the β_{eff} for the system to be 0.0068. The β_{eff} also was calculated using two methods; the two β_{eff}'s were averaged. The first method used k_{prompt}, as calculated by MCNP5, and compared it to k_{eff} to calculate β_{eff}. ($\beta_{eff} = 1 - k_{prompt}/k_{eff}$) (HEU-MET-FAST-059). The second method used MCNP5 to calculate β_{eff} directly. The two values were averaged to obtain a β_{eff} of 0.0072. This value was used for this evaluation.[c] An uncertainty in the reactivity measurements of 10% and 5% in the β_{eff} value were assumed as 1σ uncertainties, typical for this facility (HEU-MET-FAST-059 and HEU-MET-FAST-069). However, since the reactivity values were obtained from an unknown combination of experiment runs, the 1σ uncertainty was arbitrarily increased to 20%. The measured reactivity in cents, β_{eff}, and the calculated measured reactivity in terms of Δk_{eff} are given in Table 2-1.

Table 2-1. Uncertainty in Reactivity Measurement of Critical Configurations.

Case	Measured Reactivity (¢)	±	20% (1σ)	β_{eff} ± 5% (1σ)	Reactivity (Δk_{eff})	±	σ
1	-1	±	-0.2	0.0072 ± 0.00036	-0.00007	±	0.000015

2.2 Evaluation of Dimensions

According to the experimenter, the uncertainty in the dimension and mass measurements was plus or minus one in the last significant digit. This uncertainty was assumed to be a 1σ uncertainty unless stated otherwise.

2.2.1 Graphite Reflector Dimension and Mass Uncertainties

The dimensions and mass of the bottom, upper, and lower side, and the upper and lower top reflectors were perturbed individually by 10 times the given 1σ uncertainty. The mass of the reflector was

[a] F.B. Brown, R.F. Barrett, T.E. Booth, J.S. Bull, L.J. Cox, R.A. Forster, T.J. Goorley, R.D. Mosteller, S.E. Post, R.E. Prael, E.C. Selcow, A. Sood, and J. Sweezy, "MCNP Version 5," LA-UR-02-3935, Los Alamos National Laboratory (2002).
[b] M.B. Chadwick, et al., "ENDF/B-VII.0: Next Generation Evaluated Nuclear Data Library for Nuclear Science and Technology," *Nucl. Data Sheets*, **107**: 2931-3060 (2006).
[c] B.C. Kiedrowski, et al., "MCNP5-1.60 Feature Enhancements and Manual Clarifications," LA-UR-10-06217, Los Alamos National Laboratory (2010).

conserved when the dimensions were varied. When varying the thickness of the side reflectors, the outer diameter was varied while keeping the inside diameter constant. When varying the inner diameter of the side reflectors, the thickness was kept constant thus allowing the outer diameter to also vary. The results of these uncertainties are given in Table 2-2.

Table 2-2. Uncertainty in Reflector Dimensions.

Case	Deviation	Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	σ
Lower Side Reflector								
Mass	±1 kg	0.00072	±	0.00001	10	0.00007	±	<0.00001
Height	±0.1 cm	0.00052	±	0.00001	10	0.00005	±	<0.00001
Thickness (radial)	±0.1 cm	0.001165	±	0.00001	10	-0.00012	±	<0.00001
Inner Diameter	±0.01 cm	0.000255	±	0.00001	1	-0.00026	±	0.00001
Upper Side Reflector								
Mass	±1 kg	0.00109	±	0.00001	10	0.00011	±	<0.00001
Height	±0.1 cm	0.00032	±	0.00001	10	0.00003	±	<0.00001
Thickness (radial)	±0.1 cm	0.00009	±	0.00001	10	0.00001	±	<0.00001
Inner Diameter	±0.01 cm	0.00015	±	0.00001	1	0.00015	±	0.00001
Lower Top Reflector								
Mass	±1 kg	0.00065	±	0.00001	10	0.00007	±	<0.00001
Height/Thickness	±0.1 cm	0.00038	±	0.00001	10	0.00004	±	<0.00001
Diameter	±1 cm	0.00178	±	0.00001	10	0.00018	±	<0.00001
Upper Top Reflector								
Mass	±1 kg	0.00220	±	0.00001	10	0.00022	±	<0.00001
Height/Thickness	±0.1 cm	0.00003	±	0.00001	10	<0.00001	±	<0.00001
Diameter	±1 cm	0.00010	±	0.00001	10	0.00001	±	<0.00001
Bottom Reflector								
Mass	±1 kg	0.00156	±	0.00001	10	0.00016	±	<0.00001
Height/Thickness	±0.1 cm	0.00011	±	0.00001	10	0.00001	±	<0.00001
Diameter	±0.1 cm	0.00001	±	0.00001	10	<0.00001	±	<0.00001

The effect of the uncertainty in the plug and plug hole diameters was evaluated using the detailed model. The plugs were 0.437 inches or 1.11 cm in diameter, as found in the logbook. The uncertainty in this measurement would have been ±0.001 inches, or ±0.00254 cm, but due to the discrepancy between the reported plug diameter in Reference 4 and the plug diameter reported in the logbook, the 1σ uncertainty was arbitrarily increased to ±0.1 cm. The uncertainty in the diameter of the holes was ±0.01 cm. The uncertainty in the plug diameter and hole diameter were analyzed independently; mass was conserved. The effect of these uncertainties is summarized in Table 2-3.

Table 2-3. Uncertainty in Plug and Plug Hole Diameters.

Case	Deviation	Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	σ
Plug Diameter	±0.1 cm	-0.00001	±	0.00004[(a)]	1	-0.00001	±	0.00004
Hole Diameter	±0.15 cm	-0.00008	±	0.00004	15	-0.00001	±	<0.00001

(a) Despite using a scaling factor the Δk_{eff} is less than σ_{MC}, which is small, thus this uncertainty has a negligible effect as is seen in Table 2-22.

2.2.2 Fuel and Fuel Tube Dimensions Uncertainty

A total of 252 fuel tubes were used in the experiments. It is not known whether or not the dimensions of the fuel tubes were measured for multiple fuel tubes. The total uncertainty in the dimensions was given by the experimenter as plus or minus the last reported significant digit. This would have been ±0.01 cm for the fuel and fuel tube length.

Measurements in the logbook are often reported in inches to three significant digits. This would correspond to an uncertainty of ±0.001 in (or 0.00254 cm). This value is taken to the systematic component of the total uncertainty and is about 25% of the total. Thus, the 0.01 cm uncertainty in the fuel and fuel tube lengths was taken to be 25% systematic and 75% random using Equation 2.1. When fuel-tube dimensions were perturbed, all 252 fuel tubes were perturbed simultaneously.

$$\Delta k_{eff,1\sigma} = \frac{1}{Scaling\ Factor} \cdot \sqrt{\left(\Delta k_{eff} \cdot 25\%\right)^2 + \frac{\left(\Delta k_{eff} \cdot 75\%\right)^2}{N}}. \qquad \text{Equation 2.1}$$

where $\Delta k_{eff,1\sigma}$ is the combined 1σ effect on k_{eff} and Δk_{eff} is the change in k_{eff} when all 253 fuel rods were perturbed simultaneously. N is 252.

The tolerance on the outside diameter of half-inch-stainless-steel tubing sold today (2011) is ±0.005 in (±0.0127 cm).[a] This is taken to be a bounding uncertainty with an equal probable distribution; thus, the 1σ uncertainty for the fuel tube outside diameter is ±0.00733 cm (±0.0127/√3 cm). The thickness of the fuel tube was held constant when the outer diameter was varied; thus, the inside diameter was also varied. The thickness of the fuel tube could have varied by a maximum of +0.012 cm based on the pellet diameters; this value was taken to be a 3σ uncertainty; thus, the 1σ uncertainty would be +0.004 cm (+0.012/3 cm). This uncertainty, 0.004 cm, was also used for the fuel pellet diameter uncertainty. Although the derivation of the uncertainty for the fuel tube diameter, fuel tube thickness, and fuel tube pellet diameter differed from the fuel and fuel tube length, it is judged that Equation 2.1 can still be used to account for systematic and random components of the uncertainty. The outer diameter of the fuel tube was held constant while varying the thickness of the fuel tube. The effects of these uncertainties are summarized in Table 2-4.

[a] http://www.speedymetals.com/information/Material82.html#Tolerances (accessed November 12, 2011).

Table 2-4. Uncertainty in Fuel and Fuel Tube Dimensions.

Case	Deviation	Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} [(a)] (1σ)	±	σ
				Fuel				
Length	±0.05 cm	0.00001	±	0.00001	5	<0.00001	±	<0.00001
Diameter	±0.005 cm	0.00013	±	0.00004	1.25	0.00003	±	0.00001
				Fuel Tube				
Wall Thickness	±0.012 cm	0.00030	±	0.00001	3	0.00003	±	<0.00001
Length	±0.1 cm	0.00023	±	0.00001	10	0.00002	±	<0.00001
Outside Diameter	±0.0423 cm	0.00026	±	0.00001	5.77	0.00003	±	<0.00001

(a) Random and systematic components of the uncertainty were taken into account using Equation 2.1.

As discussed in HEU-COMP-FAST-001, the mass of the fuel per tube was 295.818 ± 0.063 g and the mass of the fuel tube with end caps was 46.011 ± 0.032 g. These uncertainties are the total uncertainties and account for the systematic and random components of the uncertainty in the fuel and tube masses, respectively. The effect of these mass uncertainties is summarized in Table 2-5.

It should be noted that the mass of fuel per tube, which is calculated using the reported density of 9.71 g/cm^3, and the pellet dimension is 295.57 g, which does not agree with the reported mass per tube of 295.818 g. Since a density is a derived value, the reported density of 9.71 g/cm^3 is not used in the benchmark model and the measured mass and dimensions were used in the calculation of atom densities instead.

Table 2-5. Uncertainty in Fuel and Fuel Tube Mass.

Deviation	Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	σ
			Mass of Fuel per Tube				
±1.26 g	0.00205	±	0.00001	20	0.00010	±	<0.00001
			Mass of Fuel Tube				
±0.32 g	0.00006	±	0.00001	10	0.00001	±	<0.00001

2.2.3 Fuel Tube Placement Uncertainty

The fuel tubes were in a 1.506-cm triangular lattice. The uncertainty in the pitch was taken to be ±0.001 cm. This uncertainty was taken to be 25% systematic and 75% random with an *N* of 252; thus, Equation 2.1 was used to find the 1σ uncertainty effect on Δk_{eff}.

The position of fuel tubes within the 1.506-cm triangular lattice was also varied using the URAN analysis in MCNP5.[a] This card allows for the stochastic sampling of components with random locations in a lattice. Fuel rod position was randomly varied by ±0.086 cm in the x- and y-directions; this large variation is an overestimate of the true uncertainty. Fuel rods at the periphery of the core that were in contact with the fuel rods that had been moved in were not varied in the URAN analysis. The results of

[a] X-5 Monte Carlo Team, "MCNP – A General Monte Carlo N-Particle Transport Code, Version 5, Volume II: User's Guide," LA-CP-03-0245, Los Alamos National Laboratory (October 3, 2005).

these two analyses are given in Table 2-6. Analysis using the URAN method confirms that the uncertainty obtained by simultaneously perturbing the pitch of all fuel rods is negligible.

Table 2-6. Uncertainty in Fuel Pitch and Fuel Placement.

Deviation	Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	σ
Fuel Pitch							
±0.003 cm	-0.00037	±	0.00004	3	-0.00003[(a)]	±	0.00001
Fuel Placement							
URAN[(b)]	-0.00001	±	0.00003[(c)]	1	-0.00001	±	0.00003

(a) Random and systematic components of the uncertainty were taken into account using Equation 2.1
(b) Fuel placement within the 1.506-cm triangular lattice was randomly varied using the URAN analysis in MCNP5. The maximum movement of the rods was ±0.086 cm in the x and y direction.
(c) Despite using a scaling factor the Δk_{eff} is less than σ_{MC}, which is small, thus this uncertainty has a negligible effect as is seen in Table 2-22.

2.2.4 Core Tank Dimensions Uncertainty

The dimensions and mass of the core tank were perturbed individually. The thickness of the side wall was varied by holding the outside diameter of the tank constant while varying the inside diameter. The outside diameter was varied while holding the wall thickness constant thus the inside diameter was also varied. Mass was conserved during the perturbations for the dimensions. Results are summarized in Table 2-7.

Table 2-7. Uncertainty in Core Tank Dimensions.

Case	Deviation	Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	σ
Mass	±0.01 kg	0.00004	±	0.00001	10	<0.00001	±	<0.00001
Side Wall Thickness	± 0.025 cm	0.00005	±	0.00001	25	<0.00001	±	<0.00001
Bottom Thickness	± 0.1 cm	0.00006	±	0.00001	10	0.00001	±	<0.00001
Outside Diameter	±0.05 cm	0.00005	±	0.00001	5	0.00001	±	<0.00001
Outside Length	± 0.1 cm	0.00038	±	0.00001	10	0.00004	±	<0.00001

2.2.5 Core Support Structure

Two grid plates, four grid plate spacer tubes, ten fuel clips, and five aluminum shims were used to hold the fuel in place within the core. The experimenter believes that the aluminum shims rather than the fuel clips were used to hold the outermost fuel tubes in place in the critical configurations.

The grid plates were included in the detailed benchmark model. The uncertainty in the grid plate mass, thickness, and diameter of the grid plate holes was evaluated. The 1σ uncertainty in the mass was ±1 g. The 1σ uncertainty in the thickness was ±0.001 cm. The diameter of the grid plate holes was not given but was modeled as being 1.284 cm. (This diameter is equal to the arbitrarily chosen inside diameter of the grid plate spacer tubes, see below.) The grid plate hole diameter could have been as little as 1.27 cm, the outside diameter of the fuel tubes, thus the uncertainty in the grid plate hole diameter was taken to be ±0.014 cm, bounding with a uniform distribution. Mass was conserved when evaluating the uncertainty in the plate thickness and the hole diameter. The effect of these uncertainties is given in Table 2-8.

Table 2-8. Uncertainty in Grid Plate Dimensions.

Case	Deviation	Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	σ
Mass	±10 g	-0.00001	±	0.00004[(a)]	10	<0.00001	±	<0.00001
Thickness	±0.01 cm	<0.00001	±	0.00004[(a)]	10	<0.00001	±	<0.00001
Hole Diameter	+0.014 cm	-0.00006	±	0.00004	$\sqrt{3}$	-0.00003	±	0.00002

(a) Despite using a scaling factor the Δk_{eff} is less than σ_{MC}, which is small, thus this uncertainty has a negligible effect as is seen in Table 2-22.

The placement of the grid plate spacer tube was of some concern. Based on the distribution of fuel in the core tank, there was no space for the 1.37-cm-OD spacer tubes; the inside diameter of the tubes would have been too small for them to fit around fuel tubes. It is believed that the wall thickness of the spacer tubes was incorrectly reported. In the detailed model, the spacer tubes had an outside diameter of 1.37 cm. The wall thickness was arbitrarily decreased to 0.043 cm so that the inside diameter of the tubes was 1.284 cm and the spacer tubes would fit around the fuel tubes. The 4 spacer tubes were modeled as being 90° apart at a radius of 10.433 cm. The effect of removing the grid plate spacer tubes was small (see Section 3.1.2); thus, it was judged that the uncertainty in the spacer tube dimensions and placement would be negligible.

There were no dimensions or masses provided for the five aluminum shims used to hold the fuel tubes in place. The shims were likely about 27° segments to fit tightly between the core tank and the fuel tubes. The aluminum shims were assumed to be made up of the same material as the core tank (Type 1100 Aluminum). A nominal density of 2.70 g/cm^3 was used in the model. The height of the shims was assumed to be the same as the height of the shims used in part one of the experimental series (see Reference 1). Because the effect of removing the shims was negligible (see Section 3.1.2), it was judged that the uncertainty in the aluminum shim dimensions and density would also have been negligible.

2.2.6 Support Plate Dimensions

The support structure of the vertical assembly machine provided some additional reflection to the core. The dimensions of the support plates are given in Table 1-4, except for the mass of the stainless steel plate, which should have been 31.2 kg, as given in Reference 4. Each dimension was perturbed by 10 times the uncertainty (10σ). Results are given in Table 2-9.

Table 2-9. Uncertainty in Support Plate Dimensions.

Case	Deviation	Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	σ
Lower Aluminum Support Plate								
Mass	±0.01 kg	0.00002	±	0.00001	10	<0.00001	±	<0.00001
Height/Thickness	±0.1 cm	0.00004	±	0.00001	10	<0.00001	±	<0.00001
Diameter	±0.1 cm	0.00002	±	0.00001	10	<0.00001	±	<0.00001
Upper Aluminum Support Plate								
Mass	±0.01 kg	0.00001	±	0.00001	10	<0.00001	±	<0.00001
Height/Thickness	±0.1 cm	0.00001	±	0.00001	10	<0.00001	±	<0.00001
Diameter	±0.1 cm	<0.00001	±	0.00001[(a)]	10	<0.00001	±	<0.00001
Stainless Steel Support Plate								
Mass	±1 kg	0.00006	±	0.00001	10	0.00001	±	<0.00001
Height/Thickness	±0.1 cm	0.00001	±	0.00001	10	<0.00001	±	<0.00001
Diameter	±0.1 cm	0.00001	±	0.00001	10	<0.00001	±	<0.00001
Iron Reflector Support Plate								
Mass	±1 kg	<0.00001	±	0.00001[(a)]	10	<0.00001	±	<0.00001
Height/Thickness	±0.1 cm	0.00001	±	0.00001	10	<0.00001	±	<0.00001
Outside Dimensions	±1 cm	0.00003	±	0.00001	10	<0.00001	±	<0.00001
Inside Diameter	±0.1 cm	0.00001	±	0.00001	10	<0.00001	±	<0.00001

(a) Despite using a scaling factor the Δk_{eff} is less than σ_{MC}, which is small, thus this uncertainty has a negligible effect as is seen in Table 2-22.

2.3 Evaluation of Material Properties

Material impurities were given for the uranium oxide and graphite, as well as the uranium isotopic composition, in References 1 and 4. ASTM standards were used for all other material compositions. When calculating atom densities, measured masses and calculated volumes were always used to find the material density, even if a density was reported. When calculating atom densities from material impurity data and composition data, typically three types of values were given: (1) a single value (i.e. 15 ppm or 20 wt.%), which gives the actual content of the element in the material; (2) a maximum value (i.e. < 15 ppm or < 20 wt.%), which gives the maximum amount of an element present in the material; and (3) a range of values (i.e. 15 -17 ppm or 20 – 22 wt.%), which gives the minimum and maximum amount of an element present in the material. When calculating atom densities for the models, the actual content of the element, one half of the maximum element content, and/or the middle of the range of element content were used for the material composition, respectively. When perturbing compositions, single values were perturbed by plus or minus the square root of the value,[a] maximum values were varied between zero and the maximum, and range values were varied between the top and bottom of the range. These uncertainties are assumed to be bounding with a uniform probability distribution. This method could lead to an overestimate, but was used as a best estimate of the true uncertainty.

[a] Using the square root of the content as the uncertainty was used because compositions come from spectrographic results, which report contents in ‘counts.’ The uncertainty in the composition can then be defined as the square root of the value, as is commonly assumed for spectrographic measurements with a Poisson distribution. It is believed that this method provides an overestimate of the actual uncertainty.

2.3.1 Graphite Composition

The reflectors were Type ATL Graphite. A spectrochemical analysis of the graphite was given previously in Table 1-7. The impurity content was calculated and perturbed using the methods described in Section 2.3. All impurities were varied simultaneously and results are summarized in Table 2-10.

Table 2-10. Uncertainty in Graphite Composition.

Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	σ
-0.00037	±	0.00004	$\sqrt{3}$	-0.00021	±	0.00002

2.3.2 Uranium Oxide Composition

The fuel was pellets of uranium oxide, UO_2. A spectrochemical analysis of the fuel was given previously in Table 1-5. The impurity content was calculated and perturbed using methods described in Section 2.3. All impurities were varied simultaneously and results are summarized in Table 2-11.

Table 2-11. Uncertainty in Fuel Composition.

Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	σ
-0.00018	±	0.00001	$\sqrt{3}$	-0.00011	±	0.00001

The oxygen to uranium ratio in the fuel would have been 2.0. The ratio could not have been less than 2.0 and no more than 2.02.[a] The uranium to oxygen ratio was 2.0 + 0.02, which is a one-sided bounding uncertainty. Results are summarized in Table 2-12.

Table 2-12. Uncertainty in Oxygen to Uranium Ratio.

Deviation	Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	σ
±0.05	-0.00060	±	0.00001	$2.5 \cdot 2\sqrt{3}$	-0.00024	±	<0.00001

The uncertainty in the isotopic distribution of uranium was also evaluated. According to the experimenter, the uncertainty in the ^{234}U, ^{235}U, and ^{236}U content was ±0.005 wt.%; however, typical uncertainties for this time period at Oak Ridge National Laboratory would have been 0.0017 wt.%, 0.0177 wt.%, and 0.0130 wt.% for the ^{234}U, ^{235}U, and ^{236}U, respectively. These typical values were used for the uranium isotopic uncertainties rather than the values given by the experimenter. It was assumed that the ^{238}U content was found by subtracting the ^{234}U, ^{235}U, and ^{236}U contents from unity; thus, when the content of a single isotope was perturbed, the ^{238}U content was varied to maintain unity. ^{234}U and ^{235}U were varied individually by ±0.5 wt.%, while the ^{236}U was varied by ±0.45 wt.%. Results are summarized in Table 2-13.

[a] Personal communication between J.T. Mihalczo and a Y-12 chemist, August 14, 2012.

Table 2-13. Uncertainty in Uranium Isotopic Distribution.

Case	Deviation	Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	σ
^{234}U	±0.5 wt.%	0.00014	±	0.00001	294.12	<0.00001	±	<0.00001
^{235}U	±0.5 wt.%	0.00205	±	0.00001	28.25	0.00007	±	<0.00001
^{236}U	±0.45 wt.%	-0.00007	±	0.00001	36.62	<0.00001	±	<0.00001

2.3.3 Fuel Tube Composition

The fuel pellets were in Type 347 Stainless Steel tubes. The composition of the Type 347 Stainless Steel was not given, so a standard composition was used. The standard composition and the model composition, as determined using the methods described in Section 2.3, are given in Table 2-14. The perturbation of the composition was performed on all elements simultaneously using the method described in Section 2.3. When the composition was varied, the iron content was adjusted to maintain a balance. The results of the perturbation of the composition are given in Table 2-15.

Table 2-14. Type 347 Stainless Steel Composition.

Element	Standard Composition[a][b]	Model Composition
Iron, Fe	Balance	68.7225 wt.%
Carbon, C	0.08 wt.%	0.04 wt.%
Manganese, Mn	2.00 wt.%	1.00 wt.%
Silicon, Si	1.00 wt.%	0.50 wt.%
Chromium, Cr	17.0-19.0 wt.%	18.0 wt.%
Nickel, Ni	9.0-13.0 wt.%	11.0 wt.%
Phosphorus, P	0.045 wt.%	0.0225 wt.%
Sulfur, S	0.030 wt.%	0.0150 wt.%
Tantalum+Niobium, Ta + Nb	10×C min., 1.0 wt.% max	0.7 wt.% total 0.644 wt.% Nb, 0.056 wt.% Ta[c]

(a) ASTM Standard A 312/A 312M-09.
(b) Single values are maximum values.
(c) The split between Nb and Ta was determined based on the natural abundances of Nb and Ta in the earth's crust, 8 and 0.7 ppm, respectively. Shaw, R., Goodenough, K., et. al., "Niobium-tantalum," British Geological Survery, April 2011, www.MineralsUK.com, (accessed June 8, 2012).

Table 2-15. Uncertainty in Fuel Tube Composition.

Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	σ
-0.00049	±	0.00001	$\sqrt{3}$	-0.00028	±	0.00001

2.3.4 Core Tank Composition

The core tank was made of Type 1100 Aluminum. The composition of the aluminum was not given, so a standard composition was used. Silicon and iron content was given as a maximum of the sum of the two elements. For the model, one half of the maximum was assumed as the total for both elements; thus, one quarter of the maximum content was used for silicon and iron. All other element contents were found using the methods described in Section 2.3. Aluminum was varied to maintain unity. For all of the elements except silicon and iron, perturbation methods described in Section 2.3 were used. For the uncertainty perturbation of iron and silicon, the iron content was set to the maximum, (0.95 wt. %) for the upper uncertainty, and silicon set to zero and vice versa for the lower uncertainty. The standard composition and the model composition are given in Table 2-16. The results of the perturbation of the composition are given in Table 2-17.

Table 2-16. Type 1100 Aluminum Composition.

Element	Standard Composition[a][b]	Model Composition
Aluminum, Al	99.00 wt.% minimum	99.325 wt.%
Copper, Cu	0.05-0.20 wt.%	0.125 wt.%
Silicon, Si	0.95 wt.% Si + Fe	0.2375 wt.%
Iron, Fe		0.2375 wt.%
Manganese, Mn	0.05 wt.%	0.025 wt.%
Zinc, Zn	0.1 wt.%	0.05 wt.%
Other[c]	0.03 wt.% each 0.015 wt. total	0.00 wt.%

(a) ASTM Standard B 209 - 07.
(b) Single values are maximum values.
(c) 'Other' impurities were assumed have a negligible effect on k_{eff} and thus were not included in the benchmark model.

Table 2-17. Uncertainty in Core Tank Composition.

Δk_{eff}	$\pm$	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	$\pm$	σ
-0.00004	$\pm$	0.00001	$\sqrt{3}$	-0.00002	$\pm$	0.00001

2.3.5 Composition of Core Support Structure

The grid plates were composed of Type 1100 Aluminum. The standard composition of Type 1100 Aluminum is given in Table 2-16. The composition was varied by the same method used for the evaluation of the core tank composition. The effect of the uncertainty in the grid plates is given in Table 2-18.

Table 2-18. Uncertainty in Grid Plate Composition.

Δk_{eff}	$\pm$	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	$\pm$	σ
-0.00007	$\pm$	0.00004	$\sqrt{3}$	-0.00004	$\pm$	0.00002

The grid plate spacer tubes were made of Type 347 Stainless Steel (i.e., the standard composition given in Table 2-14). It was judged that the uncertainty in the grid plate spacer tube composition would have a negligible effect (see Section 3.1.2), based on the small bias for removing the tubes.

According to the experimenter, five shims, similar to the shims used in the first experiment, were used to hold the fuel in place. The shims were included in the detailed model as 1.91-cm tall 27° sections of Type 1100 Aluminum. Because the effect of removing these shims from the model is negligible (see Section 3.1.2), it is assumed that the uncertainty in the shim composition is also negligible.

2.3.6 Composition of Support Plates

The support plates were composed of Type 1100 Aluminum, Type 304 Stainless Steel, and iron (low carbon steel). The standard compositions for these materials are given in Tables 2-16, 2-19, and 2-20, respectively. The composition for the plates was perturbed using the methods described in Section 2.3 and Section 2.3.4 for the aluminum composition. The composition of each plate was perturbed individually, except for the two aluminum plate compositions, which were perturbed at the same time. The results of these perturbations are summarized in Table 2-21.

Table 2-19. Type 304 Stainless Steel Composition.

Element	Standard Composition[(a)(b)]	Model Composition
Iron, Fe	Balance	69.9225 wt.%
Carbon, C	0.08 wt.%	0.04 wt.%
Manganese, Mn	2.00 wt.%	1.00 wt.%
Silicon, Si	1.00 wt.%	0.50 wt.%
Chromium, Cr	18.0-20.0 wt.%	19.00 wt.%
Nickel, Ni	8.0-11.0 wt.%	9.50 wt.%
Phosphorus, P	0.045 wt.%	0.0225 wt.%
Sulfur, S	0.03 wt.%	0.015 wt.%

(a) ASTM Standard A 312/A 312M-09.
(b) Single values are maximum values.

Table 2-20. Carbon Steel Composition.

Element	Standard Composition[(a)]	Model Composition
Iron, Fe	Balance	98.305 wt.%
Carbon, C	0.25 wt.%	0.25 wt.%
Magnesium, Mg	0.80–1.20 wt.%	1.00 wt.%
Phosphorus, P	0.04 wt.% max	0.02 wt.%
Sulfur, S	0.05 wt.% max	0.025 wt.%
Silicon, Si	0.40 wt.% max	0.20 wt.%
Copper, Cu	0.20 wt.%	0.20 wt.%

(a) ASTM Standard A 36/A36M 08.

Table 2-21. Uncertainty in Support Plate Compositions.

Case	Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	σ
Type 1100 Aluminum[(a)]	0.00001	±	0.00001	$\sqrt{3}$	<0.00001	±	0.00001[(b)]
Type 304 Stainless Steel	0.00006	±	0.00001	$\sqrt{3}$	0.00003	±	0.00001
Carbon Steel	-0.00003	±	0.00001	$\sqrt{3}$	-0.00002	±	0.00001

(a) The compositions of both aluminum plates were perturbed at the same time.
(b) Δk_{eff} is less than σ_{MC}, which is small, thus this uncertainty has a negligible effect as is seen in Table 2-22.

2.4 Temperature Uncertainty

The experiments were carried out at 22°C or 295.15 K. The temperature in the facility could have varied a few degrees (1°C is 1σ). The temperature coefficient for bare, highly enriched uranium metal experiments at this facility was 0.3 ¢/ΔT(°C). The temperature coefficient for this experiment would have been less than this because of the reflector and thus the effect of the uncertainty in the temperature on k_{eff} would have been negligible.[a]

2.5 Total Uncertainty in Critical Configuration

All 1σ uncertainties were compiled and are summarized in Table 2-22. An uncertainty is considered to have a negligible effect (NEG) when the magnitude of the 1σ Δk_{eff} is ≤0.00010. The main contributors to the total uncertainty were the inner diameter of the lower side reflector, the mass of the upper top reflector, and the graphite and fuel tube composition. The total uncertainty was 0.00059 Δk_{eff}. The experimental uncertainty in HEU-COMP-FAST-001 was approximately 0.0005 Δk_{eff}; it is believed that the higher uncertainty in this experiment is due to the more complicated reflector configuration. The statistical uncertainties in the Monte Carlo calculation were not preserved in Table 2-22, as they were all considered negligible, but can be found in the preceding sections if necessary.

The described experiment is judged to be acceptable as a criticality safety benchmark experiment.

[a] Personal email communication with J.T. Mihalczo, November 14, 2011

Table 2-22. Total Uncertainty in Experimental Configuration.

		Parameter Value[a]	$\pm\Delta k_{eff}$ (1σ)
Reactivity of Critical Configuration		-1 ± 0.2 ¢	NEG
Dimension Uncertainties			
Lower Side Reflector	Mass	388.6 ± 0.1 kg	NEG
	Height	46.63 ± 0.01 cm	NEG
	Thickness (radial)	27.90 ± 0.01 cm	-0.00012
	Inner Diameter	26.13 ± 0.01 cm	-0.00026
Upper Side Reflector	Mass	55.0 ± 0.1 kg	0.00011
	Height	7.63 0.01 cm	NEG
	Thickness (radial)	25.53 ± 0.01 cm	NEG
	Inner Diameter	26.14 ± 0.01 cm	-0.00015
Lower Top Reflector	Mass	124.1 ± 0.1 kg	NEG
	Height/Thickness	15.25 ± 0.01 cm	NEG
	Diameter	76.2 ± 0.1 cm	-0.00018
Upper Top Reflector	Mass	28.5 ± 0.1 kg	0.00022
	Height/Thickness	8.36 ± 0.01 cm	NEG
	Diameter	50.8 ± 0.1 cm	NEG
Bottom Reflector	Mass	19.21 ± 0.1 kg	0.00016
	Height/Thickness	22.86 ± 0.01 cm	NEG
	Diameter	25.42 ± 0.01 cm	NEG
Foil Hole	Plug Diameter	1.11 ± 0.1 cm	NEG
	Foil Hole Diameter	1.27 ± 0.01 cm	NEG
Fuel	Fuel Length	29.88 ± 0.01 cm[b]	NEG
	Fuel Diameter	1.141 ± 0.001 cm[b]	NEG
Fuel Tube	Fuel Tube Wall Thickness	0.051 ± 0.004 cm[b]	NEG
	Fuel Tube Length	30.48 ± 0.01 cm[b]	NEG
	Fuel Tube OD	1.27 ± 0.00423 cm[b]	NEG
	Fuel Mass	295.818 ± 0.063 g	0.00010
	Fuel Tube Mass	46.01114 ± 0.032 g	NEG
	Fuel Pitch	1.506 ± 0.001 cm[b]	NEG
	Fuel Placement	Section 2.2.3	NEG
Core Tank	Mass	2.125 ± 0.001 kg	NEG
	Side Wall Thickness	0.254 ± 0.001 cm	NEG
	Bottom Thickness	0.33 ± 0.01 cm	NEG
	OD	25.96 ± 0.01 cm	NEG
	Outside Length	31.04 ± 0.01 cm	NEG
Core Support Structure	Mass	139 ± 1 g	NEG
	Thickness (radial)	0.314 ± 0.001 cm	NEG
	Hole Diameter	1.284 ± 0.014/√3 cm	NEG
	Grid Plate Spacer Tubes	Section 2.2.5	NEG
	Aluminum Shims	Section 2.2.5	NEG

Table 2-22. Total Uncertainty in Experimental Configuration.

		Parameter Value[(a)]	$\pm\Delta k_{eff}$ (1σ)
Reactivity of Critical Configuration		-1 ± 0.2 ¢	NEG
Dimension Uncertainties			
Lower Aluminum Support Plate	Mass	2.787 ± 0.001 kg	NEG
	Height/Thickness	0.63 ± 0.01 cm	NEG
	Diameter	45.72 ± 0.01 cm	NEG
Upper Aluminum Support Plate	Mass	2.787 ± 0.001 kg	NEG
	Height/Thickness	1.94 ± 0.01 cm	NEG
	Diameter	21.6 ± 0.01 cm	NEG
Stainless Steel Support Plate	Mass	31.2 ± 0.1 kg	NEG
	Height/Thickness	2.38 ± 0.01 cm	NEG
	Diameter	45.72 ± 0.01 cm	NEG
Iron Table	Mass	136.7 ± 0.1 kg	NEG
	Height/Thickness	1.27 ± 0.01 cm	NEG
	Outside Dimensions	121.9 ± 0.1 cm	NEG
	Inside Diameter	26.67 ± 0.01 cm	NEG
Composition Uncertainties			
Graphite Composition		Section 2.3.1	-0.00021
Fuel Composition		Section 2.3.2	-0.00011
Oxygen to Uranium Ratio		2.00 ± $0.02/2\sqrt{3}$	NEG
^{234}U Abundance		1.01 ± 0.005 wt.%	NEG
^{235}U Abundance		93.15 ± 0.005 wt.%	NEG
^{236}U Abundance		0.47 ± 0.005 wt.%	NEG
Fuel Tube Composition		Section 2.3.3	-0.00028
Core Tank Composition		Section 2.3.4	NEG
Grid Plate Composition		Section 2.3.5	NEG
Grid Plate Spacer Tube Composition		Section 2.3.5	NEG
Aluminum Shim Composition		Section 2.3.5	NEG
Aluminum Support Plate Composition		Section 2.3.6	NEG
Stainless Steel Support Plate Composition		Section 2.3.6	NEG
Iron Table Composition		Section 2.3.6	NEG
Temperature Uncertainty		Section 2.4	NEG
Total		**0.00060**	

(a) Uncertainty is 1σ uncertainty unless stated otherwise.
(b) This uncertainty is 25% systematic and 75% random (see Section 2.2.2)

3.0 BENCHMARK SPECIFICATIONS

Detailed and simple benchmark models were created with MCNP5 using ENDF/B-VII.0 neutron cross section libraries. The biases of any simplifications or assumptions were calculated for both the detailed and simple models. All models were run in MCNP5 such that the statistical uncertainty (1σ) of k_{eff} was not more than 0.00006, and for many cases it was 0.00002. Benchmark specifications for both the detailed and a simple model are described in Sections 3.2 and 3.3.

The method for determining the simplification bias was as follows. First, the detailed benchmark model was created. The biases of simplifications in the detailed benchmark model were calculated. This included the bias of room return, replacing air with void, and the modeling of the grid plates. Next, the biases of individual simplifications used to obtain the simple benchmark model were calculated. This included the bias of removal of the support structures within the core, homogenization of the fuel and fuel tubes, and the removal of material impurities. The overall biases for the detailed and simple benchmark models were found by comparing the benchmark models to a model with no simplifications.

A simplification is considered negligible if the effect on k_{eff} is $\leq$0.00010.

3.1 Description of the Model

3.1.1 Description of the Detailed Benchmark Model Simplifications

3.1.1.1 Room Return and Effect or Air

As stated in Reference 2, the vertical assembly machine was located in the experiment cell such that the center of the core was 12.336 ft from the 4.92-ft-thick west wall, 12.79 ft from the 1.97-ft-thick north wall, and 9.19 ft above the concrete floor in the 35.10×35.10-ft-square 29.86-ft-tall room. The walls were modeled as described (i.e., the east and south walls were modeled as being 2 ft thick) with a 2-ft-thick concrete floor and ceiling, using Oak Ridge concrete (HEU-MET-FAST-081).[a] The results of this simplification bias are provided in Table 3-1.

The simplification bias of removing air (density of 1.19 kg/m^3) from the model and replacing it with void is summarized in Table 3-1.

3.1.1.2 Grid Plates

As can be seen in Figure 1-5, the grid plate holes were cut through the edge of the grid plate in twenty locations. Rather than model each cut out explicitly, a modeling simplification was used. The cut outs were modeled as being five circle segments removed from the grid plate flush with the surface of the 4 fuel tubes. The circle segments were 27° sections and the mass conserved. This simplification is shown in Figure 3-1.

The twelve rods at the periphery of the core that have been moved in are highlighted in red. These rods were moved in until they were just touching the other fuel rods.

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[a] *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation*, ORNL/TM-2005/39 Version 5, Volume III, Section M.8, Oak Ridge National Laboratory, April 2005.

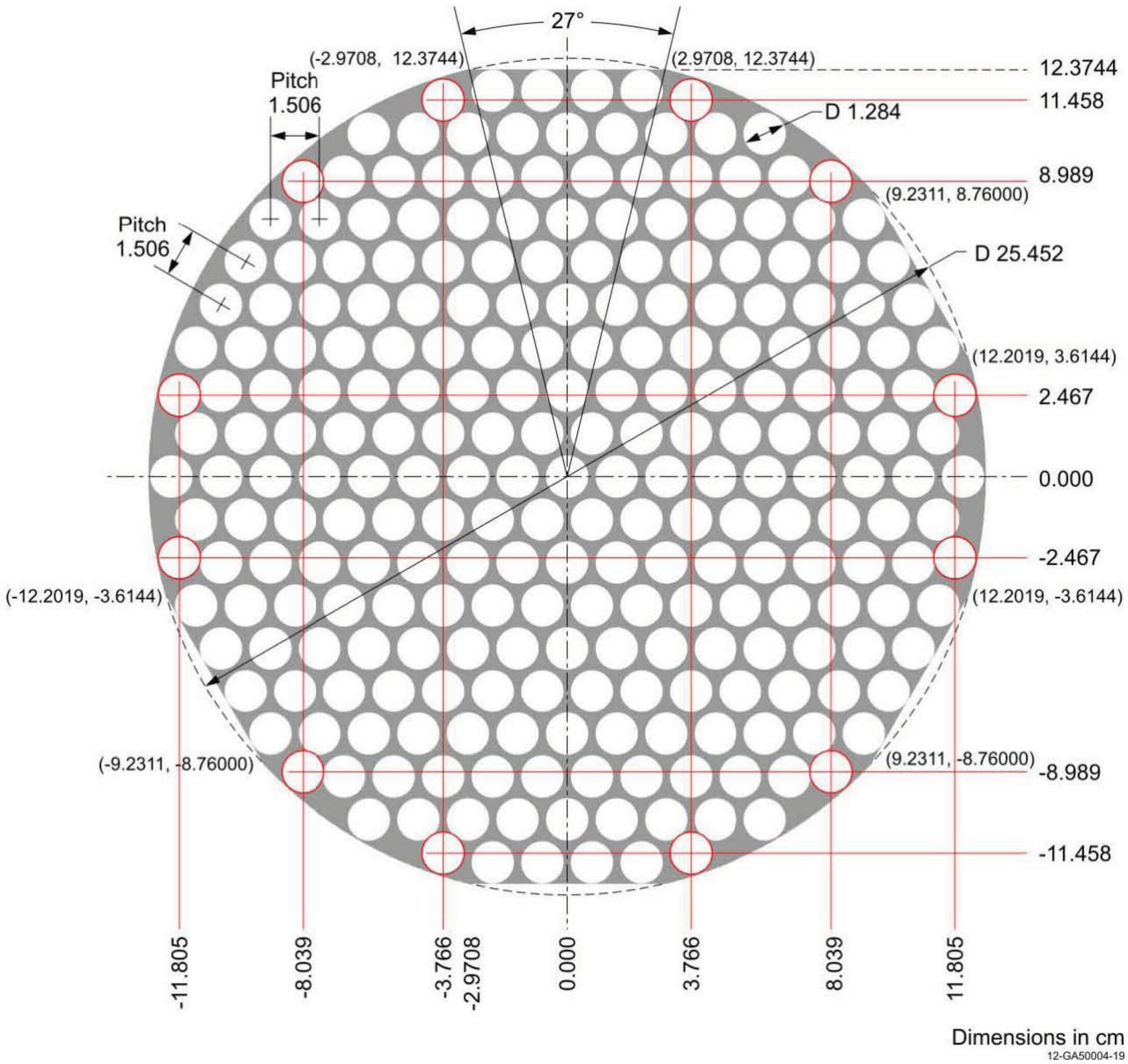

Figure 3-1. Detailed Benchmark Model of Grid Plates.

To determine the bias associated with this modeling simplification, a second grid plate geometry was modeled, as is shown in Figure 3-2. In this model, the mass of the grid plate was spread over the area of the cut outs.

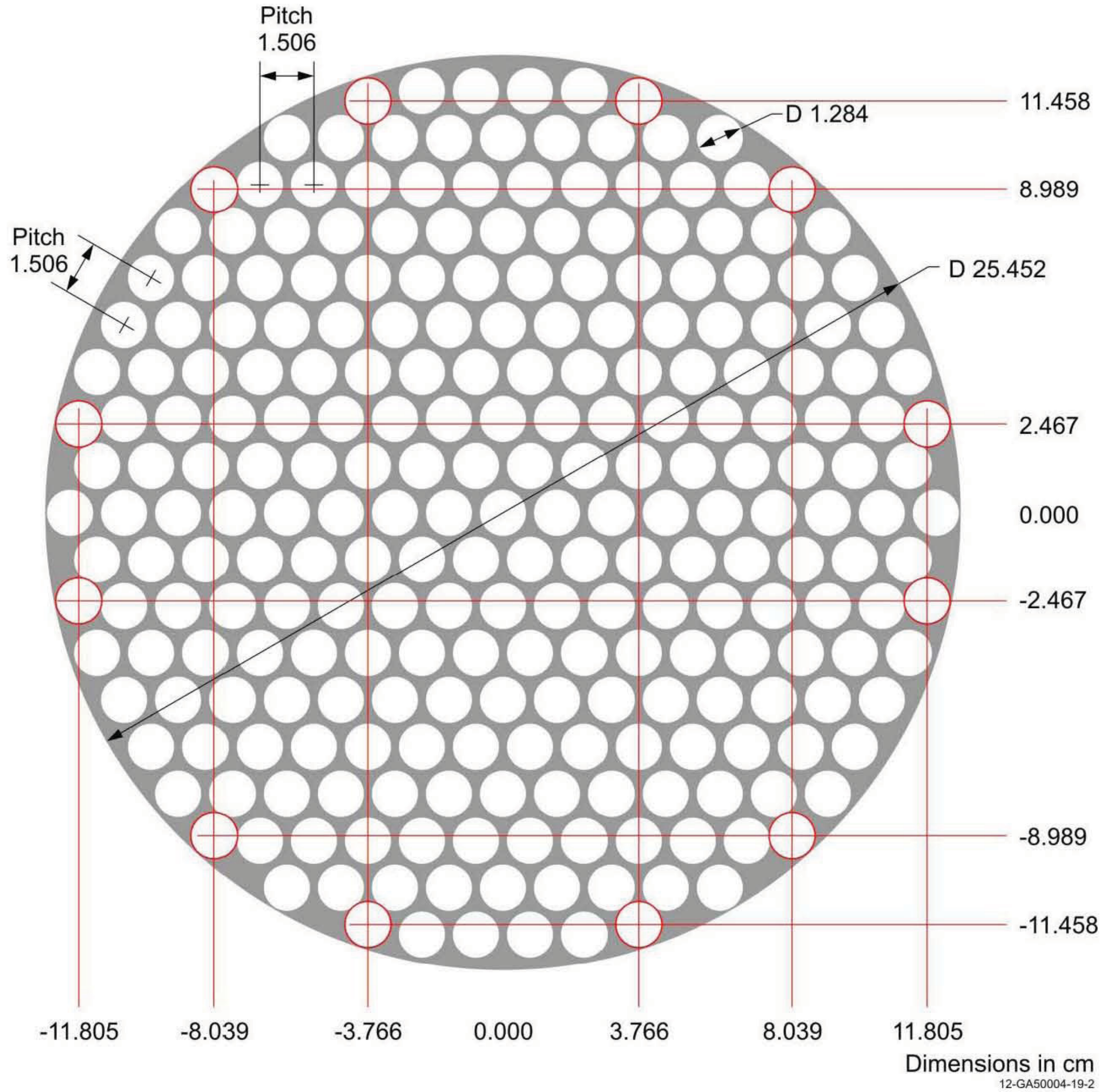

Figure 3-2. Detailed Benchmark Model of Grid Plates.

It was found that the effect of modeling the cut out was about 0.00012 ± 0.00008 Δk_{eff}. This approach was used due to the uncertainty in the exact dimensions of the grid plate at the edges. The reactivity of the true grid plate would have been somewhere between the reactivity of the models as shown in Figures 3-1 and 3-2; thus, the 0.00012 ±0.0008 Δk_{eff} was taken to be half bias and half uncertainty. Thus, the modeling bias for the grid plates was 0.00006 ± 0.00009 Δk_{eff}, which is negligible.

3.1.1.3 Fuel Tube End Caps

The end caps in the fuel tubes were not solid cylinders but rather cup like, which created wells. The end caps were modeled as solid plugs with a reduced density. The height of each plug was found by taking half of the difference between the fuel tube length (30.48 cm) and the length of 26 stacked pellets (29.88 cm). Thus, the bias of this model simplification was believed to be negligible.

3.1.1.4 Temperature

The experiments were performed at 22°C or 295.15 K. The model temperature was 293.6 K. The bias of this temperature change is negligible.

3.1.1.5 Summary of Simplification Biases for Detailed Benchmark Model

The overall simplification bias was found by comparing the most detailed model to the detailed benchmark model. The overall simplification bias is given in Table 3-1. The biases associated with the individual simplifications are also given in Table 3-1 for reference.

Table 3-1. Summary of Simplification Biases for the Detailed Benchmark Model.

	Detailed Benchmark Model
Room Return	-0.00027 ± 0.00003
Replacing Air with Void	-0.00011 ± 0.00003
Grid Plate Simplification	NEG
Fuel Tube End Cap Simplification	NEG
Temperature Bias	NEG
Overall Simplification Bias[(a)]	**-0.00035 ± 0.00006**

(a) Found by comparing the detailed benchmark model against a model with no simplifications.

3.1.2 Description of the Simple Benchmark Model Simplifications

The simplification biases applied to the detailed benchmark model would also have applied to the simple benchmark model. These are included in Table 3-2.

3.1.2.1 Simplification of Reflectors

The inside diameter of the lower and upper section of the side reflector were 26.13 and 26.14 cm, respectively. For ease of modeling, these diameters were averaged to 26.135 cm in the simple benchmark model. The bias associated with this simplification is given in Table 3-2.

Six radial foil holes were present in the lower side reflector and one axial hole in the top reflectors. Five of the side reflector holes were also plugged, as well as the hole through the top reflectors. These holes and plugs were homogenized in to the lower side reflector and the top reflectors. The effect of this simplification is given in Table 3-2.

As was discussed in Section 3.1.1.3, the inside diameters of the lower and upper side reflector were averaged. The effect of this simplification is given in Table 3-2.

3.1.2.2 Simplification of Core Region

The support structure for the fuel tubes in the core was removed in the simple benchmark model. The five aluminum shims were removed, the grid plate spacer tubes were removed, and the grid plates were removed. The biases of these simplifications are given in Table 3-2.

3.1.2.3 Simplification of Fuel

The fuel tube geometry was simplified by homogenizing the mass of the fuel tube and the two end caps (46.01114 g) over the entire fuel tube volume, rather than having separate material densities for the fuel tube and the two end caps. The mass of the fuel (295.818 g) was homogenized over the length of the fuel (1.141-cm diameter, 29.88-cm long). The biases of the simplifications are also given in Table 3-2.

3.1.2.4 Removal of Impurities

The impurities, as given in Tables 1-5 and 1-7, were replaced with void in the fuel and the graphite. This reduced the total material weight percentage for the fuel and graphite. The effect on k_{eff} of removing these impurities is given in Table 3-2.

3.1.2.5 Summary of Simplification Biases for Simple Benchmark Model

The overall simplification bias was found by comparing the simple benchmark model against a model with no simplifications. Because the bias was relatively large, the calculation was repeated using other cross section libraries (JEFF-3.1 and JENDL-3.3). The overall simplification bias is given in Table 3-2. The biases associated with the individual simplifications are also given in Table 3-2 for reference.

Table 3-2. Summary of Simplification Biases for Simple Benchmark Model.

	Simple Benchmark Model
Room Return	-0.00027 ± 0.00003
Replacing Air with Void	-0.00011 ± 0.00003
Homogenizing Holes and Plug in Reflectors	NEG
Temperature Bias	NEG
Side Reflector Inside Diameter Averaging	-0.00013 ± 0.00008
Removing Shims	NEG
Removing Grid Plate Spacer Tubes	-0.00015 ± 0.00007
Removing Grid Plates	-0.00104 ± 0.00008
Grid Plate Simplification	NEG
Fuel Tube End Cap Simplification	NEG
Simplification of Fuel Tube	-0.00066 ± 0.00008
Homogenization of Fuel	0.00022 ± 0.00007
Removing Fuel Impurities	0.00016 ± 0.00008
Removing Graphite Impurities	0.00105 ± 0.00008
Overall Simplification Bias[(a)]	**-0.00135 ± 0.00006**
ENDF/B-VII.0	-0.00138 ± 0.00006
JEFF3.1	-0.00135 ± 0.00006
JENDL-3.3	-0.00131 ± 0.00006

(a) Found by comparing the simple benchmark model against a model with no simplifications.

3.1.3 Total Bias for Detailed and Simple Benchmark Models

In addition to the simplification bias discussed in Sections 3.1.1 and 3.1.2, there is an experimental bias from the measured reactivity of the critical configuration, -1 ¢. In terms of Δk_{eff}, the reactivity would be -0.00007 ± 0.000008 (see Section 2.1). The experimental bias and the simplification biases were added to obtain the total bias. The total bias of the benchmark model is given in Table 3-3.

Table 3-3. Summary of Benchmark Model Biases.

	Detailed Benchmark Model	Simple Benchmark Model
Experimental Bias	-0.00007 ± 0.000015[(a)]	-0.00007 ± 0.000015[(a)]
Overall Simplification Bias[(b)]	-0.00035 ± 0.00006	-0.00135 ± 0.00006
Total Bias	-0.00042 ± 0.00006	-0.00142 ± 0.00006

(a) The uncertainty in the measured reactivity of the critical configuration was included in the measurement uncertainty given in Section 2.
(b) Found by comparing the detailed or simple benchmark model against a model with no simplifications.

3.2 Benchmark Model Dimensions

3.2.1 Detailed Benchmark Model Dimensions

3.2.1.1 Reflectors

The dimensions of the five sections of the graphite reflector are given in Table 3-4. The lower side reflector had six 1.27-cm-diameter radial foil holes 7.63 cm below the midplane of the core. Five of the six holes were filled with 1.11-cm graphite plugs. Similarly, a 1.27-cm-diameter radial hole ran axially through the center of the lower and upper top reflectors and was filled with a 1.11-cm graphite plug. The dimensions of the reflector and location of the foil holes can be seen in Figure 3-3.

Table 3-4. Reflector Dimensions.

Side Reflector -Graphite (Type ATL)		
Height (cm)	Lower Section	46.63
	Upper Section	7.63
Thickness (cm)	Lower Section	27.9
	Upper Section	25.53
Inside Diameter (cm)	Lower Section	26.135
	Upper Section	26.135
Mass (kg)	Lower Section(a)	388.6
	Upper Section	55.0
Volume (cm^3)	Lower Section	220771.5(b)
	Upper Section	31617.01
Top Reflector Graphite (Type ATL)		
Height (cm)	Lower Section	15.25
	Upper Section	8.36
Diameter (cm)	Lower Section	76.2
	Upper Section	50.8
Mass (kg)	Lower Section	124.1
	Upper Section	28.5
Volume (cm^3)	Lower Section	69541.01(c)
	Upper Section	16941.8(d)
Bottom Reflector -Graphite (Type ATL)		
Height (cm)		22.86
Diameter (cm)		25.42
Mass (kg)		19.21
Volume (cm^3)		11601.58

(a) This mass includes the mass of the plugs.
(b) This volume does not include the volume of the 6 radial holes (35.3495 cm^3 per hole) but does include the volume of the 5 plugs (27.0014 cm^3 per plug).
(c) This volume does not include the volume of the axial hole (19.318 cm^3) but does include the volume of the plug (14.757 cm^3).
(d) This volume does not include the volume of the axial hole (10.590 cm^3) but does include the volume of the plug (8.090 cm^3).

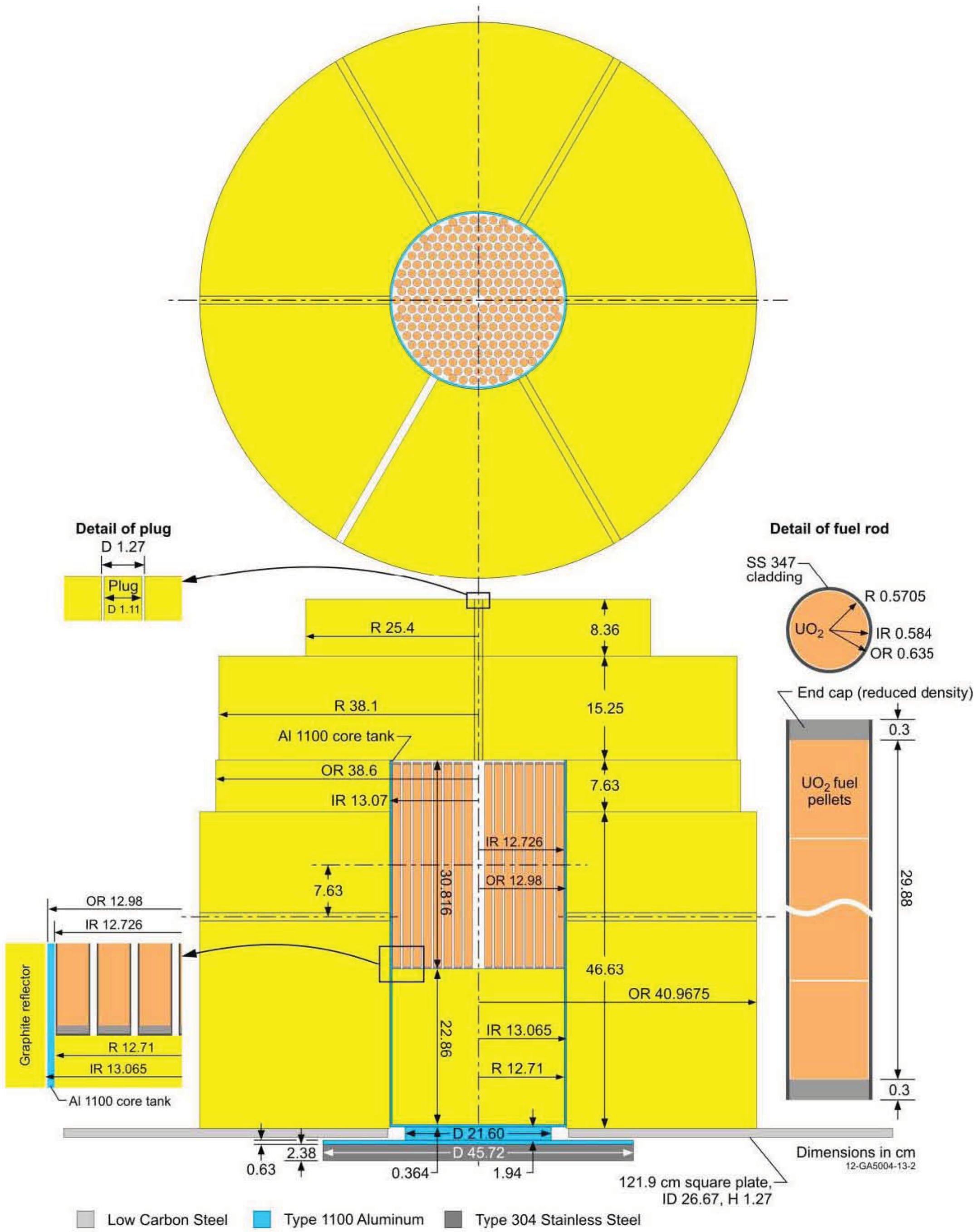

Figure 3-3. Reflector Dimensions in Detailed Benchmark Model.

3.2.1.2 Fuel and Fuel Tubes

The fuel tubes were modeled as 1.27-cm-OD stainless steel tubes with a 0.3-cm-tall end caps. The fuel region was made up of 26, 1.141-cm-diameter, 1.145-cm-tall pellets. Small voids between each pellet yielded a total fuel length of 29.88 cm. The dimensions of the fuel and fuel tubes are given in Figure 3-4. The volume of each pellet was 1.17076 cm^3 and the mass of 26 pellets was 295.818 g. The mass and volume of the fuel tube were 44.729 g and 5.95304 cm^3 while for one end cap, the measurements were 0.64107 g and 0.321438 cm^3.

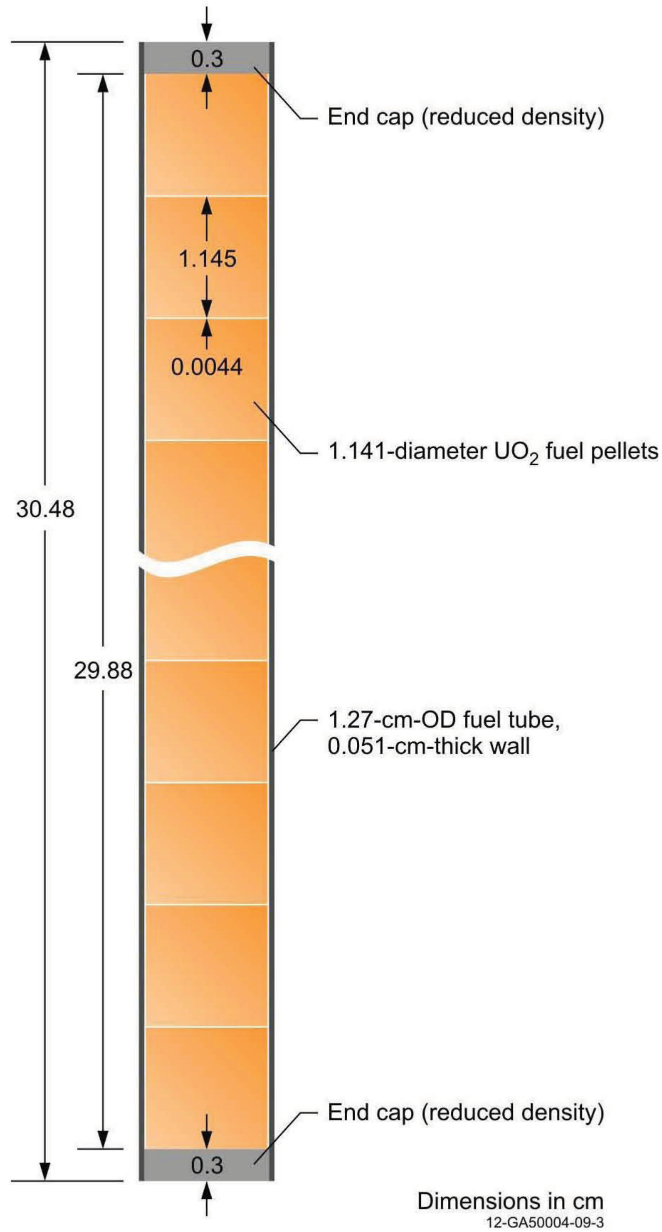

Figure 3-4. Fuel and Fuel Tube Dimensions in the Detailed Benchmark Model.

3.2.1.3 The Core

The core consisted of a 253 fuel tube array, a 1.506-cm-triangular pitch lattice with the centermost rod removed, which yielded a total of 252 fuel rods in the core. Grid plates, grid plate spacer tubes, and aluminum shims were used to hold the fuel tubes in place. The core support structure is shown in Figure 3-5.

The fuel tubes were held in place with two 0.317-cm-thick aluminum grid plates. The holes in the grid plates for the detailed benchmark model had a diameter of 1.284 cm and 27° circle segments on five sides of the grid plate represented the cutouts in the grid plate (see Figure 3-1). Each grid plate weighed 139 g and had a volume of 44.098 cm^3.

The lower grid plate was on top of the bottom reflector in the core tank; four grid plate spacer tubes, 27.94-cm long, support the upper grid plate. The grid plate spacer tubes have an outside diameter of 1.37 cm and a wall thickness of 0.043 cm. Each grid plate spacer tube had a mass and volume 37.5 g and 5.0086 cm^3.

On the five sides where the grid plate was cut out (see Figure 3-1), aluminum shims were used to hold in the four corresponding fuel tubes. The aluminum shims were modeled as 27° circle segments, 1.91-cm tall, located at the midplane of the core. The volume of each shim was 2.667 cm^3 and a nominal density of 2.70 g/cm^3 was used.

The core tank had an outside diameter of 25.96 cm, a side-wall thickness of 0.254 cm, a bottom thickness of 0.364 cm, and an outside length of 54.04 cm. The mass and volume of the core tank was 3.387 kg and 1293.692 cm^3.

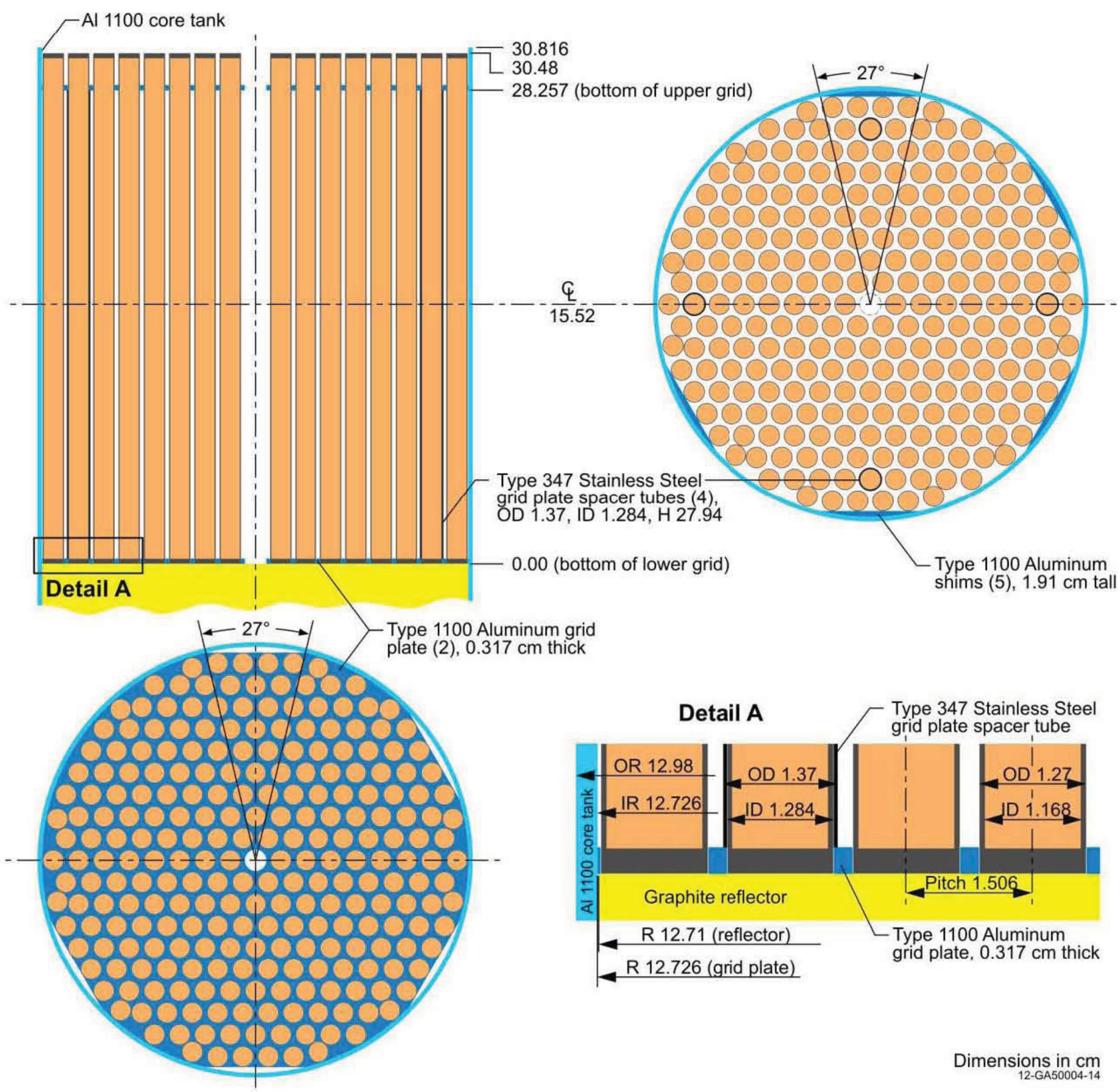

Figure 3-5. Core Support Structure Dimensions in the Detailed Benchmark Model.

3.2.1.4 Support Plates and Table

Two support plates were under the bottom of the core tank on the steel top of the vertical lift. The side and top reflector were placed on the upper iron support table. The dimensions of the support plates and the table are given in Table 3-5. The locations of the support plates and table can be seen in Figure 3-3.

Table 3-5. Support Plate Dimensions.

1.94-cm-Thick Type 1100 Aluminum Plate	21.60 cm Diameter, 1.920 kg
0.63-cm-Thick Type 1100 Aluminum Plate	45.72 cm Diameter, 2.787 kg
2.38-cm-Thick Type 304 Stainless Steel Table Top	45.72 cm Diameter, 31.2 kg
1.27-cm-Thick Iron Table	121.9×121.9 cm square table with 26.67 cm diameter cutout[(a)], 136.7 kg

(a) A cut out in the middle of the table allowed the core and bottom reflector to be lifted into the side reflector.

3.2.2 Simple Benchmark Model Dimensions

3.2.2.1 Reflectors

The reflectors in the simple benchmark model were solid masses of graphite. The dimensions of the reflectors are given in Figure 3-6 (the dimensions are the same as in the detailed benchmark model except the foil holes and plugs have been homogenized into the reflector).

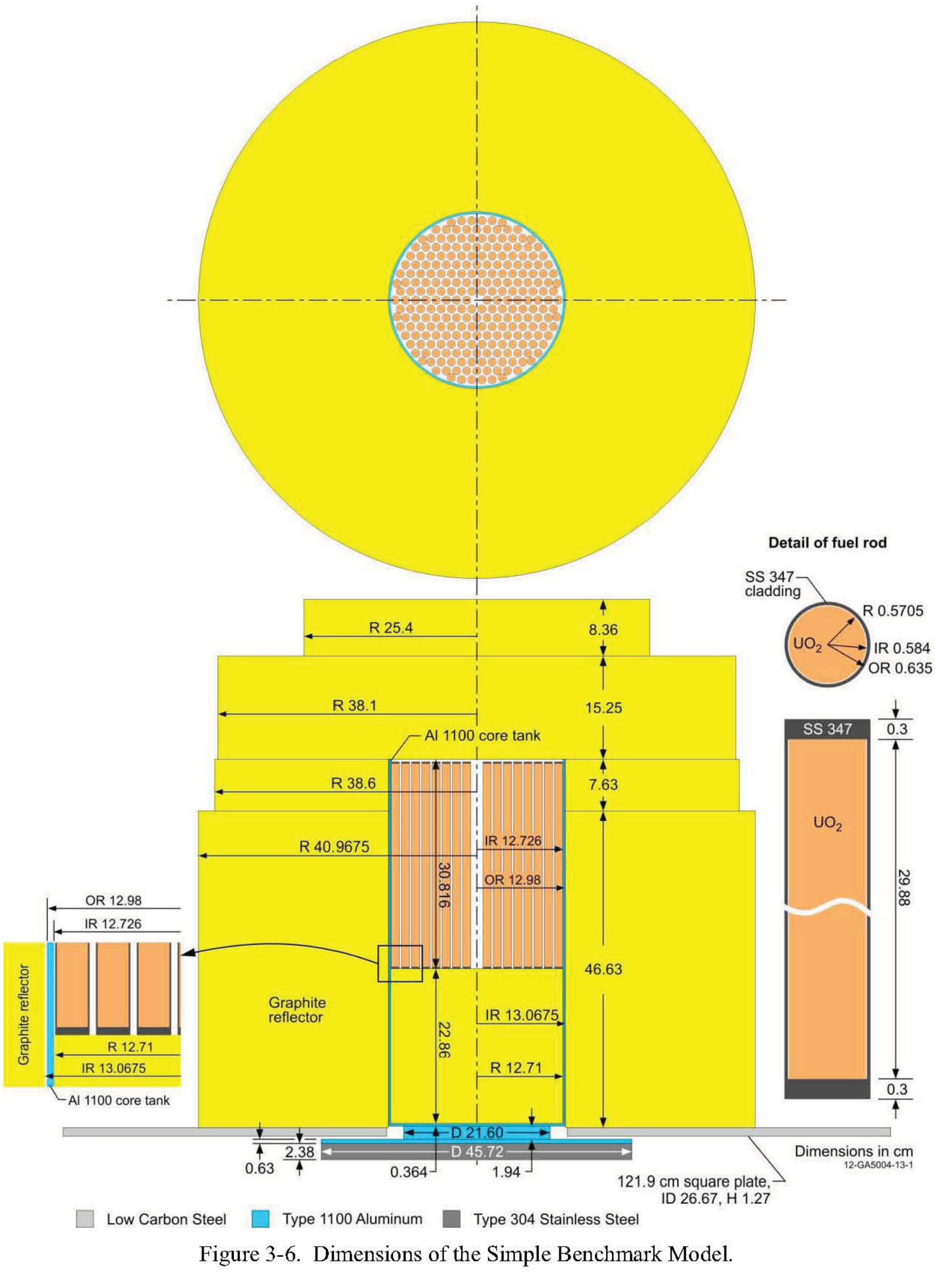

Figure 3-6. Dimensions of the Simple Benchmark Model.

3.2.2.2 Fuel and Fuel Tubes

The fuel was modeled as solid 1.141-cm-diameter, 29.88-cm-tall fuel rods in the simple benchmark model. The fuel tubes were modeled as 1.27-cm-OD, 0.051-cm-thick-wall stainless steel tubes with 0.3 cm tall end caps. The dimensions of the fuel and fuel tubes can be seen in Figure 3-6.

3.2.2.3 The Core

The core consisted of a 253 fuel tube array, 1.506-cm-triangular lattice, with the centermost rod removed, yielding a total of 252 fuel rods in the core. The array was held in a core tank with an outside diameter of 25.96 cm, a side-wall thickness of 0.254 cm, a bottom thickness of 0.33 cm and an outside length of 31.04 cm.

3.2.2.4 Support Plates and Table

The dimensions of the support plates and table were the same as in the detailed benchmark model (see Section 3.2.1.4).

3.3 Benchmark Model Material Data

Atomic masses from the International Criticality Safety Benchmark Evaluation Project (ICSBEP) Document Content and Format Guide were used to derive atom densities for all material.

3.3.1 Detailed Benchmark Material Data

3.3.1.1 Reflectors

Impurities in Type ATL Graphite were included in the detailed benchmark model. For each section of reflector, the mass (given in Figure 3-3) was averaged over the volume of the reflectors. Plugs have the same material composition and density as the reflector into which they were inserted. The graphite compositions are given in Table 3-6.

Table 3-6. Reflector Composition.

Element	wt. %	Lower Side Reflector[(a)] Atom/barn-cm	Upper Side Reflector Atom/barn-cm	Lower Top Reflector[(a)] Atom/barn-cm	Upper Top Reflector[(a)] Atom/barn-cm	Bottom Reflector Atom/barn-cm
Al	0.0270	1.0608E-05	1.0482E-05	1.0754E-05	1.0138E-05	9.9783E-06
Ba	0.0022	1.6983E-07	1.6781E-07	1.7217E-07	1.6229E-07	1.5974E-07
B	0.00005	4.9029E-08	4.8445E-08	4.9703E-08	4.6853E-08	4.6117E-08
Ca	0.0820	2.1690E-05	2.1432E-05	2.1988E-05	2.0727E-05	2.0402E-05
Co	0.0003	5.3965E-08	5.3322E-08	5.4707E-08	5.1570E-08	5.0760E-08
Cr	0.0016	3.2621E-07	3.2233E-07	3.3070E-07	3.1173E-07	3.0684E-07
Cu	0.0001	1.6682E-08	1.6484E-08	1.6912E-08	1.5942E-08	1.5692E-08
Fe	0.3940	7.4790E-05	7.3900E-05	7.5818E-05	7.1471E-05	7.0348E-05
K	0.0005	1.3557E-07	1.3396E-07	1.3743E-07	1.2955E-07	1.2752E-07
Li	0.0002	3.0546E-07	3.0182E-07	3.0966E-07	2.9190E-07	2.8732E-07
Lu	0.0001	6.0589E-09	5.9867E-09	6.1422E-09	5.7900E-09	5.6990E-09
Mg	0.0001	4.3617E-08	4.3097E-08	4.4216E-08	4.1681E-08	4.1026E-08
Mn	0.0001	1.9296E-08	1.9067E-08	1.9562E-08	1.8440E-08	1.8150E-08
Mo	0.0005	5.5248E-08	5.4591E-08	5.6008E-08	5.2796E-08	5.1967E-08
Na	0.0003	1.3834E-07	1.3669E-07	1.4024E-07	1.3220E-07	1.3012E-07
Ni	0.0027	4.8769E-07	4.8189E-07	4.9440E-07	4.6605E-07	4.5873E-07
Si	0.0054	2.0383E-06	2.0140E-06	2.0663E-06	1.9478E-06	1.9172E-06
Sr	0.0005	6.0494E-08	5.9774E-08	6.1326E-08	5.7810E-08	5.6902E-08
Ti	0.0054	1.1956E-06	1.1814E-06	1.2120E-06	1.1425E-06	1.1246E-06
V	0.0220	4.5782E-06	4.5237E-06	4.6412E-06	4.3751E-06	4.3063E-06
Y	0.0011	1.3116E-07	1.2960E-07	1.3297E-07	1.2534E-07	1.2337E-07
Yb	0.0003	6.7390E-08	6.6588E-08	1.8632E-08	1.7563E-08	1.7288E-08
C	99.45355	8.7779E-02	8.6734E-02	8.8986E-02	8.3883E-02	8.2566E-02
Total	100 wt.%	8.7896E-02	8.6849E-02	8.9104E-02	8.3995E-02	8.2676E-02

(a) The plugs in this section of graphite had the same composition.

3.3.1.2 Fuel

The composition of the fuel is given in Table 3-7.

Table 3-7. Fuel Composition.

Element/Isotope	wt. %	Atom/barn-cm
^{234}U	0.8887	2.2222E-04
^{235}U	81.9608	2.0407E-02
^{236}U	0.4135	1.0253E-04
^{238}U	4.7250	1.1616E-03
O	11.9708	4.3788E-02
Ag	1.9992E-03	1.0847E-06
Be	1.4994E-05	9.7367E-08
Cr	2.2991E-03	2.5877E-06
Li	7.4969E-05	6.3211E-07
Ni	1.2495E-03	1.2251E-06
Sn	1.4994E-03	7.3919E-07
Al	1.6493E-03	3.5774E-06
Ca	4.9979E-03	7.2982E-06
Cu	1.8992E-03	1.7491E-06
Mg	5.9975E-04	1.4441E-06
P	4.9979E-03	9.4434E-06
B	4.9979E-05	2.7056E-07
Fe	1.2995E-02	1.3617E-05
Mn	3.9984E-04	4.2593E-07
Ba	4.9979E-04	2.1299E-07
K	2.4990E-03	3.7406E-06
Na	4.9979E-04	1.2723E-06
Si	2.9988E-03	6.2487E-06
Total	100 wt.%	6.5737E-02

3.3.1.3 Fuel Tubes

The compositions of the fuel tubes and end caps are given in Table 3-8.

Table 3-8. Fuel Tube and End Cap Composition.

Element	wt. %	Fuel Tube Atom/barn-cm	End Caps Atom/barn-cm
Fe	68.7225	5.5680E-02	1.4779E-02
C	0.04	1.5069E-04	3.9998E-05
Mn	1.00	8.2362E-04	2.1862E-04
Si	0.50	8.0554E-04	2.1382E-04
Cr	18.00	1.5664E-02	4.1578E-03
Ni	11.00	8.4806E-03	2.2511E-03
P	0.0225	3.2869E-05	8.7246E-06
S	0.0150	2.1164E-05	5.6176E-06
Nb	0.644	3.1349E-04	8.3211E-05
Ta	0.056	1.4084E-05	3.7383E-06
Total	100 wt.%	8.1986E-02	2.1762E-02

3.3.1.4 The Core Tank

The composition of the core tank is given in Table 3-9.

Table 3-9. Core Tank Composition.

Element	wt. %	Atom/barn-cm
Al	99.325	5.8040E-02
Cu	0.125	3.1014E-05
Si	0.2375	1.3333E-04
Fe	0.2375	6.6861E-05
Mn	0.025	7.1746E-06
Zn	0.050	1.2056E-05
Total	100 wt.%	5.8290E-02

3.3.1.5 Grid Plates

The composition of the grid plates is given in Table 3-10.

Table 3-10. Grid Plate Composition.

Element	wt. %	Atom/barn-cm
Al	99.325	6.9878E-02
Cu	0.125	3.7339E-05
Si	0.2375	1.6052E-04
Fe	0.2375	8.0725E-05
Mn	0.025	8.6380E-06
Zn	0.050	1.4515E-05
Total	100 wt.%	7.0179E-02

3.3.1.6 Grid Plate Spacer Tubes

The composition of the grid plate spacer tubes is given in Table 3-11.

Table 3-11. Grid Plate Spacer Tube Composition.

Element	wt. %	Atom/barn-cm
Fe	68.7225	5.5483E-02
C	0.04	1.5016E-04
Mn	1.00	8.2071E-04
Si	0.50	8.0270E-04
Cr	18.00	1.5609E-02
Ni	11.00	8.4507E-03
P	0.0225	3.2753E-05
S	0.0150	2.1089E-05
Nb	0.644	3.1238E-04
Ta	0.056	1.4034E-05
Total	100 wt.%	8.1697E-02

3.3.1.7 Aluminum Shims

The composition of the aluminum shims is given in Table 3-12.

Table 3-12. Aluminum Shim Composition.

Element	wt. %	Atom/barn-cm
Al	99.325	5.9856E-02
Cu	0.125	3.1984E-05
Si	0.2375	1.3750E-04
Fe	0.2375	6.8952E-05
Mn	0.025	7.3991E-06
Zn	0.050	1.2433E-05
Total	100 wt.%	6.0114E-02

3.3.1.8 Support Plates and Table

The compositions of the aluminum plates are given in Table 3-13.

Table 3-13. Aluminum Plate Composition.

Element	wt.%	1.94-cm-Thick Al Reflector Atoms/barn-cm	0.63-cm-Thick Al Reflector Atoms/barn-cm
Al	99.325	5.9875E-02	5.9736E-02
Cu	0.125	3.1994E-05	3.1920E-05
Si	0.2375	1.3754E-04	1.3722E-04
Fe	0.2375	6.8974E-05	6.8814E-05
Mn	0.025	7.4015E-06	7.3843E-06
Zn	0.050	1.2437E-05	1.2408E-05
Total	100 wt.%	6.0133E-02	5.9994E-02

The stainless steel plate composition is given in Table 3-14.

Table 3-14. Stainless Steel Plate Composition.

Element	wt. %	Atoms/barn-cm
Fe	69.9225	6.0206E-02
C	0.04	1.6014E-04
Mn	1.00	8.7529E-04
Si	0.50	8.5607E-04
Cr	19.00	1.7571E-02
Ni	9.50	7.7836E-03
P	0.0225	3.4931E-05
S	0.015	2.2491E-05
Total	100 wt.%	8.7510E-02

The composition of the iron table is given in Table 3-15.

Table 3-15. Iron Table Composition.

Element	wt. %	Atoms/barn-cm
Fe	98.305	7.9785E-02
C	0.25	9.4343E-04
Mg	1.00	1.8649E-03
P	0.02	2.9267E-05
S	0.025	3.5334E-05
Si	0.20	3.2277E-04
Cu	0.20	1.4266E-04
Total	100 wt.%	8.3124E-02

3.3.2 Simple Benchmark Material Data

3.3.2.1 Reflectors

Impurities in the graphite were replaced with void in the simple benchmark model. The composition of the graphite is given in Table 3-16.

Table 3-16. Reflector Composition.

Element	wt. %	Lower Side Reflector Atom/barn-cm	Upper Side Reflector Atom/barn-cm	Lower Top Reflector Atom/barn-cm	Upper Top Reflector Atom/barn-cm	Bottom Reflector Atom/barn-cm
C[(a)]	99.45355%	8.7740E-02	8.6742E-02	8.8980E-02	8.3871E-02	8.2566E-02

(a) Impurities in the graphite were replaced with void.

3.3.2.2 Fuel

Impurities in the fuel were replaced with void in the simple benchmark model. The composition of the fuel is given in Table 3-17.

Table 3-17. Fuel Composition.

Element/Isotope	wt. %	Atom/barn-cm
^{234}U	0.8887	2.2140E-04
^{235}U	81.9608	2.0332E-02
^{236}U	0.4135	1.0215E-04
^{238}U	4.7250	1.1573E-03
O	11.9708	4.3627E-02
Total	99.9588 wt.%[(a)]	6.5440E-02

(a) Impurities were replaced with void.

3.3.2.3 Fuel Tubes and End Caps

The mass of the fuel tubes plus the end caps was averaged over the volume of the fuel tubes and end caps. The composition of the fuel tubes and end caps is given in Table 3-18.

Table 3-18. Fuel Tube and End Cap Composition.

Element	wt. %	Atom/barn-cm
Fe	68.7225	5.1693E-02
C	0.04	1.3990E-04
Mn	1.00	7.6465E-04
Si	0.50	7.4787E-04
Cr	18.00	1.4542E-02
Ni	11.00	7.8734E-03
P	0.0225	3.0516E-05
S	0.0150	1.9648E-05
Nb	0.644	2.9104E-04
Ta	0.056	1.3076E-05
Total	100%	7.6116E-02

3.3.2.4 The Core Tank

The composition of the core tank was the same in the simple benchmark model as in the detailed benchmark model (see Table 3-9).

3.3.2.5 Support Plates and Table

The composition of the support plates and table was the same in the simple benchmark model as in the detailed benchmark model (see Tables 3-13 through 3-15).

3.4 Benchmark Model Temperature Data

The benchmark model temperature is 293.6 K.

3.5 Benchmark Model k_{eff} and Uncertainties

The experimental configuration had an excess reactivity of -1 ¢. This bias and the simplification bias were applied to obtain the detailed and simple benchmark model experiment k_{eff} values found in Table 3-19. The uncertainty in the benchmark model was found by adding in quadrature the uncertainty derived in Section 2 and the uncertainty in the bias derived in Section 3.1.

Table 3-19. Benchmark Experiment Eigen Values.

	Detailed Benchmark Model, $k_{eff} \pm 1\sigma$	Simple Benchmark Model, $k_{eff} \pm 1\sigma$
Benchmark k_{eff}	0.9996 ± 0.0006	0.9986 ± 0.0006

4.0 RESULTS OF SAMPLE CALCULATIONS

Models were created with MCNP5 and KENO-VI[a] using ENDF/B-VII.0 continuous energy neutron cross section libraries. Thermal scattering treatments, S(α,β), were used for the uranium dioxide fuel, the aluminum, and the graphite reflectors. Cross section data was not available for ytterbium (Yb), so it was replaced with void in the fuel. Example input files for the benchmark model can be found in Appendix A. Results of the MCNP5 sample calculations are approximately 0.22%, or about 3.7σ greater than the benchmark value for the detailed and simple benchmark models. Results are summarized in Table 4-1. KENO-VI results for the simple benchmark model are also presented in Table 4-1.

Table 4-1. Sample Results for the Benchmark Model, ENDB/B-VII.0.

Model	Benchmark			Calculated							
				MCNP5 ENDF/B-VII.0[(a)]			$\frac{C-E}{E}^{(d)}$	KENO-VI ENDF/B-VII.0[(b,c)]			$\frac{C-E}{E}^{(d)}$
	k_{eff}	±	σ	k_{eff}	±	σ		k_{eff}	±	σ	
Detailed	0.9996	±	0.0006	1.00180	±	0.00002	0.22%		-		
Simple	0.9978	±	0.0006	1.00077	±	0.00002	0.22%	1.00061	±	0.00009	0.28%

(a) Results obtained using 100,000 histories for 2150 cycles, skipping the first 150 cycles.
(b) Results provided by John D. Bess from Idaho National Laboratory.
(c) Results obtained using 100,000 histories for 1150 cycles, skipping the first 150 cycles.
(d) 'E' is the expected or benchmark value. 'C' is the calculated value.

The first experimental configuration was evaluated in HEU-COMP-FAST-001. The calculational bias for part one of the experimental series was 0.5% with ENDF/B-VII.0 cross section libraries. The reason for the large difference in the calculation bias between these two highly correlated experiments is unknown.

Sample calculation results for the simple benchmark model are also provided using JEFF-3.1 and JENDL-3.3 cross section libraries in Table 4.2. Isotopes that were not available in the respectively cross section libraries were replaced with void. For JEFF-3.1, strontium-64, dysprosium-156 and -168, and lutetium-175 and 176 were replaced with void. For JENDL-3.3, dysprosium-156, -168, -160, -162, -163, and -164 were replaced with void and oxygen-17 was converted to oxygen-16. Thermal scattering treatments for ENDF/B-VII.0 were used when they were not available.

[a] D.F. Hollenbach, L.M. Petrie, S. Goluoglu, N.F. Landers, and M.E. Dunn, "KENO-VI: A General Quadratic Version of the KENO Program," ORNL/TM-2005/39 Version 6 Vol. II, Sect. F17, Oak Ridge National Laboratory (January 2009).

Table 4-2. Sample Results for the Benchmark Model, JEFF-3.1 and JENDLG-3.3.

Model	Benchmark			Calculated							
				JEFF-3.1(a)(b)			$\frac{C-E}{E}^{(c)}$	JENDL-3.3(a)(b)			$\frac{C-E}{E}^{(c)}$
	k_{eff}	±	σ	k_{eff}	±	σ		k_{eff}	±	σ	
Simple	0.9978	±	0.0006	0.99672	±	0.00002	-0.19%	0.99812	±	0.00002	-0.05%

(a) Results obtained using 100,000 histories for 2150 cycles, skipping the first 150 cycles.
(b) Results provided by John D. Bess from Idaho National Laboratory.
(c) 'E' is the expected or benchmark value. 'C' is the calculated value.

Models were also run with MCNP5 using ENDF/B-V.2 cross section libraries. Sulfur isotopes -33, -34, and -36 were not available, so they were replaced with void. Oxygen -17 was converted to -16. Thermal scattering treatment for graphite was used but no others were available for this cross section library. These results are given in Table 4-3.

Table 4-3. Sample Results for the Benchmark Model, ENDB/B-V.2.

Model	Benchmark			Calculated			
				MCNP5 ENDF/B-V.2(a)			$\frac{C-E}{E}^{(d)}$
	k_{eff}	±	σ	k_{eff}	±	σ	
Simple	0.9978	±	0.0006	0.99577	±	0.00002	-0.28%

(a) Results obtained using 100,000 histories for 2150 cycles, skipping the first 150 cycles.
(b) Results provided by John D. Bess from Idaho National Laboratory.
(c) Results obtained using 100,000 histories for 1150 cycles, skipping the first 150 cycles.
(d) 'E' is the expected or benchmark value. 'C' is the calculated value.

5.0 REFERENCES

1. J.T. Mihalczo, "A Small Graphite-Reflected UO_2 Critical Assembly," ORNL-TM-450, Oak Ridge National Laboratory (1962).

2. J.T. Mihalczo, "A Small Graphite-Reflected UO_2 Assembly," *Proc. 5th Int. Conf. Nucl. Crit. Safety*, Albuquerque, NM, September 17-21 (1995).

3. J.T. Mihalczo, "A Small Graphite-Reflected UO2 Critical Assembly, Part II," ORNL-TM-561, Oak Ridge National Laboratory (1963).

4. J.T. Mihalczo, "A Small Beryllium-Reflected UO2 Assembly," ORNL-TM-655, Oak Ridge National Laboratory (1963).

5. J.T. Mihalczo, "A Small, Beryllium-Reflected UO_2 Critical Assembly," *Trans. Am. Nucl. Soc.,* **72**, 196-198 (1995).

APPENDIX A: SAMPLE INPUT DECKS

Models were creating using Monte Carlo n-Particle, version 5-1.60, (MCNP) and ENDF/B-VII.0 neutron cross section libraries. Isotopic abundances for all elements except uranium were taken from "Nuclides and Isotopes: Chart of the Nuclides," Sixteenth Edition, KAPL, 2002. MCNP5.1.60 models were run for 2000 active cycles (150 inactive cycles) with 100,000 histories per cycle.

MCNP5 Input Deck for Detailed Benchmark Models:
<u>Case 1</u>

```
SCCA-FUND-EXP-002-001 and HEU-COMP-FAST-002
C
C
C   Cell Cards
1   1  6.57372E-02  (-25 22 -26) u=10 imp:n=1        $fuel pellet
2   0      -22:(25 22 -26 ):26 u=10 imp:n=1  $void around pellet
3   0      -28  lat=1 u=11 imp:n=1 fill= 0:0  0:0 -1:26
       11 10 10 10 10 10 10 10 10 10 10 10 10 10
        10 10 10 10 10 10 10 10 10 10 10 10 10 11
C       Normal Fuel Tube
4   0    -21 22 -23  fill=11 u=12 imp:n=1
15   15 8.19858E-02 (1 -24 -20 21) u=12 imp:n=1  $Fuel tube
16   16 2.17619E-02 (1 -22 -21):(23 -24 -21) u=12 imp:n=1  $end caps
17   20 7.01794E-02 -160 166  u=12 imp:n=1 $Grid Plate
18   20 7.01794E-02 -161 166  u=12 imp:n=1 $Grid Plate
700  0  -160 -166 20 u=12 imp:n=1
701  0  -161 -166 20 u=12 imp:n=1
19   0    -1:(1  160 161 20 -24):24 u=12 imp:n=1
C    Fuel tubes that have been moved in
20  0    -21 22 -23  fill=11 u=13 imp:n=1
21   15 8.19858E-02 (21) u=13 imp:n=1  $Fuel tube
22   16 2.17619E-02 (-22 -21):(23 -21) u=13 imp:n=1  $end caps
C    Fuel tubes with grid plates
29  0    -21 22 -23  fill=11 u=14 imp:n=1
30   15 8.19858E-02 (1 -24 -20 21) u=14 imp:n=1  $Fuel tube
31   16 2.17619E-02 (1 -22 -21):(23 -24 -21) u=14 imp:n=1  $end caps
32   20 7.01794E-02 -160 166  u=14 imp:n=1 $Grid Plate
33   20 7.01794E-02 -161 166  u=14 imp:n=1 $Grid Plate
702  0  -160 -166 20 u=14 imp:n=1
703  0  -161 -166 20 u=14 imp:n=1
34   0     20 -163 164 -165 u=14 imp:n=1
35   21 8.16965E-02 -162 163 u=14 imp:n=1 $Spacer Tube
36   0    -1:(164 162 -165):(165 161 20 -24):24 u=14 imp:n=1
C    Normal Fuel Tube
110  0   -12 fill=12 u=1 imp:n=1
C    Fuel Tubes that have been moved in
111  0   -13 fill=13 (-3.766 -11.458 0) imp:n=1
112  0   -14 fill=13 (3.766 -11.458 0) imp:n=1
113  0   -15 fill=13 (3.766 11.458 0) imp:n=1
114  0   -16 fill=13 (-3.766 11.458 0) imp:n=1
115  0   -17 fill=13 (-8.039 -8.989 0) imp:n=1
116  0   -18 fill=13 (8.039 -8.989 0) imp:n=1
117  0   -19 fill=13 (-8.039 8.989 0) imp:n=1
118  0   -30 fill=13 (8.039 8.989 0) imp:n=1
119  0   -31 fill=13 (-11.805 -2.467 0) imp:n=1
120  0   -32 fill=13 (11.805 -2.467 0) imp:n=1
121  0   -33 fill=13 (-11.805 2.467 0) imp:n=1
122  0   -34 fill=13 (11.805 2.467 0) imp:n=1
C
C    Void Universe w/ Grid plate
127  20 7.01794E-02 -160 u=9 imp:n=1
128  20 7.01794E-02 -161 u=9 imp:n=1
```

```
129  0  -999 161 160 u=9 imp:n=1
C    Center Location w/ hole in grid plate
123  20 7.01794E-02 -160 166 u=8 imp:n=1
124  20 7.01794E-02 -161 166 u=8 imp:n=1
706  0  -160 -166 u=8 imp:n=1
707  0  -161 -166 u=8 imp:n=1
126  0  -999 161 160 u=8 imp:n=1
C   Core Assembly
130  0   -11  lat=2  u=2 imp:n=1 fill= -10:10 -10:10 0:0
    9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9  $ROW 1
     9 9 9 9 9 9 9 9 9 9 9 9 1 1 1 1 9 9 9 9 9  $ROW 2
      9 9 9 9 9 9 9 9 9 9 1 1 1 1 14 1 1 1 1 9 9  $ROW 3
       9 9 9 9 9 9 9 9 9 1 1 1 1 1 1 1 1 1 1 9 9  $ROW 4
        9 9 9 9 9 9 9 1 1 1 1 1 1 1 1 1 1 1 1 1 9  $ROW 5
         9 9 9 9 9 9 1 1 1 1 1 1 1 1 1 1 1 1 1 1 9  $ROW 6
          9 9 9 9 9 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 9  $ROW 7
           9 9 9 9 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 9  $ROW 8
            9 9 9 9 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 9 9  $ROW 9
             9 9 9 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 9 9  $ROW 10
              9 9 1 14 1 1 1 1 1 1 8 1 1 1 1 1 1 14 1 9 9  $ROW 11
               9 9 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 9 9 9  $ROW 12
                9 9 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 9 9 9 9  $ROW 13
                 9 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 9 9 9 9  $ROW 14
                  9 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 9 9 9 9 9  $ROW 15
                   9 1 1 1 1 1 1 1 1 1 1 1 1 1 1 9 9 9 9 9 9  $ROW 16
                    9 1 1 1 1 1 1 1 1 1 1 1 1 1 9 9 9 9 9 9 9  $ROW 17
                     9 9 1 1 1 1 1 1 1 1 1 1 1 9 9 9 9 9 9 9 9  $ROW 18
                      9 9 1 1 1 1 14 1 1 1 1 9 9 9 9 9 9 9 9 9 9  $ROW 19
                       9 9 9 9 1 1 1 1 9 9 9 9 9 9 9 9 9 9 9 9 9  $ROW 20
                        9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9 9  $ROW 21
C   Core Tank
131  0   -151 1 -153 13 14 15 16 17 18 19 30 31 32 33 34
         -101  -103  -105  -107  -109      fill=2 imp:n=1
132  22 6.01138E-02 -151 113 -114 #131 imp:n=1  $Al Shims
133  0   -151 1 -113 #131 13 14 15 16 17 18 19 30 31 32 33 34 imp:n=1
134  0   -151 114 -153 #131 13 14 15 16 17 18 19 30 31 32 33 34 imp:n=1
135  0  -210 -211 150  imp:n=1
136  0  -152 -150 220 213 250  imp:n=1
137  0  -310 -212 150  imp:n=1
140  2 5.82903E-02 (-153 154 -150 151):(-154 152 -150) imp:n=1 $Core Tank
C
C  Reflectors
50  10 8.91041E-02 -200 237  imp:n=1   $Lower Top reflector
77  10 8.91041E-02 -238 -200 imp:n=1
78  0   -237 238 -200 imp:n=1
51  11 8.39948E-02 200 -201  237 imp:n=1 $Upper Top Refleltor
79  11 8.39948E-02 -238 -201 imp:n=1
80  0  -237 238 -201 imp:n=1
52  8  8.78956E-02 310 -212 225 227 229 231 233 235 imp:n=1 $Lower Side Reflector
65  8  8.78956E-02 -212 310 -226 imp:n=1
66  8  8.78956E-02 -212 310 -228 imp:n=1
67  8  8.78956E-02 -212 310 -230 imp:n=1
68  8  8.78956E-02 -212 310 -232 imp:n=1
69  8  8.78956E-02 -212 310 -234 imp:n=1
71  0   -212 310 -235 imp:n=1
72  0   -212 310 -233 234 imp:n=1
73  0   -212 310 -231 232 imp:n=1
74  0   -212 310 -229 230 imp:n=1
75  0   -212 310 -227 228 imp:n=1
76  0   -212 310 -225 226 imp:n=1
81  0   -1 -151 154 220 imp:n=1
53  9  8.68493E-02 210 -211 imp:n=1 $Upper Side Reflector
54  12 8.26756E-02 -220   imp:n=1   $bottom Reflector
C  Support Structure/Additional Reflectors
60  30 6.01329E-02 -250 imp:n=1 $Uppwer Al Plate
61  31 5.99935E-02 -251 imp:n=1 $Lower Al Plate
```

```
62  32 8.75101E-02 -252 imp:n=1 $SS304 Plate
63  33 8.31237E-02 -253 254 imp:n=1 $Iron Table
64  0  -999 #60 #61 #62 #63 212 211 200 201  imp:n=1
999  0  999 imp:n=0

C   Surface Cards
1    pz   0.     $bottom of fuel
20   cz   0.635   $OR Clad
21   cz   0.584   $IR Clad
22   pz   0.3     $top of bottom cap
23   pz  30.18    $bottom of top cap
24   pz  30.48    $Top of fuel tube
25   cz   0.5705  $OR of Pellet
26   pz   1.445   $Top of bottom fuel pellet
28   rpp  -0.9 0.9  -0.9 0.9  0.2978 1.4472  $pellet lattice box
11   rhp  0 0 -10  0 0 50   0.753 0 0
12   rhp  0 0 -11  0 0 52   1 0 0
C  13   rcc  0 0 0  0 0 30.48  0.635
13   rcc  -3.766 -11.458 0  0 0 30.48  0.635
14   rcc  3.766 -11.458 0  0 0 30.48  0.635
15   rcc  3.766 11.458 0  0 0 30.48  0.635
16   rcc  -3.766 11.458 0  0 0 30.48  0.635
17   rcc  -8.039 -8.989 0  0 0 30.48  0.635
18   rcc  8.039 -8.989 0  0 0 30.48  0.635
19   rcc  -8.039 8.989 0  0 0 30.48  0.635
30   rcc  8.039 8.989 0  0 0 30.48  0.635
31   rcc  -11.805 -2.467 0  0 0 30.48  0.635
32   rcc  11.805 -2.467 0  0 0 30.48  0.635
33   rcc  -11.805 2.467 0  0 0 30.48  0.635
34   rcc  11.805 2.467 0  0 0 30.48  0.635
C  Core Tank
150  cz  12.98  $OR Core Tank
151  cz  12.726 $IR Core Tank
152  pz  -23.224  $Bottom of Core Tank
154  pz  -22.86   $top of bottom of core tank
153  pz  30.816  $Top of Core Tank
C  Grid Plate
160   rcc 0 0 0  0 0 0.317  12.8 $bottom grid plate
161   rcc 0 0 28.257  0 0 0.317  12.8 $top grip plate
166   cz 0.642
C  Grid Plate Spacer Tubes
162   rcc 0 0 0.317  0 0 27.94  0.685
163   cz  0.642
164   pz 0.317
165   pz 28.257
C    Al Shims
101   p -2.9708 12.3744 15  0.0000 12.3744 30  2.9708 12.3744 15
103   p 9.2311 8.7600 15  10.7165 6.1872 30  12.2019 3.6144 15
105   p 12.2019 -3.6144 15  10.7165 -6.1872 30  9.2311 -8.7600 15
107   p 2.9708 -12.3744 15  0.0000 -12.3744 30  -2.9708 -12.3744 15
109   p -9.2311 -8.7600 15  -10.7165 -6.1872 30  -12.2019 -3.6144 15
113   pz 14.4
114   pz 16.31
C   Al Fuel Tube Clips
115  rcc 0 0 14.99  0 0 0.5  12.8
C  Reflectors
C   Top Reflectors
200  rcc 0 0 30.816   0 0 15.25   38.1 $Lower Top Reflector
201  rcc 0 0 46.066   0 0 8.36    25.4 $Upper Top Reflector
C  Side Reflectors
210  cz  13.07  $IR Upper Side Reflector
211  rcc 0 0 23.186   0 0 7.63   38.6  $Upper Side Reflector
310  cz  13.065  $IR Lower Side Reflector
212  rcc 0 0 -23.444  0 0 46.63  40.9675 $Lower Side Reflector
213  pz -23.444 $surface for creating void regions
C  Bottom Reflector
```

```
220  rcc 0 0 -22.86  0 0 22.86  12.71 $bottom reflector
C  Foil Holes in lower side and top reflector
225  rcc 0 0 7.61 -50 0 0 0.635 $west hole
226  rcc 0 0 7.61 -50 0 0 0.555 $west plug
227  rcc 0 0 7.61 -40 69.3 0 0.635 $nnw hole
228  rcc 0 0 7.61 -40 69.3 0 0.555 $nnw plug
229  rcc 0 0 7.61 40 69.3 0 0.635 $nne hole
230  rcc 0 0 7.61 40 69.3 0 0.555 $nne plug
231  rcc 0 0 7.61 50 0 0 0.635 $west hole
232  rcc 0 0 7.61 50 0 0 0.555 $west plug
233  rcc 0 0 7.61 40 -69.3 0 0.635 $sse hole
234  rcc 0 0 7.61 40 -69.3 0 0.555 $sse plug
235  rcc 0 0 7.61 -40 -69.3 0 0.635 $ssw hole
236  rcc 0 0 7.61 -40 -69.3 0 0.555 $ssw plug
237  cz  0.635
238  cz  0.555
239  pz  45.96
240  pz 54.32
C  Additional Bottom Reflectors
250  rcc 0 0 -25.164  0 0 1.94  10.8  $Al Upper Plate
251  rcc 0 0 -25.794  0 0 0.63  22.86 $Al Lower Plate
252  rcc 0 0 -28.174  0 0 2.38  22.86 $SS304 Plate
253  rpp -60.95 60.95  -60.95 60.95  -24.82 -23.55 $Iron Table
254  cz 13.335
C
999   rpp  -500 500   -500 500  -500 500

C   Data Cards
m1    92234.70c   2.22221E-04
     92235.70c   2.04075E-02
     92236.70c   1.02532E-04
     92238.70c   1.16161E-03
     8016.70c   4.36813E-02
     8017.70c   1.06404E-04
     47107.70c   5.62272E-07
     47109.70c   5.22379E-07
     4009.70c   9.73675E-08
     24050.70c   1.12435E-07
     24052.70c   2.16820E-06
     24053.70c   2.45856E-07
     24054.70c   6.11987E-08
     3006.70c   4.74083E-08
     3007.70c   5.84702E-07
     28058.70c   8.33992E-07
     28060.70c   3.21252E-07
     28061.70c   1.39646E-08
     28062.70c   4.45253E-08
     28064.70c   1.13393E-08
     50112.70c   7.17017E-09
     50114.70c   4.87867E-09
     50115.70c   2.51325E-09
     50116.70c   1.07479E-07
     50117.70c   5.67700E-08
     50118.70c   1.79032E-07
     50119.70c   6.34966E-08
     50120.70c   2.40829E-07
     50122.70c   3.42246E-08
     50124.70c   4.27992E-08
     13027.70c   3.57743E-06
     20040.70c   7.07498E-06
     20042.70c   4.72195E-08
     20043.70c   9.85261E-09
     20044.70c   1.52241E-07
     20046.70c   2.91929E-10
     20048.70c   1.36477E-08
     29063.70c   1.20986E-06
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     29065.70c   5.39253E-07
     12024.70c   1.14073E-06
     12025.70c   1.44414E-07
     12026.70c   1.59000E-07
     15031.70c   9.44341E-06
     5010.70c   5.38407E-08
     5011.70c   2.16716E-07
     26054.70c   7.95942E-07
     26056.70c   1.24946E-05
     26057.70c   2.88555E-07
     26058.70c   3.84013E-08
     25055.70c   4.25932E-07
     56130.70c   2.25774E-10
     56132.70c   2.15124E-10
     56134.70c   5.14807E-09
     56135.70c   1.40406E-08
     56136.70c   1.67286E-08
     56137.70c   2.39235E-08
     56138.70c   1.52713E-07
     19039.70c   3.48837E-06
     19040.70c   4.37645E-10
     19041.70c   2.51747E-07
     11023.70c   1.27230E-06
     14028.70c   5.76320E-06
     14029.70c   2.92641E-07
     14030.70c   1.92911E-07   $ TOT   6.57372E-02
C   Fuel Clad
m15   26054.70c   3.25448E-03
     26056.70c   5.10884E-02
     26057.70c   1.17985E-03
     26058.70c   1.57017E-04
     6000.70c   1.50688E-04
     25055.70c   8.23618E-04
     14028.70c   7.42946E-04
     14029.70c   3.77250E-05
     14030.70c   2.48686E-05
     24050.70c   6.80598E-04
     24052.70c   1.31247E-02
     24053.70c   1.48823E-03
     24054.70c   3.70452E-04
     28058.70c   5.77334E-03
     28060.70c   2.22388E-03
     28061.70c   9.66705E-05
     28062.70c   3.08228E-04
     28064.70c   7.84965E-05
     15031.70c   3.28690E-05
     16032.70c   2.00907E-05
     16033.70c   1.60844E-07
     16034.70c   9.07921E-07
     16036.70c   4.23273E-09
     41093.70c   3.13488E-04
     73181.70c   1.40839E-05   $ tot   8.19858E-02
C   End Caps
m16   26054.70c   8.63854E-04
     26056.70c   1.35607E-02
     26057.70c   3.13175E-04
     26058.70c   4.16778E-05
     6000.70c   3.99979E-05
     25055.70c   2.18617E-04
     14028.70c   1.97204E-04
     14029.70c   1.00135E-05
     14030.70c   6.60099E-06
     24050.70c   1.80655E-04
     24052.70c   3.48374E-03
     24053.70c   3.95029E-04
     24054.70c   9.83310E-05
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     28058.70c  1.53245E-03
     28060.70c  5.90295E-04
     28061.70c  2.56597E-05
     28062.70c  8.18144E-05
     28064.70c  2.08357E-05
     15031.70c  8.72458E-06
     16032.70c  5.33276E-06
     16033.70c  4.26936E-08
     16034.70c  2.40994E-07
     16034.70c  1.12352E-09
     41093.70c  8.32108E-05
     73181.70c  3.73835E-06  $ tot  2.17619E-02
C   Core Tank
m2  13027.70c  5.80397E-02
     29063.70c  2.14522E-05
     29065.70c  9.56154E-06
     14028.70c  1.22966E-04
     14029.70c  6.24391E-06
     14030.70c  4.11603E-06
     26054.70c  3.91905E-06
     26056.70c  6.15207E-05
     26057.70c  1.42078E-06
     26058.70c  1.89080E-07
     25055.70c  7.17463E-06
     30000.70c  1.20557E-05  $ Tot  5.82903E-02
C   Grid Plate
m20  13027.70c  0.069877686
     29063.70c  2.58277E-05
     29065.70c  1.15117E-05
     14028.70c  1.48047E-04
     14029.70c  7.51744E-06
     14030.70c  4.95555E-06
     26054.70c  4.71840E-06
     26056.70c  7.40687E-05
     26057.70c  1.71057E-06
     26058.70c  2.27645E-07
     25055.70c  8.63800E-06
     30000.70c  1.45146E-05  $ Tot  7.01794E-02
C   Grid Plate Spacer Tube
m21  26054.70c  3.24300E-03
     26056.70c  5.09082E-02
     26057.70c  1.17569E-03
     26058.70c  1.56463E-04
     6000.70c  1.50157E-04
     25055.70c  8.20712E-04
     14028.70c  7.40325E-04
     14029.70c  3.75919E-05
     14030.70c  2.47808E-05
     24050.70c  6.78197E-04
     24052.70c  1.30784E-02
     24053.70c  1.48298E-03
     24054.70c  3.69145E-04
     28058.70c  5.75297E-03
     28060.70c  2.21603E-03
     28061.70c  9.63294E-05
     28062.70c  3.07140E-04
     28064.70c  7.82196E-05
     15031.70c  3.27530E-05
     16032.70c  2.00198E-05
     16033.70c  1.60276E-07
     16034.70c  9.04718E-07
     16036.70c  4.21780E-09
     41093.70c  3.12383E-04
     73181.70c  1.40342E-05  $ tot  8.16965E-02
C   Al Shim
m22   13027.70c   5.98555E-02
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     29063.70c  2.21234E-05
     29065.70c  9.86068E-06
     14028.70c  1.26813E-04
     14029.70c  6.43926E-06
     14030.70c  4.24481E-06
     26054.70c  4.04166E-06
     26056.70c  6.34455E-05
     26057.70c  1.46523E-06
     25055.70c  7.39910E-06
     30000.70c  1.24328E-05   $ Tot   6.01138E-02
C   Reflectors
C  ***********************************
C  Lower Side Reflector
m8      13027.70c   1.06083E-05
     56130.70c  1.80020E-10
     56132.70c  1.71528E-10
     56134.70c  4.10479E-09
     56135.70c  1.11952E-08
     56136.70c  1.33385E-08
     56137.70c  1.90753E-08
     56138.70c  1.21765E-07
     5010.70c  9.75675E-09
     5011.70c  3.92721E-08
     20040.70c  2.10263E-05
     20042.70c  1.40333E-07
     20043.70c  2.92812E-08
     20044.70c  4.52449E-07
     20046.70c  8.67592E-10
     20048.70c  4.05599E-08
     27059.70c  5.39646E-08
     24050.70c  1.41738E-08
     24052.70c  2.73329E-07
     24053.70c  3.09933E-08
     24054.70c  7.71488E-09
     29063.70c  1.15392E-08
     29065.70c  5.14320E-09
     26054.70c  4.37148E-06
     26056.70c  6.86229E-05
     26057.70c  1.58480E-06
     26058.70c  2.10908E-07
     19039.70c  1.26429E-07
     19040.70c  1.58616E-11
     19041.70c  9.12406E-09
     3006.70c  2.29096E-08
     3007.70c  2.82552E-07
     71175.70c  5.90195E-09
     71176.70c  1.56925E-10
     12024.70c  3.44528E-08
     12025.70c  4.36167E-09
     12026.70c  4.80219E-09
     25055.70c  1.92963E-08
     42092.70c  8.19883E-09
     42094.70c  5.11046E-09
     42095.70c  8.79552E-09
     42096.70c  9.21540E-09
     42097.70c  5.27620E-09
     42098.70c  1.33314E-08
     42100.70c  5.32040E-09
     11023.70c  1.38336E-07
     28058.70c  3.32007E-07
     28060.70c  1.27889E-07
     28061.70c  5.55923E-09
     28062.70c  1.77252E-08
     28064.70c  4.51410E-09
     14028.70c  1.87988E-06
     14029.70c  9.54558E-08
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     14030.70c   6.29252E-08
     38084.70c   3.38768E-10
     38086.70c   5.96474E-09
     38087.70c   4.23460E-09
     38088.70c   4.99562E-08
     22046.70c   9.86374E-08
     22047.70c   8.89530E-08
     22048.70c   8.81400E-07
     22049.70c   6.46822E-08
     22050.70c   6.19323E-08
     23000.70c   4.57824E-06
     39089.70c   1.31163E-07
     6000.70c   8.77787E-02   $ tot   8.78956E-02
C
C  Upper Side Reflector
m9      13027.70c   1.04820E-05
     56130.70c   1.77877E-10
     56132.70c   1.69486E-10
     56134.70c   4.05593E-09
     56135.70c   1.10619E-08
     56136.70c   1.31797E-08
     56137.70c   1.88482E-08
     56138.70c   1.20315E-07
     5010.70c   9.64060E-09
     5011.70c   3.88046E-08
     20040.70c   2.07760E-05
     20042.70c   1.38663E-07
     20043.70c   2.89327E-08
     20044.70c   4.47063E-07
     20046.70c   8.57264E-10
     20048.70c   4.00771E-08
     27059.70c   5.33222E-08
     24050.70c   1.40051E-08
     24052.70c   2.70075E-07
     24053.70c   3.06243E-08
     24054.70c   7.62304E-09
     29063.70c   1.14019E-08
     29065.70c   5.08197E-09
     26054.70c   4.31944E-06
     26056.70c   6.78060E-05
     26057.70c   1.56594E-06
     26058.70c   2.08397E-07
     19039.70c   1.24924E-07
     19040.70c   1.56727E-11
     19041.70c   9.01544E-09
     3006.70c   2.26369E-08
     3007.70c   2.79188E-07
     71175.70c   5.83169E-09
     71176.70c   1.55057E-10
     12024.70c   3.40427E-08
     12025.70c   4.30974E-09
     12026.70c   4.74503E-09
     25055.70c   1.90666E-08
     42092.70c   8.10123E-09
     42094.70c   5.04962E-09
     42095.70c   8.69081E-09
     42096.70c   9.10570E-09
     42097.70c   5.21339E-09
     42098.70c   1.31727E-08
     42100.70c   5.25707E-09
     11023.70c   1.36689E-07
     28058.70c   3.28055E-07
     28060.70c   1.26366E-07
     28061.70c   5.49305E-09
     28062.70c   1.75142E-08
     28064.70c   4.46036E-09
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     14028.70c   1.85750E-06
     14029.70c   9.43195E-08
     14030.70c   6.21761E-08
     38084.70c   3.34735E-10
     38086.70c   5.89374E-09
     38087.70c   4.18419E-09
     38088.70c   4.93615E-08
     22046.70c   9.74632E-08
     22047.70c   8.78941E-08
     22048.70c   8.70907E-07
     22049.70c   6.39122E-08
     22050.70c   6.11951E-08
     23000.70c   4.52374E-06
     39089.70c   1.29601E-07
     6000.70c   8.67337E-02    $ tot   8.68493E-02
C
C  Lower Top Reflector
m10   13027.70c   1.07542E-05
     56130.70c   1.82495E-10
     56132.70c   1.73887E-10
     56134.70c   4.16123E-09
     56135.70c   1.13491E-08
     56136.70c   1.35219E-08
     56137.70c   1.93376E-08
     56138.70c   1.23439E-07
     5010.70c   9.89090E-09
     5011.70c   3.98121E-08
     20040.70c   2.13154E-05
     20042.70c   1.42263E-07
     20043.70c   2.96838E-08
     20044.70c   4.58670E-07
     20046.70c   8.79521E-10
     20048.70c   4.11176E-08
     27059.70c   5.47066E-08
     24050.70c   1.43687E-08
     24052.70c   2.77087E-07
     24053.70c   3.14194E-08
     24054.70c   7.82095E-09
     29063.70c   1.16979E-08
     29065.70c   5.21391E-09
     26054.70c   4.43159E-06
     26056.70c   6.95665E-05
     26057.70c   1.60659E-06
     26058.70c   2.13808E-07
     19039.70c   1.28167E-07
     19040.70c   1.60796E-11
     19041.70c   9.24951E-09
     3006.70c   2.32246E-08
     3007.70c   2.86436E-07
     71175.70c   5.98310E-09
     71176.70c   1.59082E-10
     12024.70c   3.49265E-08
     12025.70c   4.42164E-09
     12026.70c   4.86822E-09
     25055.70c   1.95617E-08
     42092.70c   8.31156E-09
     42094.70c   5.18073E-09
     42095.70c   8.91645E-09
     42096.70c   9.34211E-09
     42097.70c   5.34875E-09
     42098.70c   1.35147E-08
     42100.70c   5.39356E-09
     11023.70c   1.40238E-07
     28058.70c   3.36572E-07
     28060.70c   1.29647E-07
     28061.70c   5.63566E-09
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     28062.70c   1.79690E-08
     28064.70c   4.57616E-09
     14028.70c   1.90573E-06
     14029.70c   9.67682E-08
     14030.70c   6.37903E-08
     38084.70c   3.43426E-10
     38086.70c   6.04675E-09
     38087.70c   4.29283E-09
     38088.70c   5.06431E-08
     22046.70c   9.99936E-08
     22047.70c   9.01760E-08
     22048.70c   8.93518E-07
     22049.70c   6.55715E-08
     22050.70c   6.27838E-08
     23000.70c   4.64119E-06
     39089.70c   1.32966E-07
     6000.70c   8.89856E-02   $ tot   8.91041E-02
C
C  Upper Top Reflector
m11   13027.70c   1.01375E-05
     56130.70c   1.72031E-10
     56132.70c   1.63916E-10
     56134.70c   3.92262E-09
     56135.70c   1.06984E-08
     56136.70c   1.27465E-08
     56137.70c   1.82288E-08
     56138.70c   1.16361E-07
     5010.70c   9.32375E-09
     5011.70c   3.75293E-08
     20040.70c   2.00932E-05
     20042.70c   1.34105E-07
     20043.70c   2.79818E-08
     20044.70c   4.32370E-07
     20046.70c   8.29089E-10
     20048.70c   3.87599E-08
     27059.70c   5.15697E-08
     24050.70c   1.35448E-08
     24052.70c   2.61198E-07
     24053.70c   2.96178E-08
     24054.70c   7.37250E-09
     29063.70c   1.10271E-08
     29065.70c   4.91494E-09
     26054.70c   4.17748E-06
     26056.70c   6.55775E-05
     26057.70c   1.51447E-06
     26058.70c   2.01548E-07
     19039.70c   1.20818E-07
     19040.70c   1.51576E-11
     19041.70c   8.71914E-09
     3006.70c   2.18929E-08
     3007.70c   2.70012E-07
     71175.70c   5.64002E-09
     71176.70c   1.49961E-10
     12024.70c   3.29238E-08
     12025.70c   4.16810E-09
     12026.70c   4.58907E-09
     25055.70c   1.84400E-08
     42092.70c   7.83497E-09
     42094.70c   4.88366E-09
     42095.70c   8.40517E-09
     42096.70c   8.80643E-09
     42097.70c   5.04205E-09
     42098.70c   1.27398E-08
     42100.70c   5.08429E-09
     11023.70c   1.32196E-07
     28058.70c   3.17273E-07
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     28060.70c   1.22213E-07
     28061.70c   5.31251E-09
     28062.70c   1.69386E-08
     28064.70c   4.31376E-09
     14028.70c   1.79645E-06
     14029.70c   9.12195E-08
     14030.70c   6.01326E-08
     38084.70c   3.23734E-10
     38086.70c   5.70003E-09
     38087.70c   4.04667E-09
     38088.70c   4.77392E-08
     22046.70c   9.42599E-08
     22047.70c   8.50053E-08
     22048.70c   8.42283E-07
     22049.70c   6.18116E-08
     22050.70c   5.91838E-08
     23000.70c   4.37506E-06
     39089.70c   1.25342E-07
     6000.70c   8.38831E-02   $ tot   8.39948E-02
C
C  Bottom Reflector
m12   13027.70c   9.97828E-06
     56130.70c   1.69329E-10
     56132.70c   1.61342E-10
     56134.70c   3.86102E-09
     56135.70c   1.05303E-08
     56136.70c   1.25463E-08
     56137.70c   1.79425E-08
     56138.70c   1.14533E-07
     5010.70c   9.17731E-09
     5011.70c   3.69398E-08
     20040.70c   1.97776E-05
     20042.70c   1.31999E-07
     20043.70c   2.75423E-08
     20044.70c   4.25579E-07
     20046.70c   8.16067E-10
     20048.70c   3.81511E-08
     27059.70c   5.07597E-08
     24050.70c   1.33321E-08
     24052.70c   2.57096E-07
     24053.70c   2.91526E-08
     24054.70c   7.25670E-09
     29063.70c   1.08539E-08
     29065.70c   4.83775E-09
     26054.70c   4.11187E-06
     26056.70c   6.45475E-05
     26057.70c   1.49068E-06
     26058.70c   1.98383E-07
     19039.70c   1.18921E-07
     19040.70c   1.49196E-11
     19041.70c   8.58219E-09
     3006.70c   2.15490E-08
     3007.70c   2.65771E-07
     71175.70c   5.55144E-09
     71176.70c   1.47605E-10
     12024.70c   3.24067E-08
     12025.70c   4.10263E-09
     12026.70c   4.51700E-09
     25055.70c   1.81504E-08
     42092.70c   7.71192E-09
     42094.70c   4.80696E-09
     42095.70c   8.27316E-09
     42096.70c   8.66811E-09
     42097.70c   4.96286E-09
     42098.70c   1.25397E-08
     42100.70c   5.00443E-09
```

```
     11023.70c   1.30120E-07
     28058.70c   3.12290E-07
     28060.70c   1.20293E-07
     28061.70c   5.22907E-09
     28062.70c   1.66726E-08
     28064.70c   4.24601E-09
     14028.70c   1.76824E-06
     14029.70c   8.97868E-08
     14030.70c   5.91881E-08
     38084.70c   3.18649E-10
     38086.70c   5.61050E-09
     38087.70c   3.98312E-09
     38088.70c   4.69894E-08
     22046.70c   9.27794E-08
     22047.70c   8.36702E-08
     22048.70c   8.29054E-07
     22049.70c   6.08408E-08
     22050.70c   5.82542E-08
     23000.70c   4.30635E-06
     39089.70c   1.23373E-07
     6000.70c   8.25656E-02   $ tot   8.26756E-02
C    ************************************
C  Additional Bottom Reflectors
C   Al Upper Reflector
m30   13027.70c   5.98746E-02
     29063.70c   2.21304E-05
     29065.70c   9.86383E-06
     14028.70c   1.26853E-04
     14029.70c   6.44131E-06
     14030.70c   4.24616E-06
     26054.70c   4.04295E-06
     26056.70c   6.34657E-05
     26057.70c   1.46570E-06
     25055.70c   7.40146E-06
     30000.70c   1.24368E-05   $ Tot   6.01329E-02
C   Al Lower Reflector
m31   13027.70c   5.97358E-02
     29063.70c   2.20791E-05
     29065.70c   9.84096E-06
     14028.70c   1.26559E-04
     14029.70c   6.42638E-06
     14030.70c   4.23632E-06
     26054.70c   4.03358E-06
     26056.70c   6.33185E-05
     26057.70c   1.46230E-06
     25055.70c   7.38430E-06
     30000.70c   1.24080E-05   $ Tot   5.99935E-02
C   SS304 Reflector
m32   26054.70c   3.51905E-03
     26056.70c   5.52415E-02
     26057.70c   1.27577E-03
     26058.70c   1.69781E-04
     6000.70c   1.60142E-04
     25055.70c   8.75287E-04
     14028.70c   7.89554E-04
     14029.70c   4.00916E-05
     14030.70c   2.64287E-05
     24050.70c   7.63478E-04
     24052.70c   1.47229E-02
     24053.70c   1.66946E-03
     24054.70c   4.15564E-04
     28058.70c   5.29886E-03
     28060.70c   2.04111E-03
     28061.70c   8.87257E-05
     28062.70c   2.82896E-04
     28064.70c   7.20454E-05
```

```
     15031.70c   3.49310E-05
     16032.70c   2.13510E-05
     16033.70c   1.70934E-07
     16034.70c   9.64879E-07
     16034.70c   4.49827E-09   $ tot   8.75101E-02
C   Iron Table
m33   26054.70c   4.66345E-03
     26056.70c   7.32063E-02
     26057.70c   1.69065E-03
     26058.70c   2.24995E-04
     6000.70c   9.43427E-04
     12024.70c   1.47307E-03
     12025.70c   1.86488E-04
     12026.70c   2.05324E-04
     15031.70c   2.92673E-05
     16032.70c   3.35422E-05
     16033.70c   2.68536E-07
     16034.70c   1.51581E-06
     16036.70c   7.06673E-09
     14028.70c   2.97691E-04
     14029.70c   1.51160E-05
     14030.70c   9.96460E-06
     29063.70c   9.86750E-05
     29065.70c   4.39808E-05   $ tot   8.31237E-02
C   Scattering Cards
mt1   o2/u.10t  u/o2.10t
mt2   al27.12t
mt8   grph.10t
mt9   grph.10t
mt10  grph.10t
mt11  grph.10t
mt12  grph.10t
mt20   al27.12t
mt22   al27.12t
mt30  al27.12t
mt31  al27.12t
C
kcode  1000000 1 150 2150
ksrc   0 5.25 5  0 10.5 10  0 -5.25 5  0 -10.5 10
       6.0 0 5   10.5 0 10  -6.0 0 5   -10.5 0 10
       6.5 5.25 5  -6.5 5.25 10  -6.5 -5.25 5  6.5 -5.25 10
```

MCNP5 Input Deck for Simple Benchmark Models:
<u>Case 1</u>

```
SCCA-FUND-EXP-002-001 and HEU-COMP-FAST-002
C
C
C   Cell Cards
1   1  6.54398E-02  (22 -23 -25) u=10 imp:n=1        $fuel pellet
2   0      -22:(25 22 -23 ):23 u=10 imp:n=1  $void around pellet
4   0    -21 22 -23  fill=10 u=12 imp:n=1
C
C
5   15 7.63384E-02 (1 -24 -20 21):(1 -22 -21):(23 -24 -21) u=12 imp:n=1  $Fuel tube and end caps
6   0    -1:(1 20 -24):24 u=12 imp:n=1
C
C
7   0    -21 22 -23  fill=10 u=13 imp:n=1
C
C
8   15 7.63384E-02 21:-22:23 u=13 imp:n=1  $Fuel tube and end caps for u=13
C
10  0   -12 fill=12 u=1 imp:n=1
11  0   -13 fill=13 (-3.766 -11.458 0) imp:n=1
12  0   -14 fill=13 (3.766 -11.458 0) imp:n=1
```

```
13  0   -15 fill=13 (3.766 11.458 0) imp:n=1
14  0   -16 fill=13 (-3.766 11.458 0) imp:n=1
15  0   -17 fill=13 (-8.039 -8.989 0) imp:n=1
16  0   -18 fill=13 (8.039 -8.989 0) imp:n=1
17  0   -19 fill=13 (-8.039 8.989 0) imp:n=1
18  0   -30 fill=13 (8.039 8.989 0) imp:n=1
19  0   -31 fill=13 (-11.805 -2.467 0) imp:n=1
20  0   -32 fill=13 (11.805 -2.467 0) imp:n=1
21  0   -33 fill=13 (-11.805 2.467 0) imp:n=1
22  0   -34 fill=13 (11.805 2.467 0) imp:n=1
C
C
C   Core Assembly
30  0   -11  lat=2  u=2 imp:n=1 fill= -10:10 -10:10 0:0
    2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2  $ROW 1
     2 2 2 2 2 2 2 2 2 2 2 2 2 1 1 1 1 2 2 2 2  $ROW 2
      2 2 2 2 2 2 2 2 2 2 1 1 1 1 1 1 1 1 1 2 2  $ROW 3
       2 2 2 2 2 2 2 2 2 1 1 1 1 1 1 1 1 1 1 2 2  $ROW 4
        2 2 2 2 2 2 2 1 1 1 1 1 1 1 1 1 1 1 1 1 2  $ROW 5
         2 2 2 2 2 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2  $ROW 6
          2 2 2 2 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2  $ROW 7
           2 2 2 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2  $ROW 8
            2 2 2 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 2  $ROW 9
             2 2 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 2  $ROW 10
              2 2 1 1 1 1 1 1 1 1 2 1 1 1 1 1 1 1 1 2 2  $ROW 11
               2 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 2 2  $ROW 12
                2 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 2 2 2  $ROW 13
                 2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 2 2 2  $ROW 14
                  2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 2 2 2 2  $ROW 15
                   2 1 1 1 1 1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2  $ROW 16
                    2 1 1 1 1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2  $ROW 17
                     2 2 1 1 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2  $ROW 18
                      2 2 1 1 1 1 1 1 1 1 1 2 2 2 2 2 2 2 2 2 2  $ROW 19
                       2 2 2 2 1 1 1 1 2 2 2 2 2 2 2 2 2 2 2 2 2  $ROW 20
                        2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2 2  $ROW 21
C
C   Core Tank
31  0   -151 1 -153 13 14 15 16 17 18 19 30 31 32 33 34 fill=2 imp:n=1
140  2 5.88014E-02 (-153 154 -150 151):(-154 152 -150) imp:n=1 $Core Tank
33  0  150 -210 -153 213  imp:n=1
34  0  -152 -150 220 213 250  imp:n=1
81  0   -1 -151 154 220 imp:n=1
C
C  Reflectors
50  10 8.89798E-02 -200   imp:n=1   $Lower Top reflector
51  11 8.38707E-02 200 -201 imp:n=1 $Upper Top Refleltor
52  8  8.77399E-02 210 -212 imp:n=1 $Lower Side Reflector
53  9  8.67421E-02 210 -211 imp:n=1 $Upper Side Reflector
54  12 8.25656E-02 -220   imp:n=1   $bottom Reflector
C  Support Structure/Additional Reflectors
60  30 6.01489E-02 -250 imp:n=1 $Uppwer Al Plate
61  31 6.00094E-02 -251 imp:n=1 $Lower Al Plate
62  32 8.75101E-02 -252 imp:n=1 $SS304 Plate
63  33 8.31237E-02 -253 254 imp:n=1 $Iron Table
64  0  -999 #60 #61 #62 #63 212 211 200 201  imp:n=1
C
999 0  999 imp:n=0

C   Surface Cards
1   pz   0.     $bottom of core tank
20   cz   0.635   $OR Clad
21   cz   0.584   $IR Clad
22   pz   0.3     $top of bottom cap/Bottom of Fuel
23   pz  30.18    $bottom of top cap/Top of Fuel
24   pz  30.48    $Top of fuel tube
25   cz   0.5705  $OR of Pellet
```

```
28   rpp  -0.9 0.9  -0.9 0.9  0.2978 1.4472  $pellet lattice box
11   rhp  0 0 -10  0 0 50   0.753 0 0
12   rhp  0 0 -11  0 0 52   1 0 0
13   rcc  -3.766 -11.458 0  0 0 30.48  0.635
14   rcc  3.766 -11.458 0  0 0 30.48  0.635
15   rcc  3.766 11.458 0  0 0 30.48  0.635
16   rcc  -3.766 11.458 0  0 0 30.48  0.635
17   rcc  -8.039 -8.989 0  0 0 30.48  0.635
18   rcc  8.039 -8.989 0  0 0 30.48  0.635
19   rcc  -8.039 8.989 0  0 0 30.48  0.635
30   rcc  8.039 8.989 0  0 0 30.48  0.635
31   rcc  -11.805 -2.467 0  0 0 30.48  0.635
32   rcc  11.805 -2.467 0  0 0 30.48  0.635
33   rcc  -11.805 2.467 0  0 0 30.48  0.635
34   rcc  11.805 2.467 0  0 0 30.48  0.635
C
C  Core Tank
150  cz  12.98  $OR Core Tank
151  cz  12.726 $IR Core Tank
152  pz  -23.224  $Bottom of Core Tank
154  pz  -22.86   $top of bottom of core tank
153  pz  30.816  $Top of Core Tank
C
C  Reflectors
C   Top Reflectors
200  rcc 0 0 30.816   0 0 15.25   38.1 $Lower Top Reflector
201  rcc 0 0 46.066   0 0 8.36    25.4 $Upper Top Reflector
C  Side Reflectors
210  cz  13.0675  $IR
211  rcc 0 0 23.186   0 0 7.63   38.6  $Upper Side Reflector
212  rcc 0 0 -23.444  0 0 46.63  40.9675 $Lower Side Reflector
213  pz -23.444 $surface for creating void regions
C  Bottom Reflector
220  rcc 0 0 -22.86  0 0 22.86  12.71 $bottom reflector
C  Additional Bottom Reflectors
250  rcc 0 0 -25.164  0 0 1.94  10.8  $Al Upper Plate
251  rcc 0 0 -25.794  0 0 0.63  22.86 $Al Lower Plate
252  rcc 0 0 -28.174  0 0 2.38  22.86 $SS304 Plate
253  rpp -60.95 60.95  -60.95 60.95  -24.82 -23.55 $Iron Table
254  cz 13.335
C
999   rpp  -500 500   -500 500  -500 500

C   Data Cards
C  Fuel
m1   92234.70c   2.21403E-04
     92235.70c   2.03324E-02
     92236.70c   1.02154E-04
     92238.70c   1.15733E-03
     8016.70c   4.35205E-02
     8017.70c   1.06012E-04   $  Tot   6.54398E-02
C   Fuel Clad
m15   26054.70c   3.05226E-03
     26056.70c   4.79139E-02
     26057.70c   1.10654E-03
     26058.70c   1.47260E-04
     6000.70c   1.39900E-04
     25055.70c   7.64651E-04
     14028.70c   6.89755E-04
     14029.70c   3.50241E-05
     14030.70c   2.30881E-05
     24050.70c   6.31871E-04
     24052.70c   1.21850E-02
     24053.70c   1.38168E-03
     24054.70c   3.43930E-04
     28058.70c   5.35999E-03
```

```
     28060.70c  2.06466E-03
     28061.70c  8.97493E-05
     28062.70c  2.86160E-04
     28064.70c  7.28766E-05
     15031.70c  3.05157E-05
     16032.70c  1.86523E-05
     16033.70c  1.49328E-07
     16034.70c  8.42918E-07
     16036.70c  3.92969E-09   $ tot   7.63384E-02
C   Core Tank
m2  13027.70c  5.85485E-02
     29063.70c  2.16403E-05
     29065.70c  9.64537E-06
     14028.70c  1.24044E-04
     14029.70c  6.29865E-06
     14030.70c  4.15212E-06
     26054.70c  3.95341E-06
     26056.70c  6.20601E-05
     26057.70c  1.43324E-06
     26058.70c  1.90738E-07
     25055.70c  7.23754E-06
     30000.70c  1.21614E-05   $ Tot   5.88014E-02
C   Reflectors
C  ***********************************
C  Lower Side Reflector
m8   6000.70c   8.77399E-02   $ tot   8.77399E-02
C
C  Upper Side Reflector
m9   6000.70c   8.67421E-02   $ tot   8.67421E-02
C
C  Lower Top Reflector
m10   6000.70c   8.89798E-02   $ tot   8.89798E-02
C
C  Upper Top Reflector
m11   6000.70c   8.38707E-02   $ tot   8.38707E-02
C
C  Bottom Reflector
m12   6000.70c   8.25656E-02   $ tot   8.25656E-02
C    ************************************
C  Additional Bottom Reflectors
C   Al Upper Reflector
m30   13027.70c   5.98746E-02
     29063.70c  2.21304E-05
     29065.70c  9.86383E-06
     14028.70c  1.26853E-04
     14029.70c  6.44131E-06
     14030.70c  4.24616E-06
     26054.70c  4.04295E-06
     26056.70c  6.34657E-05
     26057.70c  1.46570E-06
     25055.70c  7.40146E-06
     30000.70c  1.24368E-05   $ Tot   6.01329E-02
C   Al Lower Reflector
m31   13027.70c   5.97358E-02
     29063.70c  2.20791E-05
     29065.70c  9.84096E-06
     14028.70c  1.26559E-04
     14029.70c  6.42638E-06
     14030.70c  4.23632E-06
     26054.70c  4.03358E-06
     26056.70c  6.33185E-05
     26057.70c  1.46230E-06
     25055.70c  7.38430E-06
     30000.70c  1.24080E-05   $ Tot   5.99935E-02
C   SS304 Reflector
m32   26054.70c   3.51905E-03
```

```
     26056.70c  5.52415E-02
     26057.70c  1.27577E-03
     26058.70c  1.69781E-04
     6000.70c  1.60142E-04
     25055.70c  8.75287E-04
     14028.70c  7.89554E-04
     14029.70c  4.00916E-05
     14030.70c  2.64287E-05
     24050.70c  7.63478E-04
     24052.70c  1.47229E-02
     24053.70c  1.66946E-03
     24054.70c  4.15564E-04
     28058.70c  5.29886E-03
     28060.70c  2.04111E-03
     28061.70c  8.87257E-05
     28062.70c  2.82896E-04
     28064.70c  7.20454E-05
     15031.70c  3.49310E-05
     16032.70c  2.13510E-05
     16033.70c  1.70934E-07
     16034.70c  9.64879E-07
     16034.70c  4.49827E-09   $ tot   8.75101E-02
C   Iron Table
m33   26054.70c   4.66345E-03
     26056.70c  7.32063E-02
     26057.70c  1.69065E-03
     26058.70c  2.24995E-04
     6000.70c  9.43427E-04
     12024.70c  1.47307E-03
     12025.70c  1.86488E-04
     12026.70c  2.05324E-04
     15031.70c  2.92673E-05
     16032.70c  3.35422E-05
     16033.70c  2.68536E-07
     16034.70c  1.51581E-06
     16036.70c  7.06673E-09
     14028.70c  2.97691E-04
     14029.70c  1.51160E-05
     14030.70c  9.96460E-06
     29063.70c  9.86750E-05
     29065.70c  4.39808E-05   $ tot   8.31237E-02
C   Scattering Cards
mt1   o2/u.10t  u/o2.10t
mt2   al27.12t
mt8   grph.10t
mt9   grph.10t
mt10  grph.10t
mt11  grph.10t
mt12  grph.10t
mt30  al27.12t
mt31  al27.12t
C
kcode  1000000 1 150 2000
C  kcode  100 1 10 150
ksrc   0 5.25 5  0 10.5 10  0 -5.25 5  0 -10.5 10
      6.0 0 5   10.5 0 10  -6.0 0 5   -10.5 0 10
      6.5 5.25 5  -6.5 5.25 10  -6.5 -5.25 5  6.5 -5.25 10
```

KENO Input Deck for Simple Benchmark Models:

<u>*Case 1*</u>

```
'Input generated by GeeWiz SCALE 6.1 Compiled on Mon Jun  6 11:04:33 2011
=csas6
scca-002 simple
ce_v7_endf
read composition
```

```
 c-graphite  1 0 0.08774 293.6   end
 c-graphite  2 0 0.086742 293.6   end
 c-graphite  3 0 0.08898 293.6   end
 c-graphite  4 0 0.083871 293.6   end
 c-graphite  5 0 0.082566 293.6   end
 u-234       6 0 0.0002214 293.6   end
 u-235       6 0 0.020332 293.6   end
 u-236       6 0 0.00010215 293.6   end
 u-238       6 0 0.0011573 293.6   end
 o          6 0 0.043627 293.6   end
 fe         7 0 0.0516934 296   end
 c          7 0 0.0001399 296   end
 mn          7 0 0.00076465 296   end
 si         7 0 0.00074787 296   end
 cr         7 0 0.014542 296   end
 ni         7 0 0.0078734 296   end
 p          7 0 3.0516e-05 296   end
 s          7 0 1.9648e-05 296   end
 nb          7 0 0.00029104 296   end
 ta-181      7 0 1.3076e-05 296   end
 al         9 0 0.05854 293.6   end
 cu          9 0 3.1014e-05 293.6   end
 si         9 0 0.00013333 293.6   end
 fe         9 0 6.6861e-05 293.6   end
 mn          9 0 7.1746e-06 293.6   end
 zn          9 0 1.2056e-05 293.6   end
 al         13 0 0.059875 293.6   end
 cu          13 0 3.1994e-05 293.6   end
 si         13 0 0.00013754 293.6   end
 fe         13 0 6.8974e-05 293.6   end
 mn          13 0 7.4015e-06 293.6   end
 zn          13 0 1.2437e-05 293.6   end
 al         14 0 0.059736 293.6   end
 cu          14 0 3.192e-05 293.6   end
 si         14 0 0.00013722 293.6   end
 fe         14 0 6.8814e-05 293.6   end
 mn          14 0 7.3843e-06 293.6   end
 zn          14 0 1.2408e-05 293.6   end
 fe         15 0 0.060206 293.6   end
 c          15 0 0.00016014 293.6   end
 mn          15 0 0.00087529 293.6   end
 si         15 0 0.00085607 293.6   end
 cr         15 0 0.017571 293.6   end
 ni         15 0 0.0077836 293.6   end
 p          15 0 3.4931e-05 293.6   end
 s          15 0 2.2491e-05 293.6   end
 fe         16 0 0.079785 293.6   end
 c          16 0 0.00094343 293.6   end
 mg          16 0 0.0018649 293.6   end
 p          16 0 2.9267e-05 293.6   end
 s          16 0 3.5334e-05 293.6   end
 si         16 0 0.00032277 293.6   end
 cu          16 0 0.00014266 293.6   end
end composition
read parameter
 gen=1150
 npg=100000
 nsk=150
 htm=yes
end parameter
read geometry
global unit 1
com="scca-002"
 cylinder 1  13.0675    46.63       0
 cylinder 2  40.9675    46.63       0
 cylinder 3    13.07    54.26    46.63
```

```
 cylinder 4    38.6    54.26    46.63
 cuboid 5      61      -61      61      -61      80      -5
 cylinder 6    38.1    69.51    54.26
 cylinder 7    25.4    77.87    69.51
 cylinder 24   13.335      0    -1.27
 cuboid 25   60.96   -60.96   60.96   -60.96       0    -1.27
 cuboid 26   60.96   -60.96   60.96   -60.96   77.87    -1.27
 cylinder 27   12.726   54.26    0.584
 cylinder 28    12.98   54.26    0.22
 cylinder 29    12.71   23.444    0.584
 cylinder 30     10.8    0.22    -1.72
 cylinder 31    22.86   -1.72    -2.35
 cylinder 32    22.86   -2.35    -4.73
 cuboid 33   60.96   -60.96   60.96   -60.96   -1.27    -4.73
 cylinder 34   12.726   53.924   23.444
 array 1 34 -35 -36 -37 -38 -39 -40 -41 -42 -43 -44 -45 -46  place 11 11 1 0 0 23.444
 cylinder 35    0.635   53.924   23.444   origin  x=3.766 y=-11.458 z=0
 array 2 35  place 2 2 1 3.766 -11.458 23.444
 cylinder 36    0.635   53.924   23.444   origin  x=8.039 y=-8.989 z=0
 array 2 36  place 2 2 1 8.039 -8.989 23.444
 cylinder 37    0.635   53.924   23.444   origin  x=11.805 y=-2.467 z=0
 array 2 37  place 2 2 1 11.805 -2.467 23.444
 cylinder 38    0.635   53.924   23.444   origin  x=11.805 y=2.467 z=0
 array 2 38  place 2 2 1 11.805 2.467 23.444
 cylinder 39    0.635   53.924   23.444   origin  x=8.039 y=8.989 z=0
 array 2 39  place 2 2 1 8.039 8.989 23.444
 cylinder 40    0.635   53.924   23.444   origin  x=3.766 y=11.458 z=0
 array 2 40  place 2 2 1 3.766 11.458 23.444
 cylinder 41    0.635   53.924   23.444   origin  x=-3.766 y=11.458 z=0
 array 2 41  place 2 2 1 -3.766 11.458 23.444
 cylinder 42    0.635   53.924   23.444   origin  x=-8.039 y=8.989 z=0
 array 2 42  place 2 2 1 -8.039 8.989 23.444
 cylinder 43    0.635   53.924   23.444   origin  x=-11.805 y=2.467 z=0
 array 2 43  place 2 2 1 -11.805 2.467 23.444
 cylinder 44    0.635   53.924   23.444   origin  x=-11.805 y=-2.467 z=0
 array 2 44  place 2 2 1 -11.805 -2.467 23.444
 cylinder 45    0.635   53.924   23.444   origin  x=-8.039 y=-8.989 z=0
 array 2 45  place 2 2 1 -8.039 -8.989 23.444
 cylinder 46    0.635   53.924   23.444   origin  x=-3.766 y=-11.458 z=0
 array 2 46  place 2 2 1 -3.766 -11.458 23.444
 media 1 1 -1 2
 media 2 1 -3 4
 media 3 1 6
 media 4 1 7
 media 16 1 -24 25
 media 0 1 -2 -4 -25 26 -6 -7
 media 9 1 -27 28 -35 -36 -37 -38 -39 -40 -41 -42 -43 -44 -45 -46
 media 5 1 29
 media 13 1 30
 media 14 1 31
 media 15 1 32
 media 0 1 -28 3
 media 0 1 1 -28 -30
 media 0 1 24 -30
 media 0 1 33 -30 -31 -32
 media 0 1 5 -25 -26 -33
 media 0 1 -34 -29 27 -35 -36 -37 -38 -39 -40 -41 -42 -43 -44 -45 -46
 boundary 5
unit 3
com="fuel tube position"
 cylinder 1    0.635    30.48       0
 cylinder 2    0.584    30.18      0.3
 cylinder 3   0.5705    30.18      0.3
 hexprism 31    0.753    30.48       0
 media 7 1 1 -2
 media 0 1 2 -3
```

```
 media 0 1 -1 31
 media 6 1 3
 boundary 31
unit 5
com="empty fuel tube position (void)"
 hexprism 31    0.753    30.48        0
 media 0 1 31
 boundary 31
end geometry
read array
ara=1 nux=21 nuy=21 nuz=1 typ=shexagonal gbl=1
 com="
 fill
   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5
   5   5   5   5   5   5   5   5   3   3   3   3   5   5   5   5   5   5   5   5   5
   5   5   5   5   5   5   3   3   3   3   3   3   3   3   3   5   5   5   5   5   5
   5   5   5   5   5   3   3   3   3   3   3   3   3   3   3   5   5   5   5   5   5
   5   5   5   5   3   3   3   3   3   3   3   3   3   3   3   3   3   5   5   5   5
   5   5   5   3   3   3   3   3   3   3   3   3   3   3   3   3   3   5   5   5   5
   5   5   5   3   3   3   3   3   3   3   3   3   3   3   3   3   3   3   5   5   5
   5   5   3   3   3   3   3   3   3   3   3   3   3   3   3   3   3   3   5   5   5
   5   5   5   3   3   3   3   3   3   3   3   3   3   3   3   3   3   3   5   5   5
   5   5   3   3   3   3   3   3   3   3   3   3   3   3   3   3   3   3   5   5   5
   5   5   3   3   3   3   3   3   3   3   5   3   3   3   3   3   3   3   3   5   5
   5   5   3   3   3   3   3   3   3   3   3   3   3   3   3   3   3   3   5   5   5
   5   5   5   3   3   3   3   3   3   3   3   3   3   3   3   3   3   3   5   5   5
   5   5   3   3   3   3   3   3   3   3   3   3   3   3   3   3   3   3   5   5   5
   5   5   5   3   3   3   3   3   3   3   3   3   3   3   3   3   3   3   5   5   5
   5   5   5   3   3   3   3   3   3   3   3   3   3   3   3   3   3   5   5   5   5
   5   5   5   5   3   3   3   3   3   3   3   3   3   3   3   3   3   5   5   5   5
   5   5   5   5   5   3   3   3   3   3   3   3   3   3   3   5   5   5   5   5   5
   5   5   5   5   5   5   3   3   3   3   3   3   3   3   3   5   5   5   5   5   5
   5   5   5   5   5   5   5   5   3   3   3   3   5   5   5   5   5   5   5   5   5
   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5   5  end fill
ara=2 nux=3 nuy=3 nuz=1 typ=shexagonal
 com="
 fill
   5   5   5
   5   3   5
   5   5   5  end fill
end array
end data
end
```