UNREFLECTED UO_2F_2+H_2O CYLINDRICAL ASSEMBLY SHEBA-II

Evaluator

Raphael J. LaBauve
Consultant to Los Alamos National Laboratory

Internal Reviewer

Joseph L. Sapir
Consultant to Los Alamos National Laboratory

Independent Reviewers

Yoshinori Miyoshi
Japan Atomic Energy Research Institute

Virginia Dean
Consultant to Idaho National Engineering Laboratory

UNREFLECTED UO_2F_2+H_2O CYLINDRICAL ASSEMBLY - SHEBA-II

SPECTRA

IDENTIFICATION NUMBER: LEU-SOL-THERM-001

KEY WORDS: acceptable, bare, critical experiment, cylinder, low enriched, SHEBA-II, solution, unreflected cylindrical assembly, uranium, uranyl fluoride

1.0 DETAILED DESCRIPTION

1.1 Overview of Experiment

SHEBA-II (Solution High Energy Burst Assembly-II) is a critical assembly experiment (Reference 1) currently being operated at the Los Alamos Critical Experiments Facility. It is a bare assembly fueled with an aqueous solution of about 5% enriched uranyl fluoride that is stored in four critically safe steel tanks. Figure 1 is a schematic of the cylindrical assembly vessel (CAV) and the solution storage tanks; Figure 2 shows a photograph of the SHEBA-II experiment. The solution is transferred to the critical assembly vessel by a pump. Reactivity control is effected by varying the solution level, and a safety rod may be inserted in a thimble along the central axis of the CAV for fast shutdown. Two one-inch lines are used to rapidly gravity drain the CAV for additional shutdown capability. The critical assembly is housed inside a metal building that was formerly used for the "Kinglet" experiment, and a pit beneath SHEBA-II is available for operation below ground level.

This evaluation is for the above-ground experiment only. The simple geometry provided by this cylindrical system allows for easily applied calculational methods, and thus SHEBA-II is ideally suited for use as a criticality safety benchmark experiment.

1.2 Description of Experimental Configuration

Figure 3, taken from Reference 1,[a] is a diagram of the SHEBA-II critical assembly vessel (CAV). According to engineering drawings of SHEBA-II,[b] the CAV is basically a 30-inch length of 20-inch pipe, schedule 20[c] stainless steel 304L. The base plate is a 1.125-inch-thick disk machined to fit snugly 0.5 inch into the pipe section. The center of the base plate contains a 2.5-inch-outer-diameter hole for the safety-rod thimble tube. This tube is 30.875 inches long, 2.5 inches in outer diameter with a 0.25-inch wall. The top edge of the tube is even with the top of the pipe and extends 0.75 inch into the base plate. The top cover of the CAV consists of a disk 0.75 inch thick and 22.5 inches in diameter.[d]

[a] Dimensions have been revised to as-built measurements.

[b] Los Alamos National Laboratory drawing 128Y 270639, Critical Assembly Vessel Subassembly, SHEBA (10 sheets)

[c] Recent ultrasound measurements confirmed that the wall thickness matches that of schedule 20 pipe. (Private communication, C. Cappiello, March, 1996.) The pipe was originally reported to be schedule 40.

[d] Los Alamos National Laboratory drawing 128Y 270728 D2, Vessel Cover - Cover Top Side Detail.

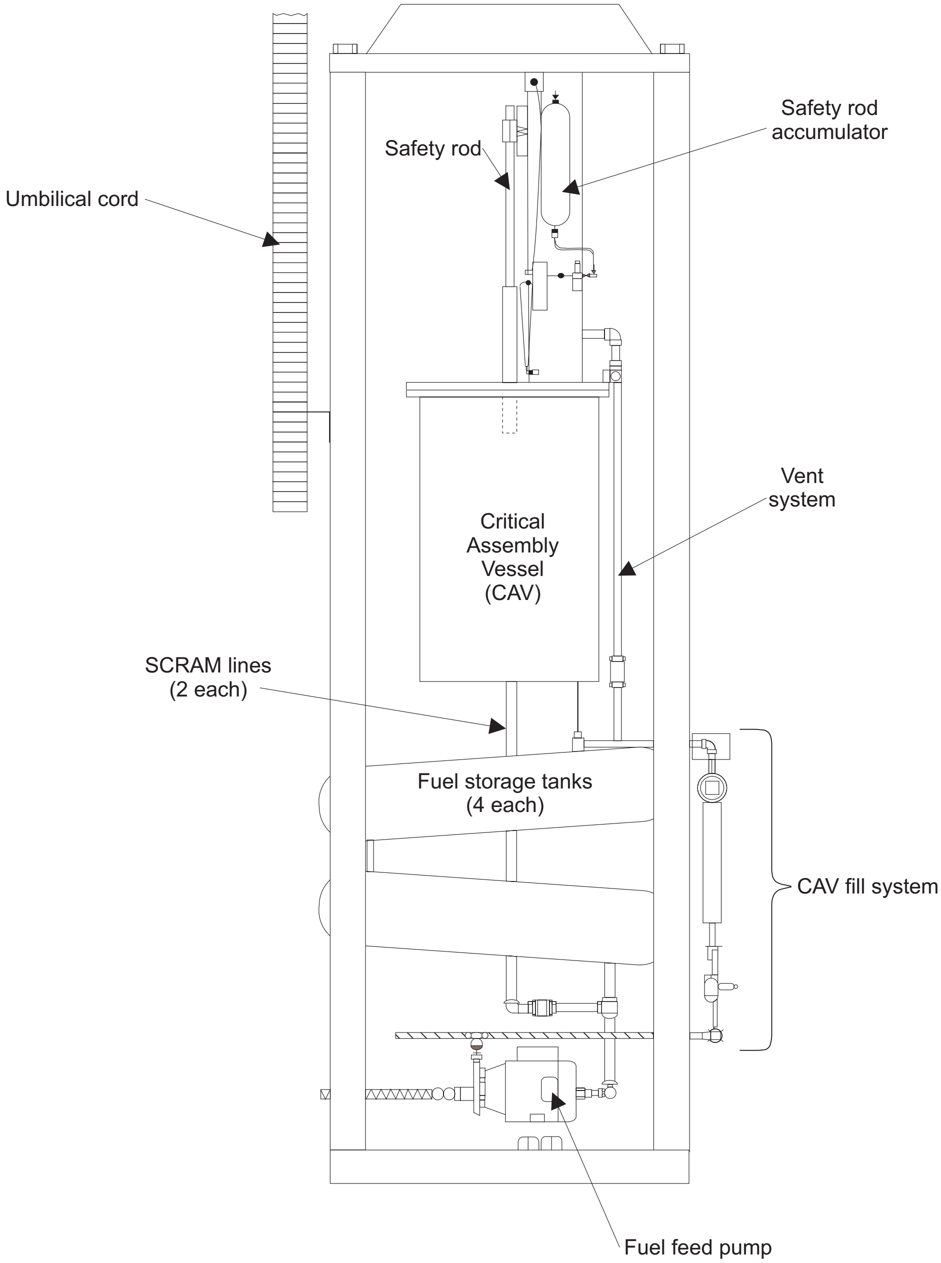

Figure 1. Schematic of SHEBA Critical Assembly.

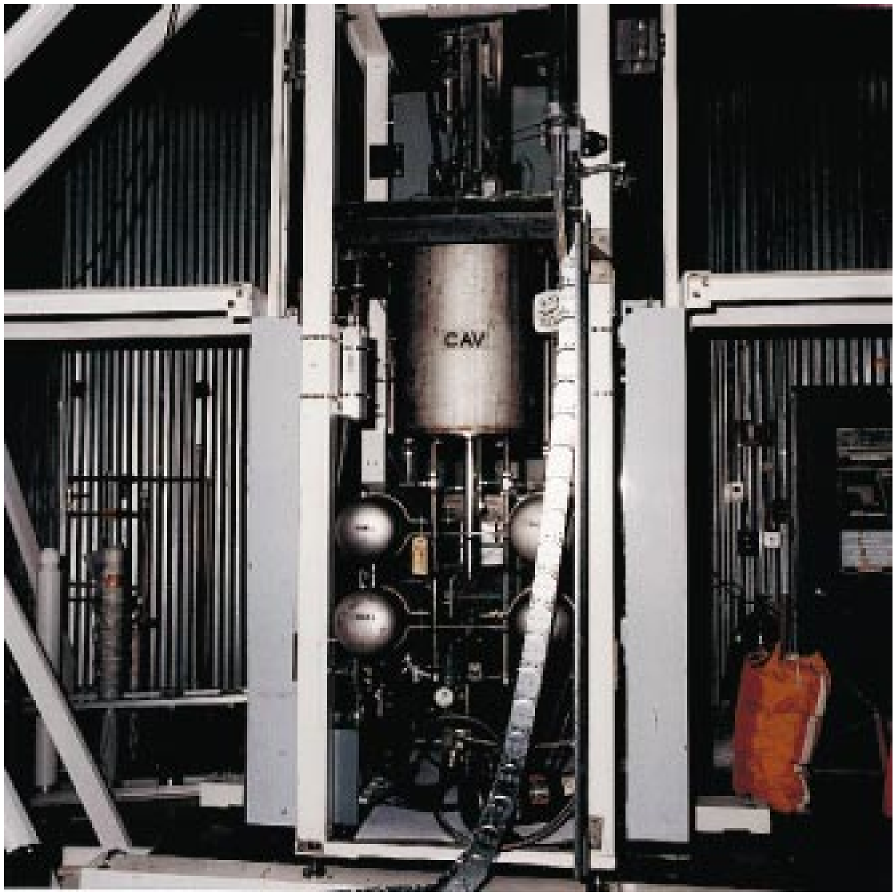

Figure 2. Photo of the SHEBA-II Assembly.

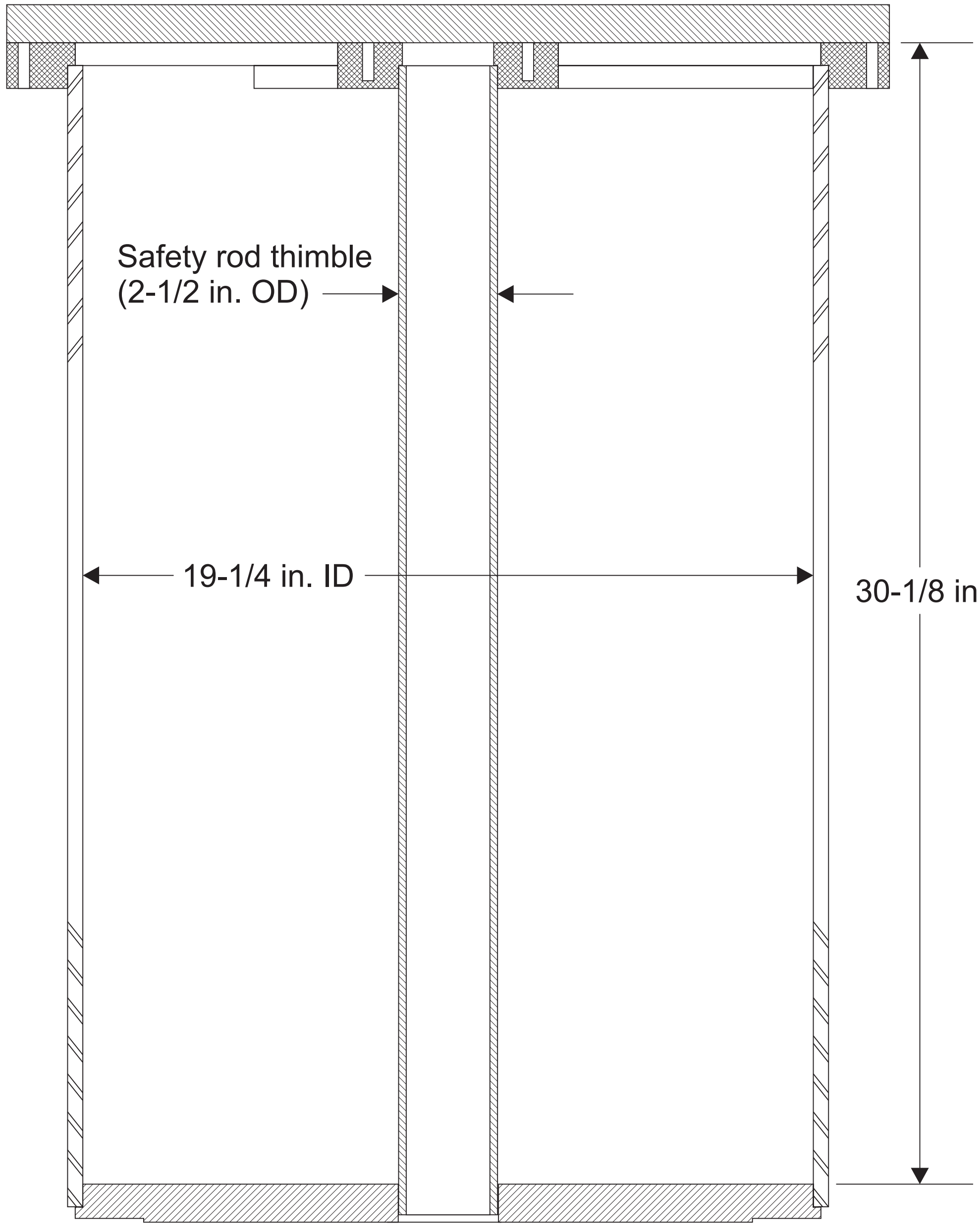

Figure 3. SHEBA-II Critical Assembly Vessel (CAV).

It is bolted to two flanges welded to the CAV and central tube. The outer flange fits tightly around the top edge of the CAV pipe and the other fits tightly around the top edge of the safety rod thimble. Both flanges are 1.13 inches thick and extend 0.63 inch above the CAV pipe. The flanges are joined by three rods of 0.5-inch-square cross section. The lip of the outer flange extends 1.25 inches outside the pipe and the lip of the inner flange extends 1.25 inches outside the central tube. The cover has a 2.5-inch central hole for the safety rod. The base plate, cover, safety-rod thimble, flanges and adjoining rods, as well as the CAV pipe, are all 304L stainless steel. The distance between the top of the base plate and the bottom of the top cover is 30.125 inches.

The safety rod consists of borated epoxy resin (30% natural boron) contained in the top 20 inches of a 40-inch-long, 304 stainless steel, 1.5-inch, schedule 5 pipe.[a] Schedule 5, 1.5-inch pipe has a 1.9-inch outer diameter and 0.065-inch wall thickness. The safety rod follower is the remaining 20 inches of empty pipe. The 20-inch follower extends to the bottom of the CAV. (Note that the safety rod configuration is not included in Figure 3.) "The up position of the safety rod is determined by a hard mechanical stop that does not move. The fixed distance from the inside bottom of the tank to the bottom of the poison part of the safety rod when the rod is retracted is 48.1 cm."[b]

Solution enters the CAV through a fill tube at the bottom of the tank, located about 6 inches from the center. The 304L stainless steel fill tube has a 0.5-inch outer diameter and a 0.035-inch wall. The tube extends into the tank about 4.93 inches, curving so that the opening is directed downward. Two stainless steel 304L drain tubes (1.0-inch outer diameter, 0.035-inch wall) are also attached to the tank bottom, but they do not extend into the tank.[c] The thermocouple well is a 0.25-inch-outer-diameter, 316 stainless steel tube which is located one inch from the outer edge and extends to 10 inches above the bottom of the CAV. Its worth is estimated at less than one cent.[d]

The SHEBA-II experiment is housed in a 20-ft. x 20-ft. x 20-ft. metal shed (wall thickness of about 1/8 inch), shown in Figure 4. The CAV is about 3 feet from the nearest wall. Other distances and a concrete crypt beneath the assembly are shown in the figure.

---

[a] Los Alamos National Laboratory drawing 128Y 270727 D1, Control Rod System, Control Rod Assembly, D2, Control Rod System.

[b] Private communication, C. Cappiello, April, 1996.

[c] Los Alamos National Laboratory drawing 128Y 270639, Critical Assembly Vessel Subassembly, SHEBA, sheet D10.

[d] Private Communication, C. Cappiello, May, 1996.

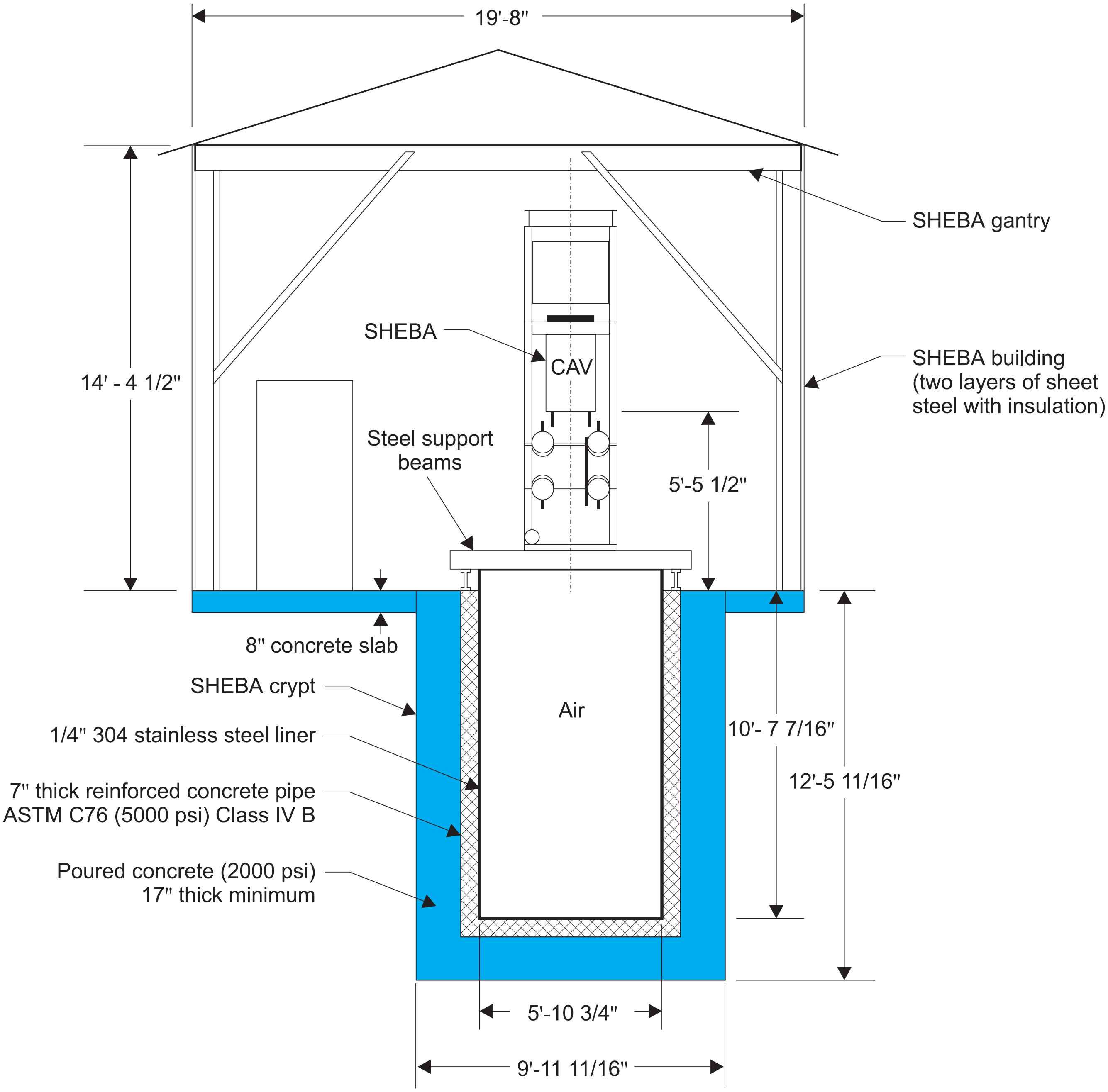

Figure 4. Elevation View of SHEBA (Looking South).

In performing a SHEBA critical experiment, a neutron source is positioned near the assembly vessel, and neutron detectors are positioned so that their line-of-sight to the source will traverse the solution when it is present. Counting rates of the neutron detectors are determined, the first count serving as the reference count. Multiplication of the system is defined as the ratio of the counting rate with the added volume of solution to the initial counting rate. As solution is added to the assembly, the inverse multiplication method is then used to obtain increasingly refined estimates of the solution critical height. Two He^3 detectors are used to monitor reactor power above delayed critical. The solution height is determined by use of sophisticated remote reading instrumentation, which include a mass-flow meter, an ultrasonic level detector, and a liquid level probe.

In addition to the eigenvalue (k_{eff}) experiment, other experimental results were obtained in the course of running SHEBA-II.

These include:

<u>Reactivity as a function of solution height</u>[a]

Period data were taken from December 1993 to June 1995 and were reduced using inhour constants from Godiva to obtain reactivity in cents. Results are shown as a function of height above delayed critical in Figure 5.

<u>Temperature coefficient of reactivity (Reference 4)</u>

Numerous measurements of delayed-critical height as a function of temperature were made during the period March 1994 to the present. Results are shown in Figure 6. Note that a very good linear fit can be made to the experimental data, giving a critical height of 44.8 cm at 20°C. Combining these data with those from Figure 5 gives a value of -4.45 cents/°C for a temperature coefficient of reactivity.

[a] Personal communication, C. Cappiello, K. B. Butterfield, and R. E. Anderson, September 1994; February 1996.

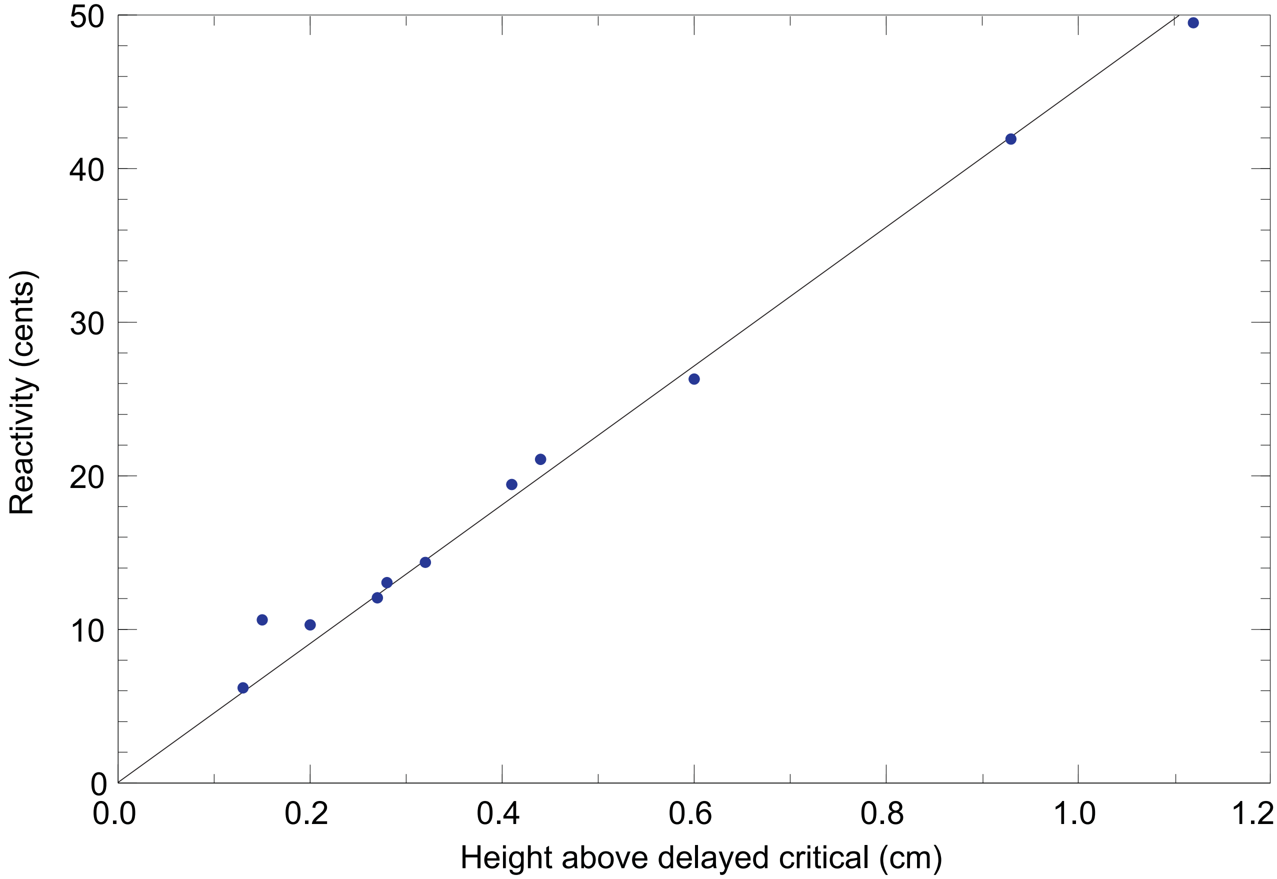

Figure 5. Reactivity as a Function of Height Above Delayed Critical.

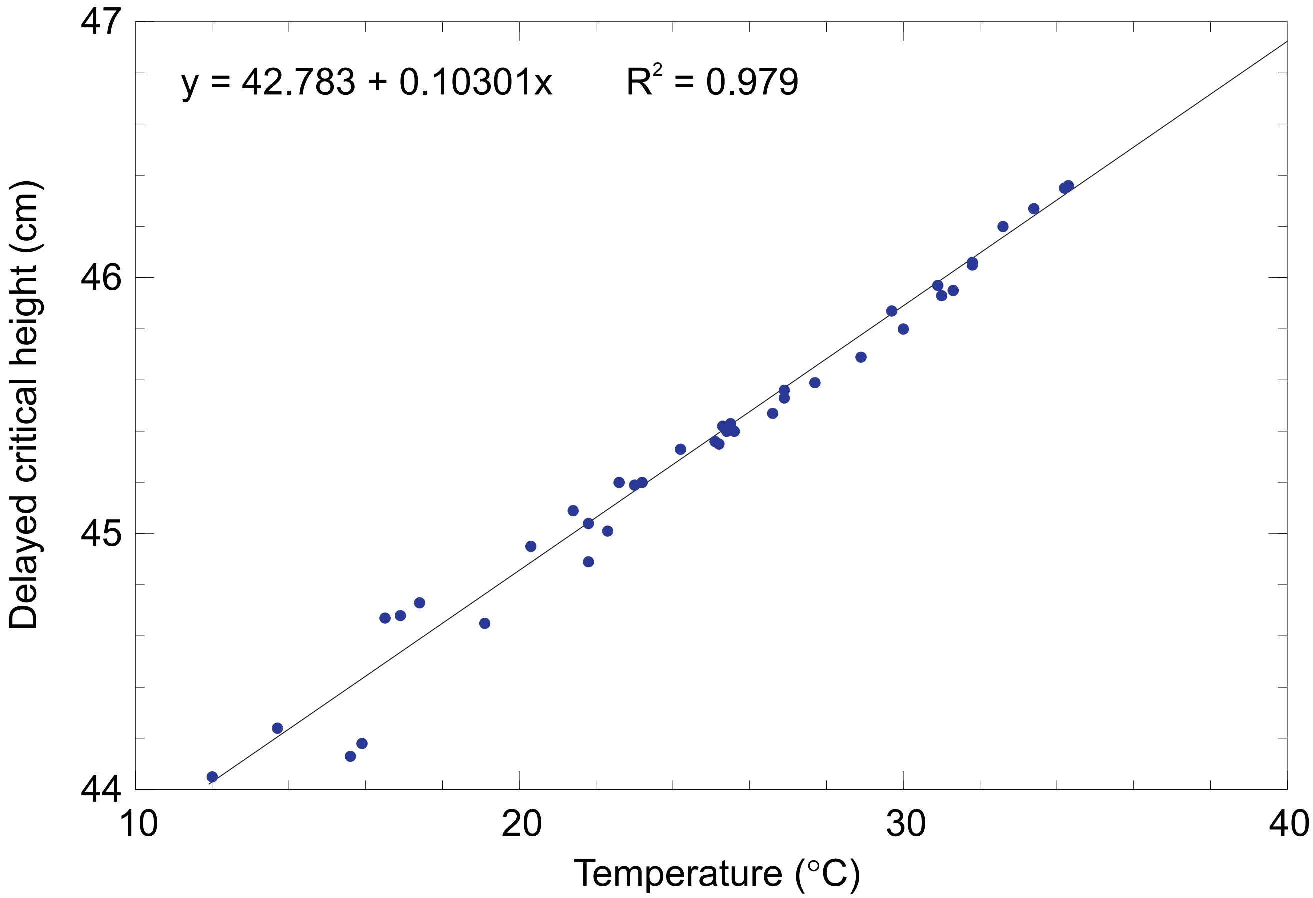

Figure 6. Measurement of the Effect of Temperature on Critical Height for SHEBA-II.

1.3 Description of Material Data

The schedule 20 pipe used for the CAV has a 20-inch outer diameter, a wall thickness of 0.375 inch, and a weight per foot of 78.60 pounds.[a] A density of 7.8419 g/cm^3 was calculated from the pipe specifications. The constituents of the stainless steel (SS304L) are given in Table 1.[b]

Table 1. Data for Stainless Steel 304L.

Element	Weight %
Mn	2
Ni	8 - 10
Cr	17 - 19
Fe	balance

The uranyl fluoride solution was prepared at the Los Alamos National Laboratory. Several analyses of the fuel were performed at LANL, and a summary of results are given in Table 2.a. As seen in Table 2.a, chemical analyses of the uranyl fluoride solution were made in 1986, 1989, 1991, and 1996, but the experiments reported here were performed between 1993 and the present (1996). It is therefore the opinion of the experimenters that only the 1996 analyses be used in determining benchmark atom densities for these experiments.[c] No acidities are reported for samples taken during 1986 (Reference 1), but 0.5M acidity is reported for samples taken in 1991,[d] and <0.4M for samples analyzed in 1996.[e] It is assumed that the acid in the solution is HF and that the total solution specific gravity is the sum of the UO_2F_2, H_2O, and HF densities.

[a] T. Baumeister, E. A. Avallone, and T. Baumeister, III, Eds, “Marks’ Standard Handbook for Mechanical Engineers,” Eight Edition, McGraw-Hill Book Company,1976.
[b] Gibbons, R. C. (Ed.), “ Woldman’s Engineering Alloys, Sixth Edition”, American Society for Metals, 1980.
[c] Private communication, C. Cappiello, March,1996.
[d] Sample analyses, CLS-1 Sample Management, Computer#s: 74807, 74808, March 19, 1991.
[e] Sample analyses, sample IDs: 200019524 and 200019525, February 5, 1996.

Table 2.a. Analyses of SHEBA-II Fuel.

Date of Analyses	No. of Samples	Average Solution Density (g/cm^3)	Average U density (g/cm^3)	Average Atom Percent			
				^{234}U	^{235}U	^{236}U	^{238}U
During 1986	5	2.16	1.042	0.0264	5.0140	0.0496	94.9100
2/89	6	2.1261	0.9888	0.0280	5.0247	0.0490	94.8983
3/91	2	2.1229	0.9916	0.0280	5.0000	0.0500	94.9220
2/96	2	2.1092[(a)]	0.9783[(b)]	0.0274	4.9977	0.0488	94.9261

(a) at 20°C.
(b) estimated precision 0.1%.

The SHEBA-II uranyl fluoride fuel solution was also analyzed for impurities by the Commercial Nuclear Fuel Division of the Westinghouse Electric Corporation.[a] Typical results from several samples are given in Table 2.b below.

Table 2.b. Measurable Impurities in SHEBA-II Fuel.

Element	Typical Concentration-ppm[(a)]
Aluminum	44.
Boron	0.3
Cadmium	0.5
Cobalt	3.0
Copper	11.
Iron	85.
Lead	3.4
Magnesium	0.5
Manganese	11.
Nickel	14.
Zinc	8.9
Barium	12.
Zirconium	57.

(a) Parts of impurity per million parts of UO_2 by weight.

[a] Private communication, T. Shannon and C. Sanders, January, 1996.

1.4 Supplemental Experimental Data

Void worths were measured at a number of positions during 1994 and 1995 and reported in Reference 5. The voids were simulated with aluminum blocks which are sectors of cylinders with radii concentric with the CAV. Delayed critical height measurements were made with the blocks placed at several inner and outer positions in the fuel solution.

2.0 EVALUATION OF EXPERIMENTAL DATA

Sensitivity calculations for SHEBA-II were run using the two-dimensional model of the experiment given in Figure 7, with a base case height of the uranyl fluoride of 44.8 cm. The code/nuclear data set used in the calculations was TWODANT/27-Group ENDF/B-IV SCALE set. A summary of the SHEBA-II sensitivity results is given in Table 3.

Table 3. Summary of SHEBA-II Sensitivity Calculations.

Parameter	Change	Effect on k_{eff}
Fuel Height	1 - inch increase	1.0% increase
Fuel Radius	1 - inch increase	4.2% increase
Acidity	0.5M decrease	0.16% increase
Vessel Wall Thickness/Density	1.0% increase	0.02% increase

2.1 Critical Height

An uncertainty of approximately ±0.1 cm in the measurements of critical height can be calculated from the spread of the temperature vs. critical height data displayed in Figure 6. Based on the fuel height sensitivity calculation in Table 3, a ±0.1 cm-change in fuel height would produce a ±0.04% change in k_{eff}.

2.2 Solution Temperature

According to the experimenters,[a] the temperature at which chemical analyses were made can be as much as 2.5°C different from 20°C. From the temperature coefficient in Section 1.2 and calculations reported in Reference 6, this would lead to an uncertainty of ±0.10% in k_{eff}. From Figure 6, the critical height at 20°C is 44.8 cm. An earlier measured value of 43.5 cm was reported in Reference 3. Initial problems with the measuring devices, which were later corrected, invalidated this measurement,[b] so it is not relevant to this evaluation.

2.3 Solution

The results of the chemical analyses of five samples of the uranyl fluoride solution reported in Reference 1 and ten later samples are given in Table 2 above. Note that these analyses fall into four groups. The first five, taken during 1986, give a solution density of 2.16 g/cm^3 and an average uranium density of 1.042 g/cm^3; the second six, taken in February 1989, give a solution density of 2.1261 g/cm^3 and an average uranium density of 0.9888 g/cm^3; the third pair, taken in March 1991, give a solution

[a] Private communication, K. B. Butterfield and R. E. Anderson, September 1994.
[b] Private communication, C. Cappiello, March, 1996.

density of 2.1229 g/cm^3 and uranium density of 0.9916 g/cm^3; and the last pair, taken February 1996, give 2.1092 and 0.9783 g/cm^3. In this evaluation an equal weight is assigned to each group in calculating the uncertainty which arises from the differences in the various chemical analyses; but, as stated above, the results of only the 1996 analyses are used for benchmark specifications.

Using atom densities derived from each of the groups of samples given in Table 2 above, k_{eff} calculations were run with TWODANT and the 27-group SCALE ENDF/B-IV cross sections. A fuel height of 44.8 cm was assumed for each case. Table 4 shows the resulting k_{eff} calculated for each of the groups. Differences from a k_{eff} of 1.0121, resulting from a TWODANT run using the average parameters calculated for the four groups of samples, are also shown in Table 4.

Table 4. Differences for Each Sample k_{eff} from the Calculated Average Value (1.0121).

Date Samples Taken	k_{eff}	Difference from Average
During 1986	1.0101	+0.0020
2/89	1.0146	-0.0025
3/91	1.0115	+0.0006
2/96	1.0102	+0.0019

The differences from average seen in the table range from -0.0025 to +0.0020. The standard deviation of the k_{eff}'s is 0.0022.

No definitive measurement for acidity (<0.4M) was reported for the 1996 samples, but earlier measurements indicated it to be 0.5M, so an "average" acidity = 0.25M is taken for this evaluation. TWODANT calculations were run with the acidity set at 0.0M and 0.5M. The k_{eff} difference was 0.16%, so the percent uncertainty in k_{eff} due to the uncertainty in the assumed acidity is ±0.08%.

Also, TWODANT calculations show that the effect of solution impurities (see Table 2.b) on k_{eff} is less than 0.01%.

2.4 Surroundings

In order to make an estimate of the effect of external material on k_{eff} of the isolated model, a TWODANT problem was run in which the SHEBA-II CAV was surrounded by a stainless steel 304L cylinder with a 2.54-cm bottom located 45 cm below the bottom of the CAV, sides 1 cm thick located 40 cm from the CAV, and 1.5-cm top located 40 cm from the top of the CAV. These dimensions were obtained from averaging the material (stainless steel 304) in the fuel storage tanks below the CAV and material surrounding and above the CAV. The resulting k_{eff} was 0.18% greater than the isolated SHEBA-II case. This value is to be considered as a bias to be subtracted from the measured value to determine the benchmark k_{eff}. Increasing these hypothetical wall thicknesses by 50% increases the calculated k_{eff} by 0.09%. It is therefore estimated that the calculated bias due to room return is uncertain by ±0.05% k_{eff}.

2.5 Vessel Wall Thickness

The wall thicknesses given for 20-inch, schedule 20 stainless steel pipe from which the CAV is constructed include a mill tolerance of 12.5%.[a] If this tolerance is considered to be an uncertainty in vessel wall thickness, TWODANT calculations indicate that increasing the wall thickness by 12.5% decreases k_{eff} by 0.12%. A 12.5% decrease in wall thickness gives a 0.08% increase in k_{eff}. In these calculations the outer diameter of the vessel was held at 20 inches.

2.6 Safety Rod Thimble

The safety rod thimble is made from round stainless steel seamless tubing having an outside diameter of 2.5 inches and a wall thickness of 0.25 inch. The tolerance on the outside diameter is 0.010 inch and the wall thickness tolerance is 12.5%.[b] Using the extreme values indicated by these tolerances on the thimble radii in TWODANT calculations give an uncertainty of ±0.08% in k_{eff}.

2.7 Safety Rod

The borated epoxy safety rod was 3.3 cm above the top of the fuel in its retracted position. It

> "was made from natural boron carbide 20% Boron-10, 80% Boron-11. The epoxy is 3M product number MR-283U000 that has 4.3% hydrogen by weight and 49.5% carbon by weight. Other constituents (oxygen and chlorine) in the epoxy have been estimated from standard epoxy compositions since 3M considers the exact composition propriety. In a 30% boron by weight mixture, ... the safety rod has the following (approximate) composition:

Boron-10	6.0%	Boron-11	24.0%	Carbon	39.0%
Hydrogen	2.6%	Oxygen	10.6%	Chlorine	17.8%

> The density of the composition was measured to be 1.49 g/cm^3."[c]

Sensitivity calculations for SHEBA-II were run using the 2-dimensional model of the experiment in Figure 7 with a base-case height of the uranyl fluoride solution of 44.8 cm. The code/nuclear data set used was TWODANT/27-Group ENDF/B-IV SCALE. Calculations indicate that the worth of the safety rod and follower is 0.09% k_{eff}, which is considered to be a bias to be added to the measured k_{eff} to determine the benchmark k_{eff}. The worth of the follower alone is 0.08%.

---

[a] Marks' Standard Handbook for Mechanical Engineers, Eight Edition, McGraw-Hill, 1985.
[b] Stock List - Earle M. Jorgensen Co., page 83.
[c] Private communication C. Cappiello, April, 1996.

2.8 Summary

Uncertainties on the calculated value of k_{eff} arise from fuel height/temperature measurements, solution parameters, acidity, and vessel dimensions. These are summarized in Table 5.

Table 5. Summary of Uncertainties on Calculated Value of k_{eff}.

Measurement Uncertainty or Model Simplification	% Change in k_{eff}
Critical Height of Solution	0.04
Solution Temperature	0.10
UO_2F_2+H_2O Solution Analyses	0.22
Acidity	0.08
Vessel Wall Thickness	0.10
Central Safety Rod Thimble	0.08
Total (square root of sum of squares)	0.29

The effects of other quantities, including the omission of the top flange in the model, the position of the safety rod relative to small changes in fuel height, and the thermocouple well were calculated to be less than 0.01% in k_{eff}. These were considered to be too small to include as uncertainties or biases. Also, TWODANT calculations show that the effect of solution impurities (see Table 2.b) on k_{eff} is less than 0.01%.

3.0 BENCHMARK SPECIFICATIONS

3.1 Description of Model

The model chosen for SHEBA-II consists of an isolated stainless steel cylinder with an empty central stainless steel thimble. The cylinder is filled to the critical level with an aqueous uranyl fluoride solution.

The benchmark dimensions are shown in Figure 7 and given in Table 6.

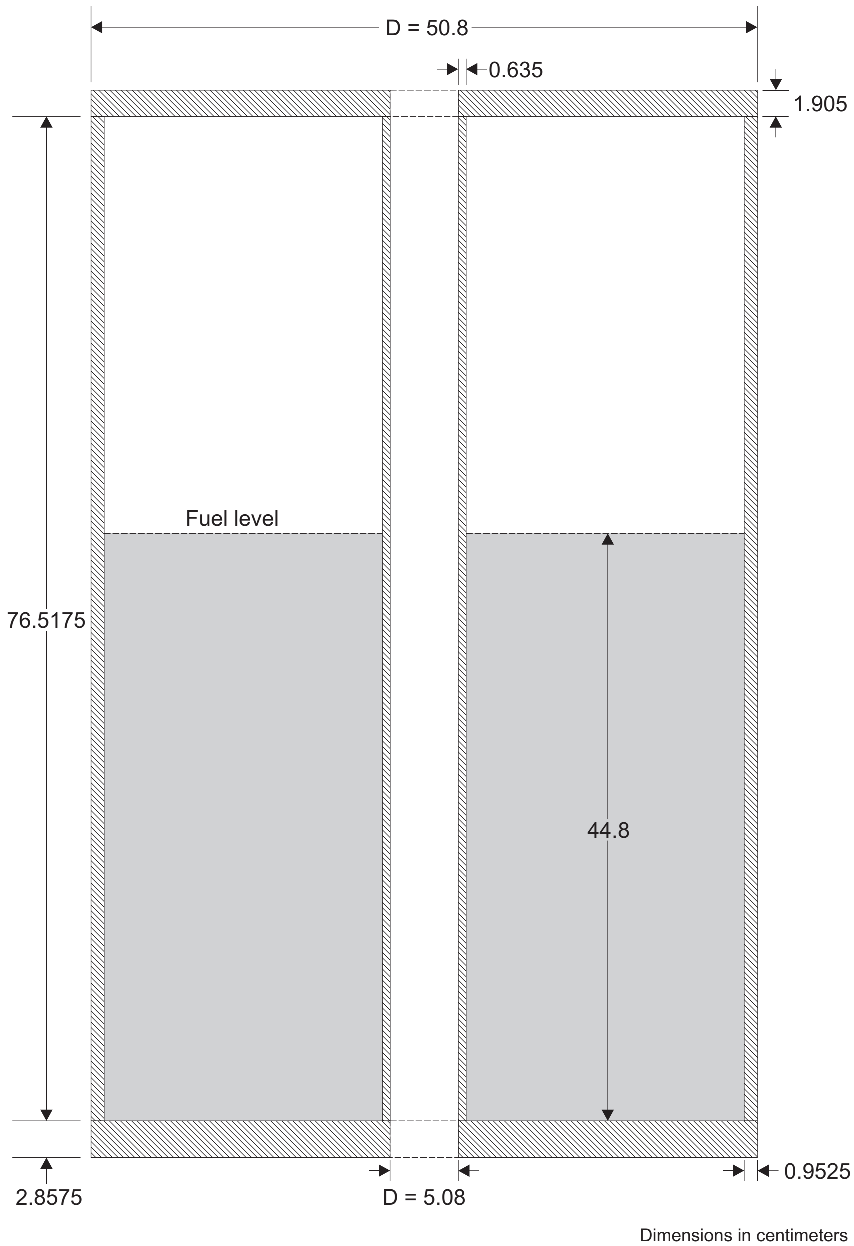

Figure 7. Model of SHEBA-II.

3.2 Dimensions

Table 6. Dimensions for SHEBA-II.

Region	Inner Radius (cm)	Outer Radius (cm)	Height (cm)	Material
Vessel Bottom	2.54	25.40	2.8575	SS304L
Central Void	--	2.54	81.28	Air
Thimble	2.54	3.175	76.5175	SS304L
Fuel	3.175	24.4475	44.8	UO_2F_2+H_2O
Above Fuel	3.175	24.4475	31.7175	Air
Outer Tank	24.4475	25.40	76.5175	SS304L
Cover	2.54	25.40	1.905	SS304L

3.3 Material Data

As discussed in Section 1.3, chemical analyses of the uranyl fluoride solution were made in 1986, 1989, 1991, and 1996; but as the experiments were performed between 1993 and the present, the experimenters have suggested that only the 1996 analyses be used in determining benchmark atom densities. Also, in absence of definitive acidity measurements for these analyses, a 0.25M HF is assumed for the benchmark. Solution atom densities resulting from averaging the 1996 analyses and an HF acidity of 0.25M are given in Table 7. These averages result in a solution density of 2.1092 g/cm^3, a uranium density of 0.9783 g/cm^3, and a ^{235}U enrichment of 4.9977 atom percent.

Table 7. Atom Densities.

Material	Isotope	Concentration (atoms/barn-cm)
SS304L[(a)] (7.8419 g/cm^3)	Cr	1.6348×10^{-2}
	Mn	1.7192×10^{-3}
	Fe	6.0038×10^{-2}
	Ni	7.2418×10^{-3}
Air [(b)]	N	3.5214×10^{-5}
	O	1.5092×10^{-5}
Fuel Solution (UO_2F_2+H_2O+0.25M HF)	H	5.6179×10^{-2}
	O	3.2967×10^{-2}
	F	5.1035×10^{-3}
	^{234}U	6.7855×10^{-7}
	^{235}U	1.2377×10^{-4}
	^{236}U	1.2085×10^{-6}
	^{238}U	2.3508×10^{-3}

(a) Average stainless steel 304L weight percents (2-Mn, 9-Ni, 18-Cr, and 71-Fe) were used.
(b) Air is assumed to be 70 at.% N and 30 at.% O at a density of 0.00122 g/cm^3.

3.4 Temperature Data

The critical height of 44.8 cm for this benchmark is taken from experimental data in Figure 6 at 20°C.

3.5 Experimental and Benchmark-Model k_{eff}

The experimental k_{eff} is 1.000.

To obtain the benchmark-model k_{eff}, a total bias of -0.09%, due to omission of the surroundings (-0.18%) and the safety rod (+0.09%) from the model, should be included. The benchmark k_{eff} is therefore 0.9991 ± 0.0029.

4.0 RESULTS OF SAMPLE CALCULATIONS

Calculated results are given in Table 8. More detailed discussions of the calculations, including input listings, are given in Appendix A. Note that all results except KENO (Hansen-Roach) are about 1% high. An MCNP calculation using ENDF/B-VI data gives a k_{eff} = 1.0076 ± 0.0008.[a]

Table 8. Sample Calculation Results.

KENO (Hansen-Roach)	KENO (27-Group ENDF/B-IV)	MCNP (Continuous Energy ENDF/B-V)	TWODANT (27-Group ENDF/B-IV)
1.0011 ± 0.0008	1.0105 ±0.0010	1.0139 ±0.0010	1.0108

[a] Private communication, R. Mosteller, April 1996.

5.0 REFERENCES

1. R. R. Paternoster, R. E. Anderson, K. B. Butterfield, C. C. Cappiello, R. E. Malenfant, and B. Q. Partain, “Safety Analysis Report for the Los Alamos Critical Experiments Facility (LACEF) and TA-18,” LA-CP-92-235, Rev. 1.0, June 1, 1994.

2. Lutz, H. (Ed.), “Blind Calculations of SHEBA,” Criticality Safety Quarterly, Spring 1994.

3. K. B. Butterfield, “The SHEBA Experiment,” ANS Transactions, Vol. 70, June 1994.

4. R. Paternoster (Ed.), “Los Alamos Critical Experiments Facility Semi-Annual Progress Report April 1, 1995 - September 30, 1995,” LA-UR-954336.

5. R. Paternoster (Ed.), “Los Alamos Critical Experiments Facility Semi-Annual Progress Report October 1, 1995 - March 30, 1995,” LA-UR-952151.

6. R. J. LaBauve and J. L. Sapir, “SHEBA-II as a Criticality Safety Benchmark Experiment,” The Fifth International Conference on Nuclear Criticality, September 17-21, 1995, Albuquerque, New Mexico, USA, pp. 6-154, 6-159.

APPENDIX A: TYPICAL INPUT LISTINGS

A.1 KENO Input Listings

The input given below is for the 16-group Hansen-Roach "stand-alone" version of KENO. Note from the input parameters that the problem was run with 1,000,000 active and 100,000 inactive histories (220 active generations, 20 skipped generations, and 5000 histories per generation). A σ_p = 10000 was used for ^{235}U and a σ_p = 500 was used for ^{238}U.

Input Listing for KENO-V.a Hansen-Roach 16-Group, Table 8.

```
SHEBA-II AV. LANL 1996 SAMPLES. CAV 20-IN, SCHEDULE 20 SS PIPE. 06/23/96.
READ PARAMETERS
LIB=41 GEN=220 NPG=5000 NSK=20
RES=110 NL8=3000
LNG=15000000 TME=2500
END PARAMETERS
READ MIXT SCT=1
MIX=1   24100   1.6348-2
        25100   1.7192-3
        26100   6.0038-2
        28100   7.2418-3
MIX=2    7100   3.5214-5
         8100   1.5092-5
MIX=3    1102   5.6179-2
         8100   3.2967-2
         9100   5.1035-3
        92400   6.7855-7
        92512   1.2377-4
        92600   1.2085-6
        92836   2.3508-3
END MIXT
READ GEOMETRY
UNIT 1
CYLINDER 2 1   2.540   41.28   39.375
CYLINDER 1 1   25.40   41.28   39.375
CUBOID   0 1   26.0   -26.0    26.0   -26.0    41.28   39.375
UNIT 2
CYLINDER 2 1    2.54   39.375    7.6575
CYLINDER 1 1    3.175   39.375    7.6575
CYLINDER 2 1   24.4475   39.375    7.6575
CYLINDER 1 1   25.40   39.375    7.6575
CUBOID   0 1   26.0   -26.0    26.0   -26.0    39.375    7.6575
UNIT 3
CYLINDER 2 1    2.54    7.6575  -37.1425
CYLINDER 1 1    3.175    7.6575  -37.1425
CYLINDER 3 1   24.4475    7.6575  -37.1425
CYLINDER 1 1   25.40    7.6575  -37.1425
CUBOID   0 1   26.0   -26.0    26.0   -26.0     7.6575  -37.1425
UNIT 4
CYLINDER 2 1   2.540  -37.1425  -40.00
CYLINDER 1 1   25.40  -37.1425  -40.00
CUBOID   0 1   26.0   -26.0    26.0   -26.0   -37.1425  -40.00
END GEOMETRY
READ ARRAY
NUX=1 NUY=1 NUZ=4
FILL 1 2 3 4
END ARRAY
END DATA
END
```

The input given below is for the KENO-V.a code as run on the ORNL SCALE code system using the CSAS option. Note from the input run parameters that the problem was run with 600,000 active and 10,000 inactive histories (300 active generations, five skipped generations, and 2000 histories per generation).

Input Listing for KENO-V.a ENDV/B-IV SCALE 27-Group, Table 8.

```
=CSAS25
SHEBA-II AV. LANL 1996 SAMPLES. CAV 20 IN, SCHEDULE 20 SS PIPE. 06/23/96.
27G  MULT
CR         1 0.0  1.6348E-02  END
MN         1 0.0  1.7192E-03  END
FE         1 0.0  6.0038E-02  END
NI         1 0.0  7.2418E-03  END
N          2 0.0  3.5214E-05  END
O          2 0.0  1.5092E-05  END
H          3 0.0  5.6179E-02  END
O          3 0.0  3.2967E-02  END
F          3 0.0  5.1035E-03  END
U-234      3 0.0  6.7855E-07  END
U-235      3 0.0  1.2377E-04  END
U-236      3 0.0  1.2085E-06  END
U-238      3 0.0  2.3508E-03  END
END COMP
SPHERICAL VACUUM REFLECTED 0 END
1 2.4  ONEEXTERMOD 2 3.0  ONEEXTERMOD 3 25.0  NOEXTERMOD
END ZONE'MORE DATA ISN=4 SZF=1.5 END
READ PARAMETERS
 GEN=305 NPG=2000 NSK=5 TME=3000
END PARAMETERS
READ GEOM
UNIT 1
CYLINDER 2 1   2.540   41.28   39.375
CYLINDER 1 1   25.40   41.28   39.375
CUBOID   0 1   26.0   -26.0    26.0   -26.0    41.28   39.375
UNIT 2
CYLINDER 2 1    2.54   39.375    7.6575
CYLINDER 1 1    3.175   39.375    7.6575
CYLINDER 2 1   24.4475   39.375    7.6575
CYLINDER 1 1   25.40   39.375    7.6575
CUBOID   0 1   26.0   -26.0    26.0   -26.0    39.375    7.6575
UNIT 3
CYLINDER 2 1    2.54    7.6575  -37.1425
CYLINDER 1 1    3.175    7.6575  -37.1425
CYLINDER 3 1   24.4475    7.6575  -37.1425
CYLINDER 1 1   25.40    7.6575  -37.1425
CUBOID   0 1   26.0   -26.0    26.0   -26.0     7.6575  -37.1425
UNIT 4
CYLINDER 2 1   2.540  -37.1425  -40.00
CYLINDER 1 1   25.40  -37.1425  -40.00
CUBOID   0 1   26.0   -26.0    26.0   -26.0   -37.1425  -40.00
END GEOMETRY
READ ARRAY
NUX=1 NUY=1 NUZ=4
FILL 1 2 3 4
END ARRAY
END DATA
END
```

A.2 MCNP Input Listings

The input given below is for MCNP using ENDF/B-V continuous energy cross section data. Note from the input listed below that the problem was run with 720,000 active and 30,000 inactive histories (240 active generations, 10 skipped generations, and 3000 histories per generation).

Input Listing for MCNP ENDF/B-V Continuous Energy, Table 8.

```
   SHEBA-II AV. LANL 1996 SAMPLES. CAV 20-IN SCHEDULE 20 SS PIPE. 06/24/96.
1      2 5.0306E-05  1 -2 -6         imp:n=1
2      1 8.5347E-02  1  6 -2  -9     imp:n=1
3      2 5.0306E-05  2 -4 -6         imp:n=1
4      1 8.5347E-02  2 -4  6 -7      imp:n=1
5      3 9.6726E-02  2 -3  7 -8      imp:n=1
6      2 5.0306E-05  3 -4  7 -8      imp:n=1
7      1 8.5347E-02  2 -4  8 -9      imp:n=1
8      2 5.0306E-05  4 -5 -6         imp:n=1
9      1 8.5347E-02  4 -5  6  -9     imp:n=1
10     0   -10 (5:9:-1)              imp:n=1
11     0    10                       imp:n=0

1     py    -40.0
2     py    -37.1425
3     py      7.6575
4     py     39.375
5     py     41.28
6     cy      2.54
7     cy      3.175
8     cy     24.4475
9     cy     25.4
10    so     60.0

m1
      24000.50c    1.6348E-02
      25055.50c    1.7192E-03
      26000.50c    6.0038E-02
      28000.50c    7.2418E-03
m2
       7014.50c    3.5214E-05
       8016.50c    1.5092E-05
m3
       1001.50c    5.6179E-02
       8016.50c    3.2967E-02
       9019.50c    5.1035E-03
      92234.50c    6.7855E-07
      92235.50c    1.2377E-04
      92236.50c    1.2085E-06
      92238.50c    2.3508E-03
mt3     lwtr.01t
kcode  3000  1.0  10   250
dbcn      7j 500000
ksrc     0.  0.  0.
print
```

A.3 TWODANT Input Listings

The input given below is for the TWODANT code with 27-group SCALE ENDF/B-IV cross sections produced by the ORNL SCALE code system. Note from the input run parameters that the problem was run S_6 quadrature, P_3 cross sections, and a convergence criterion = 0.00001. The mesh spacing of 0.5 cm was determined to be the coarsest that could be used to obtain a k_{eff} within the specified convergence.

Input Listing for TWODANT SCALE ENDF/B-IV 27-Group, Table 8.

Cross-section input

```
=CSASI
SHEBA-II AV. LANL 1996 SAMPLES. CAV 20 IN, SCHEDULE 20 SS PIPE. 6/20/96.
27G  MULT
CR        1 0.0  1.6348E-02  END
MN        1 0.0  1.7192E-03  END
FE        1 0.0  6.0038E-02  END
NI        1 0.0  7.2418E-03  END
N         2 0.0  3.5214E-05  END
O         2 0.0  1.5092E-05  END
H         3 0.0  5.6179E-02  END
O         3 0.0  3.2967E-02  END
F         3 0.0  5.1035E-03  END
U-234     3 0.0  6.7855E-07  END
U-235     3 0.0  1.2377E-04  END
U-236     3 0.0  1.2085E-06  END
U-238     3 0.0  2.3508E-03  END
END COMP
SPHERICAL VACUUM REFLECTED 0 END
1 2.4  ONEEXTERMOD 2 3.0  ONEEXTERMOD 3 25.0  NOEXTERMOD
END ZONE'MORE DATA ISN=4 SZF=1.5 END
END
```

TWODANT Input

```
    2
 SHEBA II AV.LANL 1996 SAMPLES. CAV 20-IN, SCHEDULE 20 SS PIPE. 6/21/96.
 0.5 CM MESH, 0.5M ACIDITY, CRIT. HEIGHT=44.8CM..
  /      * * * * * block i * * * * *
  igeom=7 ngroup=27 isn=-6 niso= 3 mt=3 nzone= 3 im=4 jm= 4 it=50 jt=157
   maxscm=300000 maxlcm=900000  t
  /      * * * * * block ii * * * * *
  xmesh= 0.0, 2.54,3.175,24.4475,25.4
  ymesh= 0.0,2.8575,47.6575,79.3750,81.28
  xints=5,1,41,3
  yints=6,90,57,4
  zones=
       2,1,1,1;2,1,3,1;2,1,2,1;2,1,1,1 t

/ Block 3
 lib=xs27.s96  writmxs=macbcd
 chivec= .021 .188 .215 .125 .166 .180 .090 .014 .001 18z
 maxord=3 ihm=42 iht=3 ihs=16 ititl=1 ifido=2 i2lp1=1   t

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

Input Listing for TWODANT SCALE ENDF/B-IV 27-Group, Table 8 (cont'd).

```
/ Block 5
 ievt=1 isct=3 ith=0 ibl=1 ibb=0 ibt=0 ibr=0 epsi=1.e-5
 oitm=50 t

/ Block 6
 zned=1   t
```