CRITICAL ARRAYS OF LOW-ENRICHED UO_2 FUEL RODS WITH WATER-TO-FUEL VOLUME RATIOS RANGING FROM 1.5 TO 3.0

Evaluators

Yoshinori Miyoshi
Takuya Arakawa
Japan Atomic Energy Research Insititute

Internal Reviewer
Toshihiro Yamamoto

Independent Reviewers

Carol A. Atkinson
Idaho National Engineering Laboratory

Virginia F. Dean
Consultant to INEEL

CRITICAL ARRAYS OF LOW-ENRICHED UO_2 FUEL RODS WITH WATER-TO-FUEL VOLUME RATIOS RANGING FROM 1.5 TO 3.0

IDENTIFICATION NUMBER: LEU-COMP-THERM-006 SPECTRA

KEY WORDS: acceptable, buckling, critical experiment, extrapolation length, lattice, light water, low-enriched, TCA, temperature coefficient of reactivity, uranium dioxide, volume ratio, water level, water level worth, water-moderated, water-reflected

1.0 DETAILED DESCRIPTION

1.1 Overview of Experiment

Experimental critical sizes are reported for light-water-moderated lattices with 2.6 wt.% UO_2 fuel rods. The experimental cores selected as basic benchmark experiments had fuel rods arranged in a square array. Critical sizes were determined by adjusting the water height. The water-to-fuel volume ratio in the lattice cells ranged from 1.50 to 3.00. Some physics parameters, such as temperature coefficient of reactivity, the extrapolation length and critical buckling were also given. The experiments were performed between 1963 and 1975. Eighteen configurations are judged to be acceptable as benchmark data.

1.2 Description of Experimental Configuration

The Tank-Type Critical Assembly (TCA) is a light-water-moderated critical assembly in which the core is composed of a fuel rod array supported by upper and lower grid plates. The reactor is operated by raising the water level from the bottom of the core tank by a feed water pump. A vertical cross section of the TCA is shown in Figure 1.

The experimental core lattice is constructed in an open-top cylindrical core tank having a diameter of 1.832 m and a height of 2.078 m by holding the fuel rods vertically with a set of grid plates. They are set at upper and lower positions in the core tank. The six vertical grid supports are approximately 70 cm from the center of the tank. They are made of stainless steel. Light water serves as both moderator and reflector, and there are no control rods. Reactivity control is made by adjusting the water level. Six neutron detectors are located at least 15 cm away from the periphery of the lattice.

The 1.25-cm-diameter pellets are clad by an aluminum tube. The length of the fuel region is 144.15 cm. Details of the specifications are shown in Figure 2 and Table 1.

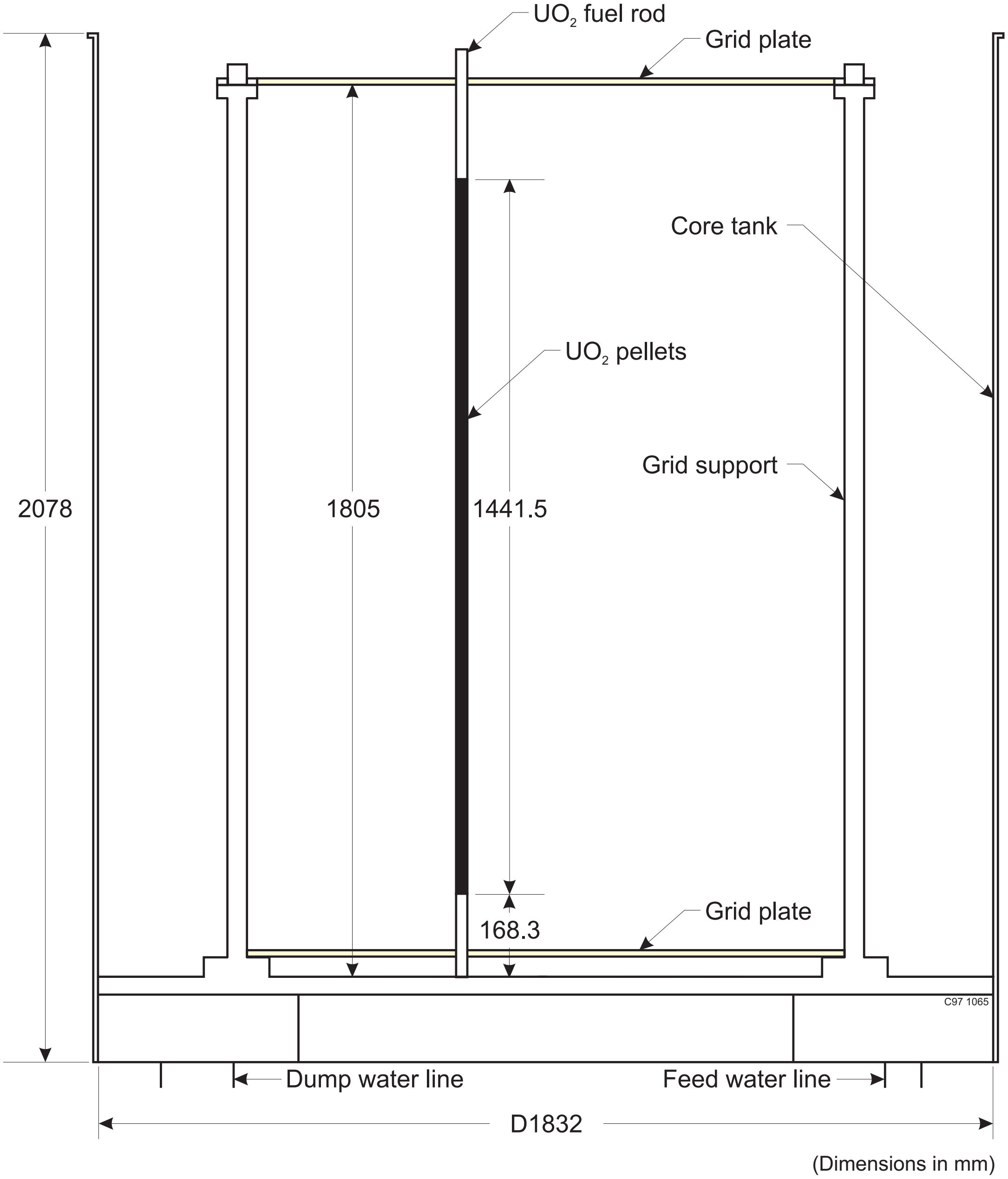

Figure 1. Vertical Cross-Sectional View of Core Tank.

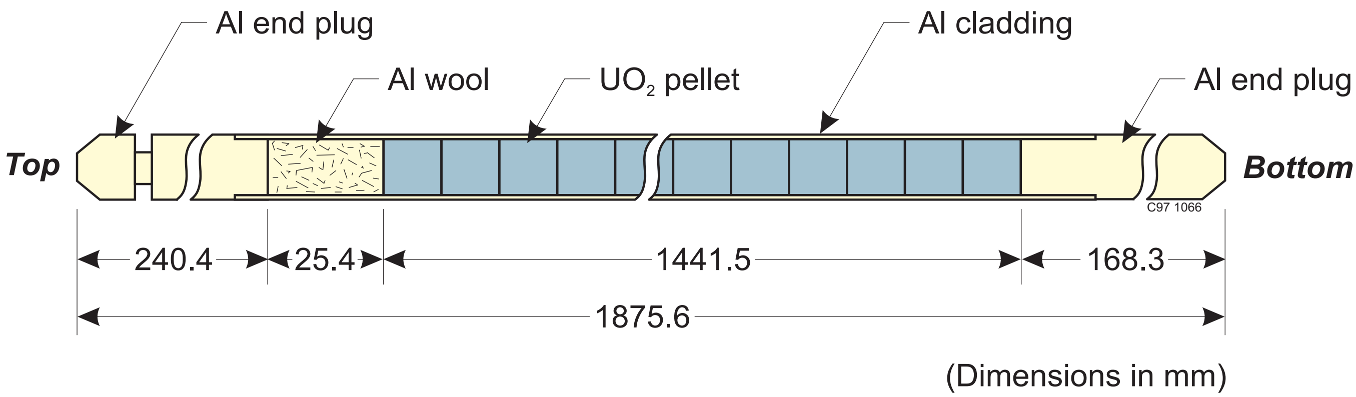

Figure 2. 2.6 Wt.% UO_2 Fuel Rod.

Table 1. Specifications of Fuel Rod.[a]

Item	Value
Uranium composition	
^{235}U (wt.%)	2.596±0.005
^{238}U (wt.%)	97.404±0.005
UO_2 pellet	
Diameter (cm)	1.25±0.005
Density (g/cm^3)	10.4±0.05
Height (cm)	1.27
Stack length (cm)	144.15±0.3
Aluminum alloy cladding	
Inner diameter (cm)	1.265±0.0005
Thickness (cm)	0.076±0.0005
O/M[b]	2.04

(a) Values taken from Reference 1, page 5. The magnitude of uncertainties in fuel rod data are taken as half the value of the least significant digit, when uncertainty is not given.

(b) Atom ratio of oxygen to metal elements.

The water-to-fuel volume ratio is changed by replacing the grid plates with another set which has a different lattice pitch. The center-to-center rod spacing of the square lattices ranges from 1.849 to 2.293 cm, which corresponds to a water-to-fuel volume ratio ranging from 1.5 to 3.0. The names of these lattices are summarized in Table 2. The lattices are centered in the tank.

Table 2. Names of Lattices.

Lattice Name	Lattice Pitch (cm)	H/U
1.50U	1.849±0.002	4.33
1.83U	1.956±0.002	5.28
2.48U	2.150±0.002	7.16
3.00U	2.293±0.002	8.65

The section below the fuel region is shown in Figure 3. It consists of the lower end plug of the fuel rod, the lower grid plate, the fuel support plates, and the interstitial water. The fuel support plate is a 12.7-mm-thick aluminum plate on top of a 22-mm-thick stainless steel plate. The fuel support plate is 13.8 cm above the tank bottom. The lower aluminum grid plate is 44.45 mm above the fuel support plate. Both grid plates are 6 mm thick. The diameter of the holes for the fuel rods is 0.570 (+0.000,-0.003) inches.

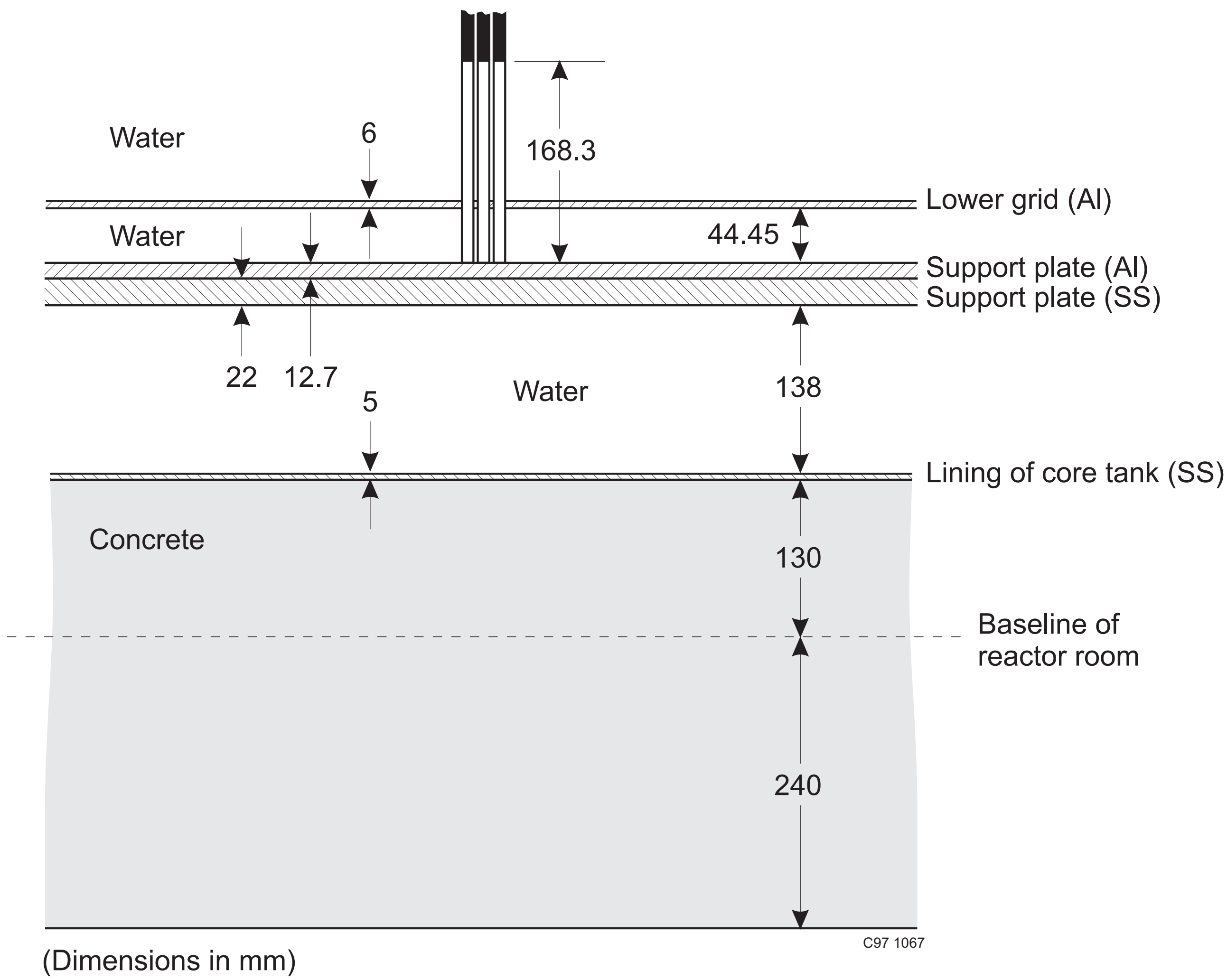

Figure 3. Details of Bottom Reflector.

The 5-mm-thick stainless steel tank sits on a concrete slab that rises 13 cm above the 24-cm-thick concrete floor. The tank is located near a corner of a room 7.1 m by 9.8 m by 13 m high. The core center is 2.9 m from the two closest walls. The thickness of the concrete wall is at least 0.9 m. The 30-cm-thick concrete ceiling is approximately 1080 cm above the top of the tank.[a]

[a] The concrete walls are 0.9 m thick to a height of 5.5 m, except the longer one of the two closest walls, which is 1.2 m thick to a height of 5.5 m. Above 5.5 m, the close shorter wall and the longer wall to 2.9 meters from the corner are 0.51-m-thick . All remaining wall is 0.25 m thick above 5.5. m. The concrete ceiling consists of 12 cm of concrete below 18 cm of mortar, as well as an approximately 30-cm-thick reinforced concrete beam. (T. Suzaki et al., "Experience to Reduce Exposures Outside a Critical Assembly Room by Additional Concrete Walls," Proc. of the Sixth Int. Conf. on Radiation Shielding, Tokyo, Japan, May 16-20, 1983.)

The critical water levels of the experimental cores were measured in the temperature range from 10 to 30 °C. Fuel rod patterns of experimental cores are shown in Figure 4. Critical water heights, measured from the bottom of the fuel, are given in Table 3.

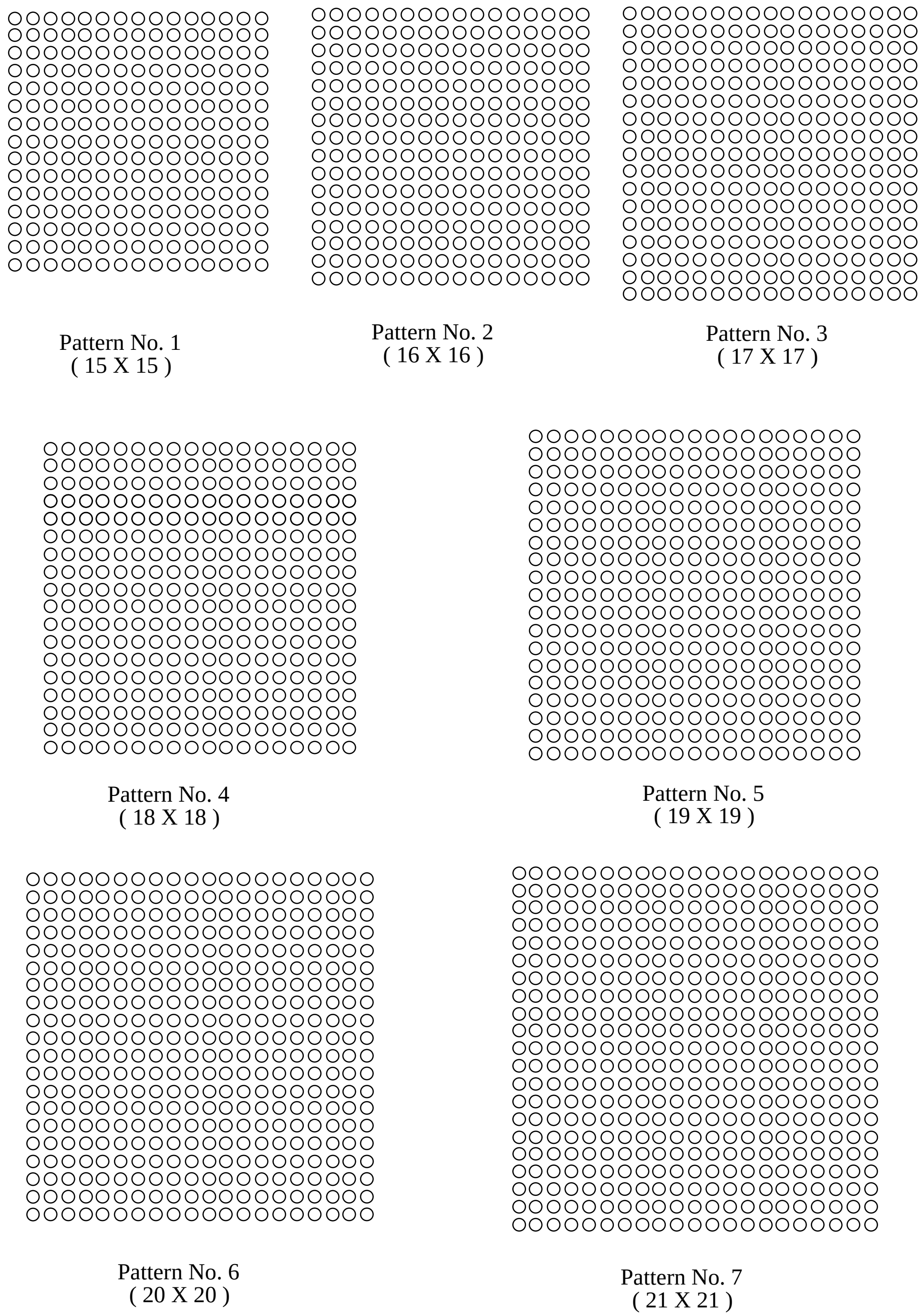

Figure 4. Fuel Rod Patterns.

Table 3. Summary of Core Configurations.

Lattice Name	Lattice Pitch (cm)	Case No.	Number of Rods in One Side (N)	Pattern No.	Dimension of One side (cm)	Measured Level (cm)	Core Temperature (°C)	Reactivity Correction (cent)	Critical Level H_c at 20°C (cm)	Average H_c at 20°C (cm)	Total Buckling B_c^2 ($\times 10^{-3}$ cm^{-2})	Run No.
		1	19	5	35.13	99.20	22.7	1.86	98.86	99.45±0.93	8.05±0.15	4108
						98.35	14.1	-3.39	98.97			4303
						99.98	15.1	-2.88	100.53			4385
1.50U	1.849	2	20	6	36.98	72.86	14.2	-3.34	73.14	73.73±0.83	8.10±0.14	4305
						74.11	16.0	-2.40	74.32			4385
		3	21	7	38.83	60.70	14.1	-3.39	60.88	60.81±0.52	8.16±0.13	4306
						61.18	16.2	-2.29	61.30			4383
						60.29	21.0	0.67	60.26			5439
		4	17	3	33.25	113.70	11.8	-1.56	114.11	114.59±1.69	9.49±0.21	582
						116.33	16.3	-0.92	116.59			4253
						114.85	16.3	-0.92	115.10			4390
						113.01	24.7	1.69	112.57			5469
		5	18	4	35.21	75.68	13.9	-4.20	76.06	75.32±0.90	9.47±0.19	4254
						75.38	16.8	-2.33	75.59			4392
						74.38	20.9	0.71	74.32			5790
1.83U	1.956	6	19	5	37.16	60.32	13.9	-4.20	60.53	60.38±0.21	9.44±0.17	4255
						60.12	17.0	-2.19	60.23			4394
		7	20	6	39.12	51.69	13.9	-4.20	51.83	51.65±0.17	9.44±0.15	4256
						51.57	17.6	-1.77	51.63			4398
						51.56	22.3	1.85	51.50			5461
		8	21	7	41.08	45.96	13.9	-4.20	46.07	46.01±0.08	9.44±0.14	4257
						46.05	18.1	-1.42	46.09			4400
						45.81	11.0	-5.83	45.96			5330
						45.81	13.8	-4.26	45.92			5351
		9	16	2	34.40	78.69	16.0	-1.65	78.85	78.67±0.25	9.75±0.13	4347
						78.36	16.5	-1.47	78.50			4372
		10	17	3	36.55	59.98	15.5	-1.83	60.07	59.96±0.10	9.76±0.11	4345
						59.82	16.7	-1.40	59.89			4373
2.48U	2.150					59.96	21.7	0.84	59.92			5447
		11	18	4	38.70	50.49	15.5	-1.83	50.55	50.52±0.04	9.77±010	4344
						50.46	17.0	-1.28	50.50			4374
		12	19	5	40.85	44.51	15.5	-1.83	44.55	44.55	9.80±0.09	4336
						44.52	17.3	-1.16	44.55			4378
		13	20	6	43.00	40.41	15.5	-1.83	40.44	40.44	9.83±0.08	4335
		14	15	1	34.40	90.65	15.6	-1.07	90.80	90.75±0.07	9.38±0.20	4362
						90.56	16.0	-0.99	90.70			4363
		15	16	2	36.69	64.39	15.6	-1.07	64.45	64.42±0.09	9.41±0.17	4361
						64.43	16.0	-0.99	64.49			4365
						64.38	23.0	0.99	64.32			5454
3.00U	2.293	16	17	3	38.98	52.88	15.5	-1.09	52.92	52.87±0.04	9.44±0.15	4360
						52.82	16.3	-0.93	52.85			4366
						52.82	16.3	-0.93	52.85			4367
		17	18	4	41.27	46.06	15.3	-1.13	46.09	46.06±0.04	9.48±0.14	4358
						46.01	16.5	-0.89	46.03			4368
		18	19	5	43.57	41.53	15.0	-1.18	41.55	41.54±0.01	9.52±0.14	4349
						41.51	16.5	-0.89	41.53			4369

A Ra-Be source is slid into a perforated aluminum tube which is located two or three pitch-lengths away from the outermost fuel rod. Before attaining criticality, this source is withdrawn. Three safety sheets of cadmium-aluminum alloy are hung above the core. The sheets are approximately 25.4 cm by 179.2 cm by 0.32 cm thick and are hung parallel to each other at a spacing of about 12 cm. The safety sheets hang through slots in the upper grid plate. The bottom edges of the sheets hang between the upper end plugs of the fuel rods and are approximately 18 cm below the upper grid plate.

To correct the measured critical water level of each experiment to the critical water levels of cores at 20 °C, the temperature coefficients of reactivity and water level worths were also measured for each experiment. The resulting values of the parameters A and B for calculating the temperature coefficients of reactivity are given in Table 4. The calculated delayed neutron fractions are also given in Table 4.

Table 4. Temperature Coefficients of Reactivity.(a)

Lattice Name	Water level H_c (cm)	A	B	Delayed Neutron Fraction β_{eff}(b)
1.50U	60	-0.11±0.04	-0.0136±0.0004	0.007484
1.83U	50	-0.22±0.07	-0.0138±0.0007	0.007478
	110	0.23±0.08	-0.0132±0.0008	
2.48U	60	0.08±0.06	-0.0137±0.0006	0.007423
3.00U	60	0.17±0.04	-0.0116±0.0004	0.007372

(a) The temperature coefficient of reactivity is obtained by $d\rho/dT = A + 2 \cdot B \cdot T$ (cent/°C)
(b) β_{eff} was calculated with the CITATION code[a]

The values of the parameter C used for evaluating the water level worth and vertical and horizontal extrapolation lengths are presented in Table 5. These are used with the temperature coefficient of reactivity to correct the water level to 20 °C. In addition, the reported geometric bucklings of typical experimental cores of each lattice type are presented in Table 6.

[a] T.B. Fowler, D.R. Vondy, G.W.Cummingham, "Nuclear Reactor Analysis Code; CITATION," ORNL-TM-2496, 1969.

Table 5. Proportional Coefficient C and Extrapolation Lengths.[(a)]

Lattice Name	C (cent·cm^2)	Extrapolation Length (cm)	
		Vertical λ_z	Horizontal λ_H
1.50U	7.57±0.11 x10^6	12.6±0.3	17.0±0.8
1.83U	7.59±0.07 x10^6	12.2±0.3	13.9±0.8
2.48U	7.64±0.11 x10^6	11.3±0.2	13.7±0.5
3.00U	7.48±0.06 x10^6	11.1±0.5	14.0±0.8

(a) $d\rho/dH = C / (H + \lambda_z)^3$

Table 6. Critical Bucklings, B_c^2.

Lattice Name	B_c^2(x10^{-2} cm^{-2})	Core Configuration
1.50U	0.833±0.010	24 x 24
1.83U	0.943±0.013	22 x 22
2.48U	0.983±0.008	20 x 20
3.00U	0.952±0.0141	19 x 19

1.3 Description of Material Data

1.3.1 Fuel Rod - The enrichment of the fuel rods is 2.596±0.005 wt.%. In Reference 1, the atom ratio of oxygen to metal, O/M, is given as 2.04. Details of the rod specifications are shown in Table 1 and Figure 2. Besides as cladding material, type 6061 aluminum is used for the top and lower end plugs. However, a detailed composition was not given in the original paper, and so its density and exact composition are not known. The ASTM Standard chemical composition limits are given in Table 7.[a] Aluminum wool fills the 25.4-mm-long space between the top end plug and fuel pellet. Its density is not known.

---

[a] Alcoa Aluminum Handbook, p 34, Aluminum Company of America.

Table 7. Standard Composition Limits[a] of 6061 Aluminum.

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Wt.%	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.15-0.35	0.25	0.15	Remainder

(a) ranges or maximum values

1.3.2 Moderator - The purity of the deionized water moderator was carefully maintained by an ion-exchange resin. The conductivity of the water moderator was kept below 4×10^{-6} ohm^{-1} cm^{-1}.

1.3.3 Others - The bottom fuel support plate is SUS 27 stainless steel. Its composition and density are not known. The top fuel support and grid plates are 6061 aluminum alloy. The cadmium-aluminum alloy safety sheets are approximately 4 wt.% Cd and 96 wt.% Al. The density is not known.

1.4 Supplemental Experimental Measurements

No supplemental experimental measurements were found.

2.0 EVALUATION OF EXPERIMENTAL DATA

No mention of the walls of the core tank or reflector room was made in Reference 1, but the side water reflector is considered infinitely thick (more than 40 cm). The ceiling is so high and far from the water surface in the core tank (more than 1100 cm) that its reflector effect is negligible.

The core configurations are very simple geometry. Experiments were well documented and carefully performed. There were no significant omissions of data. All 18 critical configurations are acceptable benchmarks.

2.1 Fuel Rod Data

Some uncertainty exists in the characterization of fuel rods. Dimensions and masses are based on the values given in Table 1 of Reference 1. Detailed data concerning the measurement techniques or uncertainties were not given. The magnitude of uncertainties in fuel rod data are given in Table 1.

The main specifications of the fuel rod include enrichment and density of the fuel pellet, diameter of the fuel pellet, inner diameter and thickness of the cladding, and lattice pitch of the unit cell. The sensitivity of the neutron multiplication factor to fuel rod characterization was calculated using TWOTRAN and JENDL-3.2 cross sections collapsed to 16 groups. Calculational results are shown in Table 8. The uncertainty of ^{235}U enrichment is ± 0.01 wt.%.

The density and exact chemical composition of the 6061 aluminum cladding are not known. The effect on k_{eff} of a 1% uncertainty of the clad density is approximately 0.002% Δk. Therefore, the lack of the information about the clad density does not affect the experimental uncertainties.

Results indicate that the effect of the uncertainties of each component in the fuel rod characterization is less than 0.10%. An uncertainty of 0.16% due to uncertainties in fuel rod characterization may be included in the benchmark-model k_{eff}.

Table 8. Sensitivity of k_{eff} to Uncertainties in Fuel Rod Characterization.

Quantity (Amount of change)	% Δk_{eff} (TWOTRAN)
Enrichment (±0.01wt.%)	±0.09
Fuel Density (±0.05 g/cc)	±0.06
Fuel Diameter (±0.05mm)	±0.09
Clad Diameter (±0.005 mm)	±0.01
Clad Thickness (±0.005 mm)	±0.03
Lattice Pitch (±0.02mm)	±0.06
Total	±0.16

2.2 Grid Plates, Safety Sheets, Source, Counters

The reactivity effects of the lower and upper grid plates are considered to be negligible, as they are remote from the fuel region. TWOTRAN (JENDL-3.2, 16-group cross sections) calculations of k_{eff} with and without the upper aluminum grid plate differed by less than 0.001%. The effect of the Cd-Al safety sheets above the fuel rods was calculated using TWOTRAN for H_c=115 cm, the case whose distance between the water surface and sheets is shortest. The k_{eff} difference between calculations with and without the safety sheets was again less than 0.001% (within the convergence criterion). The perforated aluminum pipe for the neutron source and the neutron counter also may act as scattering materials and affect the criticality. However, due to their peripheral location, these effects are considered to be negligible as well. There is no description of the neutron detectors. However, these neutron detectors were placed in the water reflector more than 15 cm away from the fuel rod region so that they had no effect on the critical water level.

2.3 Measurement Uncertainties

Main sources of experimental errors are as follows:

1. Critical water level was measured with a servo-manometer which had the smallest scale of 0.02 cm. The accuracy of the servo-manometer is 0.01 cm. The height of the lower end of the active fuel zone has an error of 0.01 cm. Therefore, the error of the water-level measurement is estimated as 0.02 cm.
2. The temperature of the moderator was measured with a resistance thermometer that varied within 0.5 °C during operation.
3. The intrinsic neutron source of the fuel rod emits neutrons. By operating the reactor above 5 watts, the effect of the neutron source was entirely negligible in the case of these experiments.
4. The error in the reactivity depends on both the temperature and the water level of the experimental core.

Standard deviations of averaged critical heights H_c at 20°C are presented in Table 3. The effects on k_{eff} of these height uncertainties were calculated using C values in Table 5. The range of Δk_{eff} calculated was 0.01-0.08%. Therefore, a critical-height measurement uncertainty effect of 0.08% is included in the uncertainty of k_{eff}.

2.4 Fuel Rod Patterns

The error of the hole position on each grid plate is within 0.1 mm. The difference between the outer diameter of the fuel rod and the inner diameter of the hole in the grid plate is less than 0.4 mm. The nominal value of the length of one side of the lattice along the x- or y-direction is the lattice pitch multiplied by the number of fuel rods in each side. Taking into account the clearance of the fuel rod and each hole in the grid plate, the error in the size of the experimental core along the x- or y-direction is less than 0.5 mm. The sensitivity of k_{eff} to this possible error (0.5 mm/N ≅ 0.02 mm) is given in Table 8.

3.0 BENCHMARK SPECIFICATIONS

3.1 Description of Model

Two benchmark models are presented: a three-dimensional model and a two-dimensional model. The thickness of the side water reflector is 30 cm for both benchmark models.

In the three-dimensional model, the vertical structure of the fuel in each fuel pin is explicitly represented. That is, the dry part of the lattices above the critical water level and the lower water reflector region are included in the three-dimensional model. There is nothing above the fuel and there is only 30 cm of water below the fuel. Grid plates, support plates, tank, and room are omitted, as well as fuel-rod end plugs and cladding above and below the fuel.

In the two-dimensional model, the vertical property of the core is represented by introducing the vertical buckling. Optionally, the unit cell may be homogenized.

3.1.1 Water Reflector - In the experiments the thickness of the side water reflector is more than 40 cm. This can be seen by noting that the cylindrical core tank has a diameter of 183.2 cm and the largest lattice array has a side dimension of 43.57 cm. The horizontal cross section of the core tank is shown in Figure 5.

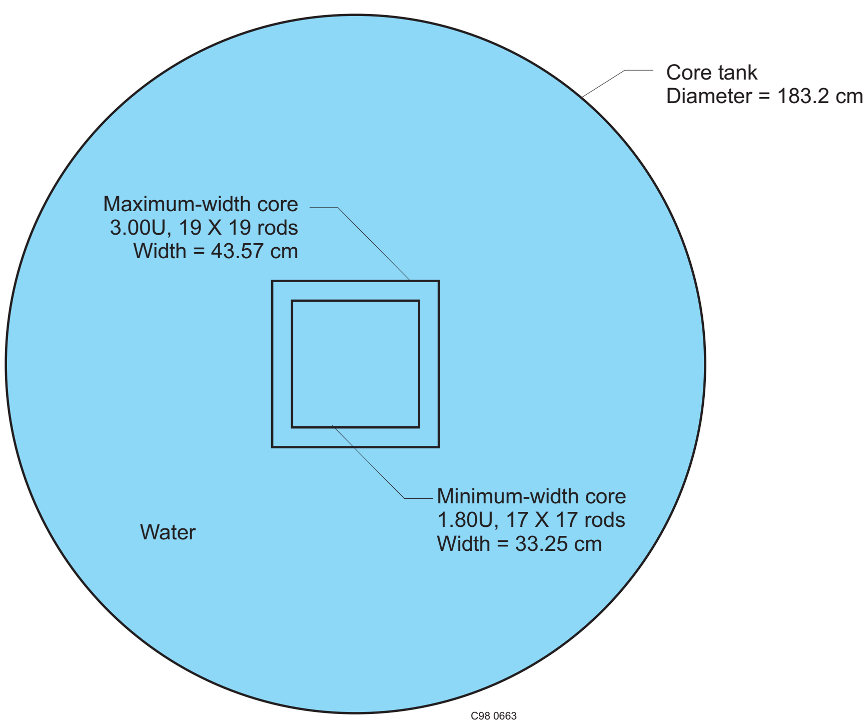

Figure 5. Horizontal Cross Section of the Core Tank.

The dependence of k_{eff} on the side reflector thickness has been calculated with MCNP 4a and continuous-energy JENDL-3.2 cross sections. This dependence is most apparent when the horizontal cross section of a core is small and its critical height is large. Thus, the calculation was made for the 17x17 rod array of the 1.83U core where the horizontal side length of the core region is minimum and the reflector effect of side water is maximum. Dependence of calculated k_{eff} on the thickness of the side reflector is shown in Table 9. The difference in k_{eff} between a 30-cm-thick side reflector and 40-cm-thick reflector is negligible. Therefore, the benchmark model has a 30-cm-thick side reflector.

Table 9. Dependence of k_{eff} on side reflector thickness.
(1.83U, 17x17, H_c=114.59 cm)

Reflector Thickness (cm)	k_{eff}
2.5	0.9440±0.0007
5.0	0.9830±0.0008
7.0	0.9949±0.0007
10.0	1.0009±0.0008
20.0	1.0011±0.0007
30.0[a]	1.0021±0.0007
40.0	1.0015±0.0007

(a) Benchmark model

The lower region below the fuel has a more complicated structure than the side water reflector, as stated in Section 1 and shown in Figure 3. To check the effect of the simplified lower reflector region in the benchmark model, the detailed model of the lower part of the core as shown in Figure 3 was considered. The benchmark models are shown in Figures 6 and 7.

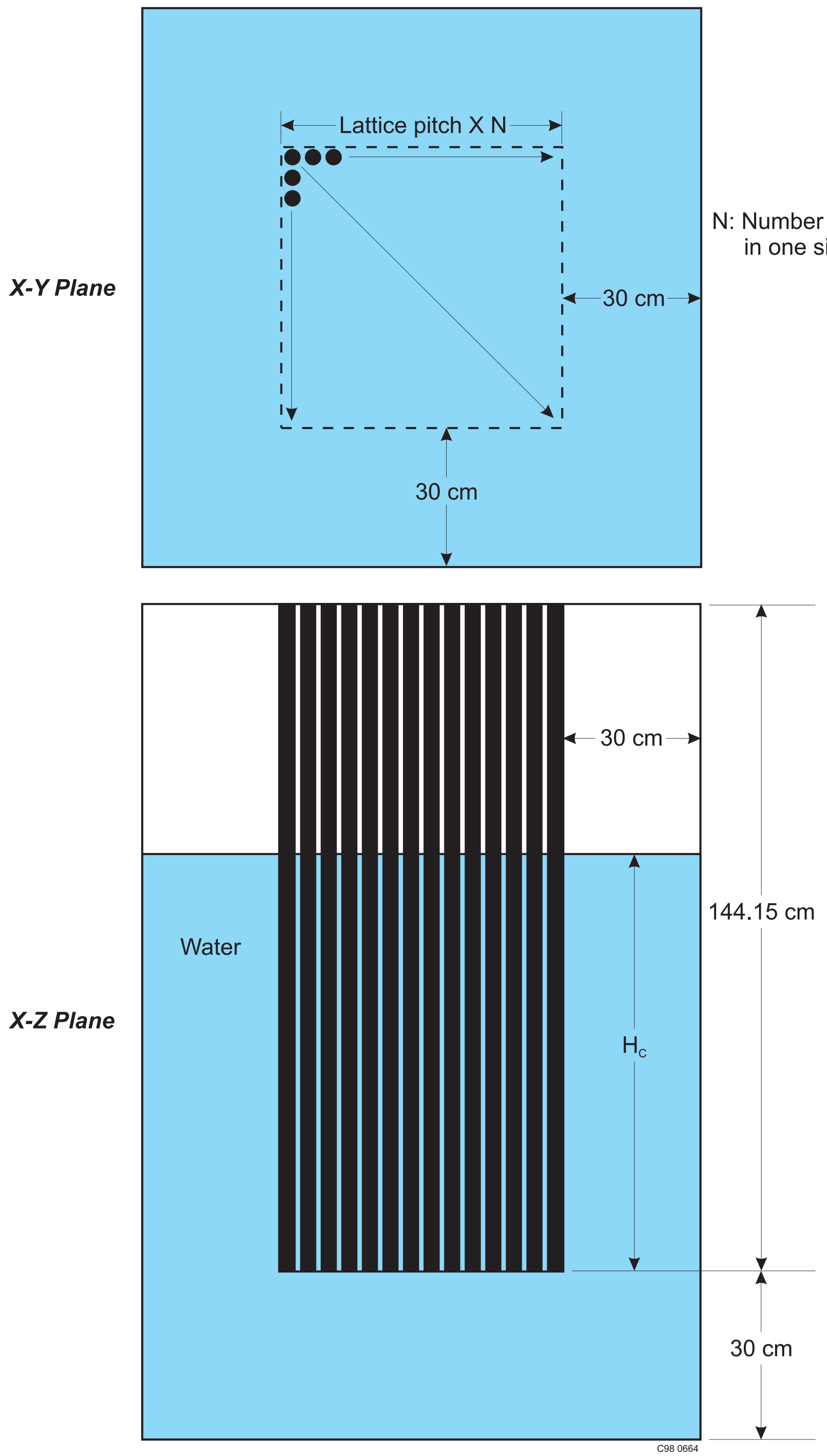

Figure 6. Three-Dimensional Benchmark Model.

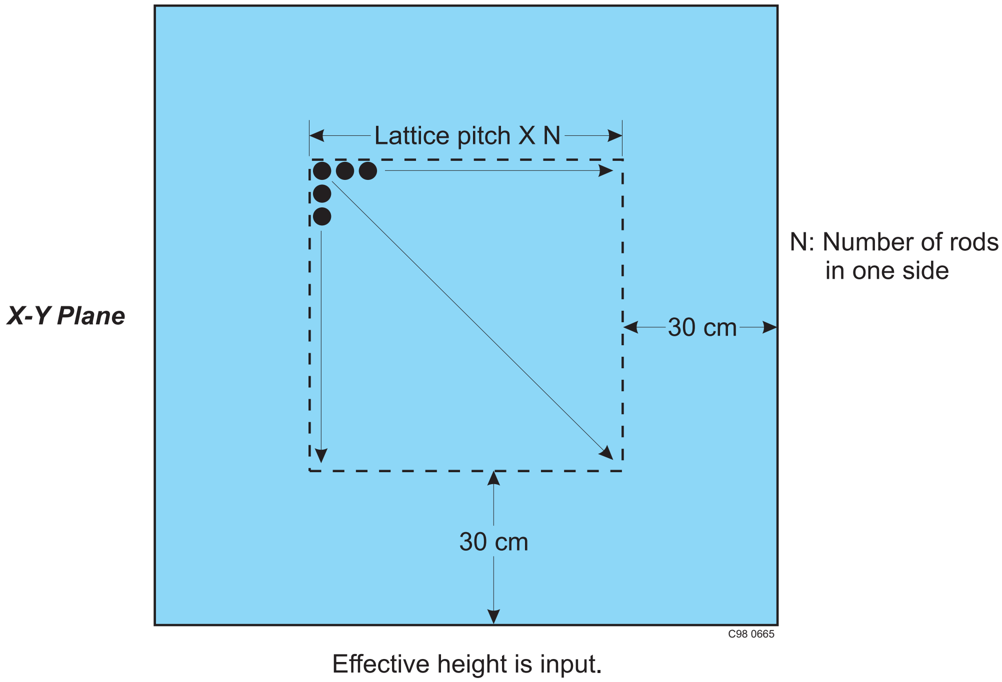

Figure 7. Two-Dimensional Benchmark Model.

For the experimental core which has the lowest critical height in each volume ratio, a calculation was made with the detailed model of the lower part of the core to estimate the effect of simplifying the lower parts. Because the density and chemical composition of stainless steel of the support plate and core tank are not known, the density (7.93 g/cm^3) and composition of stainless steel 304L were adopted. Results are given in Table 10.

Table 10. Comparison of Detailed and Simplified Lower-Reflector Models.

Lattice Name	Case Number	Number of Rods in One Side	Critical Water Level H_c (cm)	Δk_{eff}[(a)]
1.50U	3	21	60.81	-0.0009
1.83U	8	21	46.01	-0.0000
2.48U	13	20	40.44	+0.0003
3.00U	18	19	41.54	-0.0010

(a) MCNP 4a, continuous-energy JENDL-3.2 cross sections. Change from benchmark model to detailed model. The uncertainty of the difference calculation is ~±0.0010.

Therefore, to account for the effect of lower reflector simplification, an uncertainty of 0.10% should be included in the uncertainty of the benchmark-model k_{eff}.

The dependence of k_{eff} on the water-reflector thickness below the fuel-pellet region was also calculated using the Monte Carlo code MCNP 4a with continuous-energy JENDL-3.2 cross sections. This dependence is most apparent when the critical water level is low. Thus, the calculation was made for the 19x19-rod array of the 3.00U core where the critical water level is minimum and the effect of the lower reflector is maximum. Dependence of calculated k_{eff} on the thickness of the lower reflector is shown in Table 11. The difference in k_{eff} between a 30-cm-thick reflector and 40-cm-thick water reflector is negligible. Therefore, the benchmark-model has a 30-cm-thick lower reflector.

Table 11. Dependence of k_{eff} on Lower Water-Reflector Thickness.

Reflector Thickness (cm)	k_{eff}
2.5	0.9940±0.0007
5.0	0.9986±0.0007
10.0	1.0007±0.0005
20.0	1.0021±0.0005
30.0[a]	1.0028±0.0007
40.0	1.0028±0.0007

(a) Benchmark model

3.1.2 Clad Composition - Since the density and exact chemical composition of the aluminum alloy clad are not known, a pure aluminum of approximately 2.7 g/cm^3 density is assumed for the benchmark model. The sensitivity of k_{eff} to the clad density is negligible as explained in Section 2.1. The effect of the impurities was calculated using TWOTRAN. If impurities were included in 6061 aluminum alloy, k_{eff} would be reduced. Among the elements of impurities, the addition of Mg and Si have slightly positive effects and the remainders have negative ones (especially, Mn's effect is most notable). The amount of each impurity within the ASTM Standard limits of 6061 aluminum which gives the most negative effect was chosen. The composition of impurities used for this calculation is shown in Table 12. The calculated result is -0.10% Δk_{eff}. However, since this impurity composition is extreme, note that the actual effect on k_{eff} may be much smaller. Therefore, an additional uncertainty of 0.05% due to uncertainty of cladding impurities is added to the total k_{eff} uncertainty.

Table 12. Composition for Impurity Effect Calculation.

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Wt.%	0.40	0.7	0.4	0.15	0.8	0.35	-	0.15	97.05

3.1.3 Vertical Buckling - The sensitivity of k_{eff} to uncertainty in vertical buckling was calculated using TWOTRAN (JENDL-3.2, 16-group). The calculation was done for Case 18 (3.00U: 19x19) in which the sensitivity of k_{eff} due to the vertical extrapolation length uncertainty is the largest, because the uncertainty of λ_z of the 3.00U core is 0.5 cm. The calculated Δk_{eff} result was 0.20%. Therefore, this additional uncertainty in k_{eff} should be included for the two-dimensional models.

3.2 Dimensions

The core of both two- and three-dimensional benchmark models (see Figures 6 and 7) has a square horizontal cross section of which each side dimension is the lattice pitch multiplied by the number of fuel rods arrayed in the x- or y-directions. These values for each case are given in Table 13. The fuel radius is 0.625 cm. The clad outer radius is 0.7085 cm. There is no gap between fuel and clad.

In the three-dimensional model, the vertical length of the fuel rod is 144.15 cm between the upper end and lower end of the fuel region. End plugs and cladding above and below the fuel region are omitted. The critical moderator level H_c for each case is given in Table 13.

In the two-dimensional model, the effective height of the core (i.e., critical water level from Table 3 plus vertical extrapolation length from Table 5) is input. The effective heights are given in Table 13.

Table 13. Core Dimensions of Benchmark Models.

Lattice Name	Lattice Pitch (cm)	Case No.	Number of Rods in One Side (N)	H_c[a] 3-D Model (cm)	Effective Height[b] 2-D Model (cm)
1.50U	1.849	1	19	99.45	112.05
		2	20	73.73	86.33
		3	21	60.81	73.41
1.83U	1.956	4	17	114.59	126.79
		5	18	75.32	87.52
		6	19	60.38	72.58
		7	20	51.65	63.85
		8	21	46.01	58.21
2.48U	2.15	9	16	78.67	89.97
		10	17	59.96	71.26
		11	18	50.52	61.82
		12	19	44.55	55.85
		13	20	40.44	51.74
3.00U	2.293	14	15	90.75	101.85
		15	16	64.42	75.52
		16	17	52.87	63.97
		17	18	46.06	57.16
		18	19	41.54	52.64

(a) critical water level height from bottom of fuel
(b) vertical dimension of fuel (core)

3.3 Material Data

The atomic densities of the fuel pellet and cladding in the benchmark model are shown in Table 14. The fraction of ^{234}U wt.%, $0.008 \times {}^{235}U$ wt.%, was used, and the amount of ^{238}U was reduced accordingly. The atomic density derivations are shown in Appendix B.

Table 14. Atomic Number Densities

Region	Material	Wt.%	Atom Density ($x10^{24}$ atoms/cm^3)
Fuel	^{234}U[(a)]	0.021	$4.8872x10^{-6}$
	^{235}U	2.596	$6.0830x10^{-4}$
	^{238}U	97.383	$2.2531x10^{-2}$
	O	-	$4.7214x10^{-2}$
Cladding[(b)]	Aluminum	-	$5.5137x10^{-2}$
Water	H	-	$6.6735x10^{-2}$
	O	-	$3.3368x10^{-2}$

[(a)]The fraction 0.008 x ^{235}Uwt.% was assumed.

[(b)] homogenized with air gap

3.4 Temperature Data

The moderator temperature was reported for each experiment. In addition to presenting the measured critical water level at each temperature and the temperature coefficients of reactivity, the critical water levels at 20°C, corrected by using the temperature coefficients of reactivity and measured water level worths, are used to define the benchmark models.

3.5 Experimental and Benchmark-Model k_{eff}

The reported critical heights are the average of two or more critical measurements and are considered to correspond to a k_{eff} of 1.000. As a result of sensitivity and uncertainty analyses performed in developing the benchmark model from the exact model, the benchmark-model k_{eff}'s are 1.000 ± 0.002 for the three-dimensional models and 1.000 ± 0.003 for the two-dimensional models.

4.0 RESULTS OF SAMPLE CALCULATIONS

The calculations were performed with the Monte Carlo code MCNP, the multi-energy-group Monte Carlo code MULTI-KENO in the JACS system, and the two-dimensional transport code TWOTRAN in the SRAC system. The JACS and SRAC code systems were developed at JAERI for criticality-safety analysis and thermal-reactor design, respectively. The nuclear data file is JENDL-3.2 recently prepared at JAERI. The results of sample calculations are shown in Tables 16 and 17.

MULTI-KENO results are about 1% high for the small-pitch (1.50U) cases. The reasons for the slightly high results are unknown. As this is the first application of the combination of JENDL-3.2 and MULTI-KENO to TCA experiments, there is not enough knowledge to conclude anything about the calculated results. TWOTRAN results are generally about 0.5 to 1% high.

Table 15. Sample Calculation Results for Three-Dimensional Model (Japan).

Lattice Name	Code (Cross Section Set) → Case ↓	MCNP (Continuous-Energy JENDL-3.2)	MULTI-KENO (JENDL-3.2/MGCL 137-Group)
1.50U	1	1.0004±0.0008	1.0074±0.0014
	2	1.0008±0.0007	1.0105±0.0014
	3	1.0017±0.0008	1.0081±0.0013
1.83U	4	1.0010±0.0008	1.0041±0.0015
	5	0.9990±0.0007	1.0067±0.0014
	6	1.0013±0.0007	1.0051±0.0014
	7	1.0014±0.0007	1.0051±0.0013
	8	0.9992±0.0007	1.0051±0.0014
2.48U	9	1.0016±0.0007	1.0036±0.0014
	10	0.9994±0.0008	1.0044±0.0013
	11	1.0021±0.0007	1.0043±0.0015
	12	1.0014±0.0007	1.0038±0.0014
	13	1.0004±0.0007	1.0039±0.0014
3.00U	14	1.0030±0.0007	0.9986±0.0012
	15	1.0004±0.0009	1.0005±0.0012
	16	1.0020±0.0007	0.9999±0.0013
	17	1.0027±0.0007	1.0000±0.0014
	18	1.0016±0.0006	1.0028±0.0014

Table 16. Sample Calculation Results for Two-Dimensional Model (Japan).

Lattice Name	Code (Cross Section Set) → Case ↓	TWOTRAN (JENDL-3.2/ 16-Group)
1.50U	1	1.0052
	2	1.0075
	3	1.0088
1.83U	4	1.0054
	5	1.0071
	6	1.0089
	7	1.0098
	8	1.0105
2.48U	9	1.0063
	10	1.0067
	11	1.0070
	12	1.0068
	13	1.0063
3.00U	14	1.0055
	15	1.0057
	16	1.0058
	17	1.0054
	18	1.0029

5.0 REFERENCES

1. Harumichi Tsuruta, Iwao Kobayashi, Takenori Suzaki, Akio Ohno, Kiyonobu Murakami, Syojiro Matsuura, "Critical Sizes of Light Water Moderated UO_2 and PuO_2-UO_2 Lattice," JAERI-1254, 1978.

APPENDIX A: TYPICAL INPUT LISTINGS

A.1 MULTI-KENO Input Listing

MULTI-KENO was developed from KENO-IV. The main difference from KENO-IV is that it can treat a ‘SUPER BOX’ array. KENO was run using 150 active generations of 2000 neutrons each, after skipping 15 generations.

MULTI-KENO Input Listing for Case 1 of Table 15.

```
3  137    4    0    3    0    1    3
U(2.6)O2 PELLET LATTICE NAME 1.50U
   4    2    3
  3922340  3922350   3922380   3080160
 4.8872E-6 6.083E-4 2.2531E-2 4.7214E-2
   1.849     0.625    0.7085       0.0      1.487
AIRCLADDING ( WITH AN AIR GAP )
   1    0    3
  3130270
 5.5137E-2
WATER
   2    0    3
  3010010   3080160
 6.6735E-2 3.3368E-2
CASE NO.1 1.50U 19X19 HC=99.45CM WATER-REFLECTED
170.0  170 2000   20  137  137    3    3    3   34    4    1    1    4
   3    1    0 2100   00    0    0    0    0    0    0   00    0    0
 -0.0 -0.0 -0.0 -0.0 -0.0 -0.0
 1 -1 1.0  2 2 1.0  3 3 1.0
*
SUPER BOX   1     1  1  1  1
BOX TYPE  1
CUBOID    3 47.5655 -47.5655 47.5655 -47.5655 -16.83 -30.00 137R0.5
CUBOID    0 47.5655 -47.5655 47.5655 -47.5655 -16.83 -30.00 137R0.5
CELL BDY  0 47.5655 -47.5655 47.5655 -47.5655 -16.83 -30.00 137R0.5
CUBOID    0 47.5655 -47.5655 47.5655 -47.5655 -16.83 -30.00 137R0.5
*
SUPER BOX   2     2 19 19  1
BOX TYPE  1
CYLINDER  3  0.7085                          0.0  -16.83 137R0.5
CUBOID    3  0.9245  -0.9245  0.9245  -0.9245   0.0  -16.83 137R0.5
CUBOID    0  0.9245  -0.9245  0.9245  -0.9245   0.0  -16.83 137R0.5
*
BOX TYPE  2
CYLINDER  3  0.7085                          0.0  -16.83 137R0.5
CUBOID    3  0.9245  -0.9245  0.9245  -0.9245   0.0  -16.83 137R0.5
CUBOID    0  0.9245  -0.9245  0.9245  -0.9245   0.0  -16.83 137R0.5
*
CELL BDY  0 17.5655 -17.5655 17.5655 -17.5655   0.0  -16.83 137R0.5
CUBOID    3 47.5655 -47.5655 47.5655 -47.5655   0.0  -16.83 137R0.5
CUBOID    0 47.5655 -47.5655 47.5655 -47.5655   0.0  -16.83 137R0.5
*
SUPER BOX   3     2 19 19  1
BOX TYPE  1
CYLINDER  1  0.6250                         99.45   0.0  137R0.5
CYLINDER  2  0.7085                         99.45   0.0  137R0.5
CUBOID    3  0.9245  -0.9245  0.9245  -0.9245  99.45   0.0  137R0.5
CUBOID    0  0.9245  -0.9245  0.9245  -0.9245  99.45   0.0  137R0.5
*
BOX TYPE  2
CYLINDER  1  0.6250                         99.45   0.0  137R0.5
CYLINDER  2  0.7085                         99.45   0.0  137R0.5
CUBOID    3  0.9245  -0.9245  0.9245  -0.9245  99.45   0.0  137R0.5
CUBOID    0  0.9245  -0.9245  0.9245  -0.9245  99.45   0.0  137R0.5
*
CELL BDY  0 17.5655 -17.5655 17.5655 -17.5655  99.45   0.0  137R0.5
CUBOID    3 47.5655 -47.5655 47.5655 -47.5655  99.45   0.0  137R0.5
CUBOID    0 47.5655 -47.5655 47.5655 -47.5655  99.45   0.0  137R0.5
*
SUPER BOX   4     2 19 19  1
BOX TYPE  1
CYLINDER  1  0.6250                        144.15  99.45 137R0.5
```

MULTI-KENO Input Listing for Case 1 of Table 15 (cont'd).

```
CYLINDER  2  0.7085                      144.15  99.45 137R0.5
CUBOID    0  0.9245  -0.9245  0.9245  -0.9245 144.15  99.45 137R0.5
*
BOX TYPE  2
CYLINDER  1  0.6250                      144.15  99.45 137R0.5
CYLINDER  2  0.7085                      144.15  99.45 137R0.5
CUBOID    0  0.9245  -0.9245  0.9245  -0.9245 144.15  99.45 137R0.5
*
CELL BDY  0 17.5655 -17.5655 17.5655 -17.5655 144.15  99.45 137R0.5
CUBOID    0 47.5655 -47.5655 47.5655 -47.5655 144.15  99.45 137R0.5
*
CORE BDY  0 47.5655 -47.5655 47.5655 -47.5655 144.15 -30.00 137R0.5
CUBOID    0 47.5655 -47.5655 47.5655 -47.5655 144.15 -30.00 137R0.5
*
* MIXED BOX ORIENTATION CARDS FOR SUPER BOX2
 1  1 19  2  1 19  1  1  1  1  0       2  2 18  2  1 19  1  1  1  1  1
*
* MIXED BOX ORIENTATION CARDS FOR SUPER BOX3
 1  1 19  2  1 19  1  1  1  1  0       2  2 18  2  1 19  1  1  1  1  1
*
* MIXED BOX ORIENTATION CARDS FOR SUPER BOX4
 1  1 19  2  1 19  1  1  1  1  0       2  2 18  2  1 19  1  1  1  1  1
*
* MIXED SUPERBOX ORIENTATION CARDS
 1  1  1  1  1  1  1  1  1  1  0      2  1  1  1  1  1  1  2  2  1  0
 3  1  1  1  1  1  1  3  3  1  0      4  1  1  1  1  1  1  4  4  1  1
*
 -1
END KENO
```

A.2 TWOTRAN Input Listing

The cell homogenization was made with the collision probability method of the SRAC code system. The 107 group constants were collapsed to 16 groups with the neutron spectra calculated by the one-dimensional discrete-ordinates code ANISN. TWOTRAN calculations were performed with S_8 quadrature and P_1 scattering order. The convergence criteria for the eigenvalue and flux was $1x10^{-5}$.

TWOTRAN Input Listing for Case 1 of Table 16.

```
#!/bun/csh -f
#@$-C SRAC95
#
####################################################################
#
#  <<  run SRAC95 on VPP-500/42 >>
#
#  Consultant : keisuke OKUMURA, Tel 029-282-5321
#              E-mail okumura@mike.tokai.jaeri.go.jp
#
####################################################################
#  sample problem SnSmpl : Pij => ANISN => TWOTRAN
####################################################################
#
# Fortran logical unit usage (allocate if you need)
#
#       The meaning of each file depends on sub-programs used in SRAC.
#       [ ]:important files for users.
#
#   1   binary (ANISN,TWOTRAN,CIATION)
#   2   binary (ANISN,CITATION), usually scratch
#   3   binary (SRAC,ANISN,TWOTRAN,CITATION)
#   4   binary (PIJ,ANISN,TWOTRAN), usually scratch
# [ 5]  text:80 standard input
# [ 6]  text:137 standard output, message from SRAC
#   8   binary (ANISN,TWOTRAN)
#   9   binary (TWOTRAN,CITATION)
#              flux map in CITATION
#  10   binary (ANISN,TWOTRAN,CITATION)
#  11   binary (TWOTRAN,CITATION)
#  12   binary (TWOTRAN)
#  13   binary (TWOTRAN,CITATION)
#  14   binary (TWOTRAN,CITATION)
#  15   binary (CITATION), always scratch
#  16   binary (CITATION), always scratch
#  17   binary (CITATION)
#  18   binary (CITATION), always scratch
#  19   binary (CITATION), always scratch
#  20   binary (CITATION), always scratch
#  21   binary (PIJ), usually scratch
#  22   binary (PIJ,CITATION), usually scratch
#  26   binary (CITATION), always scratch
#  28   binary (CITATION), always scratch
#  31   text:80 (SRAC-CVMACT,CITATION)
#  32   binary (PIJ,ANISN,TWOTRAN,TUD,CITATION)
#              power density map in CITATION
#  33   binary (PIJ,TUD,CITATION)
#  49   device internally used to access PDS file
# [50]  text:80 burnup chain data (BURNUP)
#  51   binary (BURNUP)
#  52   binary (SRAC), always scratch
#  81   binary (PIJ), always scratch
#  82   binary (PIJ), always scratch
#  83   binary (PIJ), always scratch
#  84   binary (PIJ), always scratch
#  85   binary data table for Pij (PIJ), always required
# [89]  plot data for piflib
#  91   text:80 (CITATION), usually scratch
#  92   text:80 (CITATION), usually scratch
#  93   text:80 (BURNUP), always scratch
#  95   text:80 (SRAC-DTLIST), always scratch
#  97   binary (BURNUP), always scratch
```

TWOTRAN Input Listing for Case 1 of Table 16 (cont'd).

```
# [98]  text:137 (SRAC-BURNUP) summary of burnup results
# [99]  text:137 calculated results
#
#============= Set by user ===================================
#
#  LMN    : load module name
#          =SRACvp.50m  (for vpp- 50M : main/1.2M words, incore-PDS/7M words)
#          =SRACvp.100m (for vpp-100M : main/7.0M words, incore-PDS/10M words)
#          =SRACvp.200m (for vpp-200M : main/7.0M words, incore-PDS/30M words)
#          For burnup calculationis, SRACvp.100m/200m should be used
#  BRN    : burnup chain library data
#          =ucm65fp  : U-Np-Pu-Am-Cm & 65+1 FP & B-10 (standard model)
#          =thcm65fp : Th-Pa-U-Np-Pu-Cm & 65+1 FP & B-10 (Th model)
#          =ucm10fp  : U-Np-Pu-Am-Cm & 10+4 FP & B-10 (simple model)
#  ODR    : directory name in which output data will be stored
#  CASE   : case name which is refered as names of output files and PDS
#
#
  set LMN  = SRACvp.100m
  set BRN  = ucm65fp
  set ODR  = $HOME/srac95/outp
  set CASE = l150n19
#
  set WKU  = /wka2/`logname`
#  set VFL  = $HOME/vfl
  set WKV  = $HOME/wkvfl
#
#=============  mkdir for PDS  ================================
#
#  PDS_DIR : directory name of PDS files
#  PDS file names must be identical with those in input data
#
  set PDS_DIR = $WKU/$CASE
  mkdir $PDS_DIR
  mkdir $PDS_DIR/UFAST
  mkdir $PDS_DIR/UTHERMAL
  mkdir $PDS_DIR/UMCROSS
  mkdir $PDS_DIR/MACROWRK
  mkdir $PDS_DIR/MACRO
  mkdir $PDS_DIR/FLUX
  mkdir $PDS_DIR/MICREF
#
#=============  Change if you like ============================
#
  set SRAC_DIR = /dg05/ufs02/j9347/srac95
  set LM       = $SRAC_DIR/bin/$LMN
  set DATE     = `date +%b%d.%H.%M.%S`
#
#  TMPDIR : scratch file area, if not defined /usr/tmp(UFS) will be used.
#  setenv  TMPDIR  $WKV
#
  setenv  fu85  $SRAC_DIR/lib/kintab.dat
#  setenv  fu89  $ODR/$CASE.SFT89.$DATE
  setenv  fu99  $ODR/$CASE.SFT99.$DATE
  set OUTLST =  $ODR/$CASE.SFT06.$DATE
#
#=============  Exec SRAC code with the following input data =============
#
cat - << END_DATA | timex -H $LM >& $OUTLST
MATR
TCA EXPERIMENT 19X19 LP1.50U HEIGHT=99.45CM
 1 1 1 1 2  1 4 0 2 0  0 -2 1 0 2  2 3 0 0 0/SRAC CONT.
8.3300E-03 / BSQ FOR P1B1 LP1.50U-CRITICAL BUCKLING(JAERI-1254)
```

TWOTRAN Input Listing for Case 1 of Table 16 (cont'd).

```
/dg05/ufs02/j9347/srac95/lib/usrplib/pfast    Old      File
/dg05/ufs02/j9347/srac95/lib/usrplib/pthml    O        F
/dg05/ufs02/j9347/srac95/lib/usrplib/pmcrs    O        F
$PDS_DIR/UFAST           Scratch  Core
$PDS_DIR/UTHERMAL        S        C
$PDS_DIR/UMCROSS         S        C
$PDS_DIR/MACROWRK        S        C
$PDS_DIR/MACRO           S        C
$PDS_DIR/FLUX            S        C
$PDS_DIR/MICREF          S        C
70  37 10  6  / NEF NET NERF NERT
70(1) / NEGF
37(1) / NEGT
  5  5  5  5  8  8  9  8  9  8 / NECF
            4  6  6  6  6  9 / NECT

 4  6  6  6  1
 1  6  0  0  0
 5  0 10 15  0
 0 30  0
 0 6(0) 6(.0) / PATH ITER PARM
 1  1  1  1  1  1 /  X BY R
 1  1  2  3  3  3 /  M BY R
 0.0  0.313  0.625  0.7085  0.750  0.850  0.9245  / RX LP=1.849CM
15&
   1  0  1   8  1  1  0  2   48  1
   0  0  0   0  0  0  0  0    0  0
   0  0  0  35  0  0  0  0  500  0
   0  0  0   0  1  0
16*
   0.0     0.0   0.0001  1.420892  52.131  112.05  0.0  0.0  0.0  0.5
   0.0002  0.05  0.001   0.75
00T
 4*
   0.0   17*1.0   1*0.5655   30*1.000
 8&
  18(1)   30(2)
 9&
   4  5
19&
   1  1
27&
   1  2
00T
  5  /  NMAT
PELTXXXX 0 4   300.0   1.2500  1.0 /MAT1/  2.6WT% UO2 PELLET
XU040001 2 0   4.8872E-6
XU050001 2 0   6.0830E-4
XU080001 2 0   2.2531E-2
XO060001 0 0   4.7214E-2
CLADXXXX 0 1   300.0   0.3143  0.0 /MAT2/
XAL70001 0 0   5.5870E-2
MODLXXXX 0 2   300.0   0.0     0.0 /MAT3/  WATER AS MODELATOR
XH01H001 0 0   6.6740E-2
XO060001 0 0   3.3370E-2
MATRX01X 0 0   300.0   0.0     0.0 /MAT4/  HOMOGENIZED MATR BY PIJ
REFRXXXX 0 2   300.0  30.0     0.0 /MAT5/  WATER AS REFLECTOR
XH01H001 0 0   6.6740E-2
XO060001 0 0   3.3370E-2
```

TWOTRAN Input Listing for Case 1 of Table 16 (cont'd).

```
   0 /  PEACO
CORE
TCA EXPERIMENT 19X19 LP1.50U HEIGHT=99.45CM
 0 0 0 1 0   0 0 0  0 1   0  3 0 0 2   0 1 0 0 0 / SRAC CONTROL
 1.E-15
    1  /
TCA EXPERIMENT 19X19 LP1.50U HEIGHT=99.45CM
     0     1     8    16     4     4     1     0     1     0
     1     0     3     3     0     0     0     0     0     0
     0     0     0     0     0    30     0     0  9999     1
     0     0     1     1     0     1     3     1     0     0
     0     0                                          / 42 I
       1.00     0.0            0.0         0.0         0.0
       0.0      1.0E-03        1.0         0.0     -112.05 / 10 FLOAT
    12     2     8    10                          / FINE X MESH 23
    12     2     8    10                          / FINE X MESH 23
   0.0       16.0    1*1.5655    1*6.0        1*24.0 & COARSE X MESH
   0.0       16.0    1*1.5655    1*6.0        1*24.0 & COARSE Y MESH
& CROSS SECTION ID
  -1 -1 -2 -2                                & COARSE X MESH
  -1 -1 -2 -2                                & COARSE X MESH
  -2 -2 -2 -2                                & COARSE X MESH
  -2 -2 -2 -2                                & COARSE X MESH
 16(0) / X-REG
    2  / NMAT
MATRX01X 0 0  300.0 0.0 0.0 /MAT4/  FUEL ROD IN H2O
MATRX02X 0 0  300.0 0.0 0.0 /MAT5/  WATER AS MODELATION


END_DATA
#
#=============  Remove PDS files if you don't keep them =========
#
   rm -r $PDS_DIR
#
#  rm -r $PDS_DIR/UFAST
#  rm -r $PDS_DIR/UTHERMAL
#  rm -r $PDS_DIR/UMCROSS
#  rm -r $PDS_DIR/MACROWRK
#  rm -r $PDS_DIR/MACRO
#  rm -r $PDS_DIR/FLUX
#  rm -r $PDS_DIR/MICREF
```

A.3 MCNP Input Listing

MCNP was run using 200 active generations of 5000 neutrons each, after skipping 10 generations.

MCNP Input Listing for Case 1 of Table 15.

```
file name=case1
c    single 19* 19
c    critical water level  99.450(cm)
c    lattice pitch   1.849(cm);u(2.6)o2
c    water reflector  30.000(cm)
c
c     cellcards
c
1     1 7.035819e-2        -7      10     -12      imp:n=1 u=1
2     2 5.513700e-2         7  -8  10     -12      imp:n=1 u=1
3     3 1.001030e-1             8  10 -11          imp:n=1 u=1
4     0                      8      11 -12      imp:n=1 u=1
5     0                  -1   2  -3   4  -5   6  imp:n=1 u=2 lat=1
              fill= 0: 18 0: 18 0:  0
               1 360r
6     0                  -21  22 -23  24 -25  26  imp:n=1     fill=2
7     3 1.001300e-1    #6 (-31  32 -33  34 -35  36) imp:n=1
8     0              #6 #7  -9                  imp:n=1
9     0                      9                  imp:n=0

c
c    surface cards (origin x=0.9245 y=0.9245 z=0.0)
c    parallelpiped
 1   px    1.84900
 2   px    0.00000
 3   py    1.84900
 4   py    0.00000
 5   pz  144.15000
 6   pz    0.00000
c
c
c    cylinder
c
7     c/z  0.9245 0.9245 0.6250
8     c/z  0.9245 0.9245 0.7085
c
c    outer world
9     s   17.566 17.566  72.075 150.0
c
c    critical water level=  99.450(cm)
10    pz  0.0
11    pz  99.450
12    pz  144.15
c    pitch* 19=35.131(cm)
c    (35.131*35.131*144.15)
c    parallelpiped
21   px   35.13099
22   px    0.00001
23   py   35.13099
24   py    0.00001
25   pz  144.14999
26   pz    0.00001
c
c    water refrector=  30.000(cm)
c    parallelpiped
```

MCNP Input Listing for Case 1 of Table 15 (cont'd).

```
31   px   65.13099
32   px  -29.99999
33   py   65.13099
34   py  -29.99999
35   pz   99.44999
36   pz  -29.99999
c

c
c    data cards
c
mode  n                    $ transfort neutrons only
c
c    material cards
c
c    U(2.6)O2 pellet
m1   92235.37c 6.0830e-4             $ U-235
     92238.37c 2.2531e-2             $ U-238
     92234.37c 4.8872e-6             $ U-234
      8016.37c 4.7214e-2             $ H
c
c    al cladding (with an air gap)
m2   13027.37c 5.513700e-2           $ Al
c
c    water(300k)
m3    1001.37c 6.6735e-2             $ H
      8016.37c 3.3368e-2             $ O
mt3   lwtr.01t
c
c
c    criticality cards
c
kcode  5000 1.0  50  250
sdef  cel=d1 erg=d2 rad=d3 ext=d4 pos=0.9245 0.9245 0 axs=0 0 1
si1   l
       6:5(  0  18   0):1   6:5(  1  18   0):1   6:5(  2  18   0):1
       6:5(  0  17   0):1   6:5(  1  17   0):1   6:5(  2  17   0):1
       6:5(  0  16   0):1   6:5(  1  16   0):1   6:5(  2  16   0):1
       6:5(  0  15   0):1   6:5(  1  15   0):1   6:5(  2  15   0):1
       6:5(  0  14   0):1   6:5(  1  14   0):1   6:5(  2  14   0):1
       6:5(  0  13   0):1   6:5(  1  13   0):1   6:5(  2  13   0):1
       6:5(  0  12   0):1   6:5(  1  12   0):1   6:5(  2  12   0):1
       6:5(  0  11   0):1   6:5(  1  11   0):1   6:5(  2  11   0):1
       6:5(  0  10   0):1   6:5(  1  10   0):1   6:5(  2  10   0):1
       6:5(  0   9   0):1   6:5(  1   9   0):1   6:5(  2   9   0):1
       6:5(  0   8   0):1   6:5(  1   8   0):1   6:5(  2   8   0):1
       6:5(  0   7   0):1   6:5(  1   7   0):1   6:5(  2   7   0):1
       6:5(  0   6   0):1   6:5(  1   6   0):1   6:5(  2   6   0):1
       6:5(  0   5   0):1   6:5(  1   5   0):1   6:5(  2   5   0):1
       6:5(  0   4   0):1   6:5(  1   4   0):1   6:5(  2   4   0):1
       6:5(  0   3   0):1   6:5(  1   3   0):1   6:5(  2   3   0):1
       6:5(  0   2   0):1   6:5(  1   2   0):1   6:5(  2   2   0):1
       6:5(  0   1   0):1   6:5(  1   1   0):1   6:5(  2   1   0):1
       6:5(  0   0   0):1   6:5(  1   0   0):1   6:5(  2   0   0):1
       6:5(  3  18   0):1   6:5(  4  18   0):1   6:5(  5  18   0):1
       6:5(  3  17   0):1   6:5(  4  17   0):1   6:5(  5  17   0):1
       6:5(  3  16   0):1   6:5(  4  16   0):1   6:5(  5  16   0):1
```

MCNP Input Listing for Case 1 of Table 15 (cont'd).

```
6:5( 3 15  0):1  6:5( 4 15  0):1  6:5( 5 15  0):1
6:5( 3 14  0):1  6:5( 4 14  0):1  6:5( 5 14  0):1
6:5( 3 13  0):1  6:5( 4 13  0):1  6:5( 5 13  0):1
6:5( 3 12  0):1  6:5( 4 12  0):1  6:5( 5 12  0):1
6:5( 3 11  0):1  6:5( 4 11  0):1  6:5( 5 11  0):1
6:5( 3 10  0):1  6:5( 4 10  0):1  6:5( 5 10  0):1
6:5( 3  9  0):1  6:5( 4  9  0):1  6:5( 5  9  0):1
6:5( 3  8  0):1  6:5( 4  8  0):1  6:5( 5  8  0):1
6:5( 3  7  0):1  6:5( 4  7  0):1  6:5( 5  7  0):1
6:5( 3  6  0):1  6:5( 4  6  0):1  6:5( 5  6  0):1
6:5( 3  5  0):1  6:5( 4  5  0):1  6:5( 5  5  0):1
6:5( 3  4  0):1  6:5( 4  4  0):1  6:5( 5  4  0):1
6:5( 3  3  0):1  6:5( 4  3  0):1  6:5( 5  3  0):1
6:5( 3  2  0):1  6:5( 4  2  0):1  6:5( 5  2  0):1
6:5( 3  1  0):1  6:5( 4  1  0):1  6:5( 5  1  0):1
6:5( 3  0  0):1  6:5( 4  0  0):1  6:5( 5  0  0):1
6:5( 6 18  0):1  6:5( 7 18  0):1  6:5( 8 18  0):1
6:5( 6 17  0):1  6:5( 7 17  0):1  6:5( 8 17  0):1
6:5( 6 16  0):1  6:5( 7 16  0):1  6:5( 8 16  0):1
6:5( 6 15  0):1  6:5( 7 15  0):1  6:5( 8 15  0):1
6:5( 6 14  0):1  6:5( 7 14  0):1  6:5( 8 14  0):1
6:5( 6 13  0):1  6:5( 7 13  0):1  6:5( 8 13  0):1
6:5( 6 12  0):1  6:5( 7 12  0):1  6:5( 8 12  0):1
6:5( 6 11  0):1  6:5( 7 11  0):1  6:5( 8 11  0):1
6:5( 6 10  0):1  6:5( 7 10  0):1  6:5( 8 10  0):1
6:5( 6  9  0):1  6:5( 7  9  0):1  6:5( 8  9  0):1
6:5( 6  8  0):1  6:5( 7  8  0):1  6:5( 8  8  0):1
6:5( 6  7  0):1  6:5( 7  7  0):1  6:5( 8  7  0):1
6:5( 6  6  0):1  6:5( 7  6  0):1  6:5( 8  6  0):1
6:5( 6  5  0):1  6:5( 7  5  0):1  6:5( 8  5  0):1
6:5( 6  4  0):1  6:5( 7  4  0):1  6:5( 8  4  0):1
6:5( 6  3  0):1  6:5( 7  3  0):1  6:5( 8  3  0):1
6:5( 6  2  0):1  6:5( 7  2  0):1  6:5( 8  2  0):1
6:5( 6  1  0):1  6:5( 7  1  0):1  6:5( 8  1  0):1
6:5( 6  0  0):1  6:5( 7  0  0):1  6:5( 8  0  0):1
6:5( 9 18  0):1  6:5( 10 18  0):1  6:5( 11 18  0):1
6:5( 9 17  0):1  6:5( 10 17  0):1  6:5( 11 17  0):1
6:5( 9 16  0):1  6:5( 10 16  0):1  6:5( 11 16  0):1
6:5( 9 15  0):1  6:5( 10 15  0):1  6:5( 11 15  0):1
6:5( 9 14  0):1  6:5( 10 14  0):1  6:5( 11 14  0):1
6:5( 9 13  0):1  6:5( 10 13  0):1  6:5( 11 13  0):1
6:5( 9 12  0):1  6:5( 10 12  0):1  6:5( 11 12  0):1
6:5( 9 11  0):1  6:5( 10 11  0):1  6:5( 11 11  0):1
6:5( 9 10  0):1  6:5( 10 10  0):1  6:5( 11 10  0):1
6:5( 9  9  0):1  6:5( 10  9  0):1  6:5( 11  9  0):1
6:5( 9  8  0):1  6:5( 10  8  0):1  6:5( 11  8  0):1
6:5( 9  7  0):1  6:5( 10  7  0):1  6:5( 11  7  0):1
6:5( 9  6  0):1  6:5( 10  6  0):1  6:5( 11  6  0):1
6:5( 9  5  0):1  6:5( 10  5  0):1  6:5( 11  5  0):1
6:5( 9  4  0):1  6:5( 10  4  0):1  6:5( 11  4  0):1
6:5( 9  3  0):1  6:5( 10  3  0):1  6:5( 11  3  0):1
6:5( 9  2  0):1  6:5( 10  2  0):1  6:5( 11  2  0):1
6:5( 9  1  0):1  6:5( 10  1  0):1  6:5( 11  1  0):1
6:5( 9  0  0):1  6:5( 10  0  0):1  6:5( 11  0  0):1
6:5( 12 18  0):1  6:5( 13 18  0):1  6:5( 14 18  0):1
6:5( 12 17  0):1  6:5( 13 17  0):1  6:5( 14 17  0):1
6:5( 12 16  0):1  6:5( 13 16  0):1  6:5( 14 16  0):1
6:5( 12 15  0):1  6:5( 13 15  0):1  6:5( 14 15  0):1
6:5( 12 14  0):1  6:5( 13 14  0):1  6:5( 14 14  0):1
6:5( 12 13  0):1  6:5( 13 13  0):1  6:5( 14 13  0):1
6:5( 12 12  0):1  6:5( 13 12  0):1  6:5( 14 12  0):1
6:5( 12 11  0):1  6:5( 13 11  0):1  6:5( 14 11  0):1
6:5( 12 10  0):1  6:5( 13 10  0):1  6:5( 14 10  0):1
```

MCNP Input Listing for Case 1 of Table 15 (cont'd).

```
     6:5( 12   9   0):1  6:5( 13   9   0):1  6:5( 14   9   0):1
     6:5( 12   8   0):1  6:5( 13   8   0):1  6:5( 14   8   0):1
     6:5( 12   7   0):1  6:5( 13   7   0):1  6:5( 14   7   0):1
     6:5( 12   6   0):1  6:5( 13   6   0):1  6:5( 14   6   0):1
     6:5( 12   5   0):1  6:5( 13   5   0):1  6:5( 14   5   0):1
     6:5( 12   4   0):1  6:5( 13   4   0):1  6:5( 14   4   0):1
     6:5( 12   3   0):1  6:5( 13   3   0):1  6:5( 14   3   0):1
     6:5( 12   2   0):1  6:5( 13   2   0):1  6:5( 14   2   0):1
     6:5( 12   1   0):1  6:5( 13   1   0):1  6:5( 14   1   0):1
     6:5( 12   0   0):1  6:5( 13   0   0):1  6:5( 14   0   0):1
     6:5( 15  18   0):1  6:5( 16  18   0):1  6:5( 17  18   0):1
     6:5( 15  17   0):1  6:5( 16  17   0):1  6:5( 17  17   0):1
     6:5( 15  16   0):1  6:5( 16  16   0):1  6:5( 17  16   0):1
     6:5( 15  15   0):1  6:5( 16  15   0):1  6:5( 17  15   0):1
     6:5( 15  14   0):1  6:5( 16  14   0):1  6:5( 17  14   0):1
     6:5( 15  13   0):1  6:5( 16  13   0):1  6:5( 17  13   0):1
     6:5( 15  12   0):1  6:5( 16  12   0):1  6:5( 17  12   0):1
     6:5( 15  11   0):1  6:5( 16  11   0):1  6:5( 17  11   0):1
     6:5( 15  10   0):1  6:5( 16  10   0):1  6:5( 17  10   0):1
     6:5( 15   9   0):1  6:5( 16   9   0):1  6:5( 17   9   0):1
     6:5( 15   8   0):1  6:5( 16   8   0):1  6:5( 17   8   0):1
     6:5( 15   7   0):1  6:5( 16   7   0):1  6:5( 17   7   0):1
     6:5( 15   6   0):1  6:5( 16   6   0):1  6:5( 17   6   0):1
     6:5( 15   5   0):1  6:5( 16   5   0):1  6:5( 17   5   0):1
     6:5( 15   4   0):1  6:5( 16   4   0):1  6:5( 17   4   0):1
     6:5( 15   3   0):1  6:5( 16   3   0):1  6:5( 17   3   0):1
     6:5( 15   2   0):1  6:5( 16   2   0):1  6:5( 17   2   0):1
     6:5( 15   1   0):1  6:5( 16   1   0):1  6:5( 17   1   0):1
     6:5( 15   0   0):1  6:5( 16   0   0):1  6:5( 17   0   0):1
     6:5( 18  18   0):1
     6:5( 18  17   0):1
     6:5( 18  16   0):1
     6:5( 18  15   0):1
     6:5( 18  14   0):1
     6:5( 18  13   0):1
     6:5( 18  12   0):1
     6:5( 18  11   0):1
     6:5( 18  10   0):1
     6:5( 18   9   0):1
     6:5( 18   8   0):1
     6:5( 18   7   0):1
     6:5( 18   6   0):1
     6:5( 18   5   0):1
     6:5( 18   4   0):1
     6:5( 18   3   0):1
     6:5( 18   2   0):1
     6:5( 18   1   0):1
     6:5( 18   0   0):1
sp1     1 360r
c
sp2    -3
c
si3    h   0.0  0.6250
sp3   -21  1
c
si4        0.0  144.15
sp4   -21  0
c
prdmp  j  5000 1 3
c
print -175
```

APPENDIX B: ATOM DENSITY DERIVATIONS

26PA UO2	
Enrichment	**2.596**
Isotope ratio	
234U	**0.020768**
235U	**2.596**
238U	**97.383232**
Pellet	
Fabrication method	**sintered**
Diameter (mm)	**12.50**
Density (g/cc)	**10.40**
Stack length(mm)	**1441.5**
Stack U (g)	**1840**
Stack U235 (g)	**42**
Cladding	
Material	**Al**
Inner diameter Din (mm)	**12.65**
Thickness (mm)	**0.76**
Outer diameter Do (mm)	**14.17**
ND(Al without air gap)	**6.02393E-02**
(2) Al cladding	
MAL27: Mass number of Aluminum	
MAL	**26.9815**
So (clad) = Do *Do	**2.007889**
Sin (clad) = Din*Din	**1.600225**
Sp = Dp*Dp	**1.5625**
R=(So-Sin)/(So-Sp)	**0.915298761**
ND(with gap)=ND(without air gap) *R	
	5.5137E-02
(3) Water	
MH :	**1.0079**
MO :	**15.9994**
MH2O	**18.0152**
Mol(H2O)	**0.055408766**
Density (20deg)	**0.99820**
Reference value[(a)]	
ND(O16)	**3.3368E-02**
ND(H1)	**6.6735E-02**

(a) Chronological Scientific Tables (Rika nenpyou) (in Japanese) National Astronomical Observatory (ed.), Maruzen Co. Ltd. (1995)

	UO2 Pellet	
M4=	**Mass number of U234**	**234.0409**
M5=	**Mass number of U235**	**235.0439**
M8=	**Mass number of U238**	**238.0508**
MO=	**Mass number of O-16**	**15.9994**
W4=	**Weight % of U234**	**0.020768**
W5=	**Weight % of U235**	**2.596**
W8=	**Weight % of U238**	**97.383232**
N4/NU=	**W4*M5*M8/(W4*M5*M8+W5*M4*M8+W8*M4*M5)**	
=	**0.000211167**	
N5/NU=	**W5*M4*M8/(W4*M5*M8+W5*M4*M8+W8*M4*M5)**	
=	**0.026283282**	
N8/NU=	**W8*M4*M5/(W4*M5*M8+W5*M4*M8+W8*M4*M5)**	
=	**0.973505551**	
MU:	**Average mass number of Uranium**	
MU=	**N4/NU*M4+N5/NU*M5+N8/NU*M8**	
=	**237.970922**	
MUO2:	**Mass number of UO2**	
MUO2=	**MU+2.04*MO=**	**270.609698**
Mol(UO2):	**Mol number of UO2**	
=	**Density/MUO2=**	**0.038431734**
ND4:	**Atom density of U234 (b-cm)$^{-1}$**	
ND4=	**A0*Mol(UO2)*N4/NU/1E24**	
=		4.8872E-06
ND5:	**Atom density of U235 (b-cm)$^{-1}$**	
ND5=	**A0*Mol(UO2)*N5/NU/1E24**	
=		6.0830E-04
ND8:	**Atom density of U238 (b-cm)$^{-1}$**	
ND8=	**A0*Mol(UO2)*N8/NU/1E24**	
=		2.2531E-02
NO16:	**Atom density of O16 (b-cm)$^{-1}$**	
NO16=	**A0*Mol(UO2)*2.04/1E24**	4.7214E-02