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SPHERE OF PLUTONIUM REFLECTED BY BERYLLIUM

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IDENTIFICATION NUMBER PU-MET-FAST-019 SPECTRA

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1.0 DETAILED DESCRIPTION

1.1 Overview of Experiment

The experiment described in this evaluation is a critical configuration that was assembled in 1983 using the VNIITF Criticality Test Facility. Here, the assembly is a sphere of plutonium reflected by beryllium. This experiment was used to validate neutron data of beryllium.

Measurements were made with sufficient precision, and the configuration of the system is simple enough and defined well enough, for the experiment to be considered as a criticality safety benchmark.

1.2 Description of Experimental Configuration

The critical assembly is a plutonium sphere reflected by beryllium. A schematic of the experimental configuration is shown in Figure 1. The assembly is a spherical unit divided into two parts separated by a gap. Because these critical assemblies are more complicated than classical "unsplit" spherical assemblies, their description includes two additional parameters: (1) the critical separation, $\mathbf{h_{cr}}$, i.e., the distance between the centers of the facing hemispheres (including both the thickness of the diaphragm and the height of the void gap, but not the 0.15 cm trimmed from the flat surfaces of the reflector hemispheres); and (2) the separation radius, $\mathbf{R_{sep}}$, describing the manner of the assembly separation. $\mathbf{R_{sep}}$ is the radius of the portion of the upper hemisphere that remains with the lower, movable mass.

A neutron source of ^{252}Cf, 0.8 cm in diameter and 2.4 cm in length, which produces $1.3\text{x}10^6$ neutrons/s and does not disturb the criticality of the assembly, was placed inside the central cavity. In this experiment, neutron multiplication, **M**,[a] was measured as a function of the gap width, **h**. Remote measurements of the gap width were performed with an accuracy of 0.01 cm. The maximum value **M**=160 was obtained, with a gap width of 1.42 cm. The critical gap width, $\mathbf{h_{cr}}$=1.05 cm, was determined by extrapolation of the function 1/**M**(h) to zero. In this extrapolation only measurements with **M** > 50 were used. The combined uncertainty in $\mathbf{h_{cr}}$ from the measurements and from the extrapolation was less than 0.02 cm.

[a] Neutron multiplication is defined as a ratio of the measured neutron flux from the multiplying assembly to that from a dummy assembly in which HEU is replaced with depleted uranium or copper.

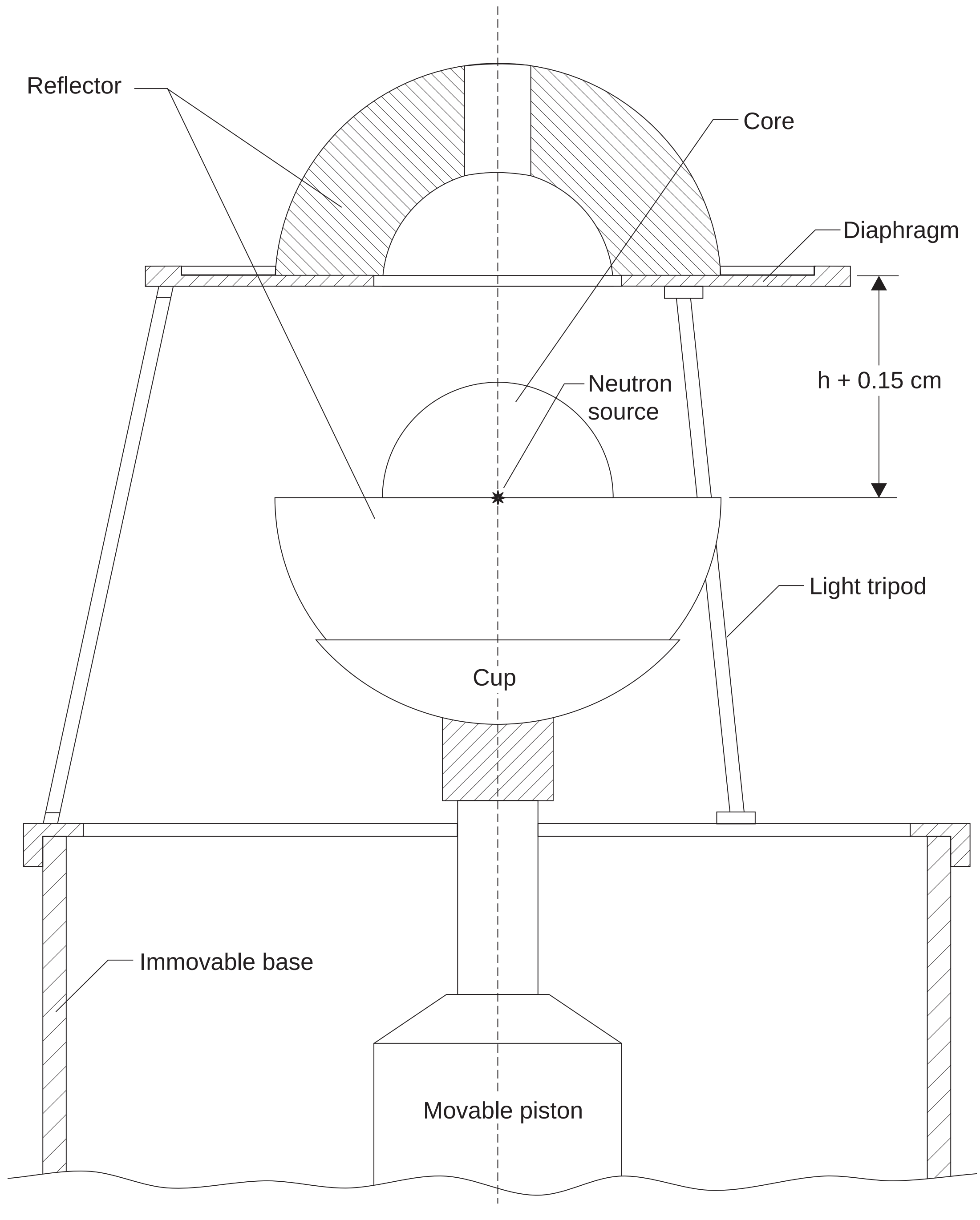

Figure 1. Configuration of the Critical-Assembly Experiment.

The critical configuration is shown in Figure 2. The plutonium sphere wholly belongs to the lower part. Therefore the separation radius $\mathbf{R_{sep}}$=5.35 cm is equal to the plutonium core outer radius.

Components of the critical assembly are made of delta-phase plutonium (core) and beryllium (reflector). The main components are pairs of matching hemispherical shells that can form complete spherical shells.

Each upper plutonium shell has a polar cylindrical hole 2.2 cm in diameter. The holes are filled by plugs of the same material. Each plutonium detail has 0.1-mm-thick nickel plating.

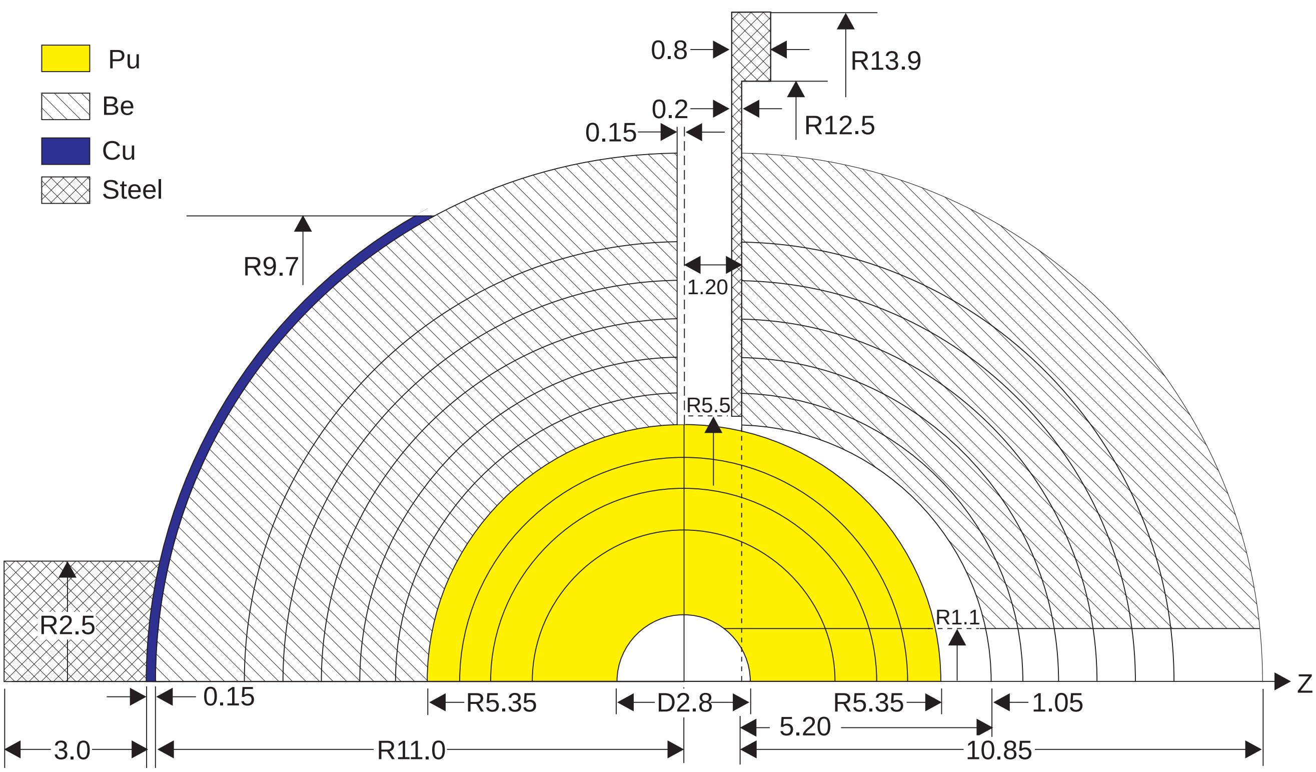

Figure 2. Critical Assembly Configuration.
Rotationally symmetric about the z-axis. The bottom is to the left. All dimensions are in cm.

The plutonium core has four spherical layers. Nominal sizes of the spherical shells (after plating) are shown in Table 1. The tolerances are 0 and -0.01 cm for outer dimensions, and 0 and +0.01 cm for inner dimensions, or better for small dimensions. The actual dimensions are measured to be inside the tolerances. The shell numbers are taken from a catalogue describing them.

Table 1. Numbers and Sizes of Plutonium Shells and Plugs.

Bottom Hemisphere	Top Hemisphere	Top Plug	Outer Diameter (cm)	Inner Diameter (cm)
10	1	11	10.70	9.32
9	2	12	9.32	8.04
8	3	13	8.04	6.30
7	4	14	6.30	2.80

The beryllium reflector has six spherical layers. Nominal sizes of the spherical shells are shown in Table 2. The tolerances are 0 and -0.02 cm for outer diameters, and 0 and +0.02 cm for inner diameters. The actual dimensions are measured to be inside the tolerances.

Table 2. Sizes of Beryllium Shells.

Outer Diameter (cm)	Inner Diameter (cm)
22.00	18.30
18.30	16.70
16.70	15.10
15.10	13.50
13.50	12.00
12.00	10.70

Each beryllium shell has been trimmed along its equatorial edge by 0.15±0.02 cm. (See Figure 2). Each beryllium shell in the assembly top has a polar cylindrical hole 2.20 cm in diameter.

The assembly top is supported by a 0.20-cm-thick steel diaphragm (tolerances are -0.01 and 0 cm). The diaphragm is an annulus with outer diameter 27.8 cm and inner diameter 11.0 cm. It rests on a light Duralumin stand (tripod) consisting of two rings fastened by three rods. This stand (about 20-cm high) is mounted on a thin-walled (0.6 cm) steel tube, 37 cm in diameter. The tube (immovable base) has three 14-cm-wide windows, therefore 36% of the tube surface is removed.

The lower (movable) part is nested in a 0.15-cm-thick copper cup supported by a movable steel shaft, 5 cm in diameter and about 3 cm in height. This shaft is fastened to a movable steel piston by a smaller shaft about 2 cm in diameter (not shown in Figure 2).

The experimental hall size is 18 m x 12 m x 8 m high. The 2.5-m-thick walls, as well as the 0.3-m-thick floor and the 1-m-thick ceiling, are made of borated concrete. The distance between the center of the critical assembly (its immovable part) and the floor is 1.8 m. The distance to the three nearest walls is 6 m, and the distance to the ceiling is 6 m also. No large apparatus that might affect criticality was near the experimental facility.

1.3 Description of Material Data

One fissile material was used in this experiment, namely, plutonium. The masses of the plutonium shells and plugs, as specified in their certificates, are given in Tables 3 and 4. The mass uncertainty of the details is 0.1 g.

Table 3. Masses of Plutonium Shells.

Bottom Shells			Top Shells		
Shell	Mass [(a)] (g)	Plating Mass (g)	Shell	Mass [(a)] (g)	Plating Mass (g)
10	1665.0	16.9	1	1620.7	14.8
9	1160.8	12.7	2	1118.2	12.8
8	1085.9	8.5	3	1028.6	9.5
7	925.5	4.6	4	809.2	4.55

(a) before plating

Table 4. Masses of Plutonium Plugs.

Plug	Mass [(a)] (g)	Plating Mass (g)
11	41.7	0.5
12	39.3	0.8
13	53.5	0.5
14	113.2	0.95

(a) before plating

One reflector material was used in the experiment, namely, beryllium. The masses of beryllium hemispheres, as specified in the detail certificates, are given in Table 5. The mass uncertainty of the details is 1 g.

Table 5. Masses of Beryllium Shells.

Outer Diameter (cm)	Inner Diameter (cm)	Top Mass (g)	Bottom Mass (g)
22.0	18.3	2105	2127
18.3	16.7	677	683
16.7	15.1	559	565
15.1	13.5	453	457
13.5	12.0	336	342
12.0	10.7	230	233

The isotopic compositions of the plutonium shells and plugs, measured by atomic spectroscopy, are given in Table 6. Uncertainties of ^{239}Pu, ^{240}Pu, and ^{241}Pu contents are 0.12 wt.%, 0.08 wt.%, and 0.05 wt.%, respectively. The uncertainty of the Ga content is 0.03 wt.%.

Table 6. Compositions of Plutonium Details, Wt.%.[(a)]

Detail	Pu-239	Pu-240	Pu-241	Ga
1	89.66	9.27	1.07	1.67
2	89.19	9.56	1.25	1.74
3	90.08	9.12	0.80	1.68
4	89.79	9.17	1.04	1.63
7	89.76	9.21	1.03	1.55
8	89.84	9.25	0.91	1.68
9	89.48	9.42	1.10	1.68
10	89.55	9.35	1.10	1.68
11-14	89.92	9.10	0.98	1.68

(a) Values for plutonium isotopes are wt.%'s of pure plutonium.
Values for gallium are wt.%'s of the plutonium-gallium alloy.

The plutonium contains 0.39±0.03 wt.% impurity represented as 0.04±0.01 wt.% C, 0.20±0.02 wt.% Fe, and 0.15±0.02 wt.% W. [a]

Beryllium shells contain 0.49±0.05 wt.% impurities (0.11±0.02 wt.% C, 0.12±0.02 wt.% O, and 0.26±0.03 wt.% Fe).

The diaphragm and the supporting shaft are made of St.10 steel containing 0.07-0.14 wt.% C, 0.17-0.37 wt.% Si, 0.35-0.65 wt.% Mn, and <0.15 wt.% Cr.[b] The reported density is 7.6 g/cm^3.

[a] Detailed impurity composition cannot be supplied because of secrecy regulations.

The tripod is made of D16 Duralumin that contains 1.2-1.8 wt.% Mg, 0.3-0.9 wt.% Mn, and 3.8-4.9 wt.% Cu, and has density 2.78 g/cm^3 at the temperature 20°C[a].

The supporting cup is made of M1 copper containing less than 0.1 wt.% impurities (the main components are <0.05 wt.% O, <0.005 wt.% Fe, and <0.005 wt.% Pb).[b] The reported density is 8.7±0.05 g/cm^3.

The supporting tube is made of St.3 steel containing 0.14-0.22 wt.% C, 0.05-0.3 wt.% Si, 0.3-1.1 wt.% Mn, <0.3 wt.% Cu, <0.3 wt.% Ni, and <0.08 wt.% Cr. [c] The reported density is 7.6 g/cm^3.

1.4 Supplemental Experimental Measurements

In addition to the value of k_{eff}, other experimental data were obtained in the course of the measurements. Reactivity worths of some components were measured in terms of $\mathbf{h_{cr}}$. Removal of the plutonium polar plugs (**R**=1.40-5.35 cm) yields $\mathbf{h_{cr}}$=0.70 cm. This measurement may be used for additional validation of calculations. These results are given in an experimental logbook.[d]

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[b] The State Standard GOST 1050-74.
[a] The State Standard GOST 4884-74.
[b] The State Standard GOST 859-78.
[c] The State Standard GOST 380-88.
[d] Logbook HT-1248, pp.79-81

2.0 EVALUATION OF EXPERIMENTAL DATA

In order to evaluate uncertainties in k_{eff} due to uncertainties in critical assembly parameters, sensitivities of k_{eff} to parameters of the critical assemblies were calculated by varying the parameters. The calculations were performed using the KLAN code (Monte Carlo method) with BAS neutron data[a] and the MCNP code[b] with ENDF/B-IV neutron data.

Usually the number of histories was 10^6, and the statistical error was 0.0006 - 0.0007 in k_{eff}. The parameters were varied in amounts giving a Δk_{eff} variation of about 0.01, to diminish statistical errors in Δk_{eff}. The absolute statistical error in Δk_{eff} was about 0.001. Therefore the uncertainties in k_{eff} due to uncertainties in assembly parameters, as shown in Table 7, were determined with an accuracy of about 10%. Small uncertainties in k_{eff} were determined with an absolute accuracy better than 0.0001.

Not included in Table 7 are the uncertainties in the critical assembly parameters that yield uncertainties in k_{eff} less than 0.0001: mass uncertainties, ^{241}Pu content in Pu, impurity contents, and Pu plating content. They are negligible in the total uncertainties in k_{eff} .

Table 7. Uncertainties in Parameters and in k_{eff}.

Parameter	Parameter Uncertainty	Uncertainty in k_{eff}
Plutonium Outer Radius	0.004 cm	0.0011
Reflector Thickness	0.01 cm	0.0003
h_{cr}	0.02 cm	0.0006
^{240}Pu Content in Pu[(a)]	0.08 wt.%	0.0003
Reflector Composition	0.05 wt.%	0.0001

(a) replaced with ^{239}Pu

The overall uncertainty in k_{eff} is 0.0014. The configuration of this system is simple enough and the uncertainties are small enough that this experiment is considered to be acceptable for use as a criticality safety benchmark experiment.

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[a] A. P. Vasilyev, Ya. Z. Kandiyev, V. I. Chitaykin, "Calculations of Some Experiments of Uranium-235 and Uranium-238 Using BAS Spectral Neutron Data," Neutron Physics, 2, 119-123, Moscow, 1984.

[b] "MCNP - A General Monte-Carlo Code for Neutron and Photon Transport," Los Alamos Scientific Laboratory report LA- 7396-M, revised April, 1981.

3.0 BENCHMARK SPECIFICATIONS

3.1 Description of Model

The model of the benchmark derived from Section 1 is presented in Figure 3. It has the following main distinctions from the actual critical assembly:

- The plating material of plutonium components was homogenized with the plutonium. This idealization gives a variation in k_{eff} of Δk_{eff} = - 0.0003±0.0001. This and other values of Δk_{eff} are given in Table 8.
- All plutonium shells and plugs with their individual compositions and densities are replaced with one region having the average value.
- The decay of ^{241}Pu to ^{241}Am was neglected.
- The plutonium impurities were substituted with the main components: C, Fe, and W (Δk_{eff}<0.0001).
- All reflector shells with their individual densities are replaced with two regions having the average value.
- The steel diaphragm was represented as Fe (Δk_{eff}<0.0001).
- The diaphragm lip was neglected (Δk_{eff}<0.0001).
- Room return and the remote machine structures were neglected.

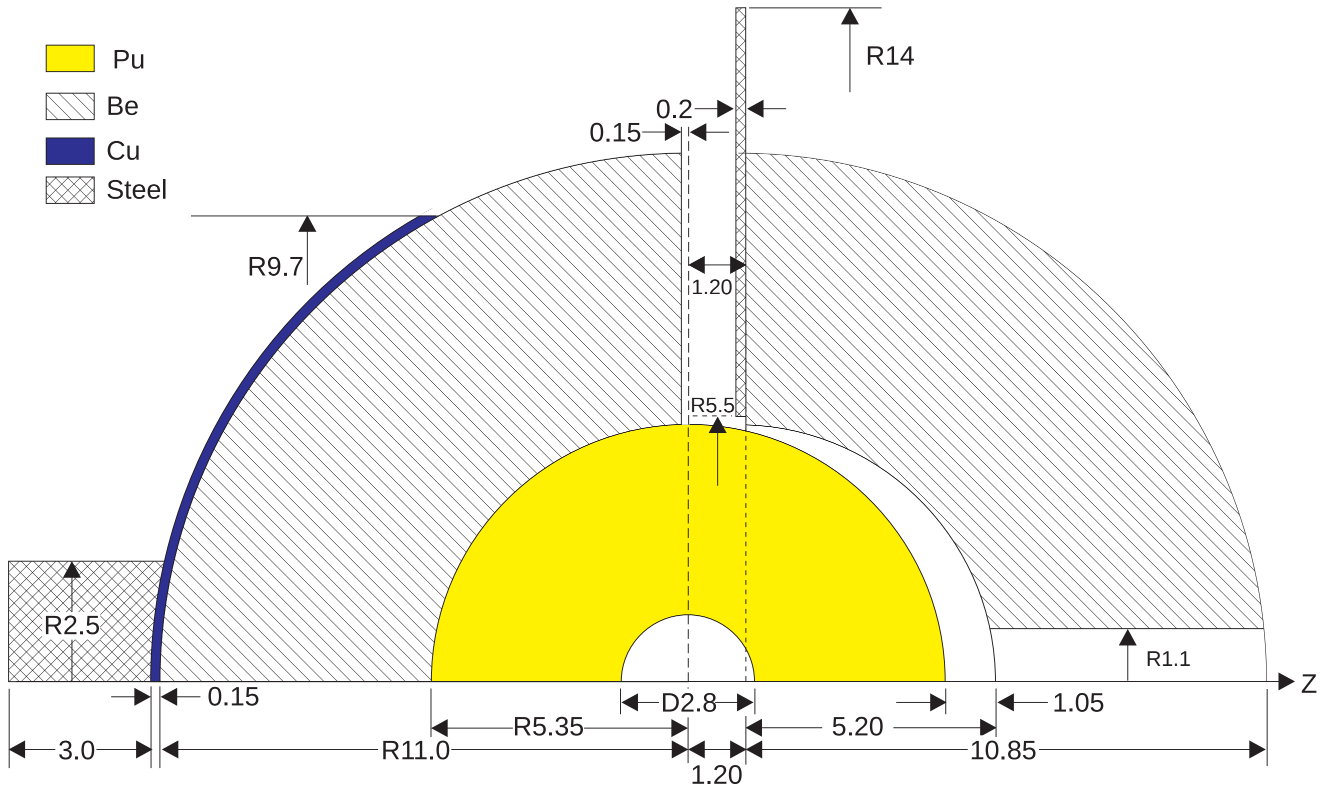

Figure 3. Benchmark Model.
Rotationally symmetric about the z-axis.
The bottom is to the left. All dimensions are in cm.

The resulting k_{eff} variations calculated using the KLAN code with BAS neutron data and the MCNP code with ENDF/B-IV neutron data, are shown in Table 8. Not included in Table 8 are the idealizations that yield k_{eff} variations less than 0.0001. They are negligible in the total k_{eff} variation.

Table 8. Changes in k_{eff} Due to Model Idealization.

Idealization	Δk_{eff} [a]
Plutonium Plating Homogenization	- 0.0003
Plutonium Density Averaging	- 0.0003
Neglecting ^{241}Pu Decay	+0.0006
Reflector Density Averaging	- 0.0002
Room and Machine Return [b]	- 0.0006 ± 0.0002

(a) The statistical uncertainty in Δk_{eff} was about 0.0001 or less (see Section 2).
(b) These calculations included the Duralumin tripod, the steel supporting tube and piston, the three closest concrete walls, floor, and ceiling.

All these idealizations, combined, give a bias of -0.0008 and an error of 0.0003 in k_{eff}. Therefore, the model shown in Figure 3 is acceptable for the benchmark calculations.

3.2 Dimensions

The dimensions from Figure 3 are used in the model calculations. The core inner and outer radii are 1.4 cm and 5.35 cm. The reflector inner and outer radii are 5.35 cm and 11.0 cm. The equatorial surfaces of the reflector hemispheres are flat and are 0.15 cm from a horizontal plane through the center of the sphere.

3.3 Material Data

Using the masses of the plutonium shells and plugs from Tables 3 and 4 in Section 1.3 (mass=9748.7 g) and the dimensions from Figure 3 (volume=629.937 cm^3), the density of 15.4757 g/cm^3 was derived for plutonium. Using the compositions of the plutonium shells and plugs from Table 6 in Section 1.3, the plutonium atom densities presented in Table 9 were obtained.

Table 9. Plutonium Atom Densities.

Nuclide	Atom/barn-cm
^{239}Pu	3.3930×10^{-2}
^{240}Pu	3.5043×10^{-3}
^{241}Pu	3.9189×10^{-4}
Ga	2.2105×10^{-3}
C	3.0246×10^{-4}
Fe	3.2525×10^{-4}
W	7.4100×10^{-5}
Ni	1.4187×10^{-3}

Using the masses of the beryllium shells from Table 5 in Section 1.3 (mass=8767 g) and the dimensions from Figure 3 (volume=4825.3 cm^3), the density of 1.8169 g/cm^3 was derived and the reflector atom densities presented in Table 10 were obtained.

Table 10. Atom Densities of the Reflector.

Nuclide	Atom Density (atoms/barn-cm)
Be	1.2081×10^{-1}
O	8.2064×10^{-5}
C	1.0020×10^{-4}
Fe	5.0939×10^{-5}

The steel (the diaphragm and the shaft) is replaced with pure Fe with the decreased density equal to 7.6 x 0.9905 = 7.5278 g/cm^3. The iron atom density is 8.1174×10^{-2} atom/barn-cm.

The M1 copper (the cup) is replaced with pure Cu having the derived density of 8.7 x 0.999 = 8.6913 g/cm^3. The Cu atom density is 8.2365×10^{-2} atom/barn-cm.

3.4 <u>Temperature Data</u>

The temperature in the experimental hall was about 290 K. All regions of the assembly are assumed to be 300 K.

3.5 Experimental and Benchmark-Model k_{eff}

Since delayed critical was not obtained, the experimental k_{eff} was less than 1.00. The maximum multiplication was 160. Including uncertainties and modeling simplifications described in Sections 2 and 3.1, the benchmark model k_{eff} is 0.9992 ± 0.0015.

4.0 RESULTS OF SAMPLE CALCULATIONS

The calculations were performed using the KLAN code with BAS neutron data and the MCNP code with ENDF/B-V neutron data. The MCNP input is given in Appendix A. The results are given in Table 11.

Table 11.a. Sample Calculation Results (Russian Federation).

KLAN (BAS)
0.9997 ± 0.0006

Table 11.b. Sample Calculation Results (United States). [(a)]

MCNP (ENDF/B-V)
1.0012 ± 0.0007

(a) Result supplied by the authors and V. F. Dean

5.0 REFERENCES

There are no published references available for this evaluation.

APPENDIX A: TYPICAL INPUT LISTINGS

A.1 KLAN Input Listings

The code KLAN is a 3-dimensional, Monte Carlo code written in the ALGOL computer language. Inputs use Cyrillic characters. Because KLAN is used at only a few locations and because input listings are difficult to extract, they are not included.

The total particle number in the calculations is about 1×10^6. Of these, approximately 10,000 were skipped for source convergence.

A.2 MCNP Input Listing

The MCNP4a calculations with discrete energy ENDF/B-V cross sections were run with 1010 generations of 1000 histories per generation and the first 10 generations skipped for a total of 1×10^6 active histories. In the MCNP model the diaphragm and shaft were limited with a spherical surface R=14 cm; its center was at the point (0 0 0). The resulting Δk_{eff} is < 0.0001.

MCNP Input Listing, Table 11.b.

```
prob30 - pmf19 - kcode
1     0 -1 $ cavity
2     1 4.2157e-2 1 -3 $ Pu Core
3     0  3 -4 12 $
4     0  3 -5 11 -12
5     2 1.2105e-1 3 -7 -16  $ Bottom Refl
6     2 1.2105e-1 4 6 -8 12 $ top refl
7     0 3 10 -11 -15
8     3 8.1174e-2 5 11 -12 -15 $ diaphragm
9     0 7 -10 13 -15
10    0  8 12 -15
11    4 8.2365e-2 7 -9 -13 -10 $ copper cup
12    3 8.1174e-2 9 -10 -14 -15 $ shaft
13    0 9 -10 -13 14 -15
14    0 3 -7 -10 16
15    0 4 -6 -8 12 $ polar hole in Top Refl
16    0 15

1     so 1.4
3     so 5.35
4     sz 1.05 5.35
5     cz 5.50
6     cz 1.1
7     so 11
8     sz 1.05 11
9     so 11.15
10    pz 0
11    pz 1
12    pz 1.20
13    cz 9.7
14    cz 2.5
15    so 14
16    pz -0.15

imp:n 1 14r  0
kcode 1000 1 10 1010
ksrc  0 0 -1.41
m1    94239.55c 3.3930-2 94240.50c 3.5043-3 94241.50c 3.9189-4
      31000.50c 2.2105-3 6000.50c 3.0246-4 28000.50c 1.4187-3
      26000.50c 3.2525-4 74182.50c 1.9577-5 74183.50c 1.0581-5
      74184.50c 2.2749-5 74186.50c 2.1193e-5
m2    4009.50c 1.2081-1 6000.50c 1.0020-4 8016.50c 8.2064-5 26000.50c 5.0939-5
mt2   be.01t
m3    26000.50c 8.1174-2
m4    29000.50c 8.2365-2
prdmp 0 0 0 2
```