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BENCHMARK CRITICAL EXPERIMENT OF A PLUTONIUM SPHERE REFLECTED BY TUNGSTEN

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BENCHMARK CRITICAL EXPERIMENT OF A PLUTONIUM SPHERE REFLECTED BY TUNGSTEN

IDENTIFICATION NUMBER: PU-MET-FAST-005 **SPECTRA**

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1.0 DETAILED DESCRIPTION

1.1 Overview of Experiment

In 1958, an experiment was performed at Los Alamos Scientific Laboratory using a slightly subcritical spherical mass of delta-phase plutonium reflected by tungsten. The experiment is considered to be acceptable as a benchmark critical experiment. This experiment was performed as part of a series of experiments. This series is covered by PU-MET-FAST-010, PU-MET-FAST-018, U233-MET-FAST-002, U233-MET-FAST-003, U233-MET-FAST-004, U233-MET-FAST-005, and MIX-MET-FAST-001.

1.2 Description of Experimental Configuration

The experiment was performed using the Planet universal assembly machine. The core was composed of two hemispheres of delta-phase plutonium alloy having a diameter of 3.970 inches and plated with 0.005-inch-thick nickel with a 0.85-inch-diameter source cavity in the center of the two hemispheres. Hemishells of various thicknesses of tungsten were constructed to enclose the plutonium hemispheres (Reference 1).

A drawing of the Planet assembly machine is shown in Figure 1, and the core setup is shown in Figure 2. The top half of the plutonium assembly (core and reflector) rested on a 0.015-inch-thick stainless-steel diaphragm. The lower half of the assembly rode on a hydraulic lift. The portion of the hydraulic lift in contact with the lower half of the assembly was a cylindrical, hollow aluminum tube. Assembly was accomplished by raising the hydraulic lift which supported the lower hemisphere. Rapid disassembly was accomplished by dropping the lift (Reference 1).

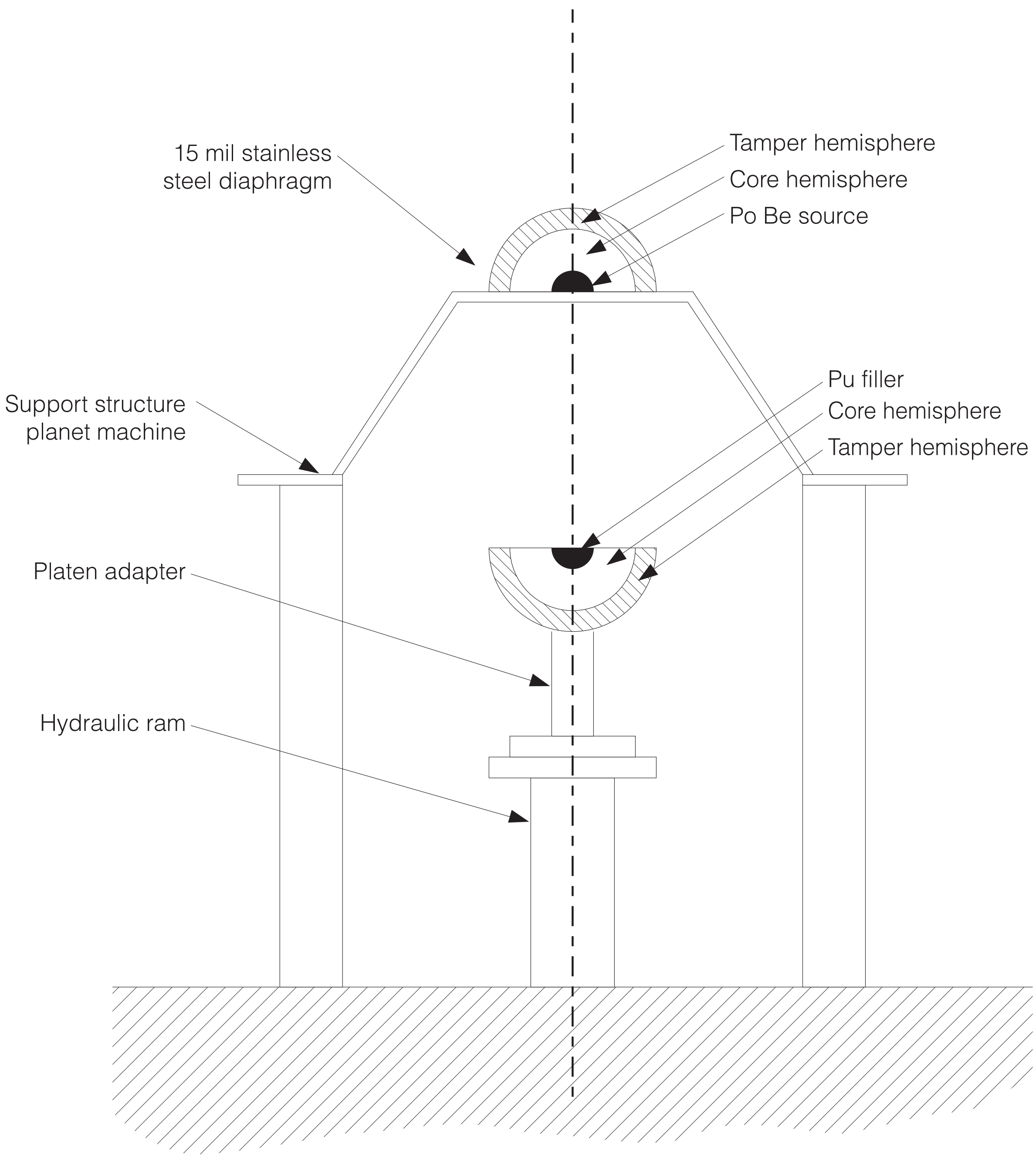

Figure 1. The Planet Assembly Machine.

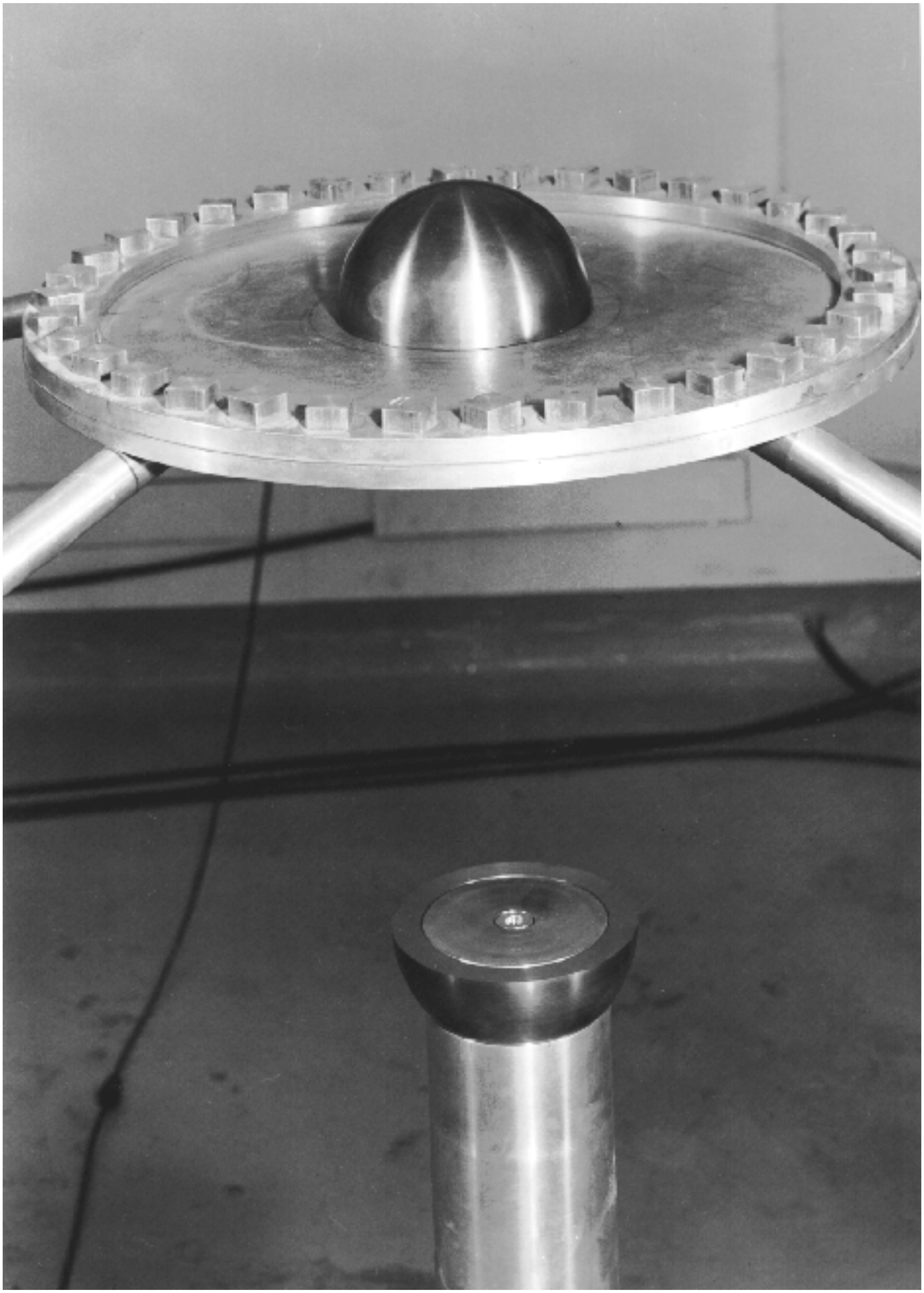

Figure 2. The Core Setup.

The counting system consisted of four polyethylene covered BF_3 detectors which were mounted on the assembly lift in such a way as to adequately monitor neutron leakage. A ^{210}PoBe source with a strength of 10^5 neutrons/sec was placed inside of the source cavity of the upper plutonium hemisphere (Reference 1). The measurements were performed on the same day such that the 138 day half-life of the source was not a factor.[a]

The lift, which supported the lower portion of the assembly, was incrementally raised, and the multiplication[b] was measured at each increment until closure. Multiplication measurements were taken for (1) the bare core, (2) a reflector thickness of 0.769 inches, (3) a reflector thickness of 0.980 inches, and (4) a reflector thickness of 1.865 inches. In order to reduce the critical specifications to a solid sphere, measurements were made with a 29.64 g hemispherical, close-fitting, plutonium filler piece in the lower core-half central source cavity (Reference 2).

The final measured multiplication for 1.865 inches of tungsten was 118.8 with the plutonium filler piece in the lower half of the source cavity and with both the upper and lower halves of the assembly in contact with the divider plate. Table 1 shows the results obtained for the actual experiment (Reference 2).

Table 1. Actual Multiplication Measurements.

Tungsten Thickness (inches)	Core Reflector Clearance (inches)	Multiplication with 29.64 g Pu filler
0.0	-	10.22
0.769	0.010	22.9
0.980	0.009	27.9
1.865	0.012	118.8

[a] The PoBe source neutron spectrum and strength changes over time because of radioactive decay, chemical and physical changes, such as recrystallization of the beryllium. If measurements are taken with the same source over a relatively long period of time, the measured multiplication and, therefore, the critical characteristic dimension determination can be affected.

[b] Multiplication, in simple terms, is the ratio of the neutron count rates as measured by external neutron counters, with and without fissile material present. That is, in a subcritical system with a neutron source, multiplication is the equilibrium ratio of the total number of fission and source neutrons to the total number of source neutrons.

Additional measurements and corrections were made to the actual experimental assembly, which led to an accurate estimate of the critical mass of a solid delta-phase plutonium sphere with a close-fitting tungsten reflector. These measurements and corrections are described in Section 2.

1.3 Description of Material Data

The delta-phase plutonium alloy core consists of 99.00 wt.% plutonium and 1.00 wt.% gallium (References 3 and 4). The core specifications from Reference 3 apply to Pu core that is surrounded by HEU, but it was determined that the same core was used for the experiment in this evaluation. The isotopic composition of the plutonium alloy is shown in Table 1 (Reference 3). The density of the core alloy is 15.778 g/cm^3.

Table 2. Composition of the Plutonium in the Core.

Isotope	At.%
^{239}Pu	94.79
^{240}Pu	4.90
^{241}Pu	0.31

The average composition of the tungsten alloy reflector is given in Table 3 (Reference 4). The density of the reflector is 17.21 g/cm^3.

Table 3. Reflector Composition.

Element	Wt.%
Tungsten	91.3
Nickel	5.5
Copper	2.5
Zirconium	0.7

Trace impurities in these materials were not given but were stated to be similar to those found in the Godiva and the Jezebel assemblies and, as such, have a negligibly small effect on the critical specifications (Reference 3).

1.4 Supplemental Experimental Measurements

No additional experimental measurements were performed with the exception of those measurements described in Section 2.

2.0 EVALUATION OF THE EXPERIMENTAL DATA

The need and value of solid spherical critical assemblies was foreseen by the experimenters, and, thus, the experimenters made some additional corrections and measurements to obtain solid spherical core-reflector critical masses.

First, the experimenters determined the effect of the 0.015-inch thick diaphragm. The results of the study indicated that the steel diaphragm had little effect other than maintaining a gap between the two halves of the assembly. The measured $\Delta 1/M$ effect of the diaphragm was approximately -0.0036 (Reference 5).

> "A plot of reciprocal multiplication (1/M) was extrapolated for an additional 0.015 inches past the closure point to obtain the effect of the diaphragm on the multiplication of the system. The validity of this extrapolation was verified by increasing the thickness of the diaphragm with an additional 0.015-inch sheet of stainless steel. The multiplication thus obtained agreed with what could have been predicted from the 1/M closure curve . . ." (Reference 1)

Figure 3 was reproduced from Reference 1 and shows the plot of normalized reciprocal multiplication versus reflector thickness.

Next, the change in multiplication was measured when a close-fitting filler piece was added to the bottom half of the central source cavity. From this measurement, a good estimate was made of the expected change in multiplication when the source cavity was completely filled (i.e., a solid spherical core-reflector critical mass) (Reference 2). The $\Delta 1/M$ correction for the central void was -0.0089 (Reference 5).

The effect of the 0.005-inch-thick nickel plating on the hemisphere parting plane and the source cavity surface was determined using material replacement data made on the ^{239}Pu Jezebel bare critical assembly. The worth of the nickel plating on the interior of the source cavity was previously mentioned, and the $\Delta 1/M$ for the nickel on the parting plane was not given in the references. The effect of the nickel on the surface of the core was estimated using data from the Topsy critical assembly for which the 0.005-inch-thick nickel plating is equivalent to a 0.005-inch-thick layer of tungsten (Reference 1).

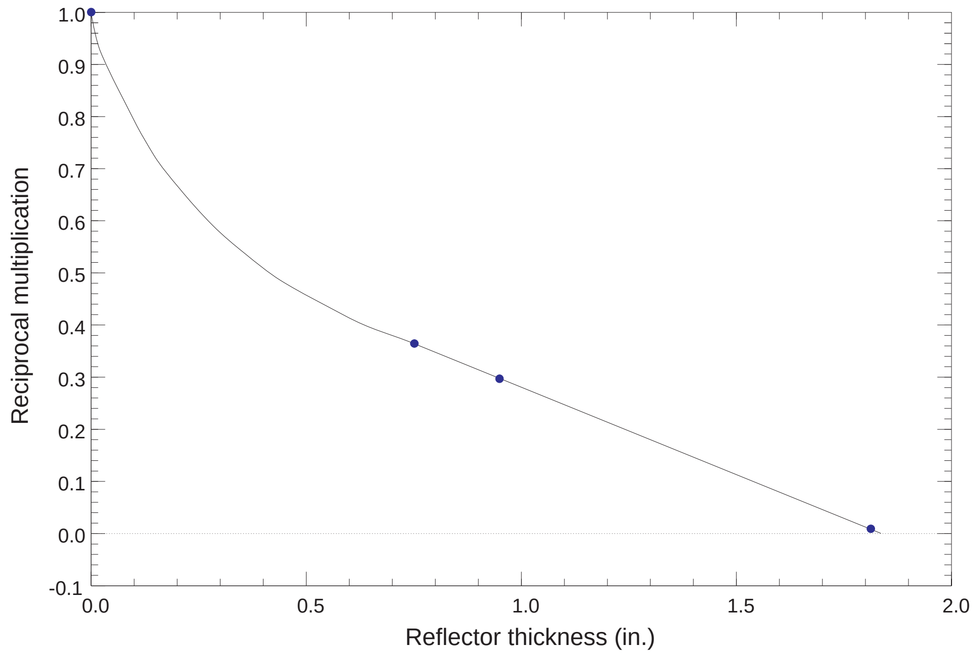

Figure 3. Corrected Reciprocal Multiplications for the Tungsten-Reflected Pu Core.

An approximate correction was made for clearances between the core and reflector as described below. Explicit values for this correction in terms of Δ1/M were not given in the references.

> "A suitable correction for the clearance between the core and reflector material, which was present in the experimental setup, was deduced from the slope of the measured curve of reciprocal multiplication versus reflector thickness. The slope at zero thickness is interpreted as giving the change in 1/M per unit thickness which would have occurred had the clearance void been filled with reflector. The external reflector radius was reduced to produce this same Δ(1/M) as indicated by the slope of the curve in this region." (Reference 1)

With the above measurements and corrections, the experimenters were able to correct their inverse multiplication versus reflector thickness curve to that for a solid spherical core of delta-phase plutonium surrounded by a close-fitting tungsten reflector. The resulting critical tungsten thickness was found to be 1.850 inches (Reference 1).

Later efforts made corrections to account for reflection by the Planet assembly machine and the surrounding room walls. The correction increased the HEU thickness by 0.003 inches (Reference 3).

The reported core density, core mass, and core enrichments are different for the three primary references (References 1, 3, and 4). The information given for Reference 3 was taken from the specifications of the Pu/HEU experiment. It was deduced from References 1, 3, and 4 that the same core was used for several experiments performed to determine critical thicknesses of various reflector materials. The reported data are summarized in Table 4. The reported critical mass in Reference 4 is believed to be a typographical error because the mass corresponds to the uncorrected core mass. This discrepancy is due to corrections made to the original experiment. The experimentalists made corrections to remove gallium from the core specifications. The core mass and density are essentially the same in References 1 and 4. However, Reference 4 states that the core contains 1.0 wt.% gallium, but the core specifications, as described in Reference 4, do not contain gallium. The discrepancies between critical specifications were studied, and the specifications reported in Reference 3 are used for the benchmark model. Besides the fact that Reference 3 is the most recent reevaluation of these experiments, it also contains the most complete and most consistent data, as shown in Table 4.

Table 4. Differences in Reported Specifications.

Parameter	Reference 1	Reference 3	Reference 4
^{239}Pu	94.79 at.%	94.79 at.%	none given
^{240}Pu	4.90 at.%	4.9 at.%	4.9 wt.%
^{241}Pu	0.31 at.%	0.31 at.%	none given
gallium wt.%	none given	1.0 wt.%	1.0 wt.%
Pu density (g/cm^3)	15.62	15.778	15.62
Core mass (g)	8386	8471	8390

With the above measurements and corrections, the experimenters were able to correct their inverse multiplications versus reflector thickness curve to that for a solid 8.471 kg spherical core of plutonium alloy of 3.970 inches diameter surrounded by a close-fitting tungsten reflector. The resulting critical reflector thickness was found to be 1.850 inches.

Because of uncertainties in applying some of the corrections, the experimenters assigned an uncertainty of ±1% in the critical reflector thickness. Thus, the idealized critical experiment, as corrected, consists of a 3.970-inch-diameter delta-phase plutonium spherical core (density = 15.778 g/cm^3) intimately surrounded by a spherical shell of tungsten 1.85-inches thick, with a density of 17.21 g/cm^3. It is this description that we accept as the benchmark model. The sensitivity of the calculational benchmark model to various parameters is studied in Appendix B.

3.0 BENCHMARK SPECIFICATIONS

3.1 Description of Model

The benchmark model is a simple plutonium alloy sphere with a density of 15.778 g/cm^3 and a mass of 8471 grams plutonium alloy with 4.699 ± 1% cm of tungsten alloy (alloyed as given in Table 2) reflection at a density of 17.21 g/cm^3. The model is an idealized configuration derived by the experimenters.

3.2 Dimensions

The radius of the 8471 gram delta-phase plutonium sphere at a density of 15.778 g/cm^3 was 5.0419 cm. The sphere was reflected by 4.699 cm of tungsten alloy (outer radius of 9.7409 cm).

3.3 Material Data

The calculated atomic number densities of the delta-phase plutonium sphere reflected by tungsten alloy for the isotopic compositions given previously in Tables 2 and 3, are shown in Table 5.

Table 5. Atom Densities for Pu Core and the Tungsten Reflector.

Isotope/Element	Atom Density (atoms/barn-cm)
Pu Core	
^{239}Pu	3.7291×10^{-2}
^{240}Pu	1.9277×10^{-3}
^{241}Pu	1.2196×10^{-4}
Gallium	1.3628×10^{-3}
Tungsten Alloy Reflector	
Tungsten	5.1468×10^{-2}
Nickel	9.7124×10^{-3}
Copper	4.0774×10^{-3}
Zirconium	7.9528×10^{-4}

3.4 Temperature Data

No mention was made in the references in regard to experimental temperature. The experimental temperature was assumed to be room temperature (293 kelvin).

3.5 Experimental and Benchmark-Model k_{eff}

At a thickness of 1.865 inches, the measured multiplication for this experiment was 118.8, and the corrected inverse multiplication was 0.0008 (Reference 2). Differences between quoted and inferred inverse multiplications are not shown here because the magnitude of some of the corrections were not given in the references. The experimental k_{eff} was 1.0000, which includes experimental corrections made for the diaphragm, the source cavity, and internal and external nickel.[a] The benchmark model k_{eff} is 1.0000 ± 0.0013, where the uncertainty in k_{eff} is due to the ±1.0% uncertainty in the thickness of the reflector. The uncertainty in k_{eff} is derived from a ONEDANT calculation shown in Appendix B.

[a] Inverse multiplication, 1/M, is related to k_{eff} by: $k_{eff} = 1 - 1/M$. This relationship is valid if the system is near critical.

4.0 RESULTS OF SAMPLE CALCULATIONS

The results of calculations performed with various codes and cross section sets are shown in Table 6. The model used for these calculations was described earlier in Sections 3.1 and 3.2.

Table 6. Sample Calculation Results (United States).

KENO (Hansen-Roach)	KENO (27-Group ENDF/B-IV)	MCNP (Continuous Energy ENDF/B-V)	ONEDANT (27-Group ENDF/B-IV)
1.0027 ± 0.0013	1.0007 ± 0.0012	1.0080 ± 0.0010	1.0009

5.0 REFERENCES

1. E. A. Plassmann and D. P. Wood, "Critical Reflector Thicknesses for Spherical U^{233} and Pu^{239} Systems," Nucl. Sci. Eng., **8**, pp. 615-620, June 1960.

2. E. A. Plassmann and D. P. Wood, N-Division Progress Report for November 21 - December 20, 1958, pp. 7-11, Los Alamos National Laboratory Archives A-86-016, 202-4.

3. G. E. Hansen and H. C. Paxton, "Reevaluated Critical Specifications of Some Los Alamos Fast-Neutron Systems," LA-4208, p. 8, September 1969.

4. H. C. Paxton, "Los Alamos Critical Mass Data," LA-3067-MS, December 1975.

5. E. A. Plassmann and D. P. Wood, N-Division Progress Report for April 21 - May 20, 1957, pp. 15-19, Los Alamos National Laboratory Archives A-86-016, 200-9.

APPENDIX A: TYPICAL INPUT LISTINGS

A.1 KENO Input Listings

Hansen-Roach Cross Sections

Listed below is the input for KENO V.a with 16-group Hansen-Roach cross sections. The model uses 300 active generations with 1500 histories per generation while skipping the first ten generations.

In the parameter section of the input file, "lib=40" is specified. This is the Los Alamos version in AMPX format of the 16-group Hansen-Roach cross-section library.

KENO-V.a Input Listing for Table 6 (16-Energy-Group Hansen-Roach Cross Sections).

```
=kenova
PU SPHERE
READ PARAM RUN=yes FAR=YES LIB=40
GEN=310 NPG=1500 NSK=10
END PARAM
READ MIXT SCT=1
MIX=1 94900 0.037291
     94000 0.0019277
     94100 0.00012196
     31100 0.0013628
MIX=2 74100 0.051468
     28100 0.0097124
     29101 0.0040774
     40100 0.00079528
END MIXT
READ GEOM
UNIT 1
  SPHERE    1 1 5.0419
  SPHERE    2 1 9.7417
END GEOM
END DATA
```

27-Group ENDF/B-IV Cross Sections

Listed below is the input for KENO V.a with SCALE4 27-group cross sections. The model specifies 300 active generations with 1500 histories per generation while skipping the first ten generations.

In the input file for KENO V.a with 27-group cross sections, copper was substituted for gallium in the plutonium core since the 27-group library does not have data for gallium. Copper was selected because of the similarities when viewing the cross-section data. Appendix B shows that such a substitution has a negligible effect.

KENO-V.a Input Listing for Table 6 (27-Energy-Group SCALE4 Cross Sections).

```
=CSAS25
PU SPHERE
27GROUPNDF4 INFHOMMEDIUM
PU-239   1 0.0 0.037291   END
PU-240   1 0.0 0.0019277  END
PU-241   1 0.0 0.00012196 END
CU       1 0.0 0.0013628  END
TUNGSTEN  2 DEN=15.71273 1 293 74182 26.028 74183
          14.330 74184 30.717 74186 28.925 END
NI       2 0.0 0.0097124  END
CU       2 0.0 0.0040774  END
ZR       2 0.0 0.00079528 END
END COMP
COPPER INSTEAD OF GALLIUM, PU(4.5)
READ PARAMETERS
 TME=1000 TBA=10
 GEN=310 NPG=1500 NSK=10
END PARAMETERS
READ GEOM
UNIT 1
 SPHERE    1 1 5.0419
 SPHERE    2 1 9.7417
END GEOM
END DATA
END
```

A.2 <u>MCNP Input Listing</u>

Listed below is the input file for MCNP 4.2 with continuous-energy ENDF/B-V cross sections with 300 active generations, 1500 histories per generation, and skipping the first ten generations.

MCNP Input Listing for Table 6.

```
TUNGSTEN REFLECTED PU(4.9) SPHERE
1    1    0.04070346 -1 imp:n=1
2    2    0.06605308  1 -2 imp:n=1
3    0     2  imp:n=0

1    so    5.0419
2    so    9.7409

m1   94239.55c 0.037291
     94240.50c 0.0019277
     94241.50c 0.00012196
     31000.50c 0.0013628
m2   74000.55c 0.051468
     28000.50c 0.0097124
     29000.50c 0.0040774
     40000.50c 0.00079528
kcode 1000 1.0 10 310
ksrc 0 0 0
print
```

A.3 ONEDANT Input Listing

Listed below are the input files for ONEDANT version 2.3e with 27-group ENDF-B/IV cross sections which have P_3 scatter data. The first file listed is used to generate the 27-group cross sections, and the second input file is the ONEDANT input. The order of angular quadrature is 48. The convergence criteria is 10^{-4} for eigenvalue and flux by default. The mesh size is approximately 20 mesh/cm in the core and 3 mesh/cm in the reflector.

As done previously, copper was substituted for gallium in the plutonium core since the 27-group library does not have data for gallium. Appendix B shows that such a substitution has a negligible effect.

ONEDANT Input Listing for Table 6.

```
=CSASI
ICE RUN TO GET XSECTS FOR PU SPHERE
27GROUPNDF4 INFHOMMEDIUM
PU-239   1 0.0 0.037291   END
PU-240   1 0.0 0.0019277  END
PU-241   1 0.0 0.00012296 END
CU       1 0.0 0.0013628  END
TUNGSTEN  2 DEN=15.71273 1 293 74182 26.028 74183
          14.330 74184 30.717 74186 28.925 END
NI       2 0.0 0.0097124  END
CU       2 0.0 0.0040774  END
ZR       2 0.0 0.00079528 END
END COMP
END

    2
Pu(4.9) sphere with a tungsten reflector
           Simplified model
/BLOCK 1
 igeom=sph ngroup=27 niso=2 isn=48  mt=2 nzone=2 im=2 it=115 t
/BLOCK 2
 xmesh=0.0,5.0419,9.7417 xints=101,14 zones=1,2  t
/BLOCK 3
 lib=xs27
 maxord=3 ihm=42 iht=3 ihs=16 ititl=1 ifido=2 i2lp1=1 t
/BLOCK 4
 matls=isos
 assign=matls  t
/BLOCK 5
 chi=.026 .203 .217 .123 .161 .172 .084 .013 .001 18z
 ievt=1 isct=3  t
```

APPENDIX B: SENSITIVITY STUDIES

The results of calculations to determine the sensitivity of the calculational models to numerous parameters are reported in this Appendix. An experimental uncertainty of ±1% in the tungsten-reflector thickness was given by the experimenters. A calculation was performed to determine the Δk associated with this uncertainty for the 10 kg experiment. The result of this calculation is given below in Table B.1 (±0.0013).

A correction for the effects of room return and the assembly machine were not made by the experimenters. Calculations were performed to determine the effect that these two parameters would have on the criticality of the system. As can be seen from Table B.1, these effects were each less than the calculated Δk associated with the experimental uncertainty in the reflector thickness. The Δk_{eff} was very small with the conservative models used herein; therefore, no correction to the benchmark k_{eff} was made due to these parameters.

To validate the two-dimensional model used to assess the worth of the assembly machine, a calculation was performed to determine the worth of the 0.015-inch-thick SSTL divider plate (diaphragm). The experimental Δ1/M for the diaphragm was given as -0.0036, which is in good agreement with the calculated Δk of -0.0035 shown below. Therefore, the similar model used to determine the effect of the assembly machine was assumed to be valid.

The substitution of copper for gallium in the plutonium was investigated because SCALE does not contain cross-section data for gallium. As seen in Table B.1, this substitution has a negligible effect. ONEDANT/TWODANT with Hansen-Roach cross sections was used for the sensitivity studies. The results are shown in Table B.1.

Table B.1. Sensitivity Studies.

Effect	Δk_{eff} [a]
±1% of tungsten thickness[b]	±0.0013
Room return	+0.0001
Assembly machine[c]	+0.0007
0.015 in. SSTL divider plate[d]	-0.0035
Substitution of copper for gallium[e]	-0.0001

(a) The Δk_{eff} is relative to a base case of 1.0032.
(b) The given uncertainty is ±1% in the tungsten thickness, which corresponds to 1.8315 and 1.8685 inches at each extreme of ±1%.
(c) Calculations performed with TWODANT using a cylindrical approximation. To approximate the assembly machine, an annular aluminum pedestal, 2.36 inches diameter and a wall thickness of 0.25 inches, was placed under the core, and a sheet of aluminum, 0.25 inches thick was placed around the core at a distance of 12.0 inches.
(d) Calculations performed with TWODANT using a cylindrical approximation. A 0.015-inch stainless-steel diaphragm was placed in the middle of the two halves of the core to approximate the effect of the diaphragm.
(e) The SCALE 27-group cross-section library does not contain data for gallium, so the effect of substituting copper for gallium was studied.