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Benchmark Critical Experiment of a Thorium Reflected Plutonium Sphere

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1.0 DETAILED DESCRIPTION

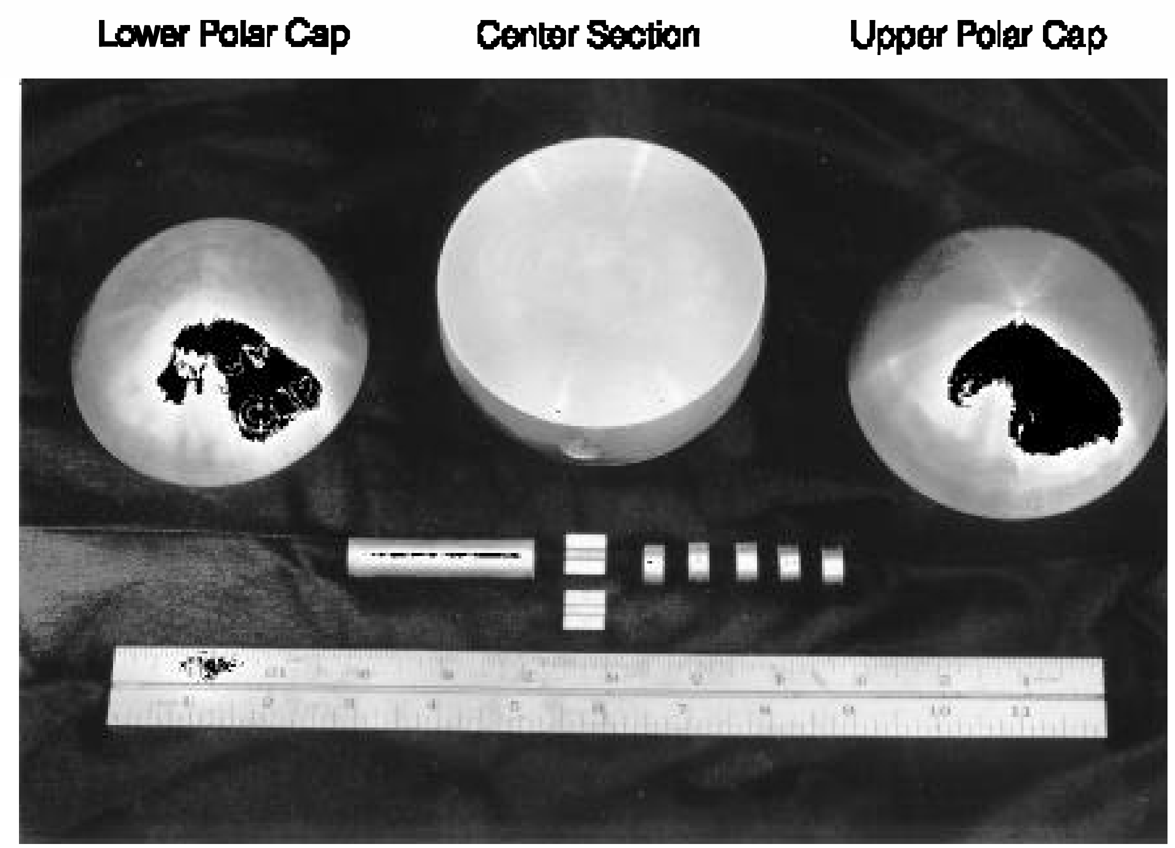
1.1 Overview of Experiment

From December 1960 through November 1961, a critical assembly was operated at Los Alamos Scientific Laboratory using a spherical mass of delta-phase plutonium closely reflected by thorium. The experiment was designed to study the neutronic properties of thorium in support of a potential fast, ^{233}U breeder reactor. Uncertainty in the critical mass of this original experiment prompted the assembly to be set up again and reactivity measurements taken. The average of the results for two critical experimental configurations was used to determine the final critical mass. The result of this experiment is considered to be acceptable as a benchmark critical experiment.

1.2 Description of Experimental Configuration

The experiment was performed using the Thor assembly machine, a modification of the Planet universal assembly machine. The modifications were to the control rod drive and safety mechanism. The plutonium core was constructed of three major parts; an upper polar cap, a lower polar cap, and a central section. Together, the three parts approximated a sphere 10.59 cm in diameter when assembled. The upper polar cap and central section remained stationary while the lower polar cap was located on a pneumatic lift. The central section had a 1.27-cm-diameter glory hole. The glory hole was filled with plutonium as needed. All plutonium parts were coated with 0.013-cm-thick nickel (Reference 1). The different pieces of the core are shown in Figure 1.

The cylindrical thorium reflector was composed of the peripheral reflector, the upper safety block, the lower safety block, and a vernier control cylinder. These combined to form a 21.0-inch-diameter cylinder with a height of 21.0 inches. The first reflector part was the peripheral reflector which was a fixed annular cylinder. The 6-inch-diameter upper safety block surrounded the upper polar cap and the central section and fit inside of the upper portion of the peripheral reflector. The 5-inch-diameter lower safety block supported the lower polar cap and fit inside of the lower portion of the peripheral reflector. The 3-inch-diameter control rod entered the bottom through the lower safety block directly under the lower polar cap. The control rod had a total travel distance of 5 inches. The upper safety block and the peripheral reflector had a 1.27-cm glory hole which lined up with the glory hole in the central section of the core. All thorium parts were coated with 0.0013 cm of chromium



The experimental setup is shown in Figure 2. Assembly was accomplished by raising the lower polar cap and lower safety block up into the assembly. Rapid disassembly, in the event of a scram, was accomplished by retracting the upper and lower safety block as well as the control rod (Reference 1). Reactivity was adjusted using the glory hole filler pieces.

Preliminary measurements resulted in delayed critical with three 0.5-inch plutonium filler pieces in the glory hole and the control rod 0.25 inch from full insertion. After these preliminary measurements, a cut of 0.127 cm was taken off the flat surface of the lower polar cap to allow placement of all of the glory hole filler pieces without the assembly being supercritical. Approximately 155 grams of plutonium were removed from the face of the lower polar cap. The remachining resulted in a 1.1 mm gap between the lower polar cap and the central section. The system was then brought to delayed critical with all the filler pieces in the glory hole and the control rod 2.7 inches from being fully inserted.

The Thor assembly was set up again in the 1970's because of a large uncertainty in the critical mass. The uncertainty was caused by the 1.1 mm gap between the lower polar cap and the central section mentioned above. The earlier records were not clear as to whether the gap was closed by a shim or not. During these more recent measurements, two reactivity determinations were made. The first measurement was taken with a 1.1 mm gap between the central section and the lower polar cap and the glory hole filled with a 1 inch Pu filler piece. This configuration was 23 _ 5 cents subcritical.[1] The second measurement was taken with the 1.1 mm gap closed and no filler pieces in the glory hole. The second configuration yielded a reactivity of 32 _ 5 cents subcritical (Reference 1). These two experimental configurations, supplemented by measured reactivity worths from the original Thor experiments, provided the basis for the final critical specifications.

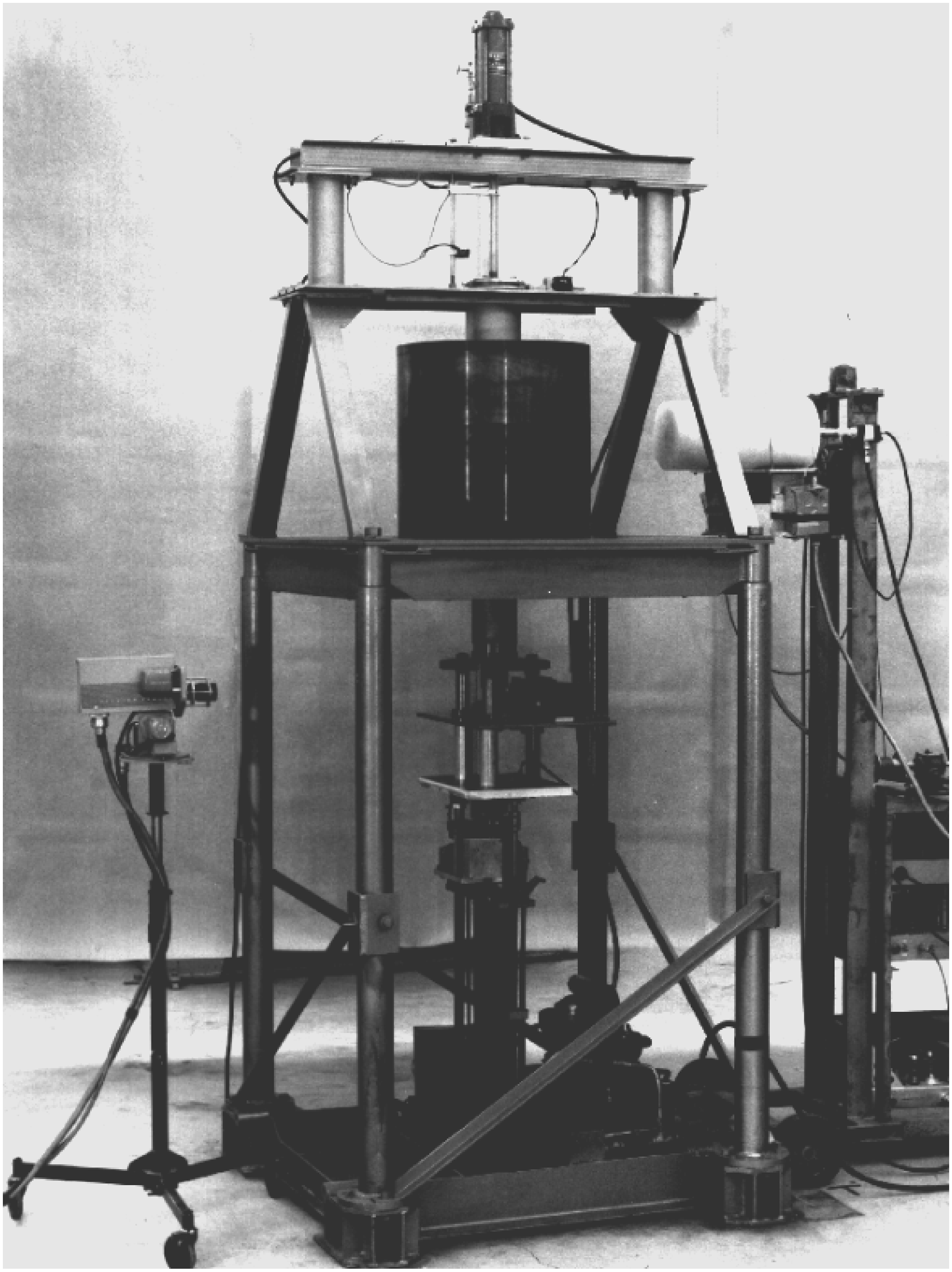
1.3 Description of Material Data

The average composition of the plutonium core is given by Table 1. The plutonium also contains 1.01 wt.% gallium. The density of the plutonium core is 15.29 g/cm^3. The reflector is 100 wt.% ^{232}Th at a density of 11.58 g.cm^3 (References 1 and 2).

Table 1. Core Composition.

Isotope/Element	Wt.%
^{239}Pu	93.59
^{240}Pu	5.10
^{241}Pu	0.30
Gallium	1.01

1 $_{eff}$ assumed to be 0.002 by the experimentalists for all reactivity measurements.

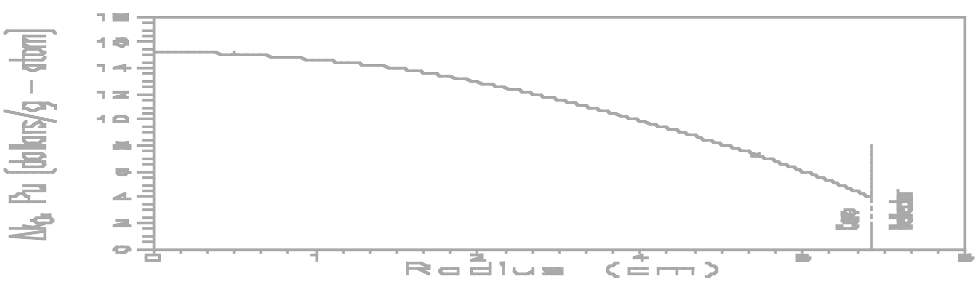


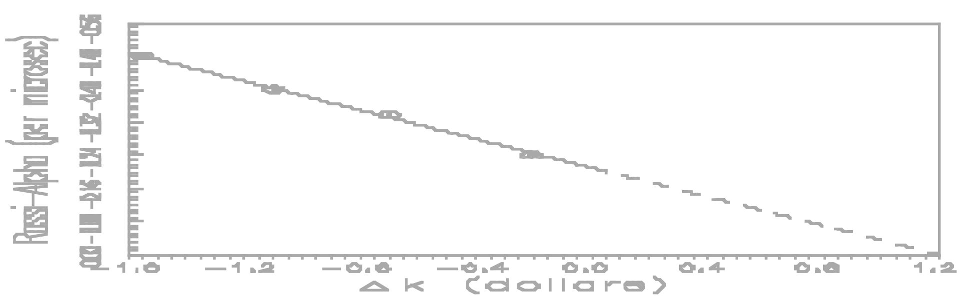
1.4 Supplemental Experimental Measurements

Following the critical mass determination, investigations of void coefficients, Rossi-_, flux distributions, and spectral indices were performed.

Positive-period measurements on the original assembly yielded information that was needed to reduce each of the two configurations to a clean critical mass of plutonium alloy. One such piece of information was the void coefficient curve shown in Figure 3 (Reference 1).

The Rossi-_ technique[2] was used at several slightly subcritical configurations. A plot of the data is shown in Figure 4. The term, _, is a linear function of reactivity (Reference 3). The subcritical data extrapolates to the value of _ at delayed critical which is -0.197 _sec^{-1}.





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2 The Rossi-_ experimental technique is summed up by the following: "Measurement of the time distribution of pairs of counts due to neutrons originating from a common ancestor in a neutron chain, yields a value for the prompt neutron period of a near critical system. Such measurement can be used to establish the mass or control increment between delayed and prompt critical and, hence, constitute a reactivity calibration without use of the Inhour relation." (Reference 3).

A radial ^{235}U fission traverse was performed along the equatorial plane. The results of this traverse are shown in Figure 5 and Table 2.

The radial distribution of various reaction rate ratios that characterize breeding in thorium were also examined. These reaction rate ratios involved the isotopes of ^{232}Th, ^{235}U, ^{237}Np, and ^{238}U.

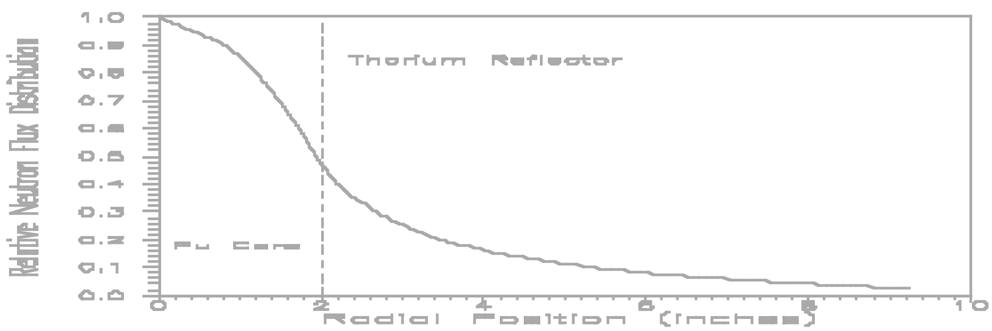

Table 2. Relative Fission Traverses.

Radius (inches)	—$_f$(^{235}U, relative)
0.0	1.000
0.25	0.970
0.75	0.908
1.25	0.784
1.75	0.588
2.25	0.388
3.25	0.222
4.25	0.148
5.25	0.104
6.25	0.0743
7.25	0.0545
8.25	0.0377
9.25	0.0247

2.0 EVALUATION OF EXPERIMENTAL DATA

Two calculational models were produced as a result of this experiment. The one-dimensional model involved corrections to reduce the experimental model to a spherical core-reflector critical mass. The two-dimensional model maintained the cylindrical shape of the reflector and the spherical core.

Approximations for both models were made to correct for nickel plating (internal and external), gaps, and cavity adjustments. These are summarized in Table 3, which was reproduced from Reference 1.

The experiment was reduced to a one-dimensional sphere as a result of reevaluation efforts in 1979 (Reference 1). The following summarizes the method used in determining the one-dimensional thorium reflector thickness.

> "Measurements of critical mass as a function of uranium reflector thickness[3] are approximately consistent with the inverse fourth-power dependence of reflector worth per unit volume upon distance from the core center. The reasonable assumption of the same dependence for Thor leads to the effective reflector radius of 29.88 cm." (Reference 1)

No corrections were made for room reflection or the presence of the assembly machine.

The enrichment as reported in the section entitled "One-Dimensional Specifications of Thor" in Reference 1 was given to be 5.9 wt.% ^{240}Pu. All other sections in Reference 1, as well as Reference 2, report the enrichment as 5.1 wt.%. The 5.9 wt.% was found to be a typographical error.[4] The reason for the difference in density and the mass of the plutonium core between References 1 and 2 could not be found.

The idealized one-dimensional plutonium sphere with a mass of 9587 _ 17 g and a density of 15.29 g/cm^3 reflected by a spherical shell of thorium with a density of 11.58 g/cm^3 and the idealized one-dimensional sphere with a mass of 9587 _ 17 g and a density of 15.29 g/cm^3 reflected by an equilateral cylinder of thorium with a density of 11.58 g/cm^3 are the accepted calculational benchmark models. The sensitivity of the calculational models to various parameters is shown in Appendix B.

[3] Reference 2.
[4] Personal communication, H. C. Paxton, January 1994.

Table 3. Reduction to a Clean Critical Mass.

	Configuration 1	Configuration 2
Cavity volume (cm^3)		
initial	634.8 _ 1.0	629.9 _ 1.0
surface nickel replaced by thorium[(a)]	624.4 _1.6	619.5 _ 1.6
Volume within plutonium surface (cm^3)	625.3 _ 1.2	617.2 _ 1.2
Initial alloy mass (g)	9595	9548
Initial excess reactivity (cents)	-23 _ 5	-32 _ 5
Initial critical mass (g)[(b)]	9602 _ 2	9557 _ 2
Critical mass correction (g)		
removal of internal nickel[(c)]	10 _ 3	10 _ 3
filling glory hole[(d)]	-34 _ 3	-71 _ 7
filling gap above lower cap[(d)]	-4	n/a
fitting core to cavity[(e)]	-7 _ 2	17 _ 5
adjustment to common cavity (radius = 5.31 cm, volume = 627 cm^3)[(f)]	24	70
Final critical mass (g)[(b)] individually	9591 _ 16	9583 _ 17
Final critical mass average	9587 _ 17 g alloy at _ (alloy) = 15.29 g/cm^3	

(a) Surface reactivity of thorium and nickel and the mass of surface nickel give the increase of thorium mass, and, hence, the decrease of cavity volume (thorium density = 11.58 g/cm^3), required to maintain reactivity when the nickel is removed.
(b) Excess reactivity and increment of critical mass are related by using Figure 3 to integrate over the core volume the effect of a small density change.
(c) From the assumed reactivity coefficient curve for nickel.
(d) Integration over voids by using Figure 3.
(e) Integration over surface volume by using surface reactivity coefficient of plutonium.
(f) Critical volume and density are related by using Figure 3 and surface reactivity coefficient of thorium to give the surface volume of plutonium-thorium required to offset a small decrease of core density.

3.0 BENCHMARK SPECIFICATIONS

3.1 Description of Model

There are two benchmark models for this experiment. The first model is a one-dimensional plutonium sphere with a density of 15.29 g/cm^3 and a mass of 9587 grams plutonium with 24.57-cm-thick thorium reflection at a density of 11.58 g/cm^3. The second benchmark model is a two-dimensional model. In this case, the core, as described above, is surrounded by a right circular cylinder with a height of 53.34 cm and a diameter of 53.34 cm and composed of thorium at a density of 11.58 g/cm^3.

3.2 Dimensions

For the one-dimensional model, the radius of the 9587 gram delta-phase plutonium sphere at a density of 15.29 g/cm^3 was 5.310 cm. The sphere was reflected by a 24.57-cm shell of thorium (outer radius of 29.88 cm).[a]

For the two-dimensional model, the radius of the 9587 gram delta-phase plutonium sphere at a density of 15.29 g/cm^3 was 5.310 cm. The sphere was reflected by a cylinder (height of 53.34 cm and a diameter of 53.34 cm) composed of thorium.[5]

3.3 Material Data

The calculated atomic number densities of the delta-phase plutonium sphere for the isotopic composition given previously in Section 1.3 are shown in Table 4.

[5] All of the benchmark specifications given in Reference 1 are reported to four significant figures. Slight round-off errors may result if more significant figures are used.

Table 4. Atom Densities.

Isotope/Element	Atom Density (atoms/barn-cm)
Plutonium Core	
^{239}Pu	3.6049_10^{-2}
^{240}Pu	1.9562_10^{-3}
^{241}Pu	1.1459_10^{-4}
Gallium	1.3338_10^{-3}
Thorium Reflector	
^{232}Th	3.0054_10^{-2}

3.4 Temperature Data

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

3.5 Experimental and Benchmark-Model k_{eff}

The experimental k_{eff} for this experiment was 1.0000. The idealized benchmark model k_{eff} is 1.000 _ 0.0006 for both calculational models. The uncertainty in k_{eff} was derived from a ONEDANT calculation based on the 17 gram uncertainty in the critical mass reported by the experimenters.

4.0 RESULTS OF SAMPLE CALCULATIONS

The results of calculations performed with various codes and cross section sets for the two models are shown in Table 5. Configuration 1 is a one-dimensional, spherical model, and Configuration 2 is the two-dimensional model (cylindrical and spherical). Both models were described previously in Section 3.2. The SCALE 27-group thorium cross sections significantly underpredict k_{eff}. This misprediction is due to an apparent deficiency in the fast thorium cross sections in this library.[6]

Table 5. Sample Calculation Results (United States).

Code (Cross Section Set)_ Case Number_	KENO (Hansen-Roach)	KENO (27-Group ENDF/B-IV)	MCNP (Continuous Energy ENDF/B-V)	ONEDANT (27-Group ENDF/V-IV)
1	0.9972 _ 0.0015	0.9803 _ 0.0013	1.0054 _ 0.0012	0.9796
2	1.0003 _ 0.0015	0.9752 _ 0.0012	1.0062 _ 0.0012	N/A[(a)]

(a) The combination of a one-dimensional sphere and a two-dimensional cylinder cannot be modeled with ONEDANT or TWODANT.

6 Personal communication, R. M. Westfall and L. M. Petrie, September 1993.

5.0 REFERENCES

1. G. E. Hansen, "Thor, A Thorium-Reflected Plutonium Metal Critical Assembly," Nucl. Sci. Eng., **71**, pp. 287-293, 1979.

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

3. J. D. Orndoff, "Prompt periods of Metal Critical Assemblies," Nucl. Sci. Eng., **2**, pp. 450-460, 1957.

APPENDIX A: TYPICAL INPUT LISTINGS

A.1 KENO Input Listings

Hansen-Roach Cross Sections and 27-Group ENDF/B-IV Cross Sections

Listed below are the input files for KENO-V.a with 16-group Hansen-Roach and 27-group SCALE4 cross sections for the one- and two-dimensional models. The models use 300 active generations with 1500 particles per generation while skipping the first five 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.

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 5 (16-Energy-Group Hansen-Roach Cross Sections).

```
PU SPHERE, ONE-D
READ PARAM  RUN=yes   FAR=YES  LIB=41
GEN=305 NPG=1500 NSK=5
END PARAM
READ MIXT SCT=1
MIX=1  94901  0.036049
       94001 0.0019562
       94100 0.00011459
       29100 0.0013338
MIX=2  90202  0.030054
END MIXT
READ GEOM
UNIT 1
  SPHERE    1 1 5.31
  SPHERE    2 1 29.88
END GEOM
END DATA
END

PU SPHERE, TWO-D
READ PARAM  RUN=yes   FAR=YES  LIB=41
GEN=305 NPG=1500 NSK=5
END PARAM
READ MIXT SCT=1
MIX=1  94901  0.036049
       94001 0.0019562
       94100 0.00011459
       29100 0.0013338
MIX=2  90202  0.030054
END MIXT
READ GEOM
UNIT 1
  SPHERE    1 1 5.31
  CYLINDER  2 1 26.67 26.67 -26.67
END GEOM
END DATA
END
```

KENO-V.a Input Listing for Table 5 (27-Energy-Group SCALE4 Cross Sections).

```
=CSAS25
THORIUM REFLECTED PU SPHERE, ONE-D MODEL
27GROUPNDF4  INFHOMMEDIUM
PU-239       1 0.0 0.036049  END
PU-240       1 0.0 0.0019562  END
PU-241       1 0.0 0.00011459  END
CU           1 0.0 0.0013338  END
TH-232       2 0.0 0.030054  END
END COMP
COPPER INSTEAD OF GALLIUM
READ PARAMETERS
  TME=1000 TBA=10
  GEN=305 NPG=1500 NSK=5
READ GEOM
UNIT 1
  SPHERE    1 1 5.31
  SPHERE    2 1 29.88
END GEOM
END DATA
END

=CSAS25
PU(5.1) SPHERE REFLECTED BY TH-232 CYLINDER
27GROUPNDF4  INFHOMMEDIUM
PU-239       1 0.0 0.036049   END
PU-240       1 0.0 0.0019562  END
PU-241       1 0.0 0.00011459 END
CU           1 0.0 0.0013338  END
TH-232       2 0.0 0.030054   END
END COMP
COPPER INSTEAD OF GALLIUM
READ PARAMETERS
  TME=1000 TBA=10
  GEN=305 NPG=1500 NSK=5
READ GEOM
UNIT 1
  SPHERE    1 1 5.31
  CYLINDER   2 1 26.67 26.67 -26.67
END GEOM
END DATA
END
```

A.2 MCNP Input Listings

Listed below are the input files for MCNP 4.2 with ENDF/B-V continuous-energy cross sections for the one- and two-dimensional models. The models use 300 active generations with 1500 particles per generation while skipping the first five generations.

MCNP Input Listing for Table 5.

```
THORIUM REFLECTED PU(5.1) SPHERE, ONE-D
1    1    0.03945359  -1 imp:n=1
2    2    0.030054  1 -2 imp:n=1
3    0    2  imp:n=0

1    so    5.31
2    so    29.88

m1    94239.55c  0.036049
      94240.50c  0.0019562
      94241.50c  0.00011459
      31000.50c  0.0013338
m2    90232.50c  0.030054
kcode 1500 1.0 5 305
ksrc 0 0 0
print
```

```
PU(5.1) SPHERE, REFLECTED BY CYLINDER OF TH-232
1    1    0.03945359  -1 imp:n=1
2    2    0.030054   1 -2 -3 4 imp:n=1
3    0    2:3:-4  imp:n=0

1    so    5.31
2    cx    26.67
3    px    26.67
4    px    -26.67

m1    94239.55c  0.036049
      94240.50c  0.0019562
      94241.50c  0.00011459
      31000.50c  0.0013338
m2    90232.50c  0.030054
kcode 1500 1.0 5 305
ksrc 0 0 0
print
```

A.3 ONEDANT Input Listings

Listed below are the input files for ONEDANT version 2.3h.2 with the 27-group SCALE4 cross sections which have P_3 scatter data. The order of angular quadrature is 48. The convergence criteria for the eigenvalue and flux is 10^{-4} by default. The mesh size is approximately 3 mesh/cm in both the core and the reflector. The first file is used to generate the SCALE 27-group cross sections. The input files are for the one-dimensional configuration since the two-dimensional case of a sphere and cylinder cannot be modeled with ONEDANT or TWODANT.

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 5.

```
=CSASI
ICE RUN TO GET XSECTS FOR PU SPHERE
27GROUPNDF4 INFHOMMEDIUM
PU-239   1 0.0 0.036049  END
PU-240   1 0.0 0.0019562  END
PU-241   1 0.0 0.00011459  END
CU      1 0.0 0.0013338  END
TH-232   2 0.0 0.030054  END
END COMP
END

   2
Pu(5.1) sphere with a thorium reflector
          Simplified model
/BLOCK 1
 igeom=sph ngroup=27 niso=2 isn=48 mt=2 nzone=2 im=2 it=90  t
/BLOCK 2
  xmesh=0.0,5.31,29.88  xints=16,74  zones=1,2  t
/BLOCK 3
 lib=xs27.w12
 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;
 .020 .184 .214 .125 .168 .183 .091 .014 .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 _17 g in the mass of the Pu core was given by the experimenters. A calculation was performed to determine the _k associated with this uncertainty. The result of this calculation is given below in Table B.1 (_0.0006).

Corrections 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 below, these effects were each less than or equal to the calculated _k associated with the experimental uncertainty. Therefore, no correction to the benchmark k_{eff} was made due to these parameters.

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 Study.

Effect	_k_{eff}[a]
_17 grams of plutonium[b]	_0.0006
Room return	+0.0006
Assembly machine[c]	+0.0005
Copper instead of gallium	+0.0001

(a) The _k_{eff} is relative to a base case of 0.9993.
(b) The given uncertainty in the critical mass is _17 grams.
(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.

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