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ORSphere: Critical, Bare, HEU(93.2)-Metal Sphere

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IDENTIFICATION NUMBER: HEU-MET-FAST-100 SPECTRA

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1.0 DETAILED DESCRIPTION

In the early 1970s Dr. John T. Mihalczo (team leader), J.J. Lynn, and J.R. Taylor performed experiments at the Oak Ridge Critical Experiments Facility (ORCEF) with highly enriched uranium (HEU) metal (called Oak Ridge Alloy or ORALLOY) in an attempt to recreate GODIVA I results with greater accuracy than those performed at Los Alamos National Laboratory in the 1950s (HEU-MET-FAST-001). The purpose of the Oak Ridge ORALLOY Sphere (ORSphere) experiments was to estimate the unreflected and unmoderated critical mass of an idealized sphere of uranium metal corrected to a density, purity, and enrichment such that it could be compared with the GODIVA I experiments. "The very accurate description of this sphere, as assembled, establishes it as an ideal benchmark for calculational methods and cross-section data files." (Reference 1) While performing the ORSphere experiments care was taken to accurately document component dimensions (±0.0001 in.), masses (±0.01 g), and material data. The experiment was also set up to minimize the amount of structural material in the sphere proximity. A three part sphere was initially assembled with an average radius of 3.4665 in. and was then machined to an average radius of 3.4420 in. (3.4425 in. nominal[a]). These two spherical configurations were evaluated and judged to be acceptable benchmark experiments; however, the two experiments are highly correlated.

Information for the evaluation was compiled from Reference 1 and 2, the experimental logbook;[b] additional drawings and notes provided by the experimenter; and communication with the lead experimenter, John T. Mihalczo.

1.1 Overview of Experiment

The uranium metal sphere used in the ORSphere experiments was originally used to "measure the neutron leakage spectrum in slightly subcritical systems [in order] to validate calculation models" at the General Atomic Company linear accelerator in San Diego in 1965 (Reference 1). The vertical assembly machine in the East cell of ORCEF was used to assemble the sphere (see Figure1-1). Support structures were constructed to support the three parts of the sphere. Various modifications were made to the ORSphere from 1971 until 1975 when it was ultimately sent to the Oak Ridge Y-12 plant for destruction by recasting. The changes and modifications pertinent to this evaluation include the use of HEU pins to convert the original five part sphere into three primary parts (see Figure1-2 and Figure1-3), filling of a 1.000-in-diameter target

[a] The nominal radius was the dimension on the work request to the Y-12 machine shops for fabrication. Personal communication with J.T. Mihalczo, July 8, 2013.
[b] Radiation Safety Information Computation Center (RSICC), The ORNL Critical Experiments Logbooks, Book 108r, http://rsicc.ornl.gov/RelatedLinks.aspx?t=criticallist.

hole, filling of a thermocouple groove at the top of the center plate, drilling of a 0.136-in-dia diametral hole, and re-machining of the sphere from a 3.4665-in. average radius to a 3.4420-in. average radius.

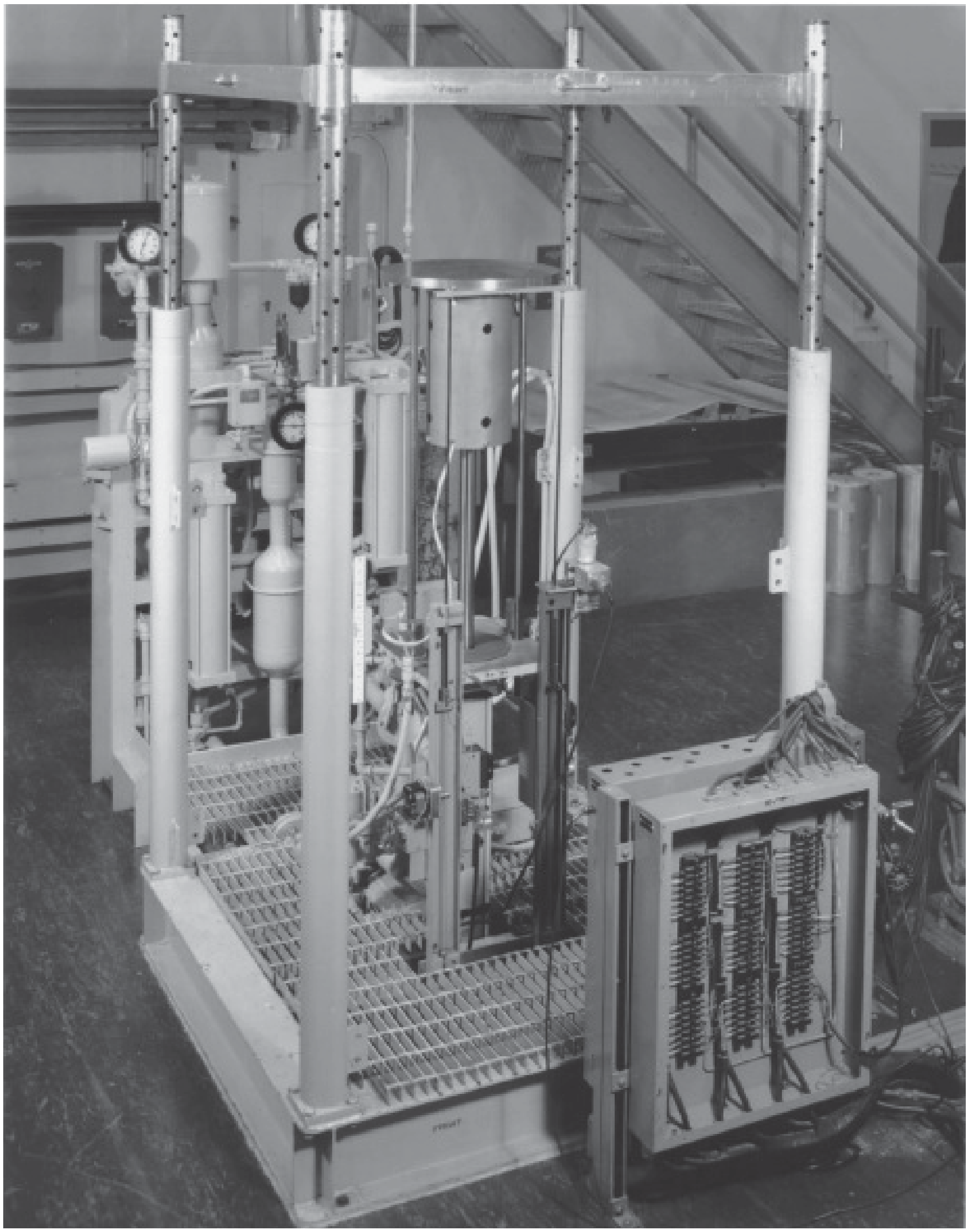

Figure1-1. Photograph of the Vertical Assembly Machine.[a]

[a] E. R. Rohrer, et al., "Neutron Physics Division Annual Progress Report, September 1, 1961," ORNL-3193, Oak Ridge National Laboratory (1961).

Figure1-2. Photograph of the Disassembled Three Part Sphere.

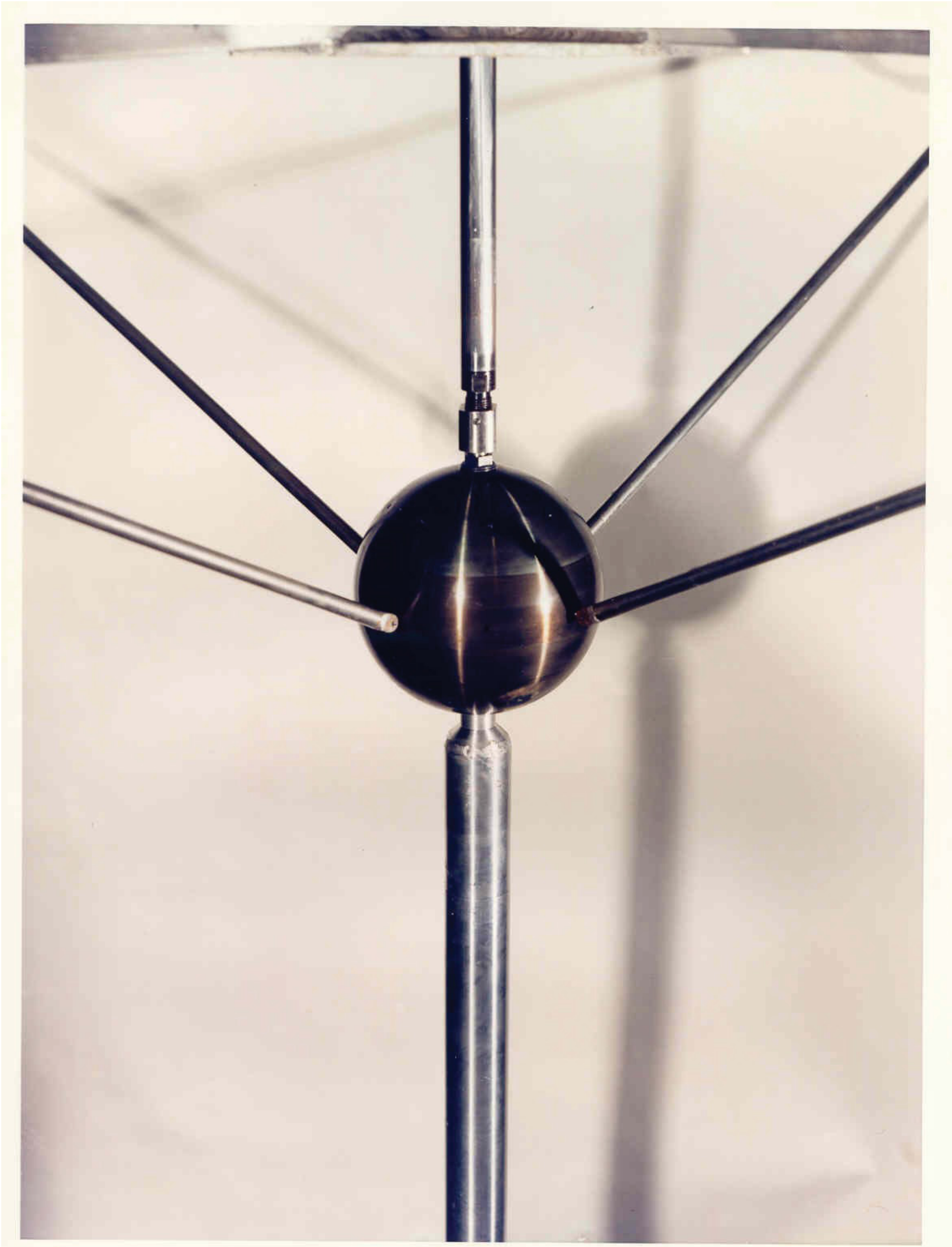

Figure1-3. Photograph of the Assembled Three Part Sphere (3.4665-in.-radius).

1.2 Description of Experimental Configuration

The ORSphere had five major parts, a lower polar cap, a lower plate, a central plate, an upper plate, and an upper polar cap. The sphere, when assembled, was as shown in Figure 1-4. Dimensions and masses of the sphere were measured to high accuracies at Y-12 plant at 70°F. Non-spherical dimensions were measured to ±0.0001 in. and certified masses were measured to ±0.01 g, as was typical for measurements performed at Y-12 to support ORCEF ORALLOY experiments.[a] The spherical dimensions were also measured to ±0.0001 in. When the sphere was assembled the gaps between the plates were generally $0.0000^{+0.0001}_{-0.0000}$ in. However, there was one exception for the 3.4665-in.-average-radius sphere which had a gap between the lower plate and the central plate of 0.0045 in. on one side of the sphere and no gap on the opposite side caused by a projection of a pin. The tilt of the center plate did not cause the center plate to overhang past the edge of the lower plate; this was prevented by the center support structure.[b] The worth of this gap was 5.0 ± 0.2 ¢ (based on 2.25×10^{-3} in. average gap and 2.2 ± 0.1 ¢ per thousandth of an inch gap worth) (Reference 1). Spherical surfaces were machined to a finish of 32×10^{-6} in. Machining specifications stated that flat surfaces were to be finished "to less than 0.002 in. total indicator reading (TIR). However, the flatness was actually very much better than this, typically less than ± 0.0001 in." (Reference 1). Cutoff alignment cones were used to ensure accurate lateral alignment when the sphere was assembled. Figure 1-5 through Figure 1-14 are drawings of the five sphere parts and are taken from Reference 1. Underlined dimensions are measured values. All other dimensions are manufacturing drawing dimensions. Figure 1-15 is reproduced from a drawing provided by the experimenter that had handwritten dimensions. Various details of the sphere are described below.

"A polonium/beryllium source was used. It was on a thin rod (~1/4 inch) and was withdrawn about 4 feet into a small shield. When performing measurements the fission rate in the assembly was sufficiently high that the source contribution was negligible. When Cf sources in ionization chambers were used for special measurements the Po/Be source was removed from the room."[c]

When assembled the reactivity of the 3.4665-in.-average-radius ORSphere was 68.1 ± 2.0 ¢. The uncertainty of ±2.0 ¢ "include assembly reproducibility, reactor period measurements uncertainty, and uncertainties in the delayed neutron parameters" (Reference 1). The 3.4420-in.-average-radius ORSphere had a reactivity of -23.4 ¢.[d] The diametral rod was filled with a 0.1293-in.-diameter ORALLOY filler rod for both spheres. Reference 1 gives the effective delayed neutron fraction of the sphere was 0.0066 ± 0.00005 based on GODIVA measurements. The effective delayed neutron fraction was derived from a central void reactivity measurement using the ORSphere. A value of 0.00657 ± 0.00002 was obtained.[e] A description of this measurement and the derivation of the delayed neutron fraction are given in Section 1.5.

The effect of moving the sphere from its location 11.7 ft from the 5-ft-thick concrete west wall, 12.7 ft from the 2-ft-thick concrete north wall and 9.2 ft above the concrete floor of the 35×35×30-ft-high east cell of the

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[a] J. T. Mihalczo, T. Gregory Schaaff, "Uncertainties in Masses, Dimensions, Impurities, and Isotopics of HEU Metal Used in Critical Experiments at ORCEF," ORNL/TM-2012/32, Oak Ridge National Laboratory (2012).
[b] Personal email communication with J.T. Mihalczo, July 17, 2013.
[c] Personal email communication with J.T. Mihalczo, June 19, 2013.
[d] Reference 1 gives a reactivity of -23 ¢. The logbook, gives an average reactivity of -23.4 ¢.
[e] J. T. Mihalczo, J. J. Lynn, and J. R. Taylor, "The Central Void Reactivity in the Oak Ridge National Laboratory Enriched Uranium (93.2) Metal Sphere," *Nucl. Sci. Eng.*, **130**, 153-163 (1998).

critical experiments facility to the center of the cell was less than the reproducibility of sphere reconfiguration, which is given as approximately 0.3 ¢ in Reference 1. The sphere reproducibility was measured for the 3.4420-in.-average-radius sphere as 0.17 ¢ on the same day and approximately 0.27 ¢ from day to day.

It should be noted that the distance from the center of the sphere to the bottom of the upper polar cap in Figure 1-14 does not equal one half the height of the center plate plus the height of the upper plate (0.5626+0.7662 in.=1.3288 in.) minus the shift of the center of the center plate below the center of the sphere (-0.02 in.). The value in Figure 1-14 is 1.3488 and is believed to be incorrect simply due to the addition rather than subtraction of the shift of the center of the plate below the center of the sphere.

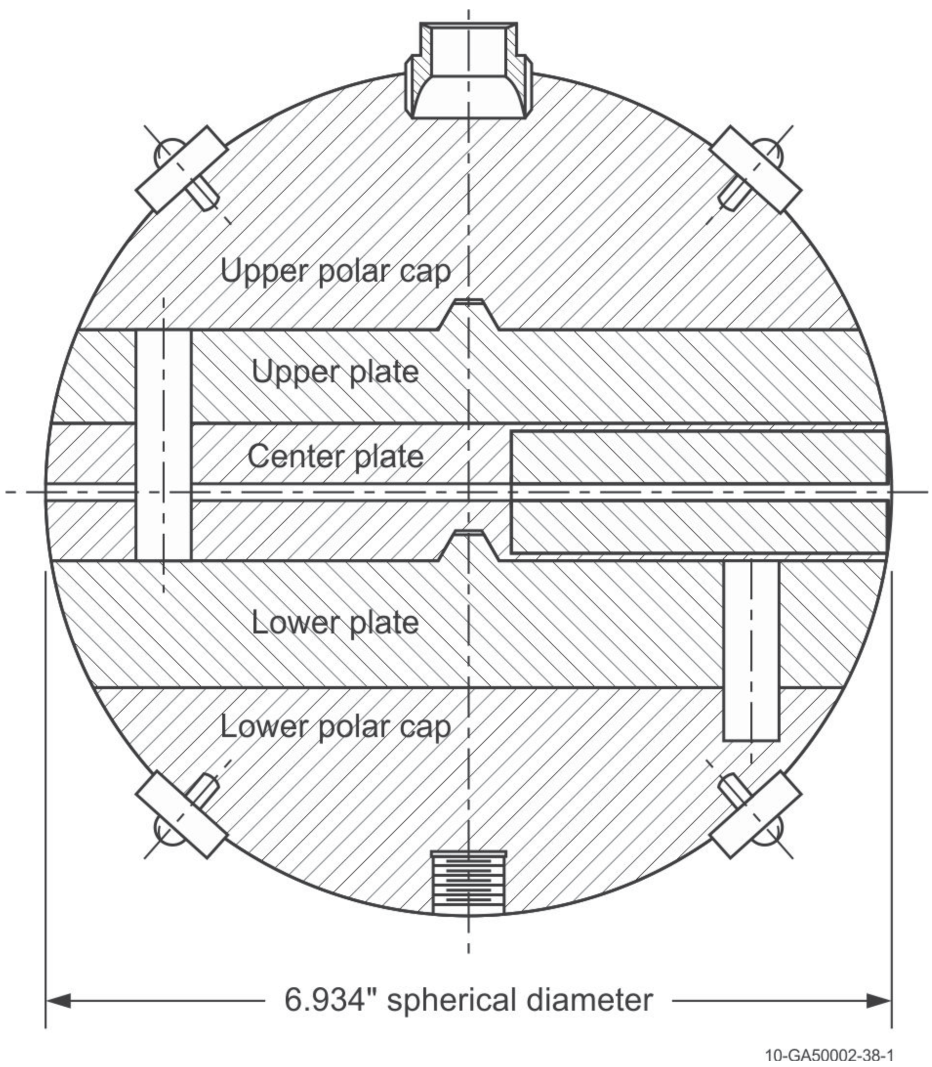

Figure 1-4. Sketch of the Assembly of Five Sphere Parts.[a]

[a] Redrawn from Reference 1. Although not shaded the pins in the lower polar cap and lower plate and the upper plate and center plate and the mass adjustment buttons were all HEU. The diameter should be given as 6.933 in. to correspond to the 3.4665 in. radius sphere. Personal communication with J.T. Mihalczo, July 8, 2013.

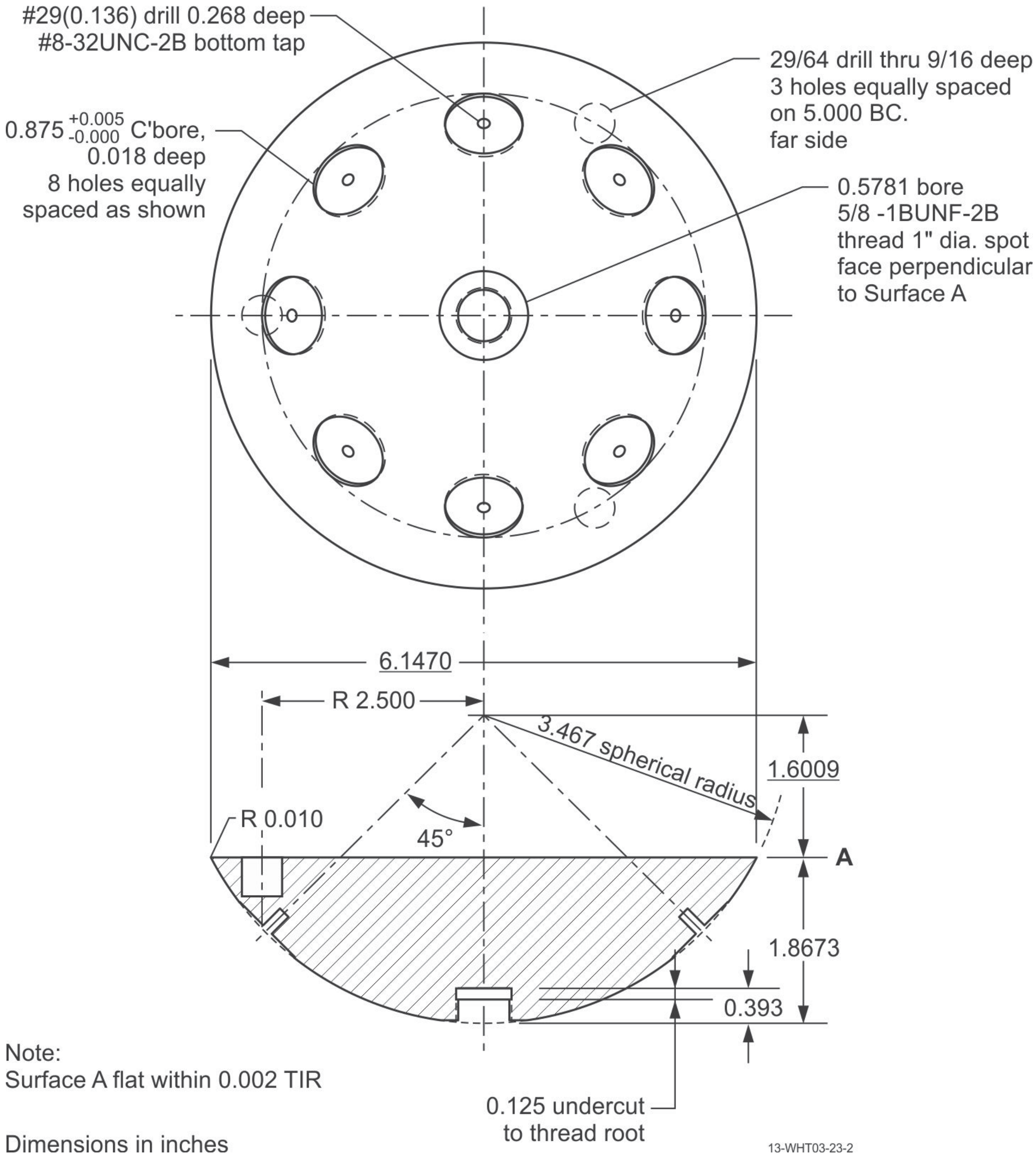

Figure 1-5. Lower Polar Cap of 3.4665-in.-average-radius Sphere.[a]

[a] Redrawn from Reference 1. BC stands for bolt circle which is the theoretical circle upon which the center of the HEU pins are equally spaced. Nominal radius is given.

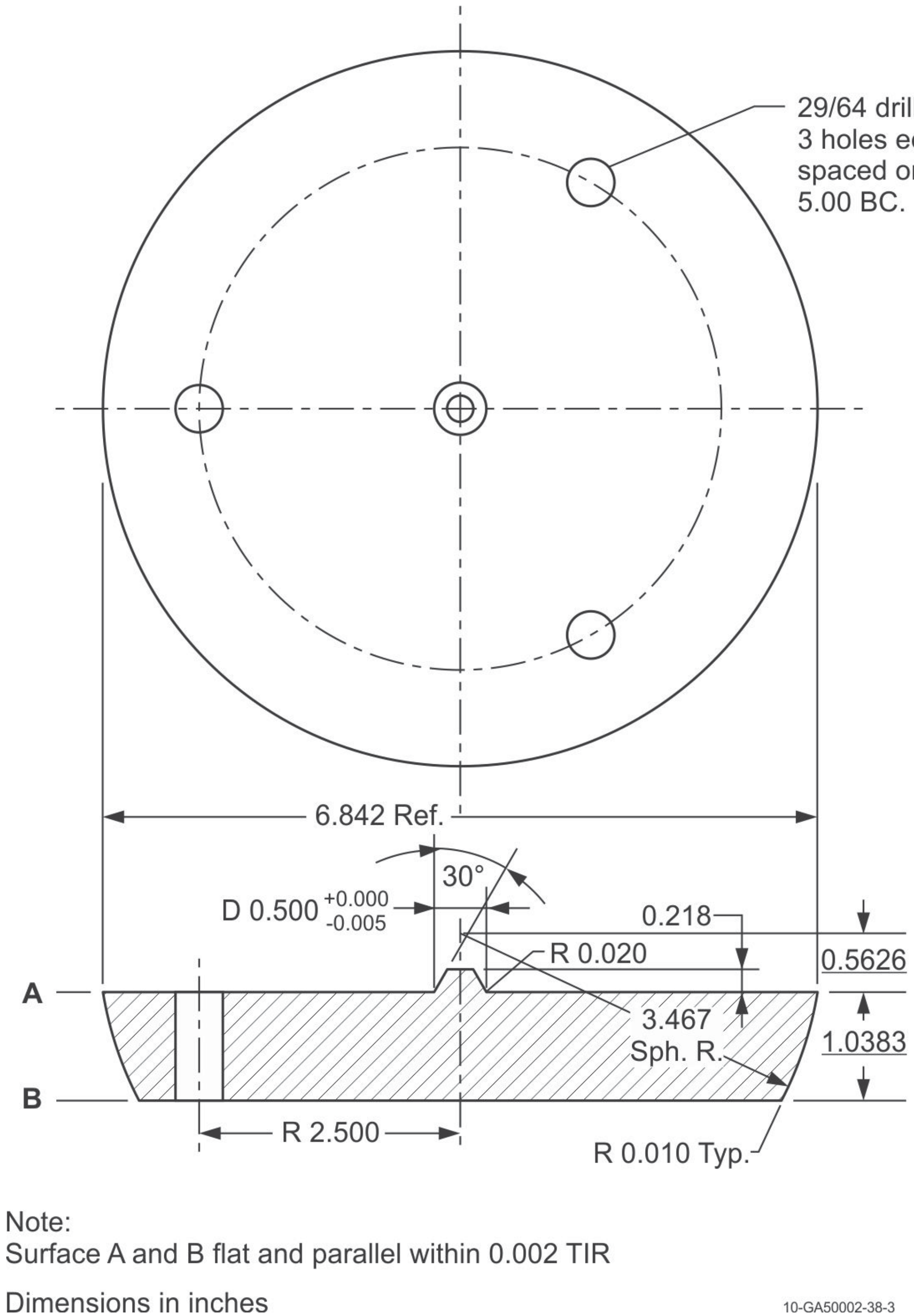

Figure 1-6. Lower Plate of 3.4665-in.-average-radius Sphere.[a]

[a] Redrawn from Reference 1. BC stands for bolt circle which is the theoretical circle upon which the center of the HEU pins are equally spaced. Nominal radius given.

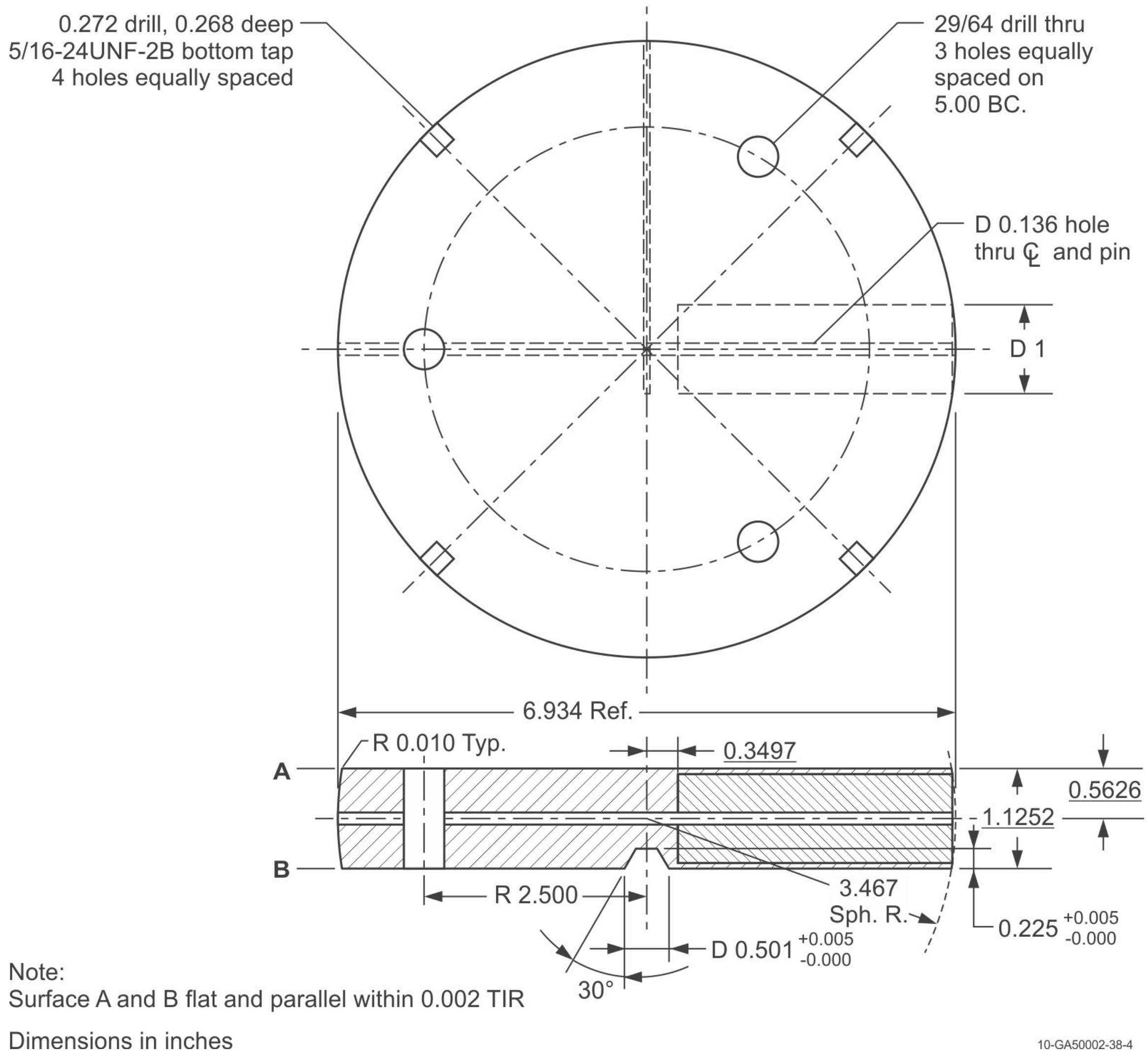

Figure 1-7. Center Plate of 3.4665-in.-average-radius Sphere.[a]

[a] Redrawn from Reference 1. BC stands for bolt circle which is the theoretical circle upon which the center of the HEU pins are equally spaced. Nominal radius given.

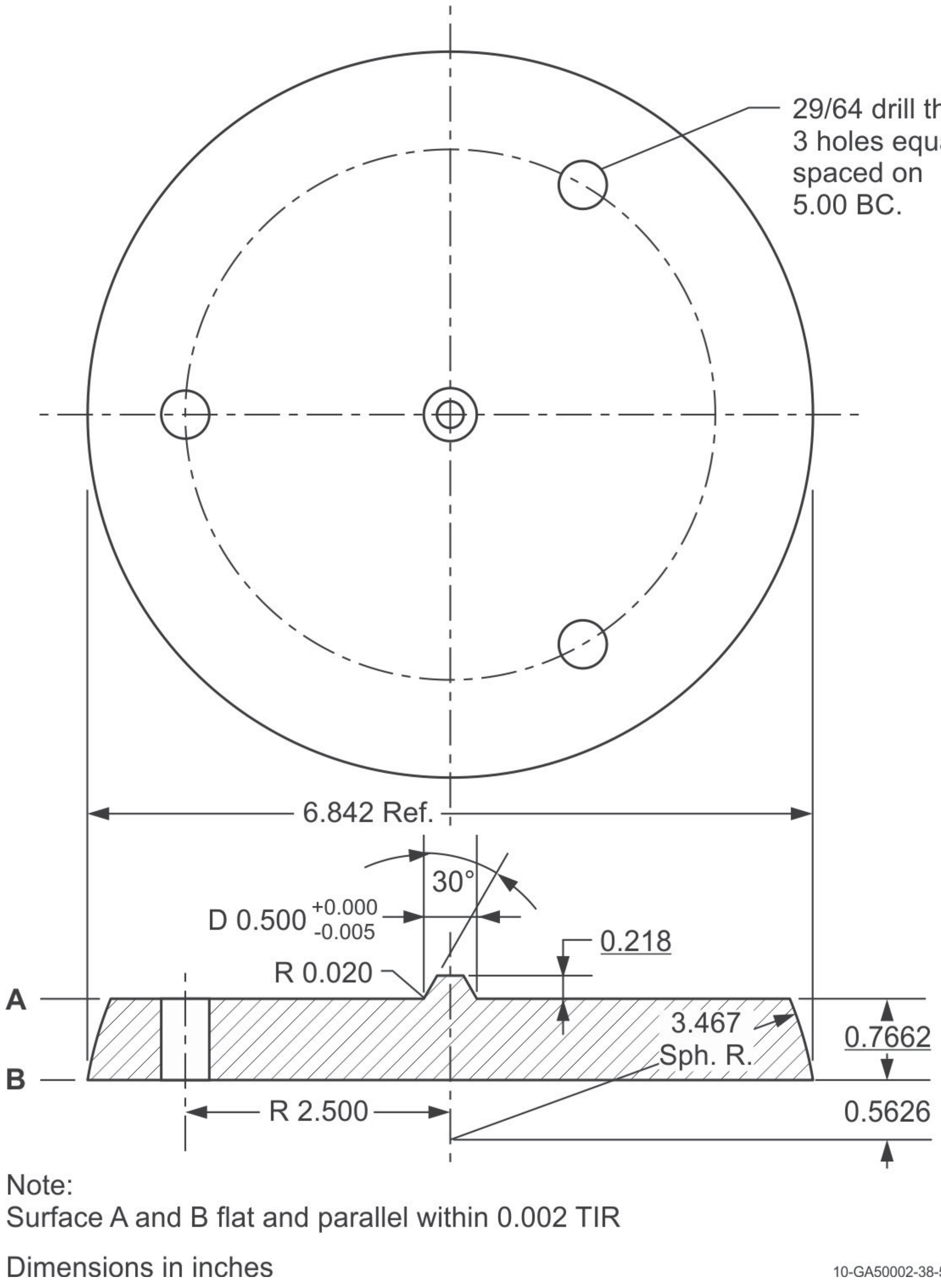

Figure 1-8. Upper Plate of 3.4665-in.-average-radius Sphere.[a]

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[a] Redrawn from Reference 1. BC stands for bolt circle which is the theoretical circle upon which the center of the HEU pins are equally spaced. Nominal radius given.

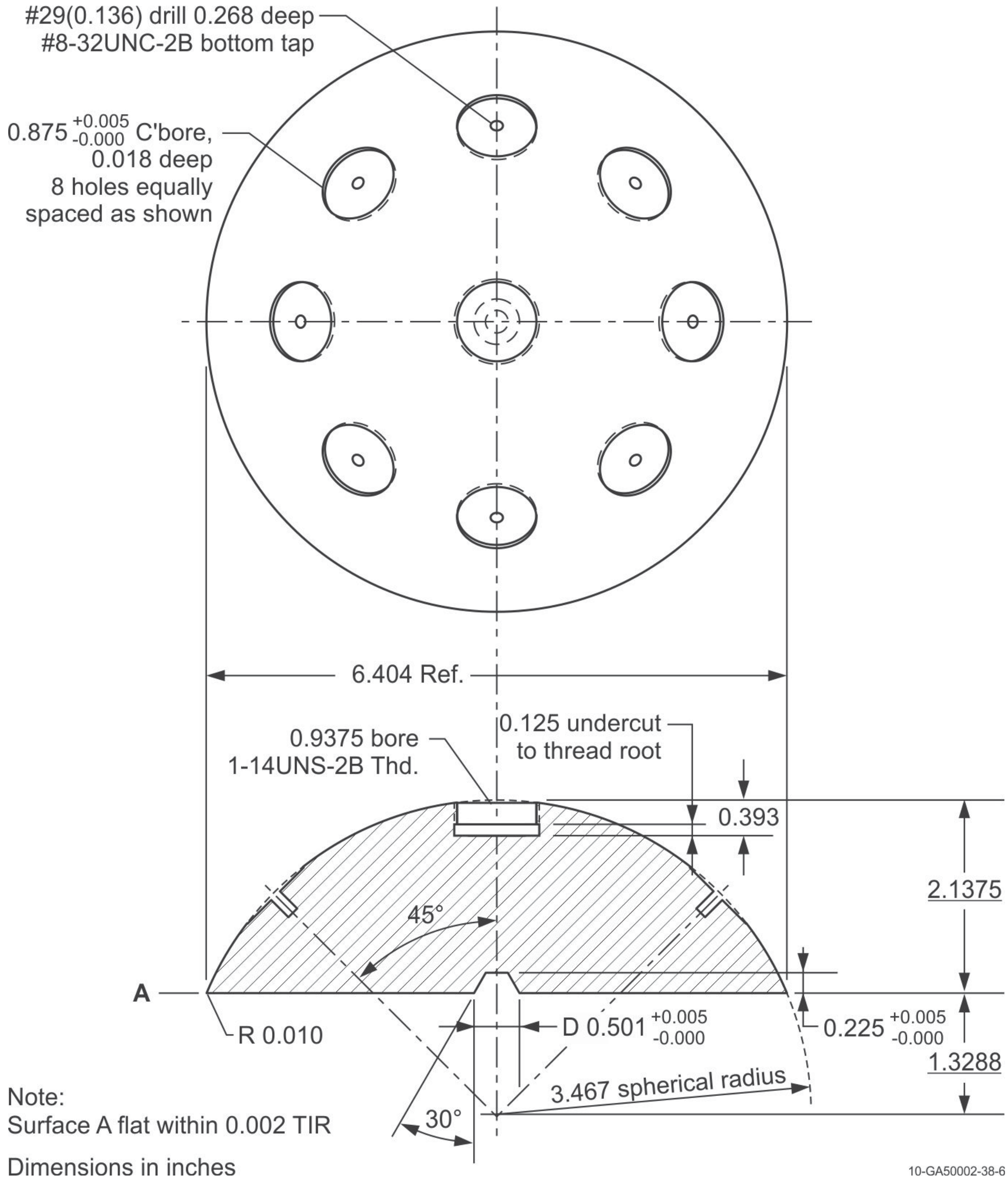

Figure 1-9. Upper Polar Cap of 3.4665-in.-average-radius Sphere.[a]

[a] Redrawn from Reference 1. Nominal radius given.

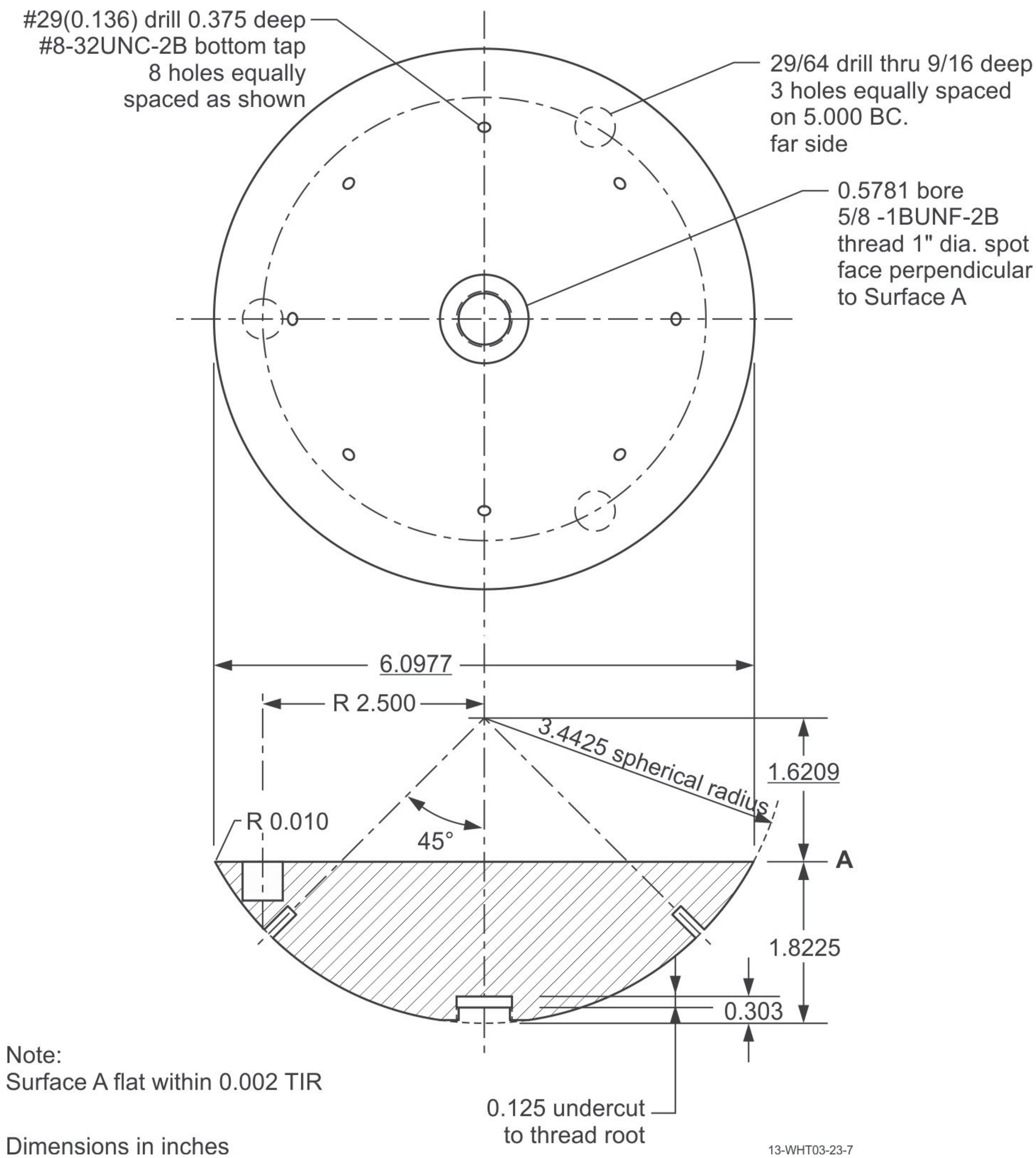

Figure 1-10. Lower Polar Cap of 3.4425-in.-nominal-radius (3.4420-in.-average-radius) Sphere.[a]

[a] Redrawn from Reference 1. BC stands for bolt circle which is the theoretical circle upon which the center of the HEU pins are equally spaced.

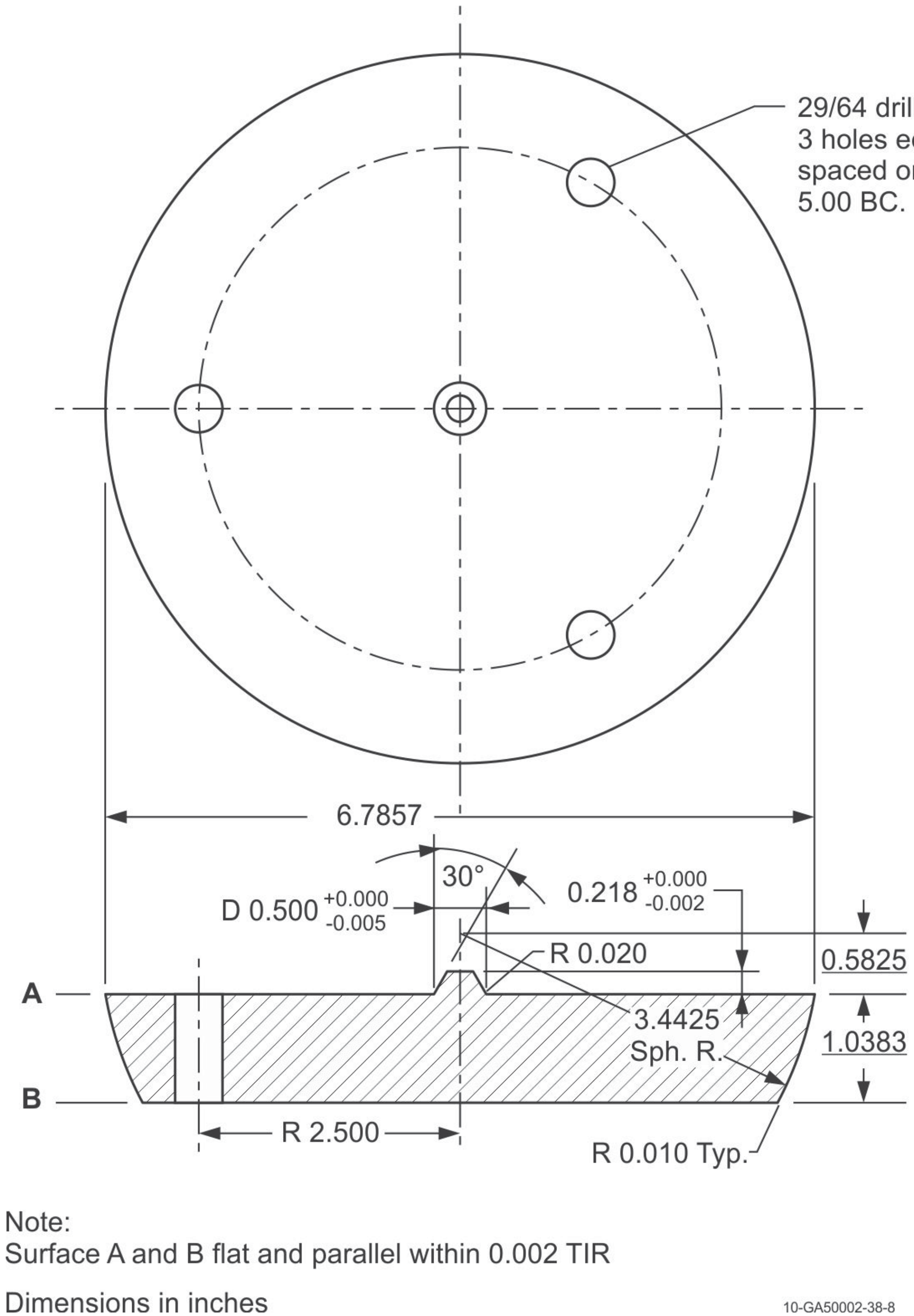

Figure 1-11. Lower Plate of 3.4425-in.-nominal-radius (3.4420-in.-average-radius) Sphere.[a]

[a] Redrawn from Reference 1. BC stands for bolt circle which is the theoretical circle upon which the center of the HEU pins are equally spaced.

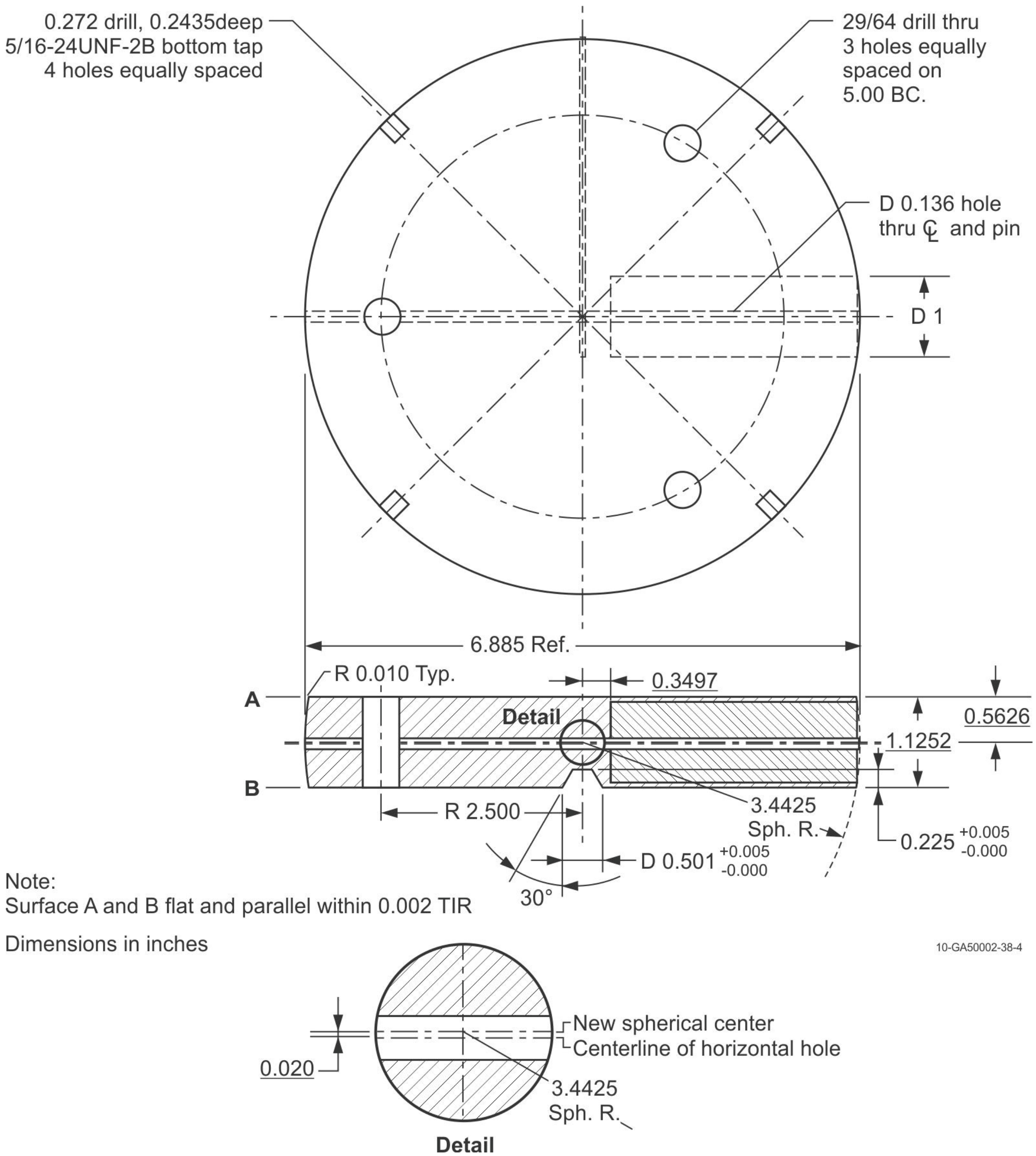

Figure 1-12. Center Plate of 3.4425-in.-nominal-radius (3.4420-in.-average-radius) Sphere.[a]

[a] Redrawn from Reference 1. BC stands for bolt circle which is the theoretical circle upon which the center of the HEU pins are equally spaced.

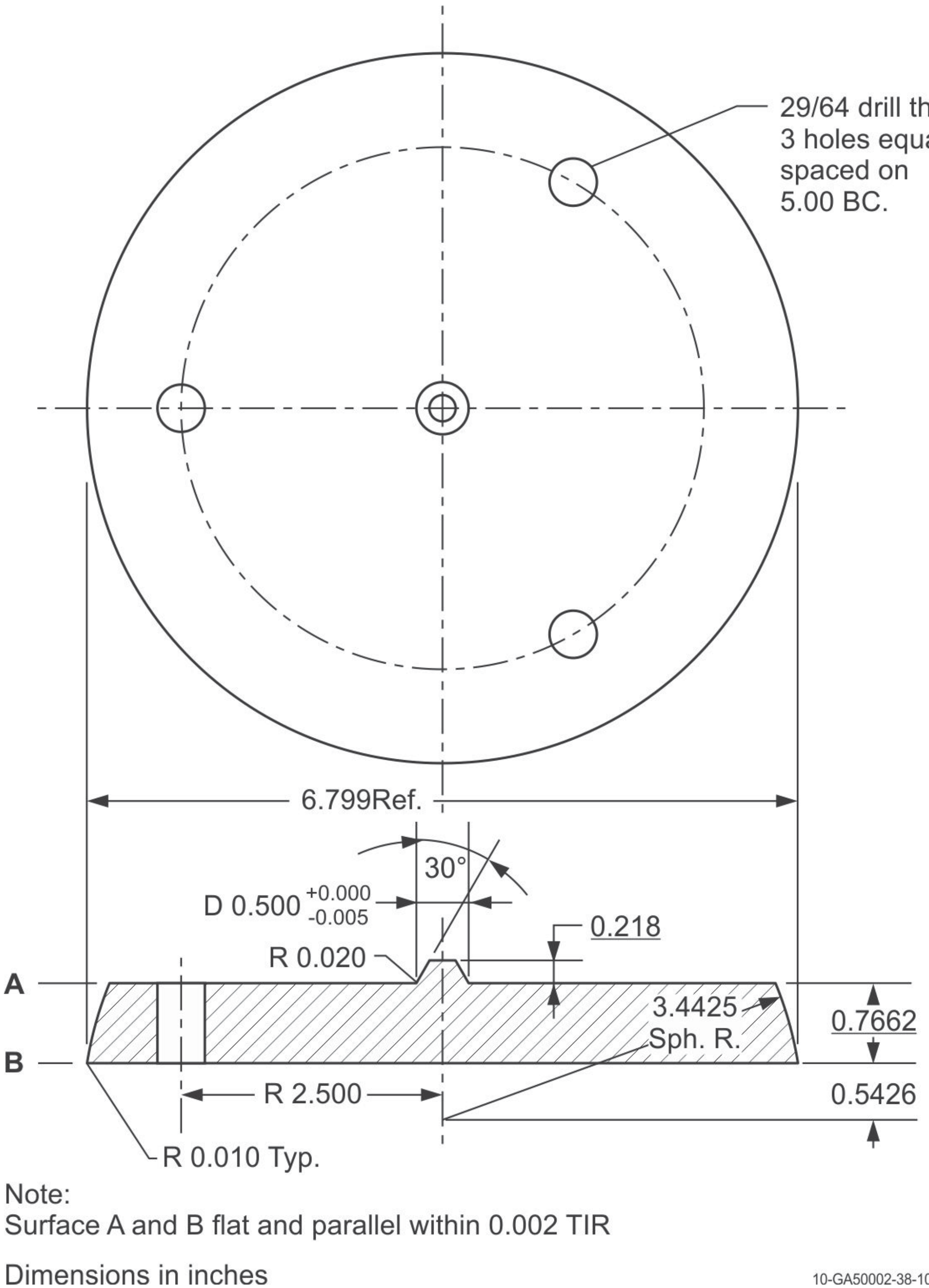

Figure 1-13. Upper Plate of 3.4425-in.–nominal-radius (3.4420-in.-average-radius) Sphere.[a]

[a] Redrawn from Reference 1. BC stands for bolt circle which is the theoretical circle upon which the center of the HEU pins are equally spaced.

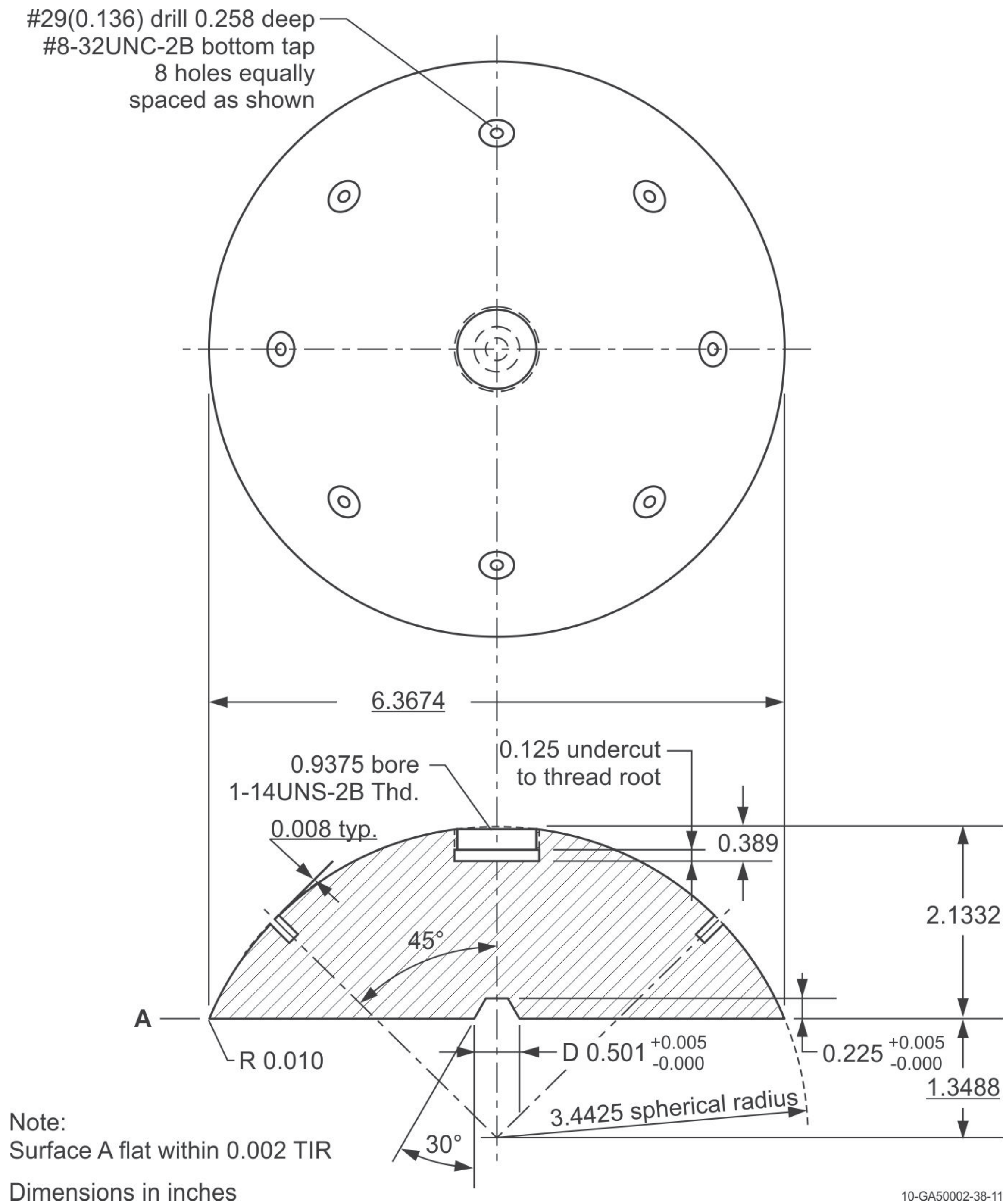

Figure 1-14. Upper Polar Cap of 3.442- in.–nominal-radius (3.4420-in.-average-radius) Sphere.[a]

[a] Redrawn from Reference 1. The distance from the center of the sphere to the bottom of the upper polar cap should actually have been 1.3088 in. It is believed this is simply a calculation error caused by adding rather than subtracting the 0.02 in. shift in the center of the sphere from the larger sphere to the smaller sphere.

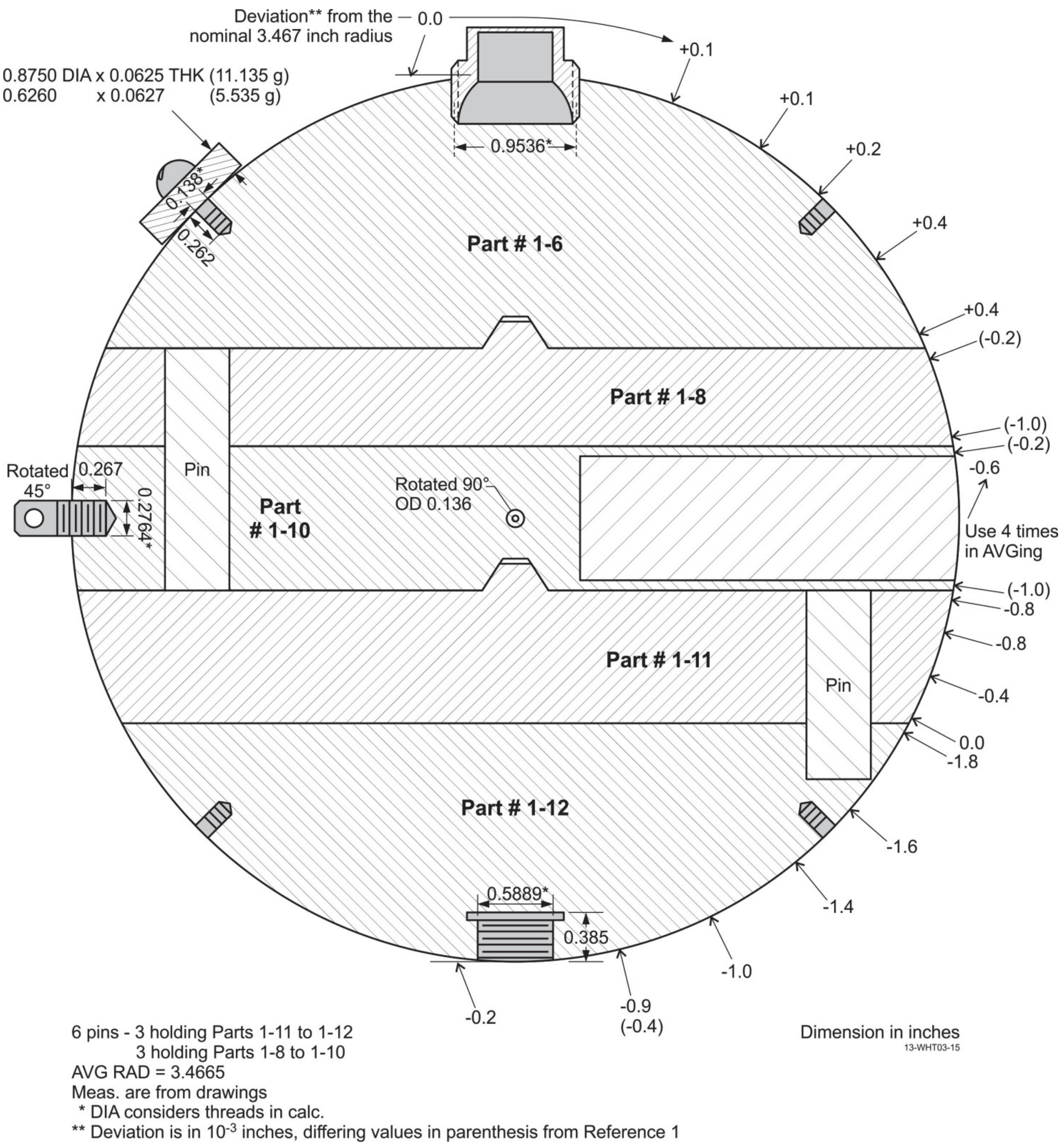

Figure 1-15. Measured Dimensions.[a]

[a] Redrawn from handwritten dimensions on a drawing provided by the experimenter and personal communication with the experimenter, J.T. Mihaclzo, July 2013. The pin does not break the surface of the sphere. Multiple deviation from spherical measurements were equally spaced (see Table 1-1).

1.2.1 Pins

After the ORSphere parts were returned to Oak Ridge National Laboratory from the General Atomic Company linear accelerator (LINAC) facility various changes were made. The tapped screws holes that were originally used with stainless steel screws to hold the lower polar cap to the lower plate and the center plate to the upper plate were drilled to a diameter of 0.4530 in. (the drawings gave a drill diameter of 29/64 in., which is slightly larger). Six (three in each section) slightly oversized diameter pins of HEU metal replaced the screws to attach the lower polar cap to the lower plate and the center plate to the upper plate. The HEU pins were cooled, inserted, and then warmed to ambient temperature (shrink fit) to ensure no voids were present around the pins. The three pins in each section were at a diameter of 5.000 in. and were equally spaced. The pins in the central section extended from the bottom of the center plate to the top of the upper plate. The pins in the lower section extended only partially into the lower polar cap. According to Figure 1-5 and Figure 1-10 they extended 9/16 in. (0.5625 in. or 1.42875 cm) deep. According to the experimenter the pins were not deep enough to extend into the mass button recesses and did not break the curve of the surface of the 3.4665-in.-average-radius sphere.[a] This discrepancy is discussed in Section 2.2.7. For the 3.4665-in. sphere the top of one of the pins in the bottom section was flush with the surface of the lower plate. One of the pins extended beyond the lower plate upper surface by 2.3×10^{-3} in. and the top of the third pin sat below the upper surface of the lower plate by 0.0005 in. This pin projection caused a 0.0045-in. gap on the side of the sphere closest to the pin and no gap on the opposite side of the sphere. When the sphere was machined to an average radius of 3.4420 in. the pin that extended beyond the upper surface of the lower plate was machined until it was 0.0005 in. below the upper surface of the plate. Thus, for the second sphere the top of two of the pins were 0.0005 in. below the upper surface of the lower plate and one pin was flush with the surface.

1.2.2 Target Hole Plug and Diametral Hole and Rod

The original 1.000-in.-diameter target hole, which extended radially to within 0.350 in. (nominal, 0.3497 in. measured) of the center of the sphere, allowed “the electron beam from the linear accelerator to impinge on the uranium close to the center of the sphere” (Reference 1). This target hole was plugged by shrink fit with an HEU plug a few thousandths of an inch diametrically larger than the hole, thus there was no void introduced between the plug and the center plate. After the target hole was filled a 0.136-in.-diameter diametral hole was drilled through the center of the sphere. This hole went through the target hole plug and one of the HEU pins. Two 0.1293-in.-diameter filler rods of 4.265- and 2.745-in. lengths (17.117 and 11.046 g, respectively) were inserted into the diametral hole during the critical assembly of the parts. Dimensional certification reports give the rod lengths as 4.2650 in. and 2.7545 in. and the diameter as 0.1290/0.1295 in., which averaged to 0.1293 in. The length of the shorter filler rod did not agree between Reference 1 and the certification report, this discrepancy is discussed in Section 2.2.4. The masses on the dimensional certification report are the same as those given in Reference 1. The total length of two filler rods was greater than the length of the diametral hole.[b]

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[a] Personal email communication with J.T. Mihalczo, February 3, 2013.
[b] Personal communication with J.T. Mihalczo, April 15, 2013. The diametral filler rod was not machined to match the curve of the sphere.

1.2.3 Thermocouple

"The thermocouple groove in the center plate… [of the original sphere used at General Atomic had] a width of 0.070 in. ± 0.004 in. and accommodated a thermocouple that was 0.062 inches in diameter. This groove for the center thermocouple extended 3/8 in. past the center [of the sphere]. However, at a radius of 1.625 in. to the outer radius of the sphere the groove was cut deeper to accommodate another thermocouple at a radius of about 1.65 cm. Thus, the depth of the groove was 0.140 in. into a radius of 1.625 in. and 0.70 in. from a radius of 1.625 in. to 3/8 in. past the center."[a] A figure provided by the experimenter has the depths as being 0.058 ± 0.002 in. and 0.116 ± 0.002 in. According to the experimenter the depths in the drawing should be used.[b] The thermocouple groove was also filled by shrink fit with HEU metal and machined flat.

1.2.4 Sphere Radius

After the pin holes, target hole, and thermocouple groove were filled, the sphere was re-machined to a nominal radius of 3.467 in. (average radius of 3.4665in.). After the 3.4665-in.-radius sphere was assembled and all measurements were performed the bottom section of the sphere, made up of the lower polar cap and the lower plate, was re-machined to a radius of 3.439 in. The sphere was then reassembled. Finally the three sections of sphere were all machined to a nominal radius of 3.4425 in. (actual average radius of 3.4420 in.). When the entire sphere was re-machined to the 3.4420-in.-average radius the center of the sphere was 0.020 in. above the previous center of the sphere thus the center of the diametral hole was 0.020 in. below the center of the 3.4420-in.-average-radius sphere. This resulted in a change of angle for the mass adjustment button recesses with respect to the center of the 3.4420-in-average-radius sphere. This change in angle is not reflected in Figures 1-10 and 1-14.[c]

The machined sphere parts were not perfectly spherical. The deviation from spherical of each part was measured using a sweep gauge and is shown in Figure 1-15 for the 3.4665-in. sphere and given in Tables 1-1 and 1-2 for both spheres. Sweep gauge measurements are point measurements and are not averaged around the entire equator however due to machining techniques the radius should not have varied around the entire sphere equator at a given axial height.[d] Discrepancies between Table 1-1 and Table 1-2 and the drawing are shown in Figure 1-15. Tables 1-1 and 1-2 also give the vertical height and certified masses of each section.

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[a] Personal email communication between J.T. Mihalczo and T. Murray, December 10, 2011. The thermocouple groove was for experiments at General Atomic.
[b] Personal email communication with J.T. Mihalczo, February 4, 2013.
[c] Personal email communication with J.T. Mihalczo, July 8, 2013.
[d] Personal phone communication with J.T. Mihalczo, April 24, 2013.

Table 1-1. Measured Dimensions and Certified Masses of the Nominal 3.467-in-radius Sphere Parts (Reference 1, additions by the evaluator are *italic*).

	Number of points measured	Deviation from 3.467-in radius[(a)] (10^{-3} in.)	Vertical Height[(b)] (in.)	Certified Mass[(c)] (g)
Upper Polar Cap	6	0.0 at pole, +0.1, +0.1, +0.2, +0.4, +0.4 at bottom	2.1375[(d)]	12,042.76[(e)]
Upper Plate	2	-0.2 at top to -1.0 at bottom	1.8914	21,095.06[(f)]
Central Plate	2	-0.2 at top to -1.0 at bottom		
Lower Plate	4	-0.8 at top, -0.8, -0.4 to 0.0 at bottom	1.0383	20,310[(g)]
Lower Polar Cap	6	-1.8 at top, -1.6, -1.4, -1.0, -0.4, to -0.2 at pole	1.8673[(d)]	Included in 20,310 g of previous entry

(a) Measured with a sweep gage at 70 ^{o}F at the Y-12 Plant. Multiple readings are equally spaced. Average radius is 3.4665 in. or 8.0849 cm.

(b) The radius obtained from the sum of vertical heights, divided by 2, is 3.4673 in. or 8.8068 cm. The masses given are with all penetration of the sphere parts empty: screw holes for mass adjustment buttons, upper, lower, and central supports, voids and void around alignment cones and in the diametral hole. The masses were obtained on a large temperature and humidity controlled glass-enclosed balance traceable to the National Bureau of Standards and usually reported out to 0.01 g.

(c) Sum of these certified masses is 53,448.82 g. (*Masses actually add to 53,447.82; this is believed to be a typographical error*.)

(d) Polar height as if the parts were fabricated with no holes drilled at the poles.

(e) This mass does not include the 64 g of uranium in the socket for the attachment of the upper polar cap to its piston rod. *Although the support rod for the upper polar cap socket is referred to in Reference 1 as a piston it is technically not since the drive used in these experiments for the upper polar cap was a mechanical screw drive. (Personal communication with the experimenter, J.T. Mihalczo, July 8. 2013.)*

(f) Mass of upper and central plate after they were pinned together as one part with uranium metal pins. This mass does not include the 0.1293-in-dia., 4.265- and 2.745-in-long filler rod for the 0.136-in-dia. diametral hole which had masses of 17.117 and 11.046 g, respectively, and the uranium of the upper socket, which had a mass of 64 g. Thus the total uranium mass of the sphere was 53,240.27g, which includes the 64 g in the socket for the attachment of the upper polar cap to its piston rod. (*The 53,240.27 mass is an incorrect mass that was carried over from the older Reference 2. It is believed that the 2.745 in. length for the filler rod should actually be 2.7545 in., see Seection 1.2.2.*)

(g) Mass of the lower section consisting of the lower plate and lower polar cap was reported out only to 1-g accuracy. This mass is larger than that reported for this part in a previous publication (*Reference 2*), which omitted the mass of the pins that hold the lower polar cap and lower plate together.

Table 1-2. Measured Dimensions and Certified Masses of the 3.4420-in-radius Uranium Metal Sphere Parts. (Reference 1).

Sections [(a)]	Deviation from 3.4425-in radius[(b)] (10^{-3} in.)	Vertical Height[(c)] (in)	Certified Mass[(d)] (g)
Top	+1.2 at pole to -0.5 at bottom	2.1332[(e)]	11,883.24
Middle	-1.7 at top to -2.9 at bottom	1.8914	20,814.95
Bottom	+0.2 at top to +0.8 at pole	2.8608[(e)]	19,624.59

(a) The central section now consists of the central and upper plate pinned together, and the bottom section of the lower polar cap and lower plate pinned together.
(b) Measured with a sweep gage at 70 ^{o}F at the Y-12 Plant. There is near continuous variation between end points. Average radius is 3.4420 in. or 8.7427 cm.
(c) The radius obtained from the sum of vertical heights divided by 2 is 3.4427 in. or 8.7445 cm.
(d) The masses of the sphere sections with all penetration holes empty. The sum of these certified masses is 52,322.78 g.
(e) Polar height (to actual pole which is above the uranium metal due to the holes for the support).

The masses given in Table 1-1 and Table 1-2 can be verified with dimensional certification reports provided by the experimenter. The masses for the top and center section of Case 1; the top, middle, and bottom section of Case 2; and the diametral filler rods all match the masses given in the dimensional certification reports. For the bottom section of Case 1 the lower polar cap mass was given as 9,400.02 g and the lower plate mass was given as 10,610.27g. These masses were measured before the parts were pinned together. The 20,310 g mass in Table 1-1 was obtained from nuclear material control and accountability records.[a] Dimension certification reports were given for three pins with the following diameters, lengths and masses.

	Pin1	Pin2	Pin3
Diameter (in.)	0.4997/0.4998	0.4995/0.4997	0.4992/0.4995
Length (in.)	1.6650	1.6652	1.6655
Mass (g)	100.190	100.206	100.226

The pins did not break the surface of the lower polar cap. The parts were pinned and then the pins were machined to approximately match the surface of the plates. These dimensions and masses are further discussed in Section 2.2.7.

1.2.5 Mass Adjustment Button Recesses

Each of the two polar caps had eight equally spaced mass adjustment button recesses to partially accommodate mass adjustment buttons. In the center of the recesses there were tapped screw holes that were used with screws to hold the mass adjustment buttons in place. Mass adjustment buttons were used to add uranium mass and adjust reactivity but none were used in the two configurations evaluated here. For Case 1, the button recesses had a measured screw hole radius, which was then adjusted to account for threads to obtain a screw hole diameter of 0.138 in. as given in Figure 1-15. In the original sphere, the recesses into which the mass adjustment buttons fit had a radius of $0.875\,^{+0.005}_{-0.000}$ in. The depth of the recess was 0.018-in.

[a] Personal phone communication with J.T. Mihalczo, April 24, 2013.

deep measured at the edge of the recess.[a] When the ORSphere was re-machined the mass adjustment button recesses and screw holes were not re-drilled so the depth and diameter of the mass adjustment button recesses were reduced.[b] "The mass adjustment buttons recesses were located 45^{o} from the equator of the original GA sphere. So, when the machining moved the sphere center slightly, this angle was changed slightly in the final assembly."[c]

1.2.6 Upper Support Structure

The upper polar cap was attached to the upper support structure using a stainless steel socket that was surrounded by 64 g of HEU metal that was screwed into a tapped hole in the upper polar cap. The hole into which the socket threaded had a measured and adjusted, to account for the threads, diameter of 0.9536 in.[d] The depth of the hole was 0.393 in. for the larger sphere and 0.389 in. for the smaller sphere (see Figure 1-9 and Figure 1-14). A manufacturing drawing was provided of the socket and is given in Figure 1-16.

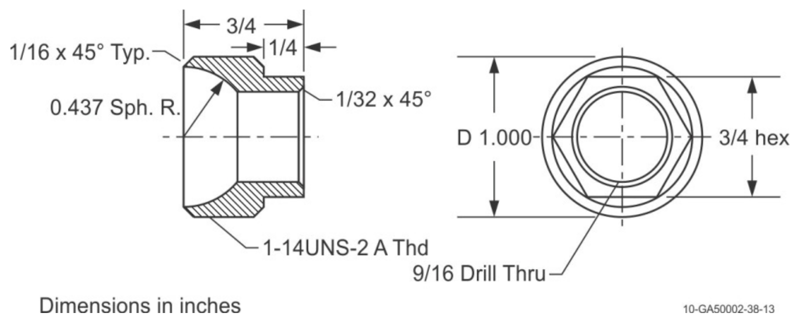

Figure 1-16. Upper Socket Dimensions.[e]

According to the experimenter, the density of the 64 g of uranium was 18.75 g/ cm^3.[f] The measured worth of the upper socket, including the 64 g of uranium, was 10.2 ± 0.1 ¢. The following method was used to measure the reactivity of the upper polar cap:

> The sphere was assembled to exactly delayed criticality by adjusting the number and location of surface uranium mass adjustment buttons and the position of a small aluminum reflector used for fine reactivity adjustment. The lower section of the sphere was lowered with the upper polar cap resting on the central section. The upper piston rod[g] was detached and withdrawn upward and the material in the upper support structure hole removed. A small hydrogenous reflector was added to the upper section of the sphere and the sphere reassembled. The presence of the hydrogenous reflector resulted in the system rising at an exponential rate with positive reactor period. At sufficiently high fission rate for measurement the hydrogenous reflector was completely removed. *The reactivity was*

[a] Personal email communication with J.T. Mihaclzo, January 30, 2013.
[b] Personal email communication with J.T. Mihaclzo, March 13, 2013.
[c] Personal email communication with J.T. Mihalczo, June 19, 2013.
[d] This diameter is to the middle of the threads. Personal email communication with J.T. Mihaclzo, February 6, 2013
[e] Redrawn from Reference 1.
[f] Personal phone communication between J.B. Briggs and J.T. Mihalczo, March 27, 2012.
[g] Although the support rod for the upper polar cap socket is referred to in Reference 1 as a piston it is technically not since the drive used in these experiments for the upper polar cap was a mechanical screw drive. (Personal communication with the experimenter, J.T. Mihalczo, July 8. 2013.)

determined from the negative stable reactor period measurement using the inhour equation with the six group delayed neutron parameters of Keepin.[a] The negative reactivity associated with removing the upper support structure was 10.2 ± 0.1 ¢ (piston rod and material in support hole. (Reference 1)

The upper socket acted as a flexible joint attaching the upper polar cap to a rod moved by a mechanical screw driver and attached to cross beam supports for the upper section of the sphere. The worth of the aluminum cross beam supports was 0.70 ± 0.09 ¢.[b] The upper polar cap was lowered 24 in. until it completely rested on the central sphere section when the sphere was assembled. Figure1-17 shows the upper polar cap, the socket, and the support rod attachment.

Figure1-17. Upper Polar Cap and Socket with Support Rod Attachment.

[a] The change to the quoted text (in italics) was made by the experimenter, J.T. Mihalczo on April 15, 2013.
[b] Material of the cross beam provided via personal communication with the experimenter, J.T. Mihalczo, July 8, 2013.

1.2.7 Central Support Structure

The center section was supported by four stainless steel tubes, which attached to the center plate by pins to threaded steel parts in the uranium. The steel parts threaded into holes with a measured and adjusted for threading diameter of 0.2764 in. (Figure 1-15). The joint between the tubes and the center plate was allowed to flex to ensure ideal positioning of the plate during assembly. Figure1-18 shows the center section of the sphere and the four thin walled stainless steel support tubes.[a] The stainless steel tubing attached to the 4-ft.-square post of the vertical assembly machine. The worth of the central support structure was determined by doubling the support structure material and then measuring the change in reactivity in a manner similar to that used to determine the worth of the upper polar cap socket. The worth of the central support structure and the lower support structure (see Section 1.2.8), including the post of the vertical assembly machine was 14.29 ± 0.05 ¢. It was measured in a manner similar to that described in Section 1.2.6, but by doubling the material present and measuring the reactivity change.

Figure1-18. Center Section and Support Structure.

[a] Material of the support tubes provided by the experimenter, J.T. Mihalczo, July 8, 2013.

1.2.8 Lower Support Structure

A brass bolt threaded into a hole at the pole of the lower polar cap. The brass bolt did not have a 1-in.-diameter as was stated in Reference 1 but a diameter of 0.5889 in., measured and adjusted for threading, as given in Figure 1-15.[a] The brass bolt was originally 0.5-in. long but was cut to 3/8 in. on February 25, 1971, to 0.320 in. on April 21, 1971, and finally to 0.303 in. on June 24, 1971.[b] "The shortest [brass bolt] was for the 3.4420-in. sphere. The middle length was for the 3.4665-in. sphere and the longest was for the first assembly of the [General Atomics] sphere."[c] The brass bolt was attached to a lightweight aluminum (Type 6061-T6) support stand that was on the moveable stainless steel table of the vertical assembly machine.

Figure 1-19 shows the lower section of sphere and the top of the attached support stand. Two stands were made to position the sphere 36 or 102 in. above the moveable table. "The taller stand raised the sphere from the vertical lift to minimize the reflection of neutrons from the lower structure of the vertical lift and increase the distance from the floor."[d] During assembly the lower polar cap and lower plate were lifted approximately 22 in. until they came into contact with the bottom of the center plate and lifted center plate, upper plate, and upper polar cap, which had already been lowered, approximately 0.020 in. Figure 1-20 is a schematic of the lower support stand. The worth of the central support structure (see Section 1.2.7) and the lower support structure, including the post of the vertical assembly machine was 14.29 ± 0.05 ¢. It was determined by doubling the support structure material and then measuring the change in reactivity in a manner similar to that used to determine the worth of the upper polar cap socket.

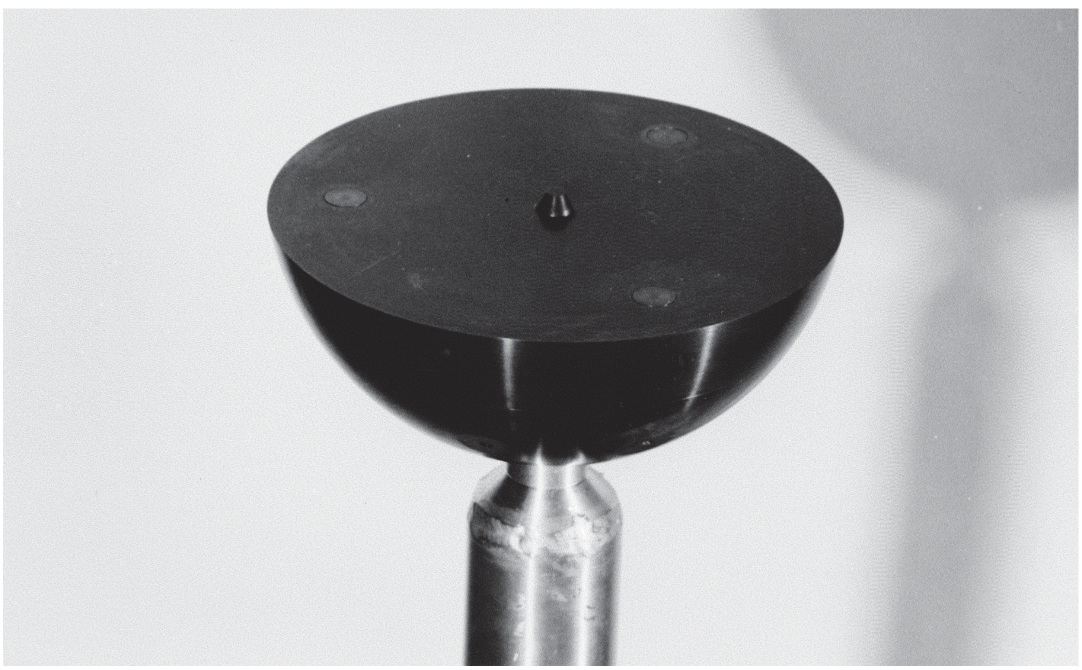

Figure 1-19. Bottom Section of Sphere with Lower Support.

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[a] Personal email communication with J.T. Mihalczo, February 14, 2013.
[b] Taken from hand written notes on a drawing provided by J.T. Mihalczo.
[c] Personal email communication with J.T. Mihalczo, March 8, 2013.
[d] Personal communication with J.T. Mihalczo, April 15, 2013.

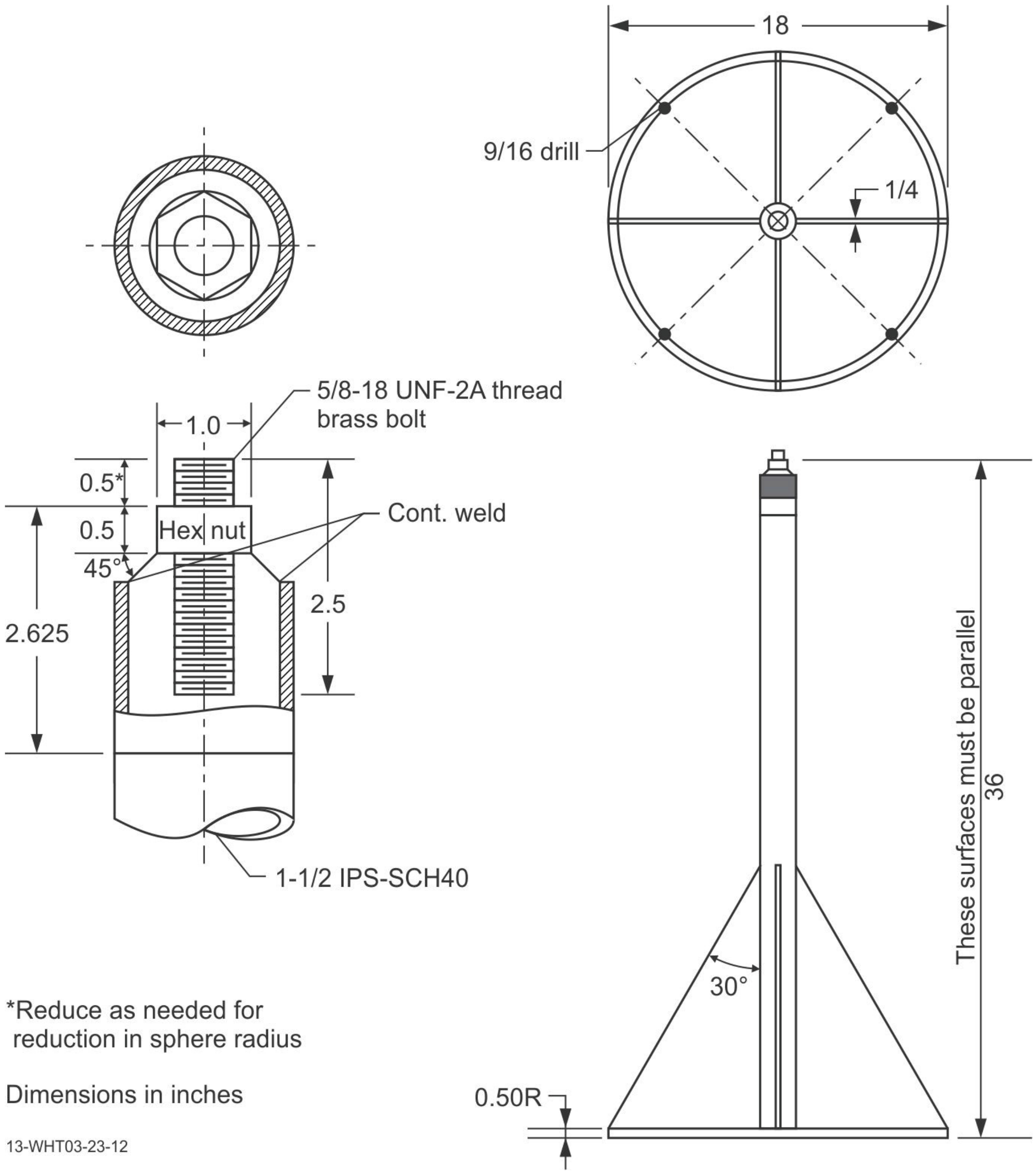

Figure 1-20. Shorter Lower Support Stand Dimensions.[a]
(The taller support stand was 102 in.)

[a] Redrawn from Reference 1.

1.3 Description of Material Data

1.3.1 Uranium

The ORSphere was made of ORALLOY, an Oak Ridge HEU alloy. Different parts of the sphere had different isotopic content as shown in Table 1-3. An impurity analysis was performed on most of the parts and is given in Table 1-4. The enrichments at Y-12 slowly decreased over time. The first six entries in Table 1-3 were measured when the sphere was originally fabricated in the 1960s and the latter entries in the table were for parts fabricated in the 1970s.

Table 1-3. Isotopic Content of Uranium Metal Parts
(Reference 1, additions by the evaluator are *italic*).

Part Description	Isotopic Content (wt.%)[(a)]			
	^{234}U	^{235}U	^{236}U	^{238}U
Upper Polar Cap	0.9844	93.21[(b)]	0.03593	5.76967
Upper Plate	0.9844	93.21 [(b)]	0.03593	5.76967
Central Plate	0.9843	93.2 [(b)]	0.03592	5.77978
Lower Plate	0.9845	93.22 [(b)]	0.03593	5.75957
Lower Polar Cap	0.9841	93.18 [(b)]	0.03592	5.79998
Mass adjustment buttons and upper socket	0.9846	93.23 [(b)]	0.03594	5.74946
Plug for target hole	0.9954	93.156	0.451	5.3976
Pins for central part	0.986	93.171	0.424	5.419
Pins for lower part	0.9954	93.156	0.451	5.3976
Filler rods for 0.136-in-dia diametral hole	0.9954	93.156	0.451	5.3976
Mass adjustment buttons (0.063 in. thick)	0.9954	93.156	0.451	5.3976

(a) These enrichments were from the average monthly enrichments of ~93.2 wt.% ^{235}U ORALLOY parts at the Y-12 for the month in which the parts were fabricated except where noted. The ^{234}U and ^{236}U are known to ±1% of the values stated, and the ^{235}U to four significant figures (i.e. ±0.005). The ^{238}U percentage is by difference and is not accurate beyond the third digit. The weighted average enrichments for these parts comprising the major parts, target hole filler and pins are 0.9844 wt.% ^{234}U, 93.20 wt.% ^{235}U, 0.04626 wt.% ^{236}U, and 5.7693 wt.% ^{238}U. (*The weighted averaged enrichment calculation could not be reproduced because the weight of the target hole filler and pins was not given.)*

(b) Measured and documented values.

Table 1-4. Impurity Content of Enriched Uranium Sphere Parts (Reference 1).

ORNL Part #	Part Description	Gram U per gram of uranium metal[(a)] x100	Impurity Content (ppm) [(c)] Boron Equiv-alent[(b)]	Be	Li	Al	Si	Total Fe, Mn, Ni, Cr, V Cu	B	Co	Ca	C	O	N
1-6	Upper Polar Cap	99.961	0.647	<0.01	<0.2	6	80	85	0.5	<1	<10	202	20	30
1-8	Upper Plate	99.966	0.408	<0.01	<0.2	4	100	34	0.3	<1	<10	159	20	30
1-10	Central Plate	99.966	0.328	<0.01	<0.2	4	200	50	0.2	<1	<10	159	20	30
1-11	Lower Plate	99.949	0.629	<0.01	<0.2	8	125	57	0.5	<1	<10	142	20	30
1-12	Lower Polar Cap	99.912	0.242	<0.01	<0.2	5	100	83	0.1	<1	<10	179	20	30
1-4	16 Mass Adjustment Buttons, 0.250-in. Thick	99.955	0.348	<0.01	<0.2	2	200	68	0.2	<1	<10	306	20	30
1-5	16 Mass Adjustment Buttons, 0.125-in. Thick	99.955	0.348	<0.01	<0.2	2	200	68	0.2	<1	<10	306	20	30
1-1	Socket for upper polar cap	99.955	0.348	<0.01	<0.2	2	200	68	0.2	<1	<10	306	20	30

(a) Reported to 5 digits; accurate to 4 digits.
(b) Boron equivalent is the parts per million boron that has the same thermal neutron absorption cross section as all impurities. Boron equivalent is only for elements in the table excluding oxygen and nitrogen. Boron equivalent is an approximation for the effect of impurities for assemblies with thermal neutron spectra where the predominant effect is boron absorption but is irrelevant for fission spectrum assemblies.
(c) In addition to these impurities, there were 20 ppm oxygen and 30 ppm nitrogen.

In Reference 1 the experimenter points out that the g U/g material and the impurity content are independently measured and the sum of the uranium weight fraction and the impurity content does not sum to the theoretical total of 1. He suggests a composition of 99.95 g of uranium per 100 g of material, 5 ppm, Al, 120 ppm Si, 62 ppm metals, 0.3 ppm B, 168 ppm C, 20 ppm O, and 30 ppm N be assumed for all uranium parts.

Table 1-3 does not provide an isotopic analysis for the filler of the thermocouple groove. The experimenter suggests the use of the same isotopics as the target hole plug since it was filled at the same time.[a] Table 1-4 does not provide an impurity analysis for the HEU pins, the filler rods, or for the target hole and thermocouple groove filler material.

[a] Personal email communication between T. Murray and J.T. Mihaclzo, December 9, 2011.

Reference 2 gives hydrostatically measured densities of 18.74, 18.77, and 18.72 g/cm^3 for the top, middle, and bottom sections of sphere. The experimenter provided a log page with the measured densities as 18.74, 18.74, and 18.72 g/cm^3.[a] Reference 1 gives a calculated density of 18.754 ±0.007 g/cm^3. The experimenter has indicated that these measured and this calculated densities should not be used but rather densities calculated using mass and dimension measurements should be used.[b]

1.3.2 Non-Uranium Components

The support structure was made of various materials. The exact composition of these materials was not given. The lower support structure was on the stainless steel moveable table of the vertical lift. The lower support structure was made of aluminum (Type 6061-T6) 1.5-in.-OD, Schedule 40 pipe and was welded to a brass bolt which screwed into the lower polar cap. The type of stainless steel or brass was not specified.[c]

The center section of the sphere was attached to the four vertical posts of the vertical assembly machine by stainless steel tubing which was attached by pins to threaded steel parts in the center plate. The type of stainless steel was not specified in the reports but stainless steel Type 304 was used.[d]

The material within the upper socket for the upper polar cap was stainless steel, but the material of the support rod above the socket and the cross beam material supporting the upper polar cap were not specified in the reports but stainless steel Type 304 was used.[c]

1.4 Temperature Data

Dimensional measurements of all parts were performed at the Y-12 plant at 70 ^{o}F (21.1 ^{o}C). All ORSphere experiments were performed at 24.5 ^{o}C (76 ^{o}F). The temperature coefficient for the ORSphere should be the same as the measured coefficient of 1/3 ¢ per degree centigrade for GODIVA I,[e] as is typically used for other ORCEF bare HEU experiments.

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[a] Personal email communication with J.T. Mihalczo, August 6, 2013.
[b] When asked about the measured densities the experimenter said, “It is not that they were wrong. They are not as accurate as the densities obtained from the very accurately measured dimensions and masses. They do not agree with those from dimensions and masses. For previous uranium metal parts we always used the densities from the masses and dimensions.” Personal phone communication with J.T. Mihalczo, April 24, and July 19, 2013.
[c] In an Appendix of Reference 1 a sample input deck created by Denise B. Pelowitz was provided. The input deck used pure copper for the brass but commented that the zinc was not included because cross section data were not available at that time.
[d] Personal communication with J.T. Mihalczo, April 15, 2013.
[e] Personal email communication with J.T. Mihalczo, March 11, 2013.

1.5 Supplemental Experimental Measurements

Various measurements were performed with the ORSphere components. As indicated previously, the five primary parts of the sphere were used to measure the neutron leakage spectrum in a subcritical HEU sphere using the LINAC at the General Atomics Company in San Diego, California.[a]

Experimental measurements were performed to assess the worth of structural components and estimate the effects of imperfections in the sphere. The reactivity worth of uranium of the surface of the sphere was obtained using measurements with the mass adjustment buttons. (References 1 and 2)

The spatial distribution of the neutron importance and fission density were performed to properly account for spatial effects in the point kinetics description of Rossi-α measurements.[b]

Prompt neutron decay constants, α, were measured at delayed criticality.[c,d,e]

The reactivity worth of a central void region of the sphere was measured to evaluate the effective delayed neutron fraction.[f,g] The worth of the central void region was measured by performing stable reactor period measurements for the sphere with and without a 0.460-in.-diameter uranium sphere inserted at the center of the ORSphere. These measurements were performed after the completion of the critical assembly measurements described in this evaluation and the diametral hole of the central plate had been reconfigured. Diametral filler rods were designed such that only a 0.460-in.-diameter sphere was void when the uranium sphere was removed. The stable reactor period with and without the small sphere of uranium present were measured 43 times with seven different detectors. The Inhour equation and delayed neutron parameters from Keepin et al.[h] was used to convert stable reactor period to reactivity in cents. The worth of the central void can then be found by comparing the system reactivity for the two states, with and without the sphere present. The worth of the region was then calculated in units of Δk using S_n transport theory methods. The ratio of the central void worth in units of cents/dollars and Δk then gives the effective delayed neutron fraction for the system. A value of 0.00657 ± 0.00002 β_{eff} was obtained.

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[a] J. L. Russell, Jr. and A. E. Profio, "Adequacy of Fast and Intermediate Cross Section Data from Measurement of Neutron Spectra in Bulk Media," GA-7059, General Atomics, San Diego, CA (April 27, 1966).
[b] J. T. Mihalczo, "Neutron Importance and Fission Density in Uranium-235-Enriched Uranium and Plutonium Metal Spheres," *Nucl. Sci. Eng.*, **56**, 271-290 (1975).
[c] J. T. Mihalczo, "The Effective Delayed Neutron Fraction from Fission in an Unreflected Uranium Sphere from Time Correlation Measurements with Californium-252," *Nucl. Sci. Eng.*, **60**, 262-275 (1976).
[d] J. T. Mihalczo, "Prompt Neutron Decay for an Unreflected and Unmoderated Uranium (HEU) Metal Sphere," *PHYSOR 1996*, Mito, Japan, September 16-20 (1996).
[e] J. T. Mihalczo, "Prompt Neutron Decay for Delayed Critical Bare and Natural-Uranium-Reflected Metal Spheres of Plutonium and Highly Enriched Uranium," *Nucl. Tech.*, **175**, 498-508 (2011).
[f] J. T. Mihalczo, J. J. Lynn, and J. R. Taylor, "The Central Void Reactivity in the Oak Ridge Enriched Uranium (93.2) Metal Sphere," ORNL/TM-13349, Oak Ridge National Laboratory (1997).
[g] J. T. Mihalczo, J. J. Lynn, and J. R. Taylor, "The Central Void Reactivity in the Oak Ridge National Laboratory Enriched Uranium (93.2) Metal Sphere," *Nucl. Sci. Eng.*, **130**, 153-163 (1998).
[h] G. R. Keepin, T. F. Wimett, and R. K. Zeigler, "Delayed Neutrons from Fissionable Isotopes of Uranium, Plutonium and Thorium," *J. Nucl. Energy*, **6**, (1957).

2.0 EVALUATION OF EXPERIMENTAL DATA

The two spherical assemblies (one slightly supercritical, one slightly subcritical) were evaluated using Monte Carlo N-Particle (MCNP) Version 5-1.60[a] and ENDF/B-VII.0[b] neutron cross section libraries. The effect of the uncertainty in measured parameters was found individually by increasing and decreasing the specified parameter value by a given amount; the Δk_{eff} for that uncertainty was found by taking one-half of the difference between the k_{eff} values for the perturbed models. All models were calculated such that the statistical uncertainty in k_{eff}, σ_{MC}, is ±0.00002. When the calculated Δk_{eff} was less than ±0.00006 ($3\sqrt{1/2\,(0.00002^2+0.00002^2)}$) the uncertainty effect cannot be determined with any certainty due to statistical uncertainty of the MCNP calculation and the effect is set as being ±0.00006 (prior to any scaling of the results, if necessary). The magnitude of most perturbations was increased beyond the specified 1σ uncertainties in order to obtain statistically significant results. The ratio of the perturbation to the 1σ uncertainty for the parameter was used as a "scaling factor" to convert the calculated Δk_{eff} to a 1σ uncertainty in k_{eff}. Statistically significant 1σ uncertainties that were less than ± 0.00001 were considered negligible.

Henceforth, the 3.4665-in.(8.80491 cm)-average-radius sphere will be referred to as Case 1 and the 3.4420-in. (8.74268 cm)-average-radius sphere will be referred to as Case 2.

2.1 Evaluation of Critical Measurement

The reactivity of Case 1 was +68.1 ± 2.0 ¢. The reactivity of Case 2 was -23.4 ¢. The same ±2.0 ¢ uncertainty given for Case 1 was also applied to Case 2. The uncertainty of the reactivity includes assembly reproducibility (±0.3 ¢), reactor period measurements uncertainties, and uncertainties in the delayed neutron parameter. The experimenter provided a β_{eff} for the system of 0.0066 ± 0.00005, based on GODIVA I measurements. It was later obtained using ORSphere void measurements data; the resultant β_{eff} value was determined to be 0.00657 ± 0.00002.[c,d] The β_{eff} was also calculated as part of this evaluation using two methods. The first method used k_{prompt}, calculated by MCNP5, and compared it to k_{eff} to calculate β_{eff} ($\beta_{eff} = 1 - k_{prompt}/k_{eff}$).[e] The second method used MCNP5 to calculate β_{eff} directly using adjoint-weighted methods capabilities in MCNP5-1.60.[f] Both methods used ENDF/B-VII.0 neutron cross section libraries. The results were slightly lower than the measured worth at approximately 0.00649. The measured β_{eff} of 0.00657 ± 0.00002 was used in this evaluation. Any systematic uncertainty in the delay neutron parameter s and nuclear data would be negligible since the reactivity is found by differences of the

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[a] F. B. Brown, R. F. Barrett, T. E. Booth, J. S. Bull, L. J. Cox, R. A. Forster, T. J. Goorley, R. D. Mosteller, S. E. Post, R. E. Prael, E. C. Selcow, A. Sood, and J. Sweezy, "MCNP Version 5," LA-UR-02-3935, Los Alamos National Laboratory (2002).
[b] M. B. Chadwick, et al., "ENDF/B-VII.0: Next Generation Evaluated Nuclear Data Library for Nuclear Science and Technology," *Nucl. Data Sheets*, **107**, 2931-3060 (2006).
[c] J. T. Mihalczo, J. J. Lynn, and J. R. Taylor, "The Central Void Reactivity in the Oak Ridge Enriched Uranium (93.2) Metal Sphere," ORNL/TM-13349, Oak Ridge National Laboratory (1997).
[d] J. T. Mihalczo, J. J. Lynn, and J. R. Taylor, "The Central Void Reactivity in the Oak Ridge National Laboratory Enriched Uranium (93.2) Metal Sphere," *Nucl. Sci. Eng.*, **130**, 153-163 (1998).
[e] R. K. Meulekamp and S. C. van der Marck, "Calculating the Effective Delayed Neutron Fraction with Monte Carlo," *Nucl. Sci. Eng.*, **152**, 142-148 (2006).
[f] B.C. Kiedrowski, et al., "MCNP5-1.60 Feature Enhancements and Manual Clarifications," LA-UR-10-06217, Los Alamos National Laboratory (2010).

system reactivity. The measured reactivity in cents, β_{eff}, and the calculated measured reactivity in terms of Δk_{eff} are given in Table 2-1.

Table 2-1. Uncertainty in Reactivity Measurement of Critical Configurations.

Case	Measured Reactivity (¢)	±	1σ	β_{eff} (1σ)	Reactivity (Δk_{eff})	±	σ
1	+68.1	±	2.0	0.00657 ± 0.00002	0.00447	±	0.00013
2	-23.4	±	2.0	0.00657 ± 0.00002	-0.00154	±	0.00013

2.2 Evaluation of Dimension and Mass Uncertainties

Dimensions and masses were measured to high accuracies using precise equipment at the Oak Ridge Y-12 plant. Non-spherical dimensions had an uncertainty of ± 0.0001 in. Masses had an uncertainty of ±0.01 g. Masses were measured on a "large glass balance with temperature and humidity control that measured the mass of 20 kilogram parts to a precision of 0.001 gram and that they normally reported out the results to 0.01 gram. … [T]his accuracy was produced by applying a correction for the difference in buoyancy of the ORALLOY and reference standard weights in air."[a] Surfaces were finished such that the gaps between plates were $0.0000^{+0.000254}_{-0.0000}$ cm, except for Case 1; the gap between the lower plate and the center plate was 0.01143 cm on one side of the sphere and 0 cm on the other due to the projection of a pin 0.005842 cm above the surface of the lower plate. The deviation from spherical for the two spheres was given in Table 1-1 and Table 1-2. Appendix B and C give example calculations for the volume of various sphere parts as well as AutoCAD® volumes calculated by Christine E. White of Idaho National Laboratory.

It should be noted that an uncertainty of 0.0004 in. rather than 0.0001 in. has been given for ORALLOY parts used in ORCEF critical experiments. This uncertainty is specifically stated as being for ORALLOY cylinders and annuli.[a] The experimenter has asserted that the uncertainty in the dimension measurements is 0.0001 in. for the ORSphere experiment.[b]

2.2.1 Sphere Radius

The uncertainty effect of the sphere radius was evaluated using the simple benchmark model. The radius of the simple benchmark model sphere was determined by creating a perfect sphere with a volume equal to the total uranium metal volume of the as-built sphere. This led to a conservation of mass and mass density in the simple benchmark model. The systematic measurement uncertainty in the radius and deviation from spherical was given as 0.254×10^{-3} cm; however, there is additional uncertainty in our ability to perfectly describe the curvature of the ellipsoidal parts with only a finite number of measurements. This additional

[a] J. T. Mihalczo, T. Gregory Schaaff, "Uncertainties in Masses, Dimensions, Impurities, and Isotopics of HEU Metal Used in Critical Experiments at ORCEF," ORNL/TM-2012/32, Oak Ridge National Laboratory (2012).
[b] Measuring to the nearest 1/10,000 inch would have been easily possible in the 1970's. Personal communication between J. Blair Briggs and Neal G. Boyce, Machinist Design Engineer, Idaho National Laboratory, 30 April, 2013.

uncertainty is discussed further is Section 2.2.2. A scaling factor was used when perturbing the sphere radius. Uranium metal mass was conserved during all perturbations. Results can be found in Table 2-2.

Table 2-2. Effect of the Uncertainty in Sphere Radius.

Case	Deviation (cm)	Δk_{eff}	±	σ_{MC}	Scaling Factor	1σ (cm)	Δk_{eff} (1σ)	±	$\sigma_{statistical}$
1	0.01	0.00187	±	0.00002	39.4	2.54×10^{-4}	0.00005	±	<0.00001
2	0.01	0.00189	±	0.00002	39.4	2.54×10^{-4}	0.00005	±	<0.00001

2.2.2 Curve of Ellipsoidal Parts

The deviation from spherical of the sphere parts was measured at a finite number of points using a sweep gage. Although the sweep gage measurements were point measurements due to the fabrication methods the deviation from spherical would be the same around the entire curve of the sphere at a given plane.[a]

However, because the curvature of the parts was described with only a finite number of measurements there is additional uncertainty in both the description and the modeling approximation of the curvature of those parts. This uncertainty is reflected in inconsistency in the uranium densities between Case 1 and Case 2. Total mass values for each configuration were accurately measured so the inconsistencies must be due to additional uncertainty in total volumes. An estimate of that uncertainty can be obtained by using the reported mass values and forcing the densities of Case 1 and 2 to be equal for each section of sphere. The deviation of the volume is then converted to a percent volume deviation for each sphere section. The mass weighted average of the absolution percent volume deviation for each sphere is 0.12%. This corresponds to a metal volume change of approximately 3.41 and 3.34 cm^3 for Case 1 and 2, respectively, for the simple benchmark model. The volume decrement translated into an uncertainty in the radius of approximately 0.0035 cm and an uncertainty in k_{eff} of about 0.00066. This method is most likely an overestimate of the uncertainty but is treated as a 1σ uncertainty and is included in the total experimental uncertainty summarized in Section 2.5.

2.2.3 Gaps Between Plates

The gap between the plates was given as $0.0000^{+0.000254}_{-0.0000}$ cm. In the detailed benchmark model the plates were modeled as touching except for between the lower plate and center plate of Case 1, which had a pin projecting above the surface of the lower plate causing a tilt to the center and upper section of the sphere. A model similar to the detailed benchmark model, except with only Si, B, and C uranium metal impurities present for ease of modeling, was used to perturb the gap between plates. Each gap was perturbed individually. When the gap between the lower plate and center plate of Case 1 was perturbed the tilt of the center plate, and all plates above it, was kept constant. Pins held the lower polar cap to the lower plate and the center plate to the upper plate. The length of the pins depended on the height of the plates so when a gap was modeled between the plates the pins were modeled as still going through those gaps thereby increasing the length of the pins. This increased the volume of the pins and thus reduced the calculated density of the material as the total mass of the section of sphere was conserved. Although the gap uncertainty was given as

[a] Personal phone communication with J.T. Mihalczo, April 24, 2013.

+0.000254 cm (0.0001 in.), because a gap of 0.0005 in. was discussed in Appendix A of Reference 1 the 1σ uncertainty in the gap was arbitrarily increased by a factor of 5 to 0.00127 cm. The results of the perturbation of the gap between plates for Case 1 and Case 2 are given in Table 2-3.

The tilt between the lower and center plate of Case 1 was also evaluated. The gap between the top of the lower plate and the bottom of the center plate was 0.01143 cm on one side of the sphere and 0 cm on the opposite. The resulting upward shift and tilt of the center plate, and all plates above it, was 0.003510385 cm and 0.0231340494 degrees (see Appendix E). The gap angle was evaluated by first creating a version of the detailed model without the pin protruding above the top surface of the lower plate; this resulted in a slight change in the density but had a negligible effect. Next, a model with the center plate sitting flat on the lower plate was created. The change in k_{eff} between these two models is a one sided bounding uncertainty for the tilt angle. The results are given in Table 2-3.

Table 2-3. Effect of the Uncertainty in the Gap Thickness Between Plates.

Case	Deviation (cm)	Δk_{eff}	±	σ_{MC}	Scaling Factor	1σ (cm)	Δk_{eff} (1σ)	±	$\sigma_{statistical}$
Lower Polar Cap/Lower Plate Interface[(a)]									
1	0.0127	0.00041	±	0.00003	10	1.27×10^{-3}	0.00004	±	<0.00001
2	0.0127	0.00044	±	0.00003	10	1.27×10^{-3}	0.00004	±	<0.00001
Lower Plate/Center Plate Interface[(b)]									
1	0.0127	0.00073	±	0.00003	10	1.27×10^{-3}	0.00007	±	<0.00001
2	0.0127	0.00111	±	0.00003	10	1.27×10^{-3}	0.00011	±	<0.00001
Center Plate/Upper Plate Interface[(a)]									
1	0.0127	0.00089	±	0.00003	10	1.27×10^{-3}	0.00009	±	<0.00001
2	0.0127	0.00076	±	0.00003	10	1.27×10^{-3}	0.00008	±	<0.00001
Upper Plate/Upper Polar Cap Interface									
1	0.0127	0.00058	±	0.00003	10	1.27×10^{-3}	0.00006	±	<0.00001
2	0.0127	0.00052	±	0.00003	10	1.27×10^{-3}	0.00005	±	<0.00001
Tilt Angle									
1	-	-0.00038	±	0.00003	$2\sqrt{3}$	-	-0.00011	±	0.00001

(a) Due to the HEU pins holding these two plates together this perturbation resulted in a material density change; the total mass was conserved.
(b) When perturbing the gap the tilt of the center plate, and thus all plates above it, was held constant.

2.2.4 Diametral Hole and Filler Rod Dimensions

A hole was drilled through the center of the Case 1 sphere with a diameter of 0.34544 cm. For Case 2, the center line of the diametral hole was 0.0508 cm below the center of the sphere. Two filler rods were placed in this hole when the sphere was taken to critical for both Case 1 and Case 2. The lengths of the shorter filler rod disagreed between Reference 1 and the dimensional certificate. Because all other masses and dimensions for the filler rods agreed between Reference 1 and the dimensional certificate it is believed that the length in Reference 1 is incorrect and the correct length is 2.7545 in. The two diametral filler rods were 10.8331- and 6.99643-cm long, had a 0.328422-cm diameter, and weighed 17.117 and 11.046 g, respectively. This corresponded to an average density of 18.64596 g/cm^3. The 1σ uncertainty in the diametral hole and filler rod diameters and filler rod length was the measurement uncertainty in non-spherical parts, 2.54×10^{-4} cm. The total length of the two filler rods was slightly larger than the length of the diametral hole and would have extended past the curve of the sphere. The results of the uncertainty analysis for the diametral hole and filler rod diameters and filler rod length are given in Table 2-4.

Table 2-4. Effect of the Uncertainty in the Diametral Hole and Filler Rod Dimensions.

Case	Deviation (cm)	Δk_{eff}	±	σ_{MC}	Scaling Factor	1σ (cm)	Δk_{eff} (1σ) ± $\sigma_{statistical}$
Diametral Hole Diameter							
1	0.00508	0.00002	±	0.00002	20	2.54×10^{-4}	NEG [(a)]
2	0.00508	0.00002	±	0.00002	20	2.54×10^{-4}	NEG [(a)]
Filler Rod Diameter							
1	0.00508	-0.00001	±	0.00002	20	2.54×10^{-4}	NEG [(a)]
2	0.00508	0.00002	±	0.00002	20	2.54×10^{-4}	NEG [(a)]
Filler Rod Length							
1	0.2	0.00004	±	0.00002	787	2.54×10^{-4}	NEG [(a)]
2	0.2	-0.00001	±	0.00002	787	2.54×10^{-4}	NEG [(a)]

(a) The effect of this perturbation is less than three times the statistical uncertainty of the Monte Carlo calculation despite using a scaling factor thus the perturbation effect was set at ±0.00006. When this value was scaled the Δk_{eff} (1σ) was negligible.

2.2.5 Brass Bolt Dimensions

The brass bolt had a 5/8-18 UNF-2A (inches) thread and fit into the bore hole at the bottom of the lower polar cap which was a 0.5781-in.-diameter-bore-hole with a 5/8-18 UNF-2B threading. Figure 1-15 gives the diameter of the bore hole and brass bolt as 1.495806 cm (0.5889 in.). This diameter takes into account the threading and is thus used in the detailed benchmark model. For Case 1 the brass bolt was 0.8128-cm long. For Case 2 the brass bolt was 0.76962-cm long. Because the length of the brass bolt was measured to three decimal places the uncertainty in the brass bolt length was ±0.005 in. (0.0127 cm). The difference between the maximum and minimum diameter of a 5/8-18UNF-2A thread is 0.0131 in. (0.033274 cm). This value was taken to be a bounding, one-sided uncertainty in the bolt diameter.[a] The dimensions of the brass

[a] Unified Screw Threads, Standard Series, http://www.efunda.com/designstandards/screws/unified.cfm?start=148&finish=227

bolt were each perturbed individually and are given in Table 2-5. The uncertainty in the bore-hole diameter is evaluated in Section 2.2.7.

Table 2-5. Effect of the Uncertainty in the Brass Bolt Dimensions.

Case	Deviation (cm)	Δk_{eff}	±	σ_{MC}	Scaling Factor	1σ (cm)	Δk_{eff} (1σ) ± $\sigma_{statistical}$
Bolt Diameter							
1	0.33274	-0.00007	±	0.00002	$10 \cdot 2\sqrt{3}$	$0.033274/2\sqrt{3}$	NEG
2	0.33274	-0.00007	±	0.00002	$10 \cdot 2\sqrt{3}$	$0.033274/2\sqrt{3}$	NEG
Bolt Length							
1	0.127	-0.00002	±	0.00002	10	2.54×10^{-3}	0.00001[(a)]
2	0.127	-0.00001	±	0.00002	10	2.54×10^{-3}	0.00001[(a)]

(a) The effect of this perturbation is less than three times the statistical uncertainty of the Monte Carlo calculation despite using a scaling factor thus the perturbation effect was set at ±0.00006 (before scaling).

2.2.6 Uncertainty in Part Masses

The masses of the bottom, center, and top sections of the sphere are given in Table 1-1 and Table 1-2. The uncertainty in the masses was ±0.01 g except for the bottom section of Case 1, which was measured to only ±1 g accuracy. The total mass of the two diametral filler rods was 28.163 g. The uncertainty in each of these masses was taken to be ±0.01 g thus the uncertainty in the total mass was ±0.014 g. The density of each part was perturbed individually to reflect the uncertainty of the part mass; the effect of these uncertainties is summarized in Table 2-6. Despite using scaling factors for some of the perturbations, the Δk_{eff} was still within the statistical noise of the MCNP calculation thus the uncertainty effect was set at ±0.00006 (before scaling).

If the mass of the lower polar cap and the lower plate given in the dimensional certification reports are added together a mass of 20,010.29 g is obtained. This is smaller than the given 20,310 g bottom section mass by approximately 300 g. This would lead one to believe that the three pins had a total mass of 300 g. However, the volume of the pins is such that the pin density would be extremely high (>20 g/cm^3). The total mass of the three pins described in the dimensional certification reports is approximately 300 grams but these pins were machined after they were fit into bottom section thus reducing the pin mass. However, the experimenter has asserted that the total section mass was measured as being 20,310 g after the bottom section was pinned together.[a] Based on this assertion the 20,310 g is used in the benchmark model for the bottom section mass and was homogenized over the entire bottom section volume as was done for the masses of other sphere sections.

[a] Personal phone communication with J.T. Mihaclzo, April 24, 2013.

Table 2-6. Effect of the Uncertainty in the Sphere Masses.

Case	Deviation (g)	Δk_{eff}	±	σ_{MC}	Scaling Factor	1σ (g)	Δk_{eff} (1σ) ± $\sigma_{statistical}$
Bottom Section Mass							
1	1	-0.00004	±	0.00002	1	1	0.00006 [(a)]
2	1	-0.00002	±	0.00002	100	0.01	NEG [(b)]
Center Section Mass							
1	1	0.00000	±	0.00002	100	0.01	NEG [(b)]
2	1	0.00000	±	0.00002	100	0.01	NEG [(b)]
Top Section Mass							
1	1	-0.00004	±	0.00002	100	0.01	NEG [(b)]
2	1	-0.00004	±	0.00002	100	0.01	NEG [(b)]
Diametral Filler Rod Mass							
1	2	-0.00003	±	0.00002	142.9	0.014	NEG [(b)]
2	2	-0.00005	±	0.00002	142.9	0.014	NEG [(b)]

(a) The effect of this perturbation is less than three times the statistical uncertainty thus the effect of the uncertainty was set at ±0.00006.
(b) The effect of this perturbation is less than three times the statistical uncertainty of the Monte Carlo calculation despite using a scaling factor thus the perturbation effect was set at ±0.00006. When this value was scaled the Δk_{eff} (1σ) was negligible.

2.2.7 Dimensions of Uranium Parts and Voids within Sphere

The masses of individual uranium parts within the sphere, including the HEU pins, target hole plug, thermocouple plug, and alignment cones, were not given, but were included in the total masses reported for the major sections of the sphere. Thus, the original densities for each individual part cannot be calculated and the densities of the smaller parts have very little or no effect on the overall density of the sphere. Each part had a slightly different enrichment thus the dimensions of each part had an effect of the averaged enrichment of the simple benchmark model sphere, which is discussed in Section 2.3. The effect of the dimensions of the HEU pins, target-hole plug, thermocouple plug, alignment cones and alignment cone holes, and the mass adjustment button recesses were evaluated using Case 1 by determining the effect each variation in dimension had on the radius and enrichment of the simple benchmark model. These variations are described below. The uncertainty in the height of the center plate had the maximum effect on the radius and enrichment of the simple benchmark model. A 0.000254 cm variation in the plate height had a change in the simple benchmark model sphere radius of 6.2×10^{-5} cm. When the effect of perturbing the sphere radius given in Table 2-2 is scaled to this value the resulting Δk_{eff} is 0.00001. This is the cutoff value for negligible thus it was judged that all the dimensions described below had a negligible effect on k_{eff}. The effects on the average enrichment were all well below the 1σ uncertainty in enrichment and were thus also negligible.

It was found that the effect of uncertainties in the dimensions of the individual uranium parts and void within the sphere had a negligible effect on k_{eff} for Case 1. The effect is judged to be negligible for Case 2 as well.

Dimensions given with respect to the center of the sphere or the center of the diametral hole, which was the same for Case 1 but 0.02 in. (0.0508 cm) apart for Case 2, are given as if the plates sit flush to one another and do not take into account of the tilt between the upper and center plate in Case 1.

Pin Depth in Lower Polar Cap The pin depth in the lower polar cap was given as 9/16 in. (1.42875 cm) in Figure 1-5 and Figure 1-10. However, based on the statement from the experimenter that the pins did not interfere with the mass adjustment buttons both of this depth is too deep. The depth of the pin was arbitrarily decreased to 7/16 in. (1.11125 cm). The pin depth did not affect the calculation of the density of the sphere but did affect the average enrichment in the simple benchmark model. When the pin depth was varied it was changed from 1.11125 cm to 1.42875 cm and had a negligible effect on enrichment.

Pin Diameter in Bottom and Center Sections The pin diameter in the bottom and center portions of the sphere was 0.453 in. (1.15062 cm). This diameter is a truncation diameter of the 29/64 in. given in the Section 1 figures. The text of Reference 1 gives the pin diameter as 0.4530 in. The pin diameter had an effect on the radius and the average enrichment of the simple benchmark model. Because of the discrepancy between the pin diameter in the drawings and the text the uncertainty in the diameter was arbitrarily increased from ±0.000254 cm to ±0.000508 cm.

Location of Top of Pins in Lower Polar Cap In Case 1 one pin extended above the top of the lower plate by 5.842×10^{-3} cm, one pin sat 1.27×10^{-3} cm below the flat surface, and the third was flush with the surface. In Case 2 one pin was flush with the top of the lower plate and the top of two pins sat 1.27×10^{-3} cm below the flat surface. The height of the top of the pins had an effect on the radius and the average enrichment of the simple benchmark model. The uncertainty in the location of the top of the pins was evaluated by making all pins flush with the top surface of the lower plate.

Cutoff Alignment Cone Cutoff alignment cones on the top of the lower plate and upper plate fit into corresponding holes in the center plate and upper polar cap. These alignment cones assured proper lateral alignment of the plates when the sphere was assembled. The diameter, height, and angle of these cones and holes were given in Figure 1-6, Figure 1-7, Figure 1-8, Figure 1-9, Figure 1-11, Figure 1-12, Figure 1-13, and Figure 1-14. The angle of both the cones and the holes was 30 ^{o}. The diameter of the cones was $1.270^{+0.000}_{-0.0127}$ cm and the diameter of the holes was $1.27254^{+0.0127}_{-0.000}$ cm. The height of the cones was $0.55372^{+0.000}_{-0.00508}$ cm (uncertainty given in Figure 1-11) and the height of the hole was $0.5715^{+0.0127}_{-0.000}$ cm. When the diameter and heights of the cones and holes were adjusted the radius and average enrichment of the simple benchmark model were affected.

Mass Adjustment Button Recesses Eight equally spaced mass adjustment button recesses were located on the lower and upper polar caps at a 45^{o} angle to the center of the original GA Sphere. When the sphere was re-machined as the ORSphere and from Case 1 to Case 2 this angle would have changed slightly. Because the true angle is unknown the button recesses are assumed to be at a 45^{o} angle to the center of the diametral hole for both cases. The effect of the uncertainty in this angle would be negligible. For Case 1, the button recesses consisted of a $1.11125^{+0.0127}_{-0.000}$-cm radius bore hole which had a depth of 0.4572 cm at the edge of the recess hole. The mass adjustment buttons were attached by screw and the screw hole had a depth of 0.268 in.

(0.68072 cm) in Figure 1-5 and Figure 1-9 (Case 1). In Figure 1-15 the screw-hole depth was given as 0.262 in. (0.66548 cm) with a measured and adjusted diameter of 0.138 in. (0.35052 cm). The uncertainty in the recess diameter was +0.0127 cm, the uncertainty in the bore-hole depth was ±0.000254 cm, and the uncertainty in the screw-hole diameter was ±0.000254 cm. The uncertainty in the screw-hole depth was evaluated by changing the depth from 0.68072 cm to 0.66548 cm. When the sphere parts were re-machined to a smaller radius the mass adjustment buttons recesses were not re-machined. Thus for the Case 2 detailed benchmark model the distance to the bottom of the screw hole and the bottom of recess from the center of the diametral hole, which was the center of the Case 1 sphere, was kept constant. The curve of the smaller sphere truncated the mass adjustment button recesses such that the depth was reduced for the upper polar cap and only a very small flat spot remained on the lower polar cap. When the dimensions of the mass adjustment button recesses were modified the radius and average enrichment of the simple benchmark model were affected.

Bottom Support Hole The diameter of the support hole for the brass bolt that provided the bottom support had a diameter of 1.495806 cm, as discussed in Section 2.2.5. The uncertainty in the bolt-hole diameter was 2.54×10^{-4} cm. For Case 1, the depth of the support hole was 0.393 in. (0.99822 cm) in Figure 1-5 and 0.385 in. (0.9779 cm) in Figure 1-15. The 0.99822 cm depth was used for the Case 1 detailed benchmark model. The support-hole depth was adjusted to 0.9779 cm in order to evaluate the effect of the uncertainty in the support-hole depth. The uncertainty in the diameter was evaluated when the diameter of the brass bolt was evaluated. The diameter of the lower support was the same for Case 2. For Case 2, the distance from the center of the diametral hole to the bottom of the support hole was the same as in Case 1. The curve of the smaller sphere made the depth of the support hole shallower. The resulting depth of the bore hole is 0.987298 cm which does not agree with the support-hole depth in Figure 1-10. It is believed that the bolt height was inadvertently put on Figure 1-10 rather than the true support-hole depth. A 1-in.-diameter (2.54 cm) spot face surrounded the bore hole in both Case 1 and 2. The uncertainty in the spot face diameter was ±0.000254 cm. The bottom support-hole dimensions affected the radius and average enrichment of the simple benchmark model.

Thermocouple A rectangular thermocouple groove at the top of the center plate was filled with HEU. The thermocouple groove had a width of 0.070 ± 0.004 in. (0.1778 ± 0.01016 cm). The depth of the thermocouple was 0.058 ± 0.002 in. (0.14732 ± 0.00508 cm) from 3/8 in. (0.9525 cm) away from the center of the sphere, through the center of the sphere, until a radius of 1.625 in. (4.1275 cm), at which point the depth increased to 0.116 ± 0.002 in. (0.29464 ± 0.00508 cm). The uncertainty in the penetration distance and depth transition location was taken to be ±0.01016 cm. Because the groove was filled by shrink fit there was no void around the HEU filler. The dimensions of the thermocouple groove did not affect the radius of the simple benchmark model but did affect the average enrichment of the simple benchmark model.

Target Hole The 1-in.-diameter (2.54 cm) target hole was filled by shrink fit with a plug so there was no void introduced. The target hole came within 0.3497 in. (0.888238 cm) of the center of the sphere. The uncertainty in these dimensions was ±0.000254 cm. The dimensions of the target hole did not affect the radius of the simple benchmark model but did affect the average enrichment of the simple benchmark model.

Screw Holes for Central Plate Support Four equally spaced screw holes were present at the center line of center plate for the four support rods. The screw holes had a depth of 0.268 in (0.68072 cm) in Figure 1-7 for Case 1. As was done with the mass adjustment button recesses the distance from the center of the plate to the bottom of the support rod screw holes was kept constant from the Case 1 detailed benchmark model to the Case 2 detailed benchmark model. The curvature of the smaller sphere made the depth of the screw holes shallower. The diameter of the screw holes was given in Figure 1-15 as 0.2764 in. (0.702056 cm), measured and adjusted for threading. The uncertainty in the diameter was ±0.000254 cm. The depth of the hole was given as 0.267 in. (0.67818 cm) in Figure 1-15. To evaluate the uncertainty in the screw-hole depth the depth was adjusted to 0.67818 cm from 0.68072 cm. The screw holes were empty in the detailed benchmark model. The dimensions of the screw holes had an effect on the radius and average enrichment of the simple benchmark model.

Upper Socket Hole The hole for the upper socket had a diameter of 2.422144 cm. The depth of the hole was 0.393 in. (0.99822 cm) for Case 1. As was done with the mass adjustment button recesses the distance from the center of the diametral hole to the bottom of the upper socket hole was kept constant from the Case 1 detailed benchmark model to the Case 2 detailed benchmark model. The curvature of the smaller sphere made the depth of the bore hole shallower. The uncertainty in the diameter and depth was ±0.000254 cm. The dimensions of the upper socket hole affected the radius and average enrichment of the simple benchmark model.

Lower Polar Cap Height The height of the lower polar cap was 1.8673 in. (4.742942 cm) for Case 1 and 1.8225 in. (4.62915 cm) for Case 2. The top surface of the lower polar cap was 1.6009 in. (4.066286 cm) from the center of the diametral hole for both cases, which was the center of the sphere for Case 1. The uncertainty in the height of the lower polar cap was ±0.000254 cm. The lower polar cap height affected the radius and average enrichment of the simple benchmark model.

Lower Plate Height The height of the lower plate was 1.0383 in. (2.637282 cm) for both Case 1 and 2. The top of the plate was 0.5626 in. (1.429004 cm) below the center of the diametral hole. The uncertainty in the height of the lower plate was ±0.000254 cm. The lower plate height affected the radius and average enrichment of the simple benchmark model.

Center Plate Height The height of the center plate was 1.1252 in. (2.858008 cm) for both Case 1 and 2. The center of the sphere was the same as the center of the center plate for Case 1, but for Case 2 the center of the sphere was 0.0508 cm above the center of the plate. The diametral hole went through the center of the plate. The uncertainty in the plate height was ±0.000254 cm. The center plate height affected the radius and average enrichment of the simple benchmark model and had the largest effect as is discussed below.

Upper Plate Height The height of the upper plate was 0.7662 in. (1.946148 cm) for both Case 1 and 2. The bottom of the upper plate was 0.1429004 cm above the center of the diametral hole in the center plate. The uncertainty in the height of the upper plate was ±0.000254 cm. The upper plate height affected the radius and average enrichment of the simple benchmark model.

Upper Polar Cap Height The height of the upper polar cap was 2.1375 in. (5.42925 cm) for Case 1 and 2.1332 in. (5.418328 cm) for Case 2. The bottom of the upper polar cap was 1.3288 in. (3.375152 cm) above the center of the diametral hole. The uncertainty in the height of the upper polar cap was ±0.000254 cm. The upper plate height affected the radius and average enrichment of the simple benchmark model.

The dimensions of all of the parts and void within the sphere were perturbed individually and the effect of the radius and average enrichment of the simple benchmark model was calculated. The effects of the variation of the parameters were all smaller then the 1σ uncertainty in the sphere radius and average enrichment. The largest effect was due to the uncertainty in the center plate height. A 0.000254 cm variation in the plate height had a change in the simple benchmark model sphere radius of 6.2×10^{-5} cm. When the effect of perturbing the sphere radius given in Table 2-2 is scaled to this value the results Δk_{eff} is 0.00001. This is the cutoff value for negligible thus it was judged that all the dimensions described in Section 2.2.7 had a negligible effect on k_{eff}. The effects on the average enrichment were all well below the 1σ uncertainty in enrichment and were thus also negligible.

2.3 Evaluation of Material Properties

2.3.1 Uranium Fraction and Impurities

The uranium metal impurity content was as given in Table 1-4. Impurity content was modeled in the detailed benchmark model as being one half the stated value if a detection limit is given or at the stated value if a measured content was given. Oxygen and nitrogen were also included in the detailed benchmark model. All impurities except silicon, boron, and carbon were removed in the simple benchmark model. For the HEU pins, the filler rods, and for the target hole and thermocouple groove filler material the suggested composition of 99.95 g of uranium per 100 g of material, 5 ppm, Al, 120 ppm Si, 62 ppm metals, 0.3 ppm B, 168 ppm C, 20 ppm O, and 30 ppm N was used. When the total weight fraction of uranium plus impurities did not add up to one the weight fractions were normalized to unity.

The impurity content for iron, manganese, nickel, chromium, vanadium, and copper was given as a total content. For the distribution of these six metal impurities the ratio of each metal element to the total content of the six impurities was calculated from impurity measurements for ORALLOY cylinders and annuli (see also HEU-MET-FAST-069).[a] Table 2-7 has the given impurity content for the six metals and ratio of the six metal impurities.

Table 2-7. Ratio of Metal Impurities in Oak Ridge Uranium Metal.[(a)]

Element	Impurity Content (ppm, by weight)	Ratio of Metal Impurity
Fe	0	0
Mn	56	0.297872
Ni	100	0.531915
Cr	7	0.037234
V	0	0
Cu	25	0.132979

(a) The metal impurity ratio was calculated from the metal impurities reported in HEU-MET-FAST-069.

The uncertainty in the uranium fraction was ±0.0001 g U/g total since it is accurate to four digits. However, a "realistic estimate of the uncertainty for [uranium weight fraction] measurements for a highly purified

[a] J. T. Mihalczo, "Graphite and Polyethylene Reflected Uranium-Metal Cylinders and Annuli," Union Carbide Corporation Nuclear Division, Oak Ridge Y-12 Plant, Y-DR-81 (April 28, 1972).

uranium metal (ORALLOY) with a skilled Y-12 workforce at the time [1960's and 1970's] would be 0.05% or lower."[a] Based on this the uncertainty in the uranium fraction was increased to ±0.0005 g U/g total.

The impurity content was perturbed ±100%. The uncertainty in impurity measurements at the Y-12 plant at the time of the experiment was ±20% for impurities measured above 10 micrograms/g-U and ±70% for impurities below 10 micrograms/g-U.[b] These were assumed to be bounding uncertainties. The 1σ uncertainty in the silicon and carbon impurities was 20%/√3. The uncertainty in the boron was 70%/√3. The boron, carbon, and silicon impurities were each varied individually. All other impurities were varied simultaneously and the 1σ uncertainty was taken to be 70%/√3. Impurities beside silicon, boron, and carbon individually had a small effect on k_{eff} and if they were perturbed individually the perturbation effect would not be above the statistical noise of the Monte Carlo calculation. The method of perturbing all the minor impurities simultaneously over estimates the true uncertainty. Case 1 was used for the impurity evaluation and it was judged that the results also applied to Case 2. Weight fractions were perturbed before normalization so; after an impurity content was perturbed the total weight fraction was normalized to one. The effects of these perturbations are summarized in Table 2-8.

[a] J. T. Mihalczo, T. Gregory Schaaff, "Uncertainties in Masses, Dimensions, Impurities, and Isotopics of HEU Metal Used in Critical Experiments at ORCEF," ORNL/TM-2012/32, Oak Ridge National Laboratory (2012).
[b] J. T. Mihalczo, T. Gregory Schaaff, "Uncertainties in Masses, Dimensions, Impurities, and Isotopics of HEU Metal Used in Critical Experiments at ORCEF," ORNL/TM-2012/32, Oak Ridge National Laboratory (2012).

Table 2-8. Effect of the Uncertainty in the Uranium Impurities.

Case	Deviation	Δk_{eff}	±	σ_{MC}	Scaling Factor	Δk_{eff} (1σ)	±	$\sigma_{statistical}$
Uranium Fraction								
1	0.001	-0.00002	±	0.00002	2	0.00003[(a)(b)]		
2			-					
Silicon Content								
1	100%	-0.00003	±	0.00002	$\left(\frac{100\%}{20\%}\right)\sqrt{3}$	0.00001[(a)(b)]		
2	-		-		-			
Boron Content								
1	100%	0.00000	±	0.00002	$\left(\frac{100\%}{70\%}\right)\sqrt{3}$	0.00002[(a)(b)]		
2	-		-		-			
Carbon Content								
1	100%	-0.00026	±	0.00002	$\left(\frac{100\%}{20\%}\right)\sqrt{3}$	-0.00003	±	<0.00001[(b)]
2	-		-		-			
All Other Impurities								
1	100%	-0.00011	±	0.00003	$\left(\frac{100\%}{70\%}\right)\sqrt{3}$	-0.00004	±	0.00001
2	100%	-0.00009	±	0.00003	$\left(\frac{100\%}{70\%}\right)\sqrt{3}$	-0.00004	±	0.00001

(a) The effect of this perturbation is less than three times the statistical uncertainty of the Monte Carlo calculation despite using a scaling factor thus the perturbation effect was set at ±0.00006 (before scaling).
(b) Case 1 was used to evaluate this uncertainty and it was judged that the results also apply to Case 2.

2.3.2 Uranium Isotopics

At the time of the experiment HEU metal isotopic content could be measured at Y-12 with an uncertainty of 0.0017 wt.% ^{234}U, 0.0177 wt.% ^{235}U, and 0.0130 wt.% ^{236}U.[a] In Table 1-3 the uncertainty in the ^{234}U and ^{236}U content was given as ±1% of the isotopic content and the uncertainty in the ^{235}U was ±0.005 wt.%. Because the typical uncertainties for the Y-12 plant were larger than the uncertainties given in Reference 1 for ^{235}U and ^{236}U the typical uncertainties are used as the 1σ uncertainties but the ±1% is used for the ^{234}U. The effect of the uncertainty in enrichment was determined using the simple benchmark model. The ^{238}U content was the difference between the unity and the sum of the other isotopic contents. When perturbing isotopic contents, in order to maintain a balance, ^{238}U content was adjusted accordingly. The results of this analysis are given in Table 2-9.

[a] J. T. Mihalczo, T. Gregory Schaaff, "Uncertainties in Masses, Dimensions, Impurities, and Isotopics of HEU Metal Used in Critical Experiments at ORCEF," ORNL/TM-2012/32, Oak Ridge National Laboratory (2012).

Table 2-9. Effect of the Uncertainty in the Uranium Enrichment.

Case	Deviation	Δk_{eff}	±	σ_{MC}	Scaling Factor	1σ	Δk_{eff} (1σ)	±	$\sigma_{statistical}$
^{234}U Content									
1	10%[(a)]	-0.00036	±	0.00002	10	1%[(a)]	-0.00004	±	<0.00001
2	10%[(a)]	-0.00037	±	0.00002	10	1%[(a)]	-0.00004	±	<0.00001
^{235}U Content									
1	0.177 wt.%	-0.00089	±	0.00002	10	0.0177 wt.%	-0.00009	±	<0.00001
2	0.177 wt.%	-0.00093	±	0.00002	10	0.0177 wt.%	-0.00009	±	<0.00001
^{236}U Content									
1	0.039 wt.%	-0.00003	±	0.00002	3	0.0130 wt.%	0.00002[(b)]		
2	0.039 wt.%	-0.00003	±	0.00002	3	0.0130 wt.%	0.00002[(b)]		

(a) It should be noted that the uncertainty in ^{234}U is 10% of the given weight percent.
(b) The effect of this perturbation is less than three times the statistical uncertainty of the Monte Carlo calculation despite using a scaling factor thus the perturbation effect was set at ±0.00006 (before scaling).

2.3.3 Non-Uranium Material

The type of brass for the brass bolt in the lower polar cap was not given. In the sample MCNP model in Appendix A of Reference 1, only copper was used but a comment indicated that zinc was left out because cross section data were not available. Based on this information C83400 Red Brass was used in the detailed benchmark model at a nominal density of 8.8 g/cm^3.[a] The brass was 90 wt.% copper and 10 wt.% zinc.

To determine the effective uncertainty in the brass the material was switched out for C85800 Yellow Brass, which has the lowest copper content of the red and yellow brass.[a] C85800 Yellow Brass had a composition of:

58 wt.%	Cu
1 wt.%	Sn
1 wt.%	Pb
40 wt.%	Zn

The 1σ uncertainty in the density of the brass was ±0.2 g/cm^3. The effect of switching out the material and of varying the density is given in Table 2-10.

[a] E. Oberg, et.al., "Machinery's Handbook," Industrial Press, Inc., New York, New York, 24th ed., 1992.

Table 2-10. Effect of the Uncertainty in the Non-Uranium Material Compositions.

Case	Deviation	Δk_{eff}	±	σ_{MC}	Scaling Factor	1σ	Δk_{eff} (1σ) ± $\sigma_{statistical}$
Brass Composition							
1	C85800 Yellow Brass	<0.00000	±	0.00002	1	-	0.00006 [(a)]
2		0.00001	±	0.00002	1	-	0.00006 [(a)]
Brass Density							
1	1 g/cm^3	-0.00002	±	0.00002	5	0.2 g/cm^3	0.00001[(b)]
2	1 g/cm^3	-0.00002	±	0.00002	5	0.2 g/cm^3	0.00001[(b)]

(a) The effect of this perturbation is less than three times the statistical uncertainty thus the effect of the uncertainty was set at ±0.00006.
(b) The effect of this perturbation is less than three times the statistical uncertainty of the Monte Carlo calculation despite using a scaling factor thus the perturbation effect was set at ±0.00006 (before scaling).

2.4 Temperature Uncertainty

The experiments were carried out at 24.5 ^{o}C. A 1σ uncertainty in temperature is taken to be ±2 ^{o}C. The temperature coefficient was -1/3 ¢/^{o}C. The effect of the uncertainty in the temperature would have been ±0.000044 Δk_{eff}.

2.5 Total Uncertainty in Critical Configuration

All 1σ uncertainties are compiled in Table 2-11. An uncertainty is considered to have a negligible effect (NEG) when the magnitude of the 1σ Δk_{eff} is ≤0.00001. The total uncertainties are ± 0.00075 Δk_{eff} for Case 1 and 0.00071 Δk_{eff} for Case 2. The experimenter indicated the total uncertainty for both cases should be approximately ±0.0004 Δk_{eff}.[a] The evaluated uncertainties are larger than this suggested value. The uncertainty for Case 1 is larger due to the larger measurement uncertainty effect and the uncertainty in the tilt angle. The two spheres are judged to be acceptable as criticality safety benchmark experiments.

[a] Personal email communication with J.T. Mihalczo, April 17, 2013.

Table 2-11. Total Uncertainty in Experimental Configuration.

			Case 1	Case 2
	±	1σ	± Δk_{eff} (1σ)	± Δk_{eff} (1σ)
Reactivity Measurement	±	2.0 ¢[(a)]	0.00013	0.00013
Radius	±	2.54×10^{-4} cm	0.00005	0.00005
Curve of Ellipsoidal Parts		See Section 2.2.2	0.00066	0.00066
Lower Polar Cap/Lower Plate Gap	±	2.54×10^{-4} cm	0.00004	0.00004
Lower Plate/Center Plate Gap	±	2.54×10^{-4} cm	0.00007	0.00011
Center Plate/Upper Plate Gap	±	2.54×10^{-4} cm	0.00009	0.00008
Upper Plate/Upper Polar Cap Gap	±	2.54×10^{-4} cm	0.00006	0.00005
Tilt Angle		See Section 2.2.3	-0.00011	-
Diametral Hole Diameter	±	2.54×10^{-4} cm	NEG	NEG
Diametral Rod Diameter	±	2.54×10^{-4} cm	NEG	NEG
Diametral Rod Length	±	2.54×10^{-4} cm	NEG	NEG
Brass Bolt Diameter	±	$0.033274/2\sqrt{3}$ cm	NEG	NEG
Brass Bolt Height	±	2.54×10^{-3} cm	0.00001	0.00001
Bottom Section Mass	±	Case 1- 1 g Case 2- 0.01 g	0.00006	NEG
Center Section Mass	±	0.01 g	NEG	NEG
Top Section Mass	±	0.01 g	NEG	NEG
Diametral Filler Rod Mass	±	0.014 g	NEG	NEG
Parts and Voids Within Sphere		See Section 2.2.7	NEG	NEG
Uranium fraction	±	0.0005 gU/gTotal	0.00003	0.00003
Silicon	±	$20\%/\sqrt{3}$	0.00001	0.00001
Boron	±	$70\%/\sqrt{3}$	0.00002	0.00002
Carbon	±	$20\%/\sqrt{3}$	-0.00003	-0.00003
Other Impurities	±	$70\%/\sqrt{3}$	-0.00004	-0.00004
^{234}U Content	±	1%	-0.00004	-0.00004
^{235}U Content	±	0.0177 wt.%	-0.00009	-0.00009
^{236}U Content	±	0.0130 wt.%	0.00002	0.00002
Brass Density	±	0.2 g/cm^3	0.00006	0.00006
Brass Composition		See Section 2.3.3	0.00001	0.00001
Temperature	±	2 ^{o}C	0.00004	0.00004
Total Experimental Uncertainty			**0.00071**	**0.00070**

(a) Reactivity Uncertainty includes reproducibility, reactor period measurement, and delayed neutron parameter uncertainties.

3.0 BENCHMARK SPECIFICATIONS

Detailed and simple benchmark models were created with MCNP5 using ENDF/B-VII.0, JEFF3.1, and JENDL-3.3 neutron cross section libraries. The biases of any simplifications or assumptions were calculated for both the detailed and simple models. All models were run in MCNP5 such that the statistical uncertainty (1σ) of k_{eff} was not more than 0.00002. Benchmark specifications for both the detailed and simple model are described in Sections 3.2 and 3.3.

The effects of individual simplifications were calculated in a step-wise fashion. The overall calculated simplification biases were found by comparing the detailed and simple benchmark model to the as-built model. The as-built model already includes measured simplification corrections. A β_{eff} of 0.00657 ± 0.00002 was used for this evaluation (see Section 2.1).

3.1 Description of Model

A simplification bias of -35 ¢ was given in Reference 1. Some explanation of this value is given in Appendix A of Reference 1 but it is impossible to determine what simplifications are included in this bias and how the bias was calculated. Because this bias cannot be accurately quantified it is not used in the derivation of the benchmark k_{eff} value.[a] Measured corrections of -14.29 ± 0.05 ¢ for the center, lower support structure, and four posts of the vertical assembly machine; -0.70 ± 0.09 ¢ for the cross beam for the upper support structure; and -10.2 ± 0.10 ¢ for the upper polar cap socket and attached support rod were given in Reference 1. These corrections yield a measured correction of approximately -25.19 ± 0.14 ¢ for the structural support. This is the value used in the derivation of the benchmark k_{eff} value because these support structures cannot be accurately modeled due to lack of dimensions and material data. The measured correction of the support structure was determined by doubling the support structure and measuring the change in reactivity. It is uncertain if doubling the support structure gives change in reactivity equal to the reactivity change for removing the structure thus the uncertainty in the measured corrections was increased to at least ±10%. This uncertainty is typical of HEU ORCEF experiments at the time (HEU-MET-FAST-051). The measured corrections for the support structure used in the benchmark models were -14.29 ± 1.429 ¢ for the center, lower support structure, and four posts of the vertical assembly machine; -0.70 ± 0.09 ¢ for the cross beam for the upper support structure (the given uncertainty of ±0.09 ¢ was retained because it was larger than a ±10% uncertainty); and -10.2 ± 1.02 ¢ for the upper polar cap socket and attached support rod. This yields a total measured correction for support structure of -25.19 ± 1.76 ¢.

A model to approximate the support structure worth was created using assumed dimensions and materials and is described in Appendix F. The support structure worth for the assumed dimensions and materials was approximately -20.3 ± 1.1 ¢. Although slightly lower than the measure structure worth, this approximation agrees with the measure value within 3σ.

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[a] This value was derived by Gordon Hansen using reactivity coefficients measured in GODIVA to make corrections. (Personal email communication with J.T. Mihaclzo, July 29, 2013.)

3.1.1 Description of Detailed Benchmark Model Simplifications

Five simplifications were made to obtain the detailed benchmark model: first, the room and air were removed, this was a calculated bias; second, the stainless steel plate of the vertical lift machine was removed, this was also a calculated bias; third, the upper support structure was removed, this was a measured correction worth 0.70 ± 0.09 ¢; fourth, the upper polar cap socket and support rod above it was removed, this was a measured correction worth 10.2 ±0.10 ¢; and fifth, the center and lower support structure was removed, this was also a measured correction worth 14.29 ± 0.05 ¢. There was also a temperature correction since all part measurements were performed at 21 ^{o}C and the experiment was completed at 24.5 ^{o}C. The temperature correction was -1/3 ¢ per ^{o}C with an assumed uncertainty of ±10%.

Measured corrections were used for the upper support structure, the upper polar cap socket and support rod, and the center and lower support structures because these features could not be accurately modeled due to lack of dimensions and material data. Calculating a simplification bias for the support structure would produce a large bias uncertainty due to the lack of information for the support structure. The measured corrections were used instead to reduce the bias uncertainty. The -0.70 ± 0.09 ¢ was used for the cross beam for the upper support structure. For the upper socket, including the 64 g of uranium, and the support rod above it a correction of -10.2 ± 0.10 ¢ was used. For the center and lower support structure a correction of -14.29 ± 0.05 ¢ was used. It is believed that the brass bolt is not a part of the correction worth for the center and lower support structure. It is believed that the screws in the center plate were accounted for in the correction for the center and lower support structure thus the screw holes are empty in the detailed benchmark model.

It is believed that the effect of the stainless steel table of the vertical lift machine, upon which the lower support structure sat, was not included in the measured bias for the center and lower support structure. The effect of the 45.72-cm diameter, 2.38-cm thick, and 31.2 kg stainless steel Type 304 table (HEU-COMP-FAST-004) was evaluated and treated as an additional bias in the detailed benchmark model.

The bias of the room return was calculated by modeling the center of the sphere as being 387.096 cm (12.7 ft) away from the 60.96-cm-(2-ft)-thick north wall, 713.232 cm (23.4 ft) from the 60.96-cm--(2-ft)-thick east wall, 682.752 cm (22.4) from the 60.96-cm--(2-ft)-thick south wall, 356.616 cm (11.7 ft) from the 152.4-cm--(5-ft)-thick west wall, 280.416 cm (9.2 ft) above the 60.96-cm--(2-ft)-thick floor and 629.7168 cm (22.66 ft) below the 60.96-cm--(2-ft)-thick ceiling. All walls, the floor and ceiling were modeled as being Oak Ridge Concrete (as was used in HEU-MET-FAST-081).[a]

The effect of moving the sphere to the center of the room had a negligible effect since the reactivity change was within the uncertainty of reproducibility. Based on this it is judged that the effect of any other equipment or structure within the experiment room would have had a negligible effect on the critical measurements.

Detailed comparison between the measured curvature of the ellipsoidal parts and the modeling approximation of that curvature shows no discernible differences. Therefore, additional modeling bias due to approximation of the measured curvature with ellipsoidal equations is insignificant. However, there is additional uncertainty in both the description and the modeling approximation of the curvature of those parts

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[a] *SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation*, ORNL/TM-2005/39 Version 5, Volume III, Section M.8, Oak Ridge National Laboratory, April 2005.

using a finite number of measurements. This uncertainty is accounted for as part of the experimental uncertainty and discussed in Section 2.2.2.

The simplification bias of the detailed benchmark model is given in Table 3-1. Biases were calculated using ENDF/B-VII.0, JEFF3.1, and JENDL-3.3 cross section libraries.[a]

Table 3-1. Summary of Simplification Biases for the Detailed Benchmark Model.

	Case 1			Case 2		
Room Return and Air	-0.00032	±	0.00003	-0.00033	±	0.00003
Stainless Steel Table	-0.00004	±	0.00003	-0.00001	±	0.00003
Calculated Simplification Bias						
ENDF/B-VII.0	-0.00037	±	0.00003	-0.00037	±	0.00003
JEFF3.1	-0.00030	±	0.00003	-0.00034	±	0.00003
JENDL-3.3	-0.00036	±	0.00003	-0.00028	±	0.00003
Overall Calculated Simplification Bias[(a,b)]	-0.00034	±	0.00005	-0.00033	±	0.00005
Upper Support Structure Correction (0.70 ±0.09 ¢)[(c)]	*-0.00005*	±	*0.00001*	*-0.00005*	±	*0.00001*
Support rod and Upper Socket Correction (10.2 ±10%)	*-0.00067*	±	*0.00007*	*-0.00067*	±	*0.00007*
Center and Lower Support Structure Correction (14.29 ± 10%)	*-0.00094*	±	*0.00009*	*-0.00094*	±	*0.00009*
Temperature Correction (1/3 ¢per ^{o}C ±10%)	*0.00008*	±	*0.00001*	*0.00008*	±	*0.00001*
Additional Equipment in Room	NEG[(d)]			NEG[(d)]		
Overall Simplification Bias	-0.00192	±	0.00013	-0.00191	±	0.00013

(a) The overall calculated simplification bias is found by comparing the detailed benchmark model to the as-built model. The as-built model already includes measured simplification biases.
(b) The calculated simplification bias is the average of the three cross section libraries. The uncertainty is the standard deviation of the three libraries' biases.
(c) The given uncertainty was retained for the upper support structure correction because it was larger than a 10% uncertainty.
(d) Because the effect of moving the sphere to the center of the room was within the reproducibility of the sphere the effect of additional equipment in the room was judged to be negligible.

3.1.2 Description of Simple Benchmark Model Simplifications

The simple benchmark model had the same five simplifications of the detailed benchmark model plus the bias of removing the brass bolt, removing all impurities except silicon, boron, and carbon, and homogenizing the uranium as one solid sphere. The effect of each of these simplifications is given in Table 3-2. The overall simplification biases were calculated using ENDF/B-VII.0, JEFF3.1, and JENDL-3.3 cross section libraries.[b]

[a] JEFF3.1 and JENDL-3.3 Results were provided by John D. Bess of Idaho National Laboratory.
[b] JEFF3.1 and JENDL-3.3 Results were provided by John D. Bess of Idaho National Laboratory.

There was also a temperature correction since all measurements were performed at 21 ^{o}C and the experiment was completed at 24.5 ^{o}C. The temperature bias was -1/3 ¢ per ^{o}C with an assumed uncertainty of ±10% and was used to adjust k_{eff} to the benchmark model temperature of 21 ^{o}C.

The geometry of each of these components is described in Section 3.2.1. When impurities were removed they were replaced with void thus reducing the total material weight fraction.

When homogenizing the uranium as one solid sphere the mass and mass density of the uranium was conserved. This essentially distributed the voids around the outside of sphere and reduced the radius. This approach is valid because the majority of the voids were at the edge of the sphere. The calculated bias of Case 1 for the homogenization of the sphere as one solid sphere was larger than the calculated bias for Case 2 because there were more mass adjustment button-recesses voids present.

Table 3-2. Summary of Simplification Biases for the Simple Benchmark Model.

	Case 1			Case 2		
Room Return and Air	-0.00032	±	0.00003	-0.00033	±	0.00003
Stainless Steel Table	-0.00004	±	0.00003	-0.00001	±	0.00003
Remove Brass Bolt	-0.00011	±	0.00003	-0.00012	±	0.00003
Remove Impurities Except Si, B, and C	-0.00011	±	0.00003	-0.00011	±	0.00003
Homogenize as One Sphere	0.00091	±	0.00003[a]	0.00030	±	0.00003[a]
Overall Calculated Simplification Bias[b]						
ENDF/B-VII.0	0.00019	±	0.00003	-0.00032	±	0.00003
JEFF3.1	0.00019	±	0.00003	-0.00029	±	0.00003
JENDL-3.3	0.00016	±	0.00003	-0.00022	±	0.00003
Overall Calculated Simplification Bias[c]	0.00018	±	0.00005	-0.00028	±	0.00005
Upper Support Structure Bias (0.70 ±0.09 ¢)[d]	*-0.00005*	±	*0.00001*	*-0.00005*	±	*0.00001*
Remove Support rod and Upper Socket (10.2 ± 10%)	*-0.00067*	±	*0.00007*	*-0.00067*	±	*0.00007*
Center and Lower Support Structure Bias (14.29 ± 10%)	*-0.00094*	±	*0.00009*	*-0.00094*	±	*0.00009*
Temperature Bias (1/3 ¢ per ^{o}C ±10%)	*0.00008*	±	*0.00001*	*0.00008*	±	*0.00001*
Additional Equipment in Room	NEG[e]			NEG[e]		
Overall Simplification Bias	-0.00140	±	0.00013	-0.00185	±	0.00013

(a) The calculated bias of Case 1 for the homogenization of the sphere as one solid sphere was larger than the calculated bias for Case 2 because there were more mass adjustment button-recesses voids present.
(b) The overall calculated simplification bias is found by comparing the simple benchmark model to the as-built model. The as-built model already includes measured simplification biases.
(c) The calculated simplification bias is the average of the three cross section libraries. The uncertainty is the standard deviation of the three libraries' biases.
(e) The given uncertainty was retained for the upper support structure correction because it was larger than a 10% uncertainty.
(d) Because the effect of moving the sphere to the center of the room was within the reproducibility of the sphere the effect of additional equipment in the room was judged to be negligible.

3.2 Benchmark Model Dimensions

3.2.1 Description of Detailed Benchmark Model

A summary of the methods used to derive ellipsoid equations, part volumes, and densities along with a summary of all part volumes, masses, and density is given in Appendices B and C.

A high number of digits on dimensions have been retained not to imply high accuracy but rather to reduce rounding error in the derivation of other dimensions and calculation of volumes.

Bottom Section The lower polar cap and the lower plate were pinned together with HEU pins to make the bottom section of the sphere. For Case 1 the two sections of sphere were machined separately before they were pinned together. For Case 2 the two sections were machined at the same time. The mass of the section was 20,310 g for Case 1 and 19,624.59 g for Case 2. The dimensions of the pins are given in Figures 3-1, -2, -3, -5, -6, and -7.

The top of one of the HEU pins extended above the top of the lower plate by 0.005842 cm, one sat 0.00127 cm below the top of the lower plate, and the third was flush with the top of the lower plate for Case 1. For Case 2 two of the pins were 0.00127 cm below the top of the lower plate and the third pin was flush with the top of the lower plate. This yields three different pin volumes for Case 1 and two for Case 2. The pin whose center is at (-6.35, 0, z) was modeled as protruding 0.005842 cm above the top of the lower plate for Case 1 and -0.00127 cm below the top of the lower plate for Case 2. The top of the pin whose center is at (3.17500, 5.49926, z) was modeled -0.00127 cm below the top of the lower plate for both cases. The top of the pin whose center is at (3.17500, -5.49926, z) was modeled flush with the top of the lower plate for both cases. It should be noted that the diametral hole was drilled through the pin in the center section whose center is at (-6.35, 0, z).

The location of the mass adjustment buttons recesses were calculated for Case 1 with respect to the center of the diametral hole and then kept constant for Case 2 (see Section 2.2.7). The average sphere radius of 8.80491 cm was used in these calculations.

The dimensions of the lower polar cap and lower plate for Case 1 are given in Figure 3-1 and Figure 3-2 and the bottom section of the sphere for Case 2 is given in Figure 3-3. The surface of the sphere was actually an ellipsoid and took into account the deviation from spherical of each section of the sphere by using the deviation at the pole/bottom and the top of each section to derive an ellipsoid equation. These equations took into account the fact that the sum of the heights of the sections of the sphere did not add to the average diameter of the sphere (Case 1 and 2) and the fact that the center of the sphere was 0.0508 cm higher than the center of the diametral hole which was the center of the model (Case 2). The equation of the resulting ellipsoid is given in Table 3-3 and Table 3-4.

Table 3-3. Ellipsoid Coefficients for Bottom Section of Sphere, Case 1.[(a)]

$Ax^2 + By^2 + C(z - \bar{z})^2 + G = 0$							
	Deviation From Spherical (cm)[(b)]		A (cm^{-2})	B (cm^{-2})	C (cm^{-2})	G (--)	$\bar{z}$[(c)] (cm)
Lower Polar Cap	-4.75E-03 at top	-5.08E-04 at pole	61.02204	61.02204	60.95049	-4724.72940	-0.004826
Lower Plate	-2.03E-03 at top	0 at bottom	14.49263	14.49263	14.45685	-1122.97037	0

(a) An example of the derivation of these coefficients is given in Appendix B.
(b) The deviation from spherical is based off a radius 8.80491 cm.
(c) This axial shift was due to the fact that the sum of the heights of the sections did not add up to the average diameter of the sphere.

Table 3-4. Ellipsoid Coefficients for Bottom Section of Sphere, Case 2.[(a)]

$Ax^2 + By^2 + C(z - \bar{z})^2 + G = 0$							
	Deviation From Spherical (cm)[(b)]		A (cm^{-2})	B (cm^{-2})	C (cm^{-2})	G (--)	$\bar{z}$[(c)] (cm)
Bottom Section	5.08E-04 at top	2.03E-03 at pole	74.30313	74.30313	74.27648	-5681.57126	0.050546

(a) An example of the derivation of these coefficients is given in Appendix B.
(b) The deviation from spherical is based off the nominal radius of 8.74395 cm.
(c) This axial shift was due to the fact that the sum of the heights of the sections did not add up to the average diameter of the sphere and the shift of the center of the sphere 0.0508 cm above the center of the diametral rod which was the center of the model.

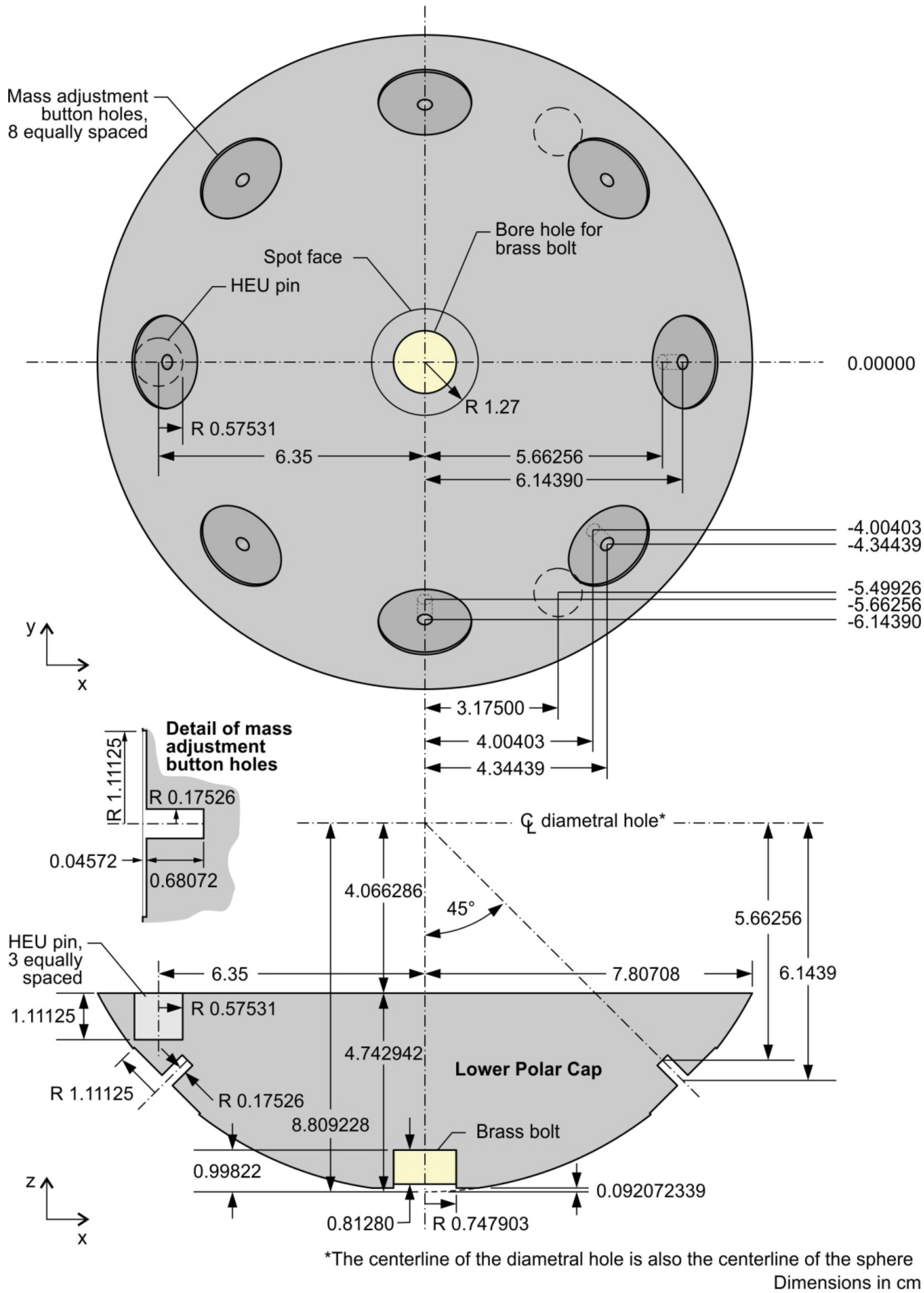

Figure 3-1. Lower Polar Cap for Case 1 (Detailed Benchmark Model).[a]

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[a] A high number of digits on dimensions have been retained not to imply high accuracy but rather to reduce rounding error in the derivation of other dimensions and the calculation of volumes.

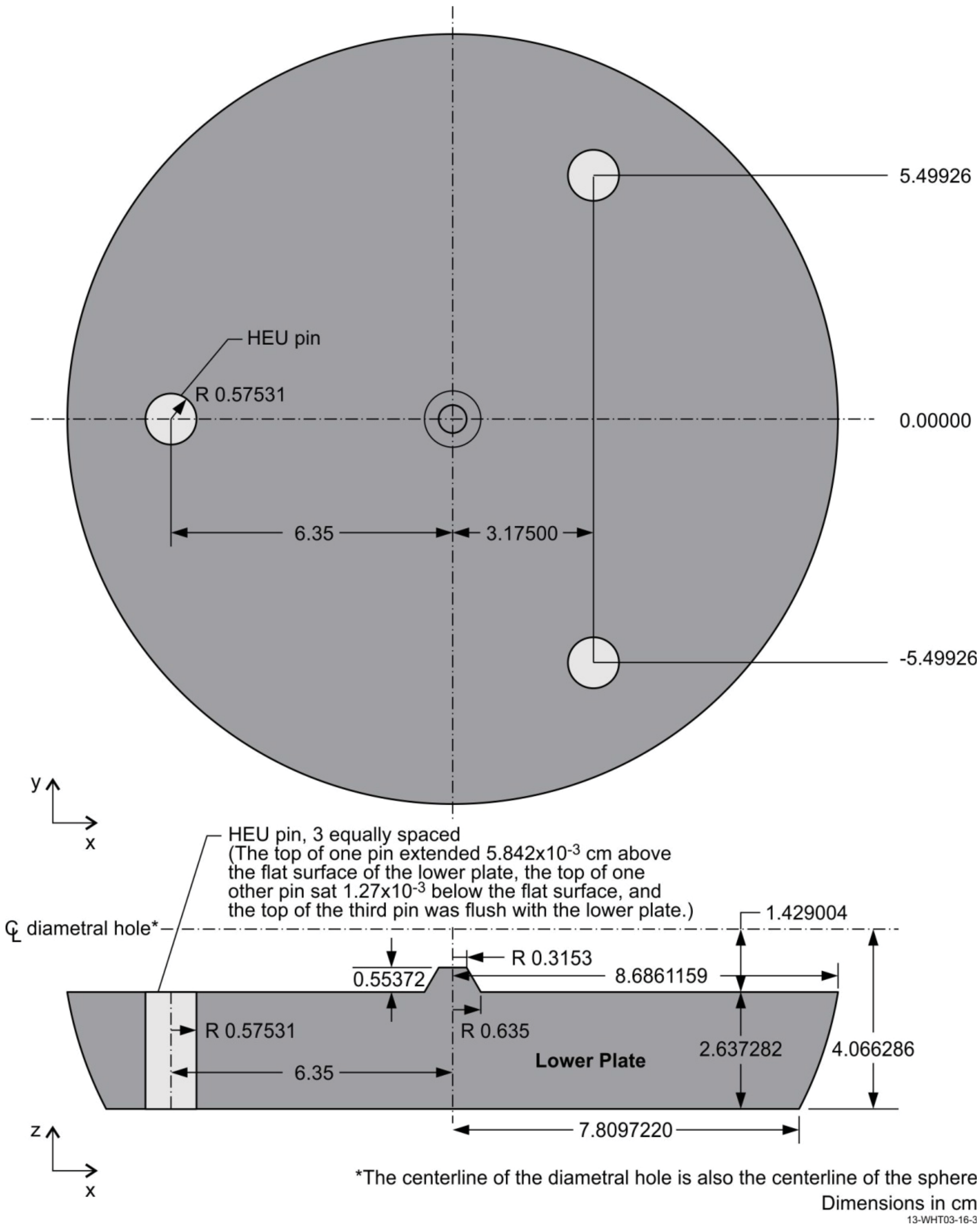

Figure 3-2. Lower Plate for Case 1(Detailed Benchmark Model).[a]

[a] A high number of digits on dimensions have been retained not to imply high accuracy but rather to reduce rounding error in the derivation of other dimensions and the calculation of volumes.

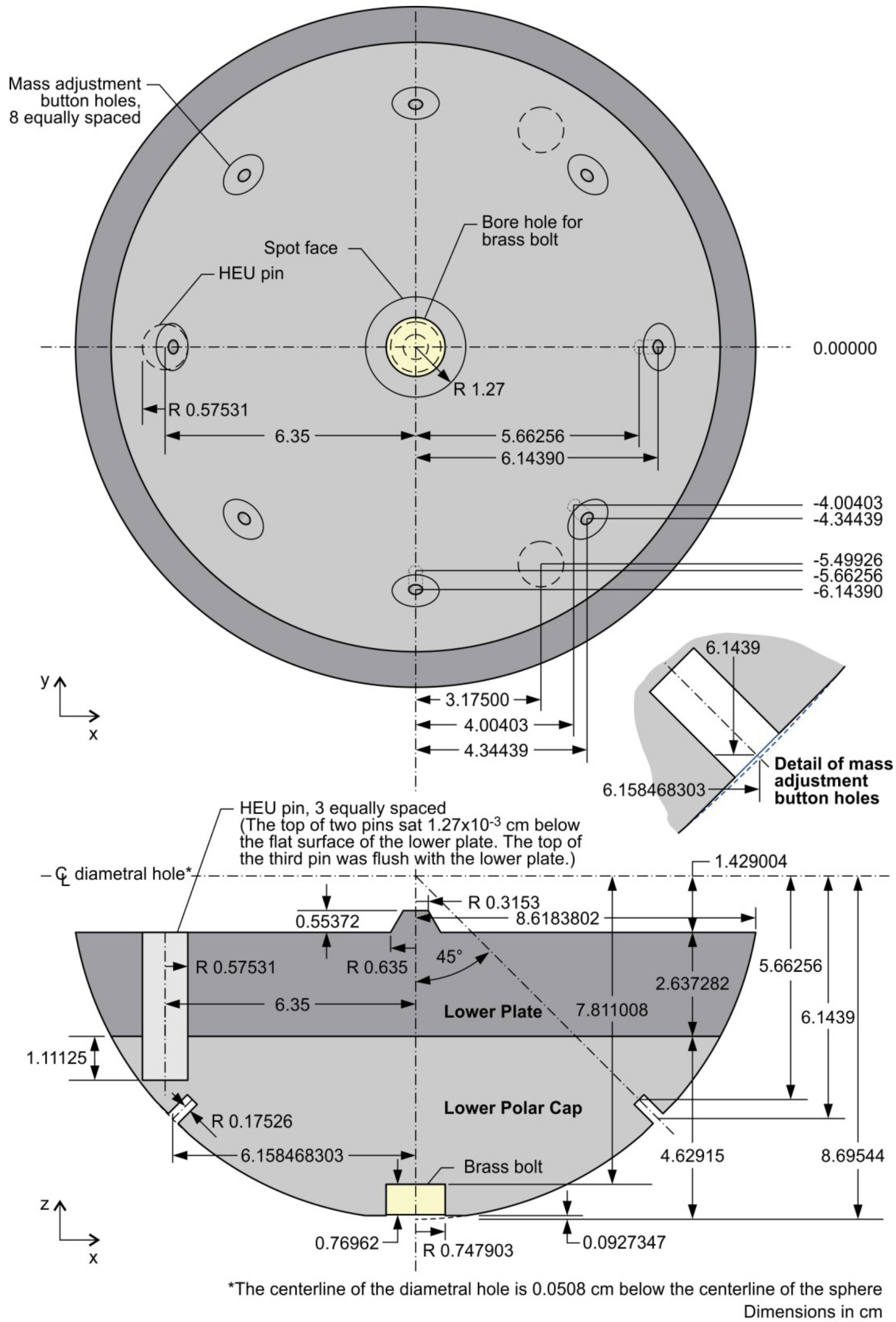

Figure 3-3. Bottom Section of Sphere for Case 2.[a]

[a] A high number of digits on dimensions have been retained not to imply high accuracy but rather to reduce rounding error in the derivation of other dimensions and the calculation of volumes.

Center Section The center plate and upper plate were pinned together with HEU pins to make the center section of the sphere. For Case 1 the two sections were machined separately and then pinned together. For Case 2 the two sections were machined at the same time. The mass of the center section of sphere was 21,095.06 g for Case 1 and 20,814.95 g for Case 2. The diametral rod was 17.82953 cm long, was centered in the diametral hole and had a mass of 28.163 g for both cases. The diameter of the diametral hole was constant across the sphere and through the target hole plug. The diametral rod could move freely within the diametral hole.

The location of the center support screw holes was calculated for Case 1 with respect to the center of the diametral hole using the average radius of 8.80491 cm and then kept constant for Case 2 (see Section 2.2.7).

Due to a protrusion of an HEU pin above the top of the lower plate in Case 1 all plates above the center plate were tilted. The gap between the top of the lower plate and the bottom of the center plate was 0.01143 cm on one side of the sphere and 0 cm on the opposite. This corresponds to a vertical shift of 0.00351038 cm and an angle of 0.0231340494 degrees (see Appendix E). The benchmark model was such that the gap was on the negative *x* side of the sphere and the plates meet on the positive *x* side of the sphere. Using the angle of 0.0231340494 degrees the center plate would have overhung the edge of the lower plate by approximately 0.008 cm. Because of the center support structure this would not have happened. It is believed that the calculated overhang is due to the unknown point of rotation of the center plate. If the point of rotation is fixed at the center of the plate, such that the centers of the lower and center plates remain perpendicular and, using the given vertical shift and angle, the edge of the plates are actually ~3.4×10^{-6} cm apart rather than touching. This gap is within the uncertainty in the gap between plates. At the opposite side of the plates the gap should be 0.01143 cm, but is only ~0.007 cm. The effect of the different gap is within the uncertainty in the tilt angle. The gap is shown in Figure 3-4.

The dimensions of the center plate and upper plate for Case 1 are given in Figure 3-5 and Figure 3-6 and for Case 2 are given in Figure 3-7. Figure 3-8 shows a three-dimensional rendering of the thermocouple groove without the HEU filler. The surface of the sphere was actually an ellipsoid and took into account the deviation from spherical of each section of the sphere by using the deviation at the bottom and top of each section to derive an ellipsoid equation. For Case 1 the deviation at the center of the plate had to be used as well and was taken from Figure 1-15 as being -0.6×10^{-3} in. (-1.52×10^{-3} cm). The equations for the ellipsoids are given in Table 3-5 and Table 3-6.

Table 3-5. Ellipsoid Coefficients for Center of Sphere, Case 1.[(a)]

$Ax^2 + By^2 + C(z - \bar{z})^2 + G = 0$							
	Deviation From Spherical (cm)[(b)]		A (cm^{-2})	B (cm^{-2})	C (cm^{-2})	G (--)	$\bar{z}$ (cm)
Center Plate-Lower Half	-2.54E-03 at bottom	-1.52E-03 at center	2.042052	2.042052	2.05994	-158.25826	0
Center Plate-Upper Half	-1.52E-03 at center	-5.08E-04 at top	2.042052	2.042052	2.024163	-158.25826	0
Upper Plate	-2.54E-03 at bottom	-5.08E-04 at top	9.349599	9.349599	9.313822	-724.34990	0

(a) An example of the derivation of these coefficients is given in Appendix B.
(b) The deviation from spherical is based off a radius 8.80491 cm.

Table 3-6. Ellipsoid Coefficients for Center Section of Sphere, Case 2.[(a)]

$Ax^2 + By^2 + C(z - \bar{z})^2 + G = 0$							
	Deviation From Spherical (cm)[(b)]		A (cm^{-2})	B (cm^{-2})	C (cm^{-2})	G (--)	$\bar{z}$ (cm)
Center Section	-7.37E-03 at bottom	-4.32E-03 at Top	9.3496	9.3496	9.29633	-713.52645	0

(a) An example of the derivation of these coefficients is given in Appendix B.
(b) The deviation from spherical is based off the nominal radius of 8.74395 cm.

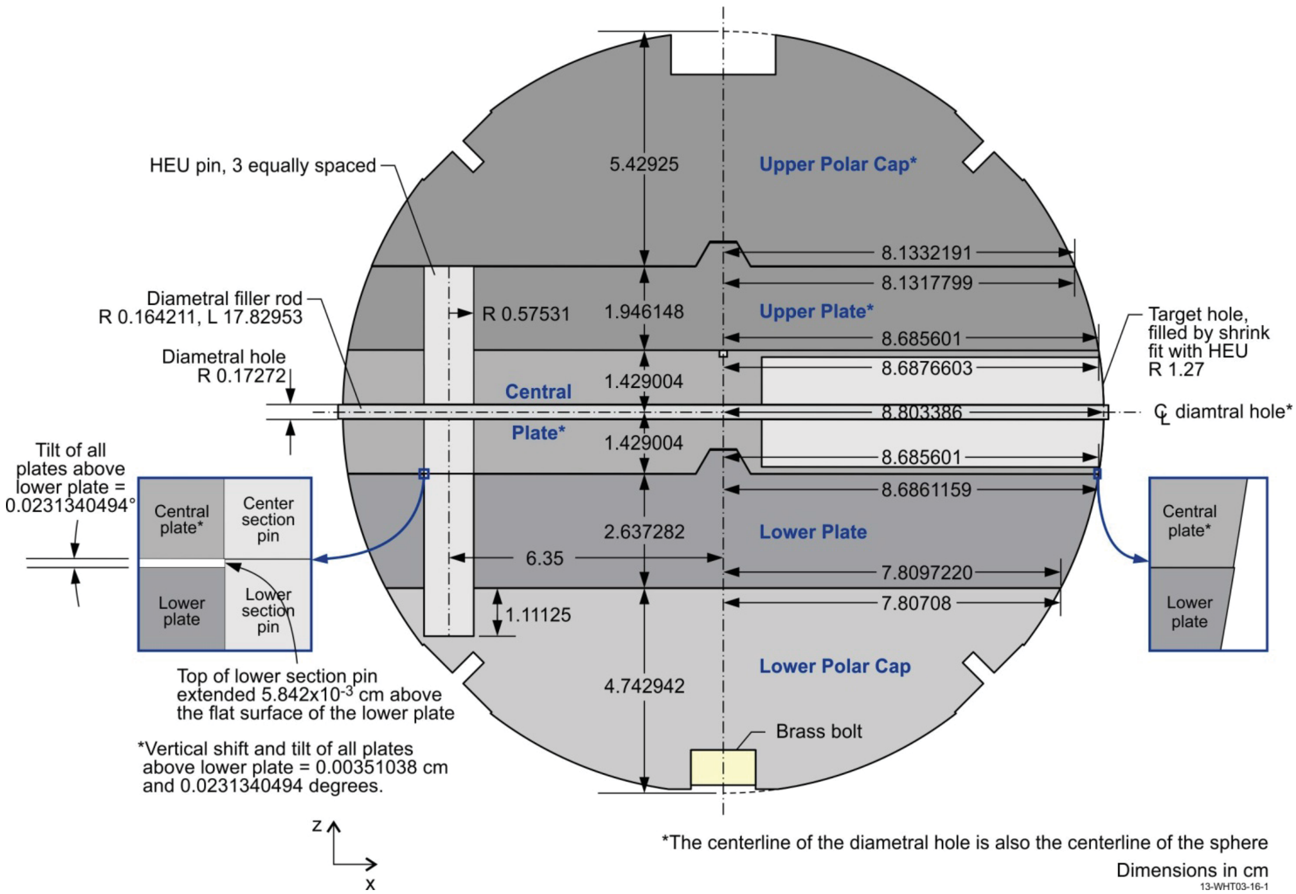

Figure 3-4. Tilt Between Lower Plate and Center Plate, Case 1(Detailed Benchmark Model).[a]

[a] A high number of digits on dimensions have been retained not to imply high accuracy but rather to reduce rounding error in the derivation of other dimensions and the calculation of volumes.

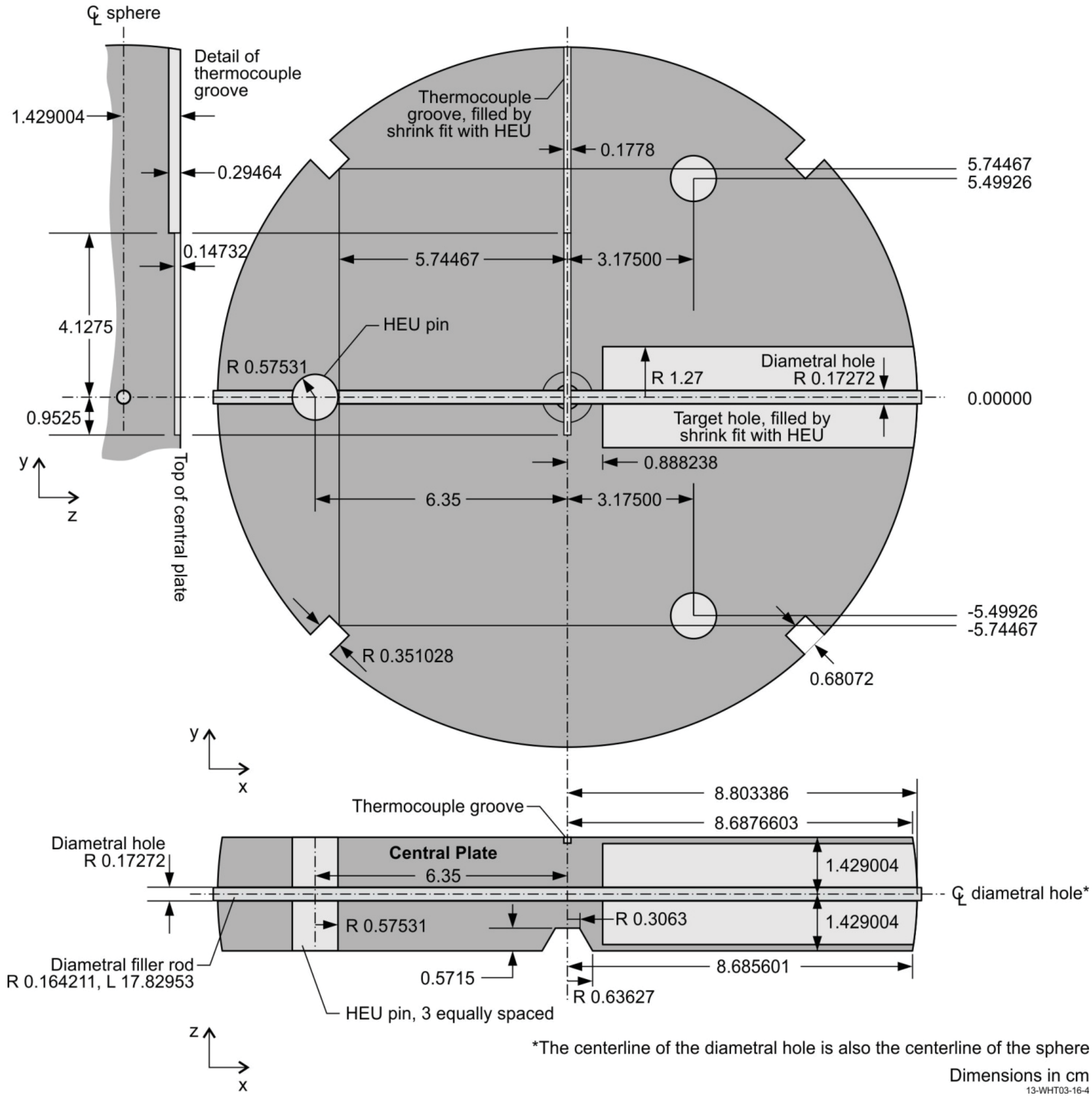

Figure 3-5. Center Plate, Case 1(Detailed Benchmark Model).[a]

[a] A high number of digits on dimensions have been retained not to imply high accuracy but rather to reduce rounding error in the derivation of other dimensions and the calculation of volumes.

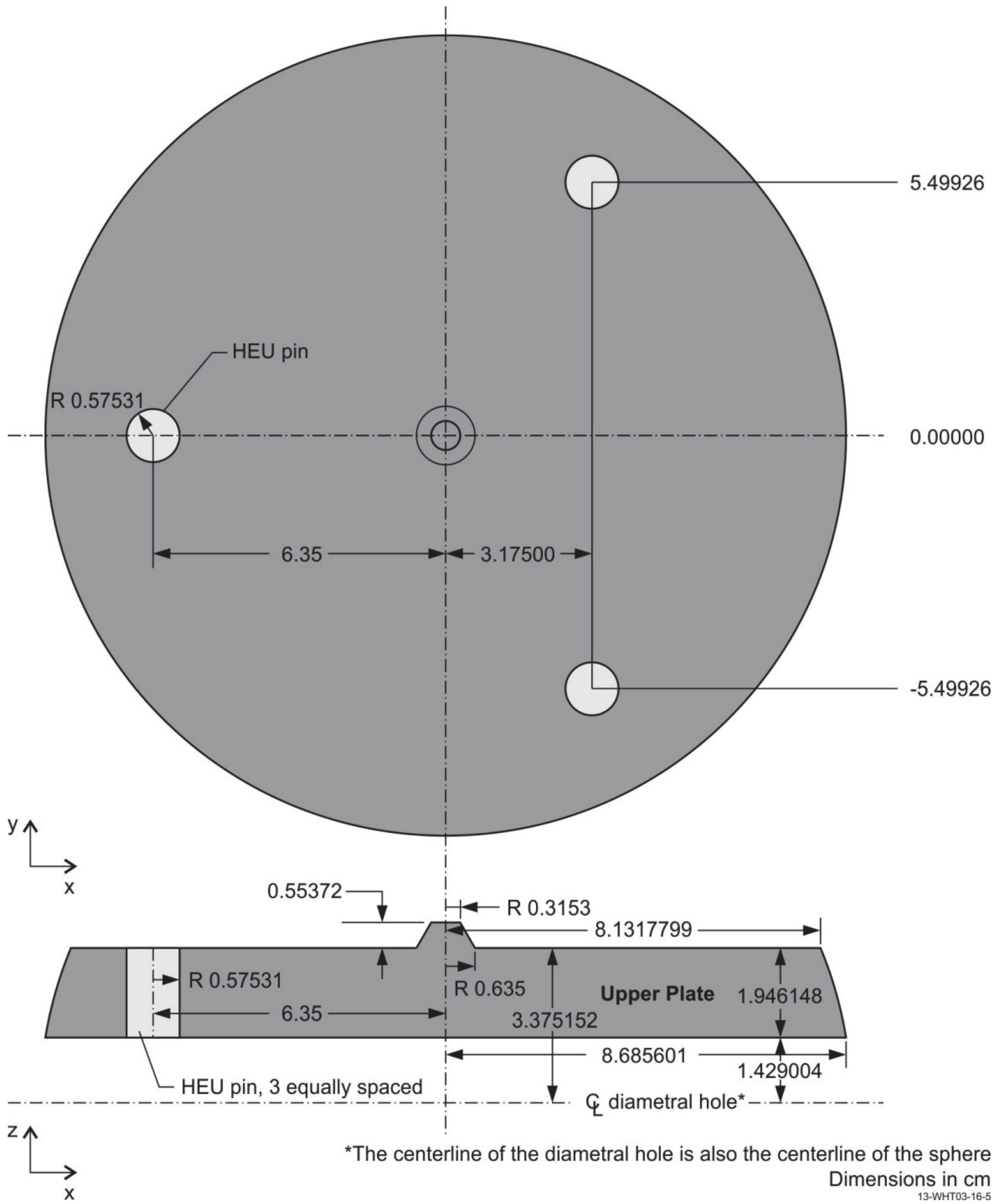

Figure 3-6. Upper Plate, Case 1(Detailed Benchmark Model).[a]

[a] A high number of digits on dimensions have been retained not to imply high accuracy but rather to reduce rounding error in the derivation of other dimensions and the calculation of volumes.

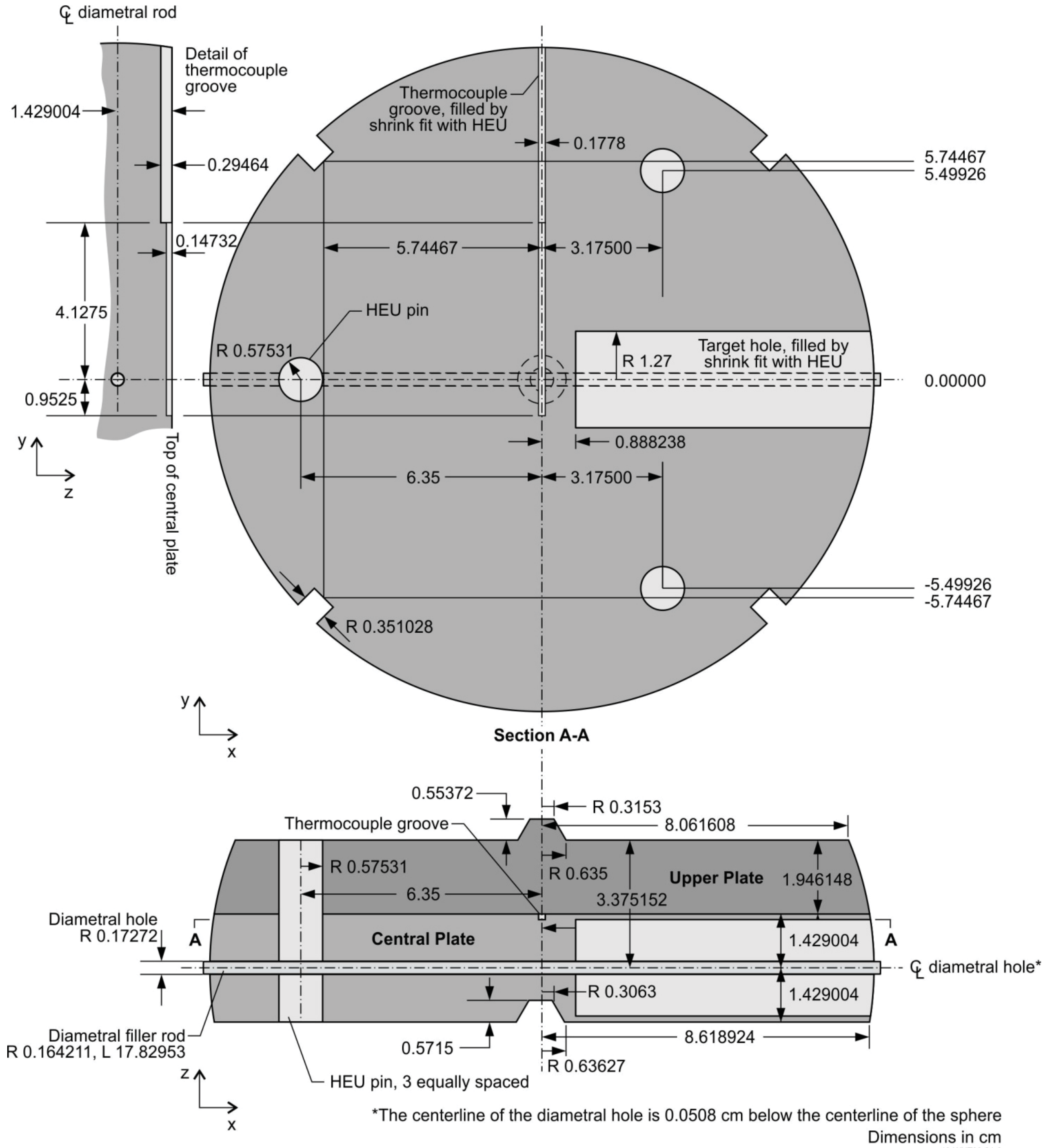

Figure 3-7. Center and Upper Plate, Case 2 (Detailed Benchmark Model).[a]

[a] A high number of digits on dimensions have been retained not to imply high accuracy but rather to reduce rounding error in the derivation of other dimensions and the calculation of volumes.

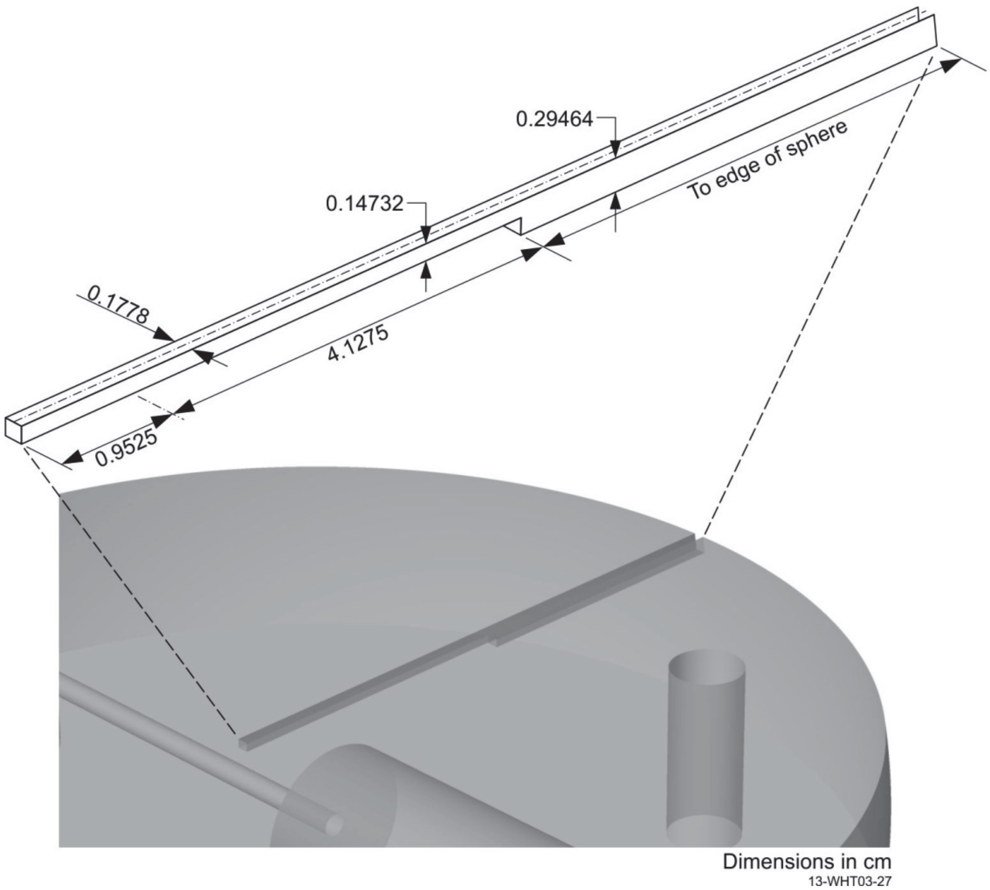

Figure 3-8. Thermocouple Groove in Center Plate, Groove is Filled with HEU, Case 2 (Detailed Benchmark Model).

Top Section The upper polar cap was the top section of the sphere for Case 1 and 2. The mass of the upper polar cap was 12,042.76 g for Case 1 and 11,883.24 g for Case 2.

The location of the mass adjustment buttons-recesses were calculated for Case 1 with respect to the center of the diametral hole and then kept constant for Case 2. The average sphere radius of 8.80491 cm was used in these calculations.

The dimensions of the upper polar cap are given in Figure 3-9 and Figure 3-10 for Case 1 and 2, respectively. The surface of the sphere was actually an ellipsoid and took into account the deviation from spherical by using the deviation at the bottom and the top pole of the upper polar cap to derive an ellipsoid equation. These equations took into account the fact that the sum of the heights of the sections of the sphere did not add up to the average diameter of the sphere (Case 1 and 2) and the fact that the center of the sphere was 0.0508 cm higher than the center of the diametral hole which was the center of the model in Case 2. The equations of the resulting ellipsoids are given in Table 3-7 and Table 3-8.

Table 3-7. Ellipsoid Coefficients for Top Section of Sphere, Case 1.[a]

$Ax^2 + By^2 + C(z - \bar{z})^2 + G = 0$							
	Deviation From Spherical (cm)[b]		A (cm^{-2})	B (cm^{-2})	C (cm^{-2})	G (--)	$\bar{z}$[c] (cm)
Upper Polar Cap	1.02E-03 at Bottom	0.0 at Top	66.13136	66.13136	66.14925	-5128.31605	-0.000508

(a) An example of the derivation of these coefficients is given in Appendix B.
(b) The deviation from spherical is based off a radius 8.80491 cm.
(c) This axial shift was due to the fact that the sum of the heights of the sections did not add up to the average diameter of the sphere and the shift of the center of the sphere 0.0508 cm above the center of the diametral hole which was the center of the model.

Table 3-8. Ellipsoid Coefficients for Top Section of Sphere, Case 2.[a]

$Ax^2 + By^2 + C(z - \bar{z})^2 + G = 0$							
	Deviation From Spherical (cm)[b]		A (cm^{-2})	B (cm^{-2})	C (cm^{-2})	G (--)	$\bar{z}$[c] (cm)
Upper Polar Cap	-1.27E-03 at bottom	3.05E-03 at top	65.4299	65.4299	65.3544	-5000.26418	0.046482

(a) An example of the derivation of these coefficients is given in Appendix B.
(b) The deviation from spherical is based on the nominal radius of 8.74395 cm.
(c) This axial shift was due to the fact that the sum of the heights of the sections did not add up to the average diameter of the sphere and the shift of the center of the sphere 0.0508 cm above the center of the diametral hole which was the center of the model.

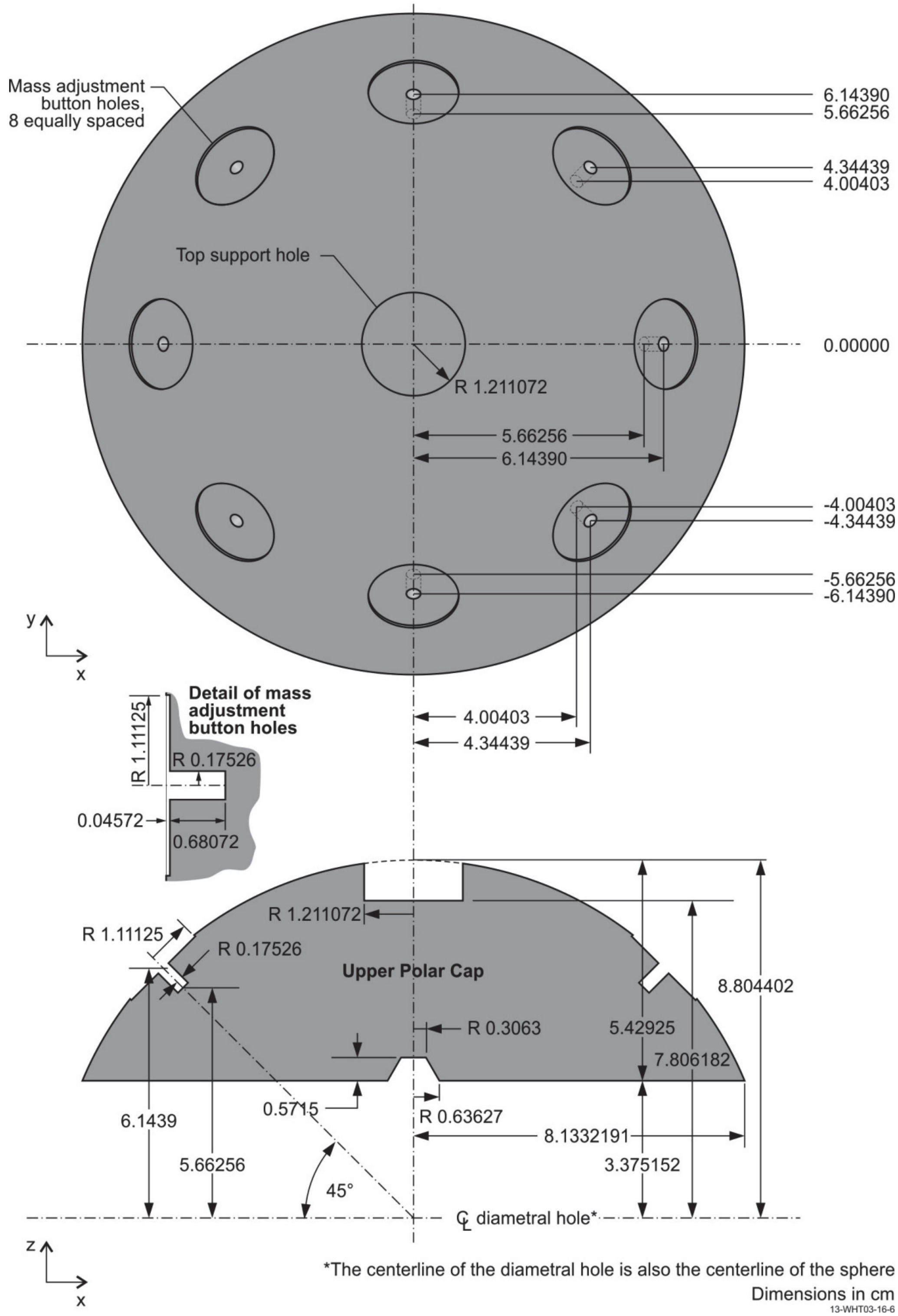

Figure 3-9. Upper Polar Cap for Case 1(Detailed Benchmark Model).[a]

[a] A high number of digits on dimensions have been retained not to imply high accuracy but rather to reduce rounding error in the derivation of other dimensions and the calculation of volumes.

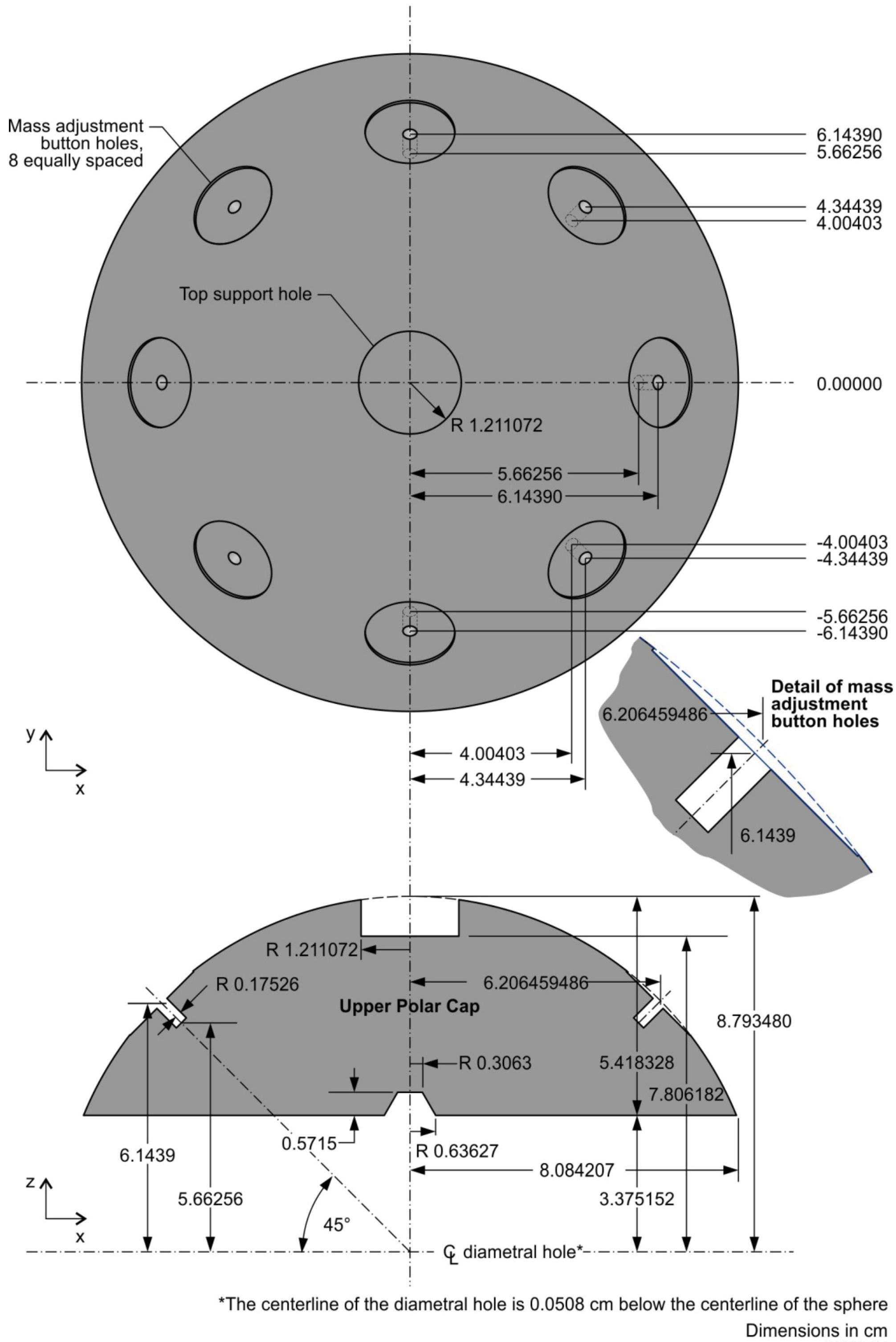

Figure 3-10. Upper Polar Cap for Case 2 (Detailed Benchmark Model).[a]

[a] A high number of digits on dimensions have been retained not to imply high accuracy but rather to reduce rounding error in the derivation of other dimensions and the calculation of volumes.

3.2.2 Description of Simple Benchmark Model

The simple benchmark model was a solid sphere of uranium. Mass and mass density were conserved. The mass of the sphere was the sum of the masses of the bottom, center, and top section of sphere, and the mass of the diametral filler rod. These masses are given in Table 3-9.

Table 3-9. Uranium Masses in Simple Benchmark Model.

Sphere Section	Case 1 Mass (g)	Case 2 Mass (g)
Bottom	20,310	19,624.59
Center	21,095.06	20,814.95
Top	12,042.76	11,883.24
Diametral Filler Rod	28.163	28.163
Total	53,475.983	52,350.943

The total uranium volume of each sphere was calculated, using part dimensions, as being 2,845.486142 cm^3 for Case 1 and 2,786.924436 cm^3 for Case 2 (see Appendix C). The resulting sphere radii were 8.79068305 cm and 8.72995881 cm for Cases 1 and 2, respectively.[a]

3.3 Material Data

3.3.1 Material Data of Detailed Benchmark Model

The material data for the uranium in the detailed benchmark model is given in Table 3-10 through Table 3-15.

[a] The density varies between Case 1 and Case 2 (18.7933 and 18.7845 g/cm^3). This inconsistency is discussed in Section 2.2.2.

Table 3-10. Uranium Masses in Bottom Section of
Detailed Benchmark Model, Case 1.

Element/ Isotope	Atom Density (atom/b-cm)		
	Lower Polar Cap	Lower Plate	Lower Section Pins
U Total	4.8117E-02	4.8119E-02	4.8120E-02
^{234}U	*4.7588E-04*	*4.7609E-04*	*4.8136E-04*
^{235}U	*4.4867E-02*	*4.4888E-02*	*4.4856E-02*
^{236}U	*1.7222E-05*	*1.7228E-05*	*2.1624E-04*
^{238}U	*2.7575E-03*	*2.7383E-03*	*2.5662E-03*
Be	6.2845E-09	6.2824E-09	-
Li	1.6320E-07	1.6314E-07	-
Al	2.0991E-06	3.3575E-06	2.0984E-06
Si	4.0332E-05	5.0398E-05	4.8381E-05
Mn	5.0977E-06	3.4996E-06	3.8065E-06
Ni	8.5210E-06	5.8498E-06	6.3628E-06
Cr	6.7326E-07	4.6220E-07	5.0274E-07
Cu	1.9675E-06	1.3507E-06	1.4691E-06
B	1.0478E-07	5.2371E-07	3.1422E-07
Co	9.6105E-08	9.6073E-08	-
Ca	1.4132E-06	1.4127E-06	-
C	1.6881E-04	1.3387E-04	1.5838E-04
O	1.4160E-05	1.4155E-05	1.4155E-05
N	2.4262E-05	2.4254E-05	2.4253E-05
Total	4.8385E-02	4.8359E-02	4.8380E-02

Table 3-11. Uranium Masses in Bottom Section of
Detailed Benchmark Model, Case 2.

Element/ Isotope	Atom Density (atom/b-cm)		
	Lower Polar Cap	Lower Plate	Lower Section Pins
U Total	4.7980E-02	4.7982E-02	4.7983E-02
^{234}U	*4.7452E-04*	*4.7473E-04*	*4.7998E-04*
^{235}U	*4.4739E-02*	*4.4760E-02*	*4.4728E-02*
^{236}U	*1.7173E-05*	*1.7179E-05*	*2.1562E-04*
^{238}U	*2.7496E-03*	*2.7305E-03*	*2.5589E-03*
Be	6.2666E-09	6.2645E-09	-
Li	1.6273E-07	1.6268E-07	-
Al	2.0931E-06	3.3479E-06	2.0924E-06
Si	4.0217E-05	5.0255E-05	4.8243E-05
Mn	5.0831E-06	3.4896E-06	3.7956E-06
Ni	8.4967E-06	5.8331E-06	6.3446E-06
Cr	6.7134E-07	4.6088E-07	5.0130E-07
Cu	1.9618E-06	1.3468E-06	1.4649E-06
B	1.0448E-07	5.2222E-07	3.1332E-07
Co	9.5830E-08	9.5798E-08	-
Ca	1.4091E-06	1.4087E-06	-
C	1.6833E-04	1.3349E-04	1.5793E-04
O	1.4119E-05	1.4115E-05	1.4114E-05
N	2.4192E-05	2.4184E-05	2.4184E-05
Total	4.8247E-02	4.8221E-02	4.8242E-02

Table 3-12. Uranium Masses in Center Section of Detailed Benchmark Model, Case 1.

Element/ Isotope	Atom Density (atom/b-cm)			
	Central Plate	Upper Plate	Pins for Center Section	Plug for Target Hole and Thermocouple Groove
U Total	4.8045E-02	4.8051E-02	4.8050E-02	4.8050E-02
^{234}U	*4.7526E-04*	*4.7537E-04*	*4.7611E-04*	*4.8065E-04*
^{235}U	*4.4809E-02*	*4.4819E-02*	*4.4798E-02*	*4.4791E-02*
^{236}U	*1.7196E-05*	*1.7203E-05*	*2.0300E-04*	*2.1593E-04*
^{238}U	*2.7437E-03*	*2.7392E-03*	*2.5726E-03*	*2.5625E-03*
Be	6.2717E-09	6.2724E-09	-	-
Li	1.6286E-07	1.6288E-07	-	-
Al	1.6759E-06	1.6761E-06	2.0953E-06	2.0953E-06
Si	8.0500E-05	4.0255E-05	4.8311E-05	4.8311E-05
Mn	3.0646E-06	2.0842E-06	3.8010E-06	3.8010E-06
Ni	5.1226E-06	3.4838E-06	6.3535E-06	6.3535E-06
Cr	4.0475E-07	2.7526E-07	5.0200E-07	5.0200E-07
Cu	1.1828E-06	8.0440E-07	1.4670E-06	1.4670E-06
B	2.0913E-07	3.1373E-07	3.1376E-07	3.1376E-07
Co	9.5908E-08	9.5919E-08	-	-
Ca	1.4103E-06	1.4105E-06	-	-
C	1.4965E-04	1.4966E-04	1.5815E-04	1.5815E-04
O	1.4131E-05	1.4133E-05	1.4134E-05	1.4134E-05
N	2.4212E-05	2.4215E-05	2.4217E-05	2.4217E-05
Total	4.8327E-02	4.8289E-02	4.8309E-02	4.8309E-02

Table 3-13. Uranium Masses in Center Section of Detailed Benchmark Model, Case 2.

Element/ Isotope	Atom Density (atom/b-cm)			
	Central Plate	Upper Plate	Pins for Center Section	Plug for Target Hole and Thermocouple Groove
U Total	4.8157E-02	4.8162E-02	4.8161E-02	4.8161E-02
^{234}U	*4.7637E-04*	*4.7647E-04*	*4.7722E-04*	*4.8177E-04*
^{235}U	*4.4913E-02*	*4.4923E-02*	*4.4902E-02*	*4.4895E-02*
^{236}U	*1.7236E-05*	*1.7243E-05*	*2.0347E-04*	*2.1643E-04*
^{238}U	*2.7501E-03*	*2.7456E-03*	*2.5786E-03*	*2.5684E-03*
Be	6.2863E-09	6.2870E-09	-	-
Li	1.6324E-07	1.6326E-07	-	-
Al	1.6798E-06	1.6800E-06	2.1002E-06	2.1002E-06
Si	8.0687E-05	4.0348E-05	4.8423E-05	4.8423E-05
Mn	3.0717E-06	2.0890E-06	3.8098E-06	3.8098E-06
Ni	5.1345E-06	3.4919E-06	6.3683E-06	6.3683E-06
Cr	4.0569E-07	2.7590E-07	5.0317E-07	5.0317E-07
Cu	1.1855E-06	8.0626E-07	1.4704E-06	1.4704E-06
B	2.0961E-07	3.1446E-07	3.1449E-07	3.1449E-07
Co	9.6131E-08	9.6142E-08	-	-
Ca	1.4136E-06	1.4137E-06	-	-
C	1.4999E-04	1.5001E-04	1.5852E-04	1.5852E-04
O	1.4164E-05	1.4165E-05	1.4167E-05	1.4167E-05
N	2.4268E-05	2.4271E-05	2.4274E-05	2.4274E-05
Total	4.8439E-02	4.8402E-02	4.8421E-02	4.8421E-02

Table 3-14. Uranium Atom Densities in Top Section and Diametral Filler Rod of Detailed Benchmark Model, Case 1.

Element/ Isotope	Atom Density (atom/b-cm)	
	Upper Polar Cap	Diametral Filler Rod
U Total	4.8150E-02	4.7722E-02
^{234}U	*4.7635E-04*	*4.7738E-04*
^{235}U	*4.4911E-02*	*4.4485E-02*
^{236}U	*1.7239E-05*	*2.1446E-04*
^{238}U	*2.7449E-03*	*2.5450E-03*
Be	6.2857E-09	-
Li	1.6323E-07	-
Al	2.5194E-06	2.0810E-06
Si	3.2272E-05	4.7981E-05
Mn	5.2214E-06	3.7751E-06
Ni	8.7279E-06	6.3102E-06
Cr	6.8961E-07	4.9858E-07
Cu	2.0152E-06	1.4570E-06
B	5.2398E-07	3.1162E-07
Co	9.6122E-08	-
Ca	1.4134E-06	-
C	1.9054E-04	1.5707E-04
O	1.4162E-05	1.4038E-05
N	2.4266E-05	2.4052E-05
Total	4.8433E-02	4.7980E-02

Table 3-15. Uranium Atom Densities in Top Section and Diametral Filler Rod of Detailed Benchmark Model, Case 2.

Element/ Isotope	Atom Density (atom/b-cm)	
	Upper Polar Cap	Diametral Filler Rod
U Total	4.8083E-02	4.7722E-02
^{234}U	*4.7569E-04*	*4.7738E-04*
^{235}U	*4.4849E-02*	*4.4485E-02*
^{236}U	*1.7215E-05*	*2.1446E-04*
^{238}U	*2.7411E-03*	*2.5450E-03*
Be	6.2770E-09	-
Li	1.6300E-07	-
Al	2.5159E-06	2.0810E-06
Si	3.2227E-05	4.7981E-05
Mn	5.2142E-06	3.7751E-06
Ni	8.7159E-06	6.3102E-06
Cr	6.8866E-07	4.9858E-07
Cu	2.0125E-06	1.4570E-06
B	5.2326E-07	3.1162E-07
Co	9.5989E-08	-
Ca	1.4115E-06	-
C	1.9028E-04	1.5707E-04
O	1.4143E-05	1.4038E-05
N	2.4233E-05	2.4052E-05
Total	4.8366E-02	4.7980E-02

The material data for the brass of the brass bolt is given in Table 3-16.

Table 3-16. Brass Atom Densities for Brass Bolt in the Detailed Benchmark Model, Case 1 and 2.

Element/ Isotope	Atom Density (atom/b-cm)
Cu	7.5056E-02
Zn	8.1044E-03
Total	8.3160E-02

3.3.2 Material Data of Simple Benchmark Model

The material data for the uranium of the simple benchmark model is given in Table 3-17.

Table 3-17. Uranium Atom Densities, Simple Benchmark Model Case 1 and 2.[(a)]

Element/ Isotope	Atom Density (atom/b-cm)	
	Case 1	Case 2
U Total	4.8097E-02	4.8075E-02
^{234}U	*4.7590E-04*	*4.7568E-04*
^{235}U	*4.4859E-02*	*4.4838E-02*
^{236}U	*2.1871E-05*	*2.1938E-05*
^{238}U	*2.7404E-03*	*2.7390E-03*
Si	4.9713E-05	4.9746E-05
B	3.4257E-07	3.4357E-07
C	1.5929E-04	1.5920E-04
Total	4.8307E-02	4.8284E-02

(a) When impurities were removed they were replaced with void.

3.4 Temperature Data

The benchmark model is evaluated at room temperature (294 K) for both the simple and detailed models.

3.5 Experimental and Benchmark-Model k_{eff} and/or Subcritical Parameters

The experimental configurations had an excess reactivity of 68.1 ±2.0 ¢ for Case 1 and -23.4 ± 2.0 ¢ for Case 2. The measured and calculated simplification biases and the temperature bias were applied to the experimental k_{eff} to obtain the detailed and simple benchmark model k_{eff} values found in Table 3-18. The uncertainty in the benchmark models was found by adding in quadrature the uncertainty derived in Section 2 and the uncertainty in the bias derived in Section 3.1. The two cases are highly correlated.

Table 3-18. Benchmark Experiment Eigenvalues.

	Case 1			Case 2		
Experimental k_{eff}	1.00447	±	0.00013[(a)]	0.99846	±	0.00013[(a)]
Detailed Model Benchmark k_{eff}	1.0026	±	0.0007[(b)]	0.9966	±	0.0007[(b)]
Simple Model Benchmark k_{eff}	1.0031	±	0.0007[(b)]	0.9966	±	0.0007[(b)]

(a) This uncertainty is accounted for in Section 2.1.
(b) This uncertainty includes the experimental and bias uncertainty.

4.0 RESULTS OF SAMPLE CALCULATIONS

Reference 1 provides a sample MCNP input deck for Case 2. When reviewing these results it should be noted that the measured k_{eff} derived in Appendix A and Table 5 of Reference 1 does not include the diametral filler rod in the configuration worth of -35¢. However, the sample input deck does include the diametral filler rod. This is a reactivity change of about 10 ¢. Various other simplifications were used in the model given in Reference 1 that were not used in the models developed for this evaluation. Some errors have also been found in the model presented in Appendix A of Reference 1.

The benchmark specifications given in Section 3 were used to create inputs for MCNP5, KENO-VI[a], MONK, COG, and XSDRNPM using ENDF/B-VII.0 continuous energy neutron cross section libraries and select other cross section libraries. Example input files for the benchmark model calculations can be found in Appendix A. Results of the MCNP5 sample calculations [(C-E)/E] range from 0.13% for Case 1 to 0.18% for Case 2, or about 1.6σ greater than the benchmark value for the Case 1 and 2.3 σ for Case 2. Results are summarized in Tables 4-1 and Table 4-2.

[a] D.F. Hollenbach, L.M. Petrie, S. Goluoglu, N.F. Landers, and M.E. Dunn, "KENO-VI: A General Quadratic Version of the KENO Program," ORNL/TM-2005/39 Version 6 Vol. II, Sect. F17, Oak Ridge National Laboratory (January 2009).

Table 4-1. Sample Calculation Results for the Detailed Benchmark Model.

			k_{eff}	±	σ	$\frac{C-E}{E}$(e)
Benchmark Model		Case 1	1.0026	±	0.0007	-
		Case 2	0.9965	±	0.0007	-
MCNP5(a)	ENDF/B-VII.0	Case 1	1.00385	±	0.00002	0.13%
		Case 2	0.99821	±	0.00002	0.17%
MCNP5(a)	JEFF-3.1	Case 1	1.00039	±	0.00002	-0.22%
		Case 2	0.99472	±	0.00002	-0.18%
MCNP5(a)	JENDL-3.3	Case 1	1.00692	±	0.00002	0.43%
		Case 2	1.00133	±	0.00002	0.48%
KENO-VI(b)	ENDF/B-VII.0-CE	Case 1	1.00495	±	0.00002	0.24%
		Case 2	0.99947	±	0.00002	0.29%
KENO-VI(b)	ENDF/B-VII.0-238g	Case 1	1.00495	±	0.00002	0.24%
		Case 2	0.99947	±	0.00002	0.29%
MONK(c)	ENDF/B-VII.0	Case 1	1.0034	±	0.0001	0.08%
		Case 2	0.9985	±	0.0001	0.20%
MONK(c)	JEFF-3.1	Case 1	0.9997	±	0.0001	-0.29%
		Case 2	0.9951	±	0.0001	-0.14%
COG11.1(d)	ENDF/B-VII.1	Case 1	1.00421	±	0.00008	0.17%
		Case 2	0.99795	±	0.00003	0.14%
COG11.1(d)	JEFF-3.1.2	Case 1	1.00054	±	0.00009	-0.20%
		Case 2	0.99439	±	0.00003	-0.22%
COG11.1(d)	JENDL-4	Case 1	1.00193	±	0.00009	-0.06%
		Case 2	0.99598	±	0.00005	-0.06%

(a) Results obtained using 500,000 histories for 2650 cycles, skipping the first 150 cycles.
(b) Results provided by John D. Bess from Idaho National Laboratory (INL). Results obtained using 500000 histories for 2650 cycles, skipping the first 150 cycles.
(c) Results provided by James Dyrda from Atomic Weapons Establishment (AWE). Results obtained using 30 settling stages plus 6000 normal stages, 1000 super histories per stage and 10 generations per super-history.
(d) Results provided by David P. Heinrichs from Lawrence Livermore National Laboratory (LLNL). Results obtained using 500,000 histories for 2650 cycles, skipping the first 150 cycles.
(e) 'E' is the expected or benchmark value. 'C' is the calculated value.

Table 4-2. Sample Calculation Results for the Simple Benchmark Model.

			k_{eff}	±	σ	$\frac{C-E}{E}$[f]
Benchmark Model		Case 1	1.0031	±	0.0007	-
		Case 2	0.9966	±	0.0007	-
MCNP5[a]	ENDF/B-VII.0	Case 1	1.00441	±	0.00002	0.18%
		Case 2	0.99826	±	0.00002	0.17%
MCNP5[a]	JEFF-3.1	Case 1	1.00088	±	0.00002	-0.17%
		Case 2	0.99477	±	0.00002	-0.18%
MCNP5[a]	JENDL-3.3	Case 1	1.00744	±	0.00002	0.49%
		Case 2	1.00139	±	0.00002	0.49%
KENO-V.a[b]	ENDF/B-VII.0-CE	Case 1	1.00416	±	0.00002	0.16%
		Case 2	0.99803	±	0.00002	0.15%
KENO-V.a[b]	ENDF/B-VII.0-238g	Case 1	1.00548	±	0.00002	0.29%
		Case 2	0.99932	±	0.00002	0.28%
MONK[c]	ENDF/B-VII.0	Case 1	1.0046	±	0.0001	0.20%
		Case 2	0.9986	±	0.0001	0.21%
MONK[c]	JEFF-3.1	Case 1	1.0013	±	0.0001	-0.13%
		Case 2	0.9952	±	0.0001	-0.13%
XSDRNPM[d]	ENDF/B-VII.0-238g	Case 1	1.00575	±	-	0.32%
		Case 2	0.99960	±	-	0.31%
XSDRNPM[d]	ENDF/B-VII.0-27n19g	Case 1	1.00760	±	-	0.50%
		Case 2	1.00145	±	-	0.49%
XSDRNPM[d]	ENDF/B-VI.8-238g	Case 1	1.00167	±	-	-0.09%
		Case 2	0.99553	±	-	-0.10%
XSDRNPM[d]	ENDF/B-V.2-238g	Case 1	1.00184	±	-	-0.07%
		Case 2	0.99573	±	-	-0.08%
COG11.1[e]	ENDF/B-VII.1	Case 1	1.00494	±	0.00003	0.19%
		Case 2	0.99875	±	0.00003	0.21%
COG11.1[e]	JEFF-3.1.2	Case 1	1.00136	±	0.00004	-0.17%
		Case 2	0.99521	±	0.00003	-0.14%
COG11.1[e]	JENDL-4	Case 1	1.00281	±	0.00004	-0.03%
		Case 2	0.99677	±	0.00005	0.02%

(a) Results obtained using 500,000 histories for 2650 cycles, skipping the first 150 cycles.
(b) Results provided by John D. Bess from INL. Results obtained using 500000 histories for 2650 cycles, skipping the first 150 cycles.
(c) Results provided by James Dyrda from AWE. Results obtained using 30 settling stages plus 6000 normal stages, 1000 super histories per stage and 10 generations per super-history.
(d) Results provided by John D. Bess from Idaho National Laboratory.
(e) Results provided by David P. Heinrichs from LLNL. Results obtained using 500,000 histories for 2650 cycles, skipping the first 150 cycles.
(f) 'E' is the expected or benchmark value. 'C' is the calculated value.

5.0 REFERENCES

1. J.T. Mihalczo, J. J. Lynn, J. R. Taylor, G. E. Hansen, and D. B. Pelowitz, "Delayed Critical ORNL Unreflected Uranium (93.20) Metal Sphere and the Pure Unreflected Uranium (93.80) Sphere Critical Mass," *Ann. Nucl. Energy*, **29**, 525-560 (2002).
2. J.T. Mihaclzo, J. J. Lynn, J. R. Taylor, and G. E. Hansen, "Measurements with an Unreflected Uranium (93.2%) Metal Sphere," *PHYSOR 1993*, Nashville, TN, September 19-23 (1993).

APPENDIX A: TYPICAL INPUT LISTINGS

A.1 MCNP Input Listing

Models were creating using Monte Carlo n-Particle, version 5-1.60, (MCNP) and ENDF/B-VII.0 neutron cross section libraries. Isotopic abundances for all elements except uranium were taken from "Nuclides and Isotopes: Chart of the Nuclides," Sixteenth Edition, KAPL, 2002. MCNP5.1.60 models were run for 2500 active cycles (150 inactive cycles) with 500,000 histories per cycle.

MCNP5 Input Detailed Model, Case 1, Table 4-1.

Case 1

```
HEU-COMP-FAST-100- Case 1-Detailed Model/ ORSphere
C
C
C   Cell Cards
C
C   ***********************************************************************
C   Lower Polar Cap-LPC
C   ***********************************************************************
100    10 4.83852E-02 -101 102 -104  150 151 152 153 154 155 156 157
        160 161 162 163 164 165 166 167 103 110 111 112   imp:n=1
C    Support Rod Hole
101    21 8.31603E-02 -105 imp:n=1 $brass bolt
102    0  -103 -101 105 imp:n=1 $ Support Rod Hole
103    0 -101 -102 103    imp:n=1 $ Spot Face
C    Pins
104    12 4.83797E-02 -110 -104 166   imp:n=1
105    12 4.83797E-02 -111 -104   imp:n=1
107    12 4.83797E-02 -112 -104   imp:n=1
C    Mass Adjustment Button Recesses
110   0 -150 160 -101   imp:n=1
111   0 -151 161 -101   imp:n=1
112   0 -152 162 -101   imp:n=1
113   0 -153 163 -101   imp:n=1
114   0 -154 164 -101   imp:n=1
115   0 -155 165 -101   imp:n=1
116   0 -156 166 -101   imp:n=1
117   0 -157 167 -101   imp:n=1
120   0 -160 -101    imp:n=1
121   0 -161 -101   imp:n=1
122   0 -162 -101   imp:n=1
123   0 -163 -101   imp:n=1
124   0 -164 -101   imp:n=1
125   0 -165 -101   imp:n=1
126   0 -166 -101   imp:n=1
127   0 -167 -101   imp:n=1
C
130   0 101 -104 -900  imp:n=1
C
C   ***********************************************************************
C   Lower Plate
C   ***********************************************************************
208    11 4.83588E-02 -201 204 -205 210 211 212 213 imp:n=1
209    11 4.83588E-02 -206 imp:n=1 $Alignment Cone
210    0 201 204 -205 -900 imp:n=1
C    Pins
214    12 4.83797E-02 -210 204  imp:n=1
215    12 4.83797E-02 -211 204 imp:n=1
216    0              -213 204 imp:n=1
217    12 4.83797E-02 -212 204 imp:n=1
C
C   ***********************************************************************
C   Central Plate
C   ***********************************************************************
```

```
300   13 4.83270E-02 (-301 303 -306) 323 324 325
          310 311 312 313 307 308 410 411 412  u=1 imp:n=1 trcl = 1 $Upper Half
301   13 4.83270E-02 (-302 -303 305) 323
          310 311 312 313 307 308 410 411 412  u=1 imp:n=1 trcl = 1 $Lower Half
302   0 -307  u=1 imp:n=1 trcl = 1
303   0 (-301 303 -308 309):(-302 -303 -308 309)  u=1 imp:n=1 trcl = 1
304   17 4.83091E-02 -323 -301 303 308  u=1 imp:n=1 trcl = 1 $Target Hole Plug
305   17 4.83091E-02 -323 -302 -303 308  u=1 imp:n=1 trcl = 1 $Target Hole Plug
306   17 4.83091E-02 -324 -301  u=1 imp:n=1 trcl = 1 $Thermocouple
307   17 4.83091E-02 -325 -301  u=1 imp:n=1 trcl = 1 $Thermocouple
308   18 4.79799E-02 -309   u=1 imp:n=1 trcl = 1 $Diametral Pin
C   Support Screw Holes
310   0  -310   u=1 imp:n=1 trcl = 1
311   0  -311   u=1 imp:n=1 trcl = 1
312   0  -312   u=1 imp:n=1 trcl = 1
313   0  -313   u=1 imp:n=1 trcl = 1
C  Pins
320   15 4.83090E-02 -410 308 -306  u=1 imp:n=1 trcl = 1
321   15 4.83090E-02 -411 308 -306  u=1 imp:n=1 trcl = 1
322   15 4.83090E-02 -412 308 -306  u=1 imp:n=1 trcl = 1
330   0 (302 -303 305 309 310 311 312 313) u=1 imp:n=1 trcl = 1
331   0 -305 u=1 imp:n=1 trcl = 1
332   0 (301 303 -306 309 310 311 312 313) u=1 imp:n=1 trcl = 1
C               imp:n=1 trcl = 1
C
C   ****************************************************************************
C   Upper Plate
C   ****************************************************************************
406   14 4.82894E-02 -401 406 -407 410 411 412 u=1  imp:n=1 trcl = 1
407   14 4.82894E-02 -408 u=1  imp:n=1 trcl = 1
408   0  401 406 -407  u=1  imp:n=1 trcl = 1
430   15 4.83090E-02 -410 308 406 -407 u=1  imp:n=1 trcl = 1
431   15 4.83090E-02 -411 308 406 -407 u=1  imp:n=1 trcl = 1
432   15 4.83090E-02 -412 308 406 -407 u=1  imp:n=1 trcl = 1
C
C   ****************************************************************************
C  Upper Polar Cap
C   ****************************************************************************
500   16 4.84326E-02 -500 501 503 508 750 751 752 753 754 755 756 757
                        760 761 762 763 764 765 766 767 u=1  imp:n=1 trcl = 1
501   0   -503 408 u=1  imp:n=1 trcl = 1
C 502   0  -500 -508 u=1  imp:n=1 trcl = 1 $ Socket
C  Mass Adjustment Button Recesses
560   0 -750 760 -500 u=1  imp:n=1 trcl = 1
561   0 -751 761 -500 u=1  imp:n=1 trcl = 1
562   0 -752 762 -500 u=1  imp:n=1 trcl = 1
563   0 -753 763 -500 u=1  imp:n=1 trcl = 1
564   0 -754 764 -500 u=1  imp:n=1 trcl = 1
565   0 -755 765 -500 u=1  imp:n=1 trcl = 1
566   0 -756 766 -500 u=1  imp:n=1 trcl = 1
567   0 -757 767 -500 u=1  imp:n=1 trcl = 1
570   0 -760 -500 u=1  imp:n=1 trcl = 1
571   0 -761 -500 u=1  imp:n=1 trcl = 1
572   0 -762 -500 u=1  imp:n=1 trcl = 1
573   0 -763 -500 u=1  imp:n=1 trcl = 1
574   0 -764 -500 u=1  imp:n=1 trcl = 1
575   0 -765 -500 u=1  imp:n=1 trcl = 1
576   0 -766 -500 u=1  imp:n=1 trcl = 1
577   0 -767 -500 u=1  imp:n=1 trcl = 1
590   0 500 501 508  u=1  imp:n=1 trcl = 1
591   0 -508  u=1  imp:n=1 trcl = 1
905   0  205 206 210 -900 fill=1 imp:n=1
910  0  900 imp:n=0

C   Surface Cards
C
C   ****************************************************************************
C   ****Lower Polar Cap- LPC****************************************************
C   ****************************************************************************
101 sq 61.0220372 61.0220372 60.9504916 0 0 0 -4724.7294008 0 0 -0.004826
102 pz -8.717156 $Spot Face
103 rcc 0 0 -7.811008  0 0 -1  0.747903 $Support Hole
```

```
104 pz   -4.066286  $Top of LPC
105 rcc 0 0 -7.811008  0 0 -0.8128  0.747903 $Bolt
C   Pins
110 rcc   -6.35    0        -5.177536   0   0   3.754374   0.57531
111 rcc    3.175   5.49926  -5.177536   0   0   3.747262   0.57531
112 rcc    3.175  -5.49926  -5.177536   0   0   3.748532   0.57531
C   LPC Mass Adjustment Button Recesses
150 rcc  0.00000  5.66256 -5.66256  0.00000  0.56345 -0.56345 0.17526
151 rcc  4.00403  4.00403 -5.66256  0.39843  0.39843 -0.56345 0.17526
152 rcc  5.66256  0.00000 -5.66256  0.56345  0.00000 -0.56345 0.17526
153 rcc  4.00403 -4.00403 -5.66256  0.39843 -0.39843 -0.56345 0.17526
154 rcc  0.00000 -5.66256 -5.66256  0.00000 -0.56345 -0.56345 0.17526
155 rcc -4.00403 -4.00403 -5.66256 -0.39843 -0.39843 -0.56345 0.17526
156 rcc -5.66256  0.00000 -5.66256 -0.56345  0.00000 -0.56345 0.17526
157 rcc -4.00403  4.00403 -5.66256 -0.39843  0.39843 -0.56345 0.17526
160 rcc  0.00000  6.1439  -6.1439   0.00000  0.08211 -0.08211 1.11125
161 rcc  4.34439  4.34439 -6.1439   0.05807  0.05807 -0.08211 1.11125
162 rcc  6.1439   0.00000 -6.1439   0.08211  0.00000 -0.08211 1.11125
163 rcc  4.34439 -4.34439 -6.1439   0.05807 -0.05807 -0.08211 1.11125
164 rcc  0.00000 -6.1439  -6.1439   0.00000 -0.08211 -0.08211 1.11125
165 rcc -4.34439 -4.34439 -6.1439  -0.05807 -0.05807 -0.08211 1.11125
166 rcc -6.1439   0.00000 -6.1439  -0.08211  0.00000 -0.08211 1.11125
167 rcc -4.34439  4.34439 -6.1439  -0.05807  0.05807 -0.08211 1.11125
C
C   ***************************************************************************
C   ****Lower Plate- LP********************************************************
C   ***************************************************************************
201 sq 14.4926294 14.4926294 14.4568504 0 0 0 -1122.9703705 0 0 0
204 pz   -4.066286  $Bottom of LP
205 pz   -1.429004  $ Top of lower plate
206 trc 0 0 -1.429004 0 0 0.55372 0.635 0.315309609 $ LP Alignment cone
C  Lower Section Pins
210 rcc -6.35   0       -4.066286 0 0 2.643124 0.57531
211 rcc  3.175  5.49926 -4.066286 0 0 2.636012 0.57531
212 rcc  3.175 -5.49926 -4.066286 0 0 2.637282 0.57531
213 rcc  3.175  5.49926 -1.430274 0 0 0.001270 0.57531
C
C   ***************************************************************************
C   ****Central Plate- CP******************************************************
C   ***************************************************************************
301 sq 2.0420524 2.0420524 2.0241629 0 0 0 -158.2582570 0 0 0 $CP Upper Section
302 sq 2.0420524 2.0420524 2.0599399 0 0 0 -158.2582570 0 0 0 $CP Lower Section
303 pz 0
305 pz -1.429004  $bottom of Central Plate
306 pz  1.429004  $Top of Central Plate
307 trc 0 0 -1.429004 0 0 0.5715 0.63627 0.306314321 $ CP Alignment Hole
308 cx  0.17272  $Diametral Hole
309 rcc  -8.914765 0 0   17.82953 0 0 0.164211 $ Diametral Pin
323 rcc  0.888238 0 0    8.80491 0 0    1.27 $ Target Hole Plug
324 rpp -0.0889   0.0889 -0.9525 4.1275  1.281684 1.429004 $Thermocouple
325 rpp -0.0889   0.0889  4.1275 8.80491 1.134364 1.429004 $Thermocouple
C    Support Rod Holes in CP
310 rcc  5.74467  5.74467 0  0.48134  0.48134 0 0.351028
311 rcc  5.74467 -5.74467 0  0.48134 -0.48134 0 0.351028
312 rcc -5.74467 -5.74467 0 -0.48134 -0.48134 0 0.351028
313 rcc -5.74467  5.74467 0 -0.48134  0.48134 0 0.351028
C
C   ***************************************************************************
C   ****Upper Plate- UP********************************************************
C   ***************************************************************************
401 sq 9.3495986 9.3495986 9.3138216 0 0 0 -724.3498994 0 0 0
406 pz 1.429004 $Bottom of Upper Plate
407 pz 3.375152 $Top Of upper Plate
408 trc 0 0 3.375152 0 0 0.55372 0.635 0.315309609 $ UP Alignment Cone
C  Central Section Pins
410 rcc -6.35 0 -1.429004 0 0 4.804156 0.57531
411 rcc 3.175 5.49926 -1.429004 0 0 4.804156 0.57531
412 rcc 3.175 -5.49926 -1.429004 0 0 4.804156 0.57531
C
C   ***************************************************************************
C   ****Upper Polar Cap- UPC***************************************************
C   ***************************************************************************
```

```
500 sq 66.1313597 66.1313597 66.1492523 0 0 0 -5128.3160452 0 0 -0.000508
501 pz 3.375152 $Bottom of UPC
508 rcc 0 0 7.806182   0 0 1.11125   1.211072 $top support hole
503 trc 0 0 3.375152 0 0 0.5715  0.63627  0.306314321 $UPC Alignment Hole
504 trc 0 0 3.375152 0 0 0.56261 0.635635 0.310811965 $Cone for modeling
C   UPC Mass Adjustment Button Recesses
750 rcc  0.00000  5.66256 5.66256  0.00000  0.56345 0.56345 0.17526
751 rcc  4.00403  4.00403 5.66256  0.39843  0.39843 0.56345 0.17526
752 rcc  5.66256  0       5.66256  0.56345  0       0.56345 0.17526
753 rcc  4.00403 -4.00403 5.66256  0.39843 -0.39843 0.56345 0.17526
754 rcc  0.00000 -5.66256 5.66256  0.00000 -0.56345 0.56345 0.17526
755 rcc -4.00403 -4.00403 5.66256 -0.39843 -0.39843 0.56345 0.17526
756 rcc -5.66256  0       5.66256 -0.56345  0       0.56345 0.17526
757 rcc -4.00403  4.00403 5.66256 -0.39843  0.39843 0.56345 0.17526
760 rcc  0.00000  6.1439  6.1439   0.00000  0.08211 0.08211 1.11125
761 rcc  4.34439  4.34439 6.1439   0.05807  0.05807 0.08211 1.11125
762 rcc  6.14390  0       6.1439   0.08211  0       0.08211 1.11125
763 rcc  4.34439 -4.34439 6.1439   0.05807 -0.05807 0.08211 1.11125
764 rcc  0.00000 -6.1439  6.1439   0.00000 -0.08211 0.08211 1.11125
765 rcc -4.34439 -4.34439 6.1439  -0.05807 -0.05807 0.08211 1.11125
766 rcc -6.14390  0       6.1439  -0.08211  0       0.08211 1.11125
767 rcc -4.34439  4.34439 6.1439  -0.05807  0.05807 0.08211 1.11125
C   ****Upper Socket************************************************************
C   ****************************************************************************
C
C
900 rpp -356.616 713.232 -682.752 387.096 -280.416 629.7168 $Inside Walls

C   Data Cards
C     Lower Polar Cap
m10   92234.70c   4.75883E-04
      92235.70c   4.48669E-02
      92236.70c   1.72224E-05
      92238.70c   2.75746E-03
      4009.70c   6.28455E-09
      3006.70c   1.23867E-08
      3007.70c   1.50811E-07
      13027.70c   2.09913E-06
      14028.70c   3.71983E-05
      14029.70c   1.88884E-06
      14030.70c   1.24514E-06
      25055.70c   5.09765E-06
      28058.70c   5.80084E-06
      28060.70c   2.23447E-06
      28061.70c   9.71310E-08
      28062.70c   3.09696E-07
      28064.70c   7.88705E-08
      24050.70c   2.92532E-08
      24052.70c   5.64118E-07
      24053.70c   6.39665E-08
      24054.70c   1.59226E-08
      29063.70c   1.36090E-06
      29065.70c   6.06569E-07
      5010.70c   2.08508E-08
      5011.70c   8.39270E-08
      27059.70c   9.61048E-08
      20040.70c   1.36996E-06
      20042.70c   9.14330E-09
      20043.70c   1.90780E-09
      20044.70c   2.94790E-08
      20046.70c   5.65274E-11
      20048.70c   2.64265E-09
      6000.70c   1.68814E-04
      8016.70c   1.41255E-05
      8017.70c   3.44086E-08
      7014.70c   2.41724E-05
      7015.70c   8.92829E-08   $ Total   4.83852E-02
C    Lower Plate
m11   92234.70c   4.76093E-04
      92235.70c   4.48877E-02
      92236.70c   1.72278E-05
      92238.70c   2.73834E-03
```

```
      4009.70c   6.28244E-09
      3006.70c   1.23825E-08
      3007.70c   1.50760E-07
      13027.70c   3.35748E-06
      14028.70c   4.64823E-05
      14029.70c   2.36026E-06
      14030.70c   1.55590E-06
      25055.70c   3.49962E-06
      28058.70c   3.98237E-06
      28060.70c   1.53400E-06
      28061.70c   6.66820E-08
      28062.70c   2.12612E-07
      28064.70c   5.41459E-08
      24050.70c   2.00828E-08
      24052.70c   3.87277E-07
      24053.70c   4.39141E-08
      24054.70c   1.09311E-08
      29063.70c   9.34277E-07
      29065.70c   4.16420E-07
      5010.70c   1.04219E-07
      5011.70c   4.19494E-07
      27059.70c   9.60725E-08
      20040.70c   1.36950E-06
      20042.70c   9.14024E-09
      20043.70c   1.90716E-09
      20044.70c   2.94691E-08
      20046.70c   5.65084E-11
      20048.70c   2.64177E-09
      6000.70c   1.33875E-04
      8016.70c   1.41208E-05
      8017.70c   3.43971E-08
      7014.70c   2.41643E-05
      7015.70c   8.92529E-08   $ Total   4.83588E-02
C    Pins for Lower Part
m12   92234.70c   4.81356E-04
      92235.70c   4.48562E-02
      92236.70c   2.16242E-04
      92238.70c   2.56620E-03
      13027.70c   2.09837E-06
      14028.70c   4.46218E-05
      14029.70c   2.26579E-06
      14030.70c   1.49362E-06
      25055.70c   3.80650E-06
      28058.70c   4.33159E-06
      28060.70c   1.66852E-06
      28061.70c   7.25294E-08
      28062.70c   2.31255E-07
      28064.70c   5.88939E-08
      24050.70c   2.18438E-08
      24052.70c   4.21237E-07
      24053.70c   4.77649E-08
      24054.70c   1.18897E-08
      29063.70c   1.01620E-06
      29065.70c   4.52936E-07
      5010.70c   6.25296E-08
      5011.70c   2.51690E-07
      6000.70c   1.58383E-04
      8016.70c   1.41204E-05
      8017.70c   3.43962E-08
      7014.70c   2.41636E-05
      7015.70c   8.92505E-08   $ Total   4.83797E-02
C    Central Plate
m13   92234.70c   4.75263E-04
      92235.70c   4.48090E-02
      92236.70c   1.71965E-05
      92238.70c   2.74372E-03
      4009.70c   6.27170E-09
      3006.70c   1.23614E-08
      3007.70c   1.50502E-07
      13027.70c   1.67587E-06
      14028.70c   7.42446E-05
      14029.70c   3.76996E-06
```

```
      14030.70c   2.48519E-06
      25055.70c   3.06460E-06
      28058.70c   3.48734E-06
      28060.70c   1.34332E-06
      28061.70c   5.83930E-08
      28062.70c   1.86183E-07
      28064.70c   4.74152E-08
      24050.70c   1.75864E-08
      24052.70c   3.39136E-07
      24053.70c   3.84553E-08
      24054.70c   9.57233E-09
      29063.70c   8.18141E-07
      29065.70c   3.64656E-07
      5010.70c   4.16163E-08
      5011.70c   1.67511E-07
      27059.70c   9.59083E-08
      20040.70c   1.36716E-06
      20042.70c   9.12462E-09
      20043.70c   1.90390E-09
      20044.70c   2.94188E-08
      20046.70c   5.64118E-11
      20048.70c   2.63725E-09
      6000.70c   1.49646E-04
      8016.70c   1.40967E-05
      8017.70c   3.43383E-08
      7014.70c   2.41230E-05
      7015.70c   8.91004E-08   $ Total   4.83270E-02
C   Upper Plate
m14   92234.70c   4.75367E-04
      92235.70c   4.48190E-02
      92236.70c   1.72032E-05
      92238.70c   2.73924E-03
      4009.70c   6.27243E-09
      3006.70c   1.23628E-08
      3007.70c   1.50520E-07
      13027.70c   1.67606E-06
      14028.70c   3.71266E-05
      14029.70c   1.88520E-06
      14030.70c   1.24274E-06
      25055.70c   2.08417E-06
      28058.70c   2.37167E-06
      28060.70c   9.13561E-07
      28061.70c   3.97119E-08
      28062.70c   1.26619E-07
      28064.70c   3.22461E-08
      24050.70c   1.19601E-08
      24052.70c   2.30639E-07
      24053.70c   2.61526E-08
      24054.70c   6.50994E-09
      29063.70c   5.56400E-07
      29065.70c   2.47995E-07
      5010.70c   6.24317E-08
      5011.70c   2.51295E-07
      27059.70c   9.59194E-08
      20040.70c   1.36731E-06
      20042.70c   9.12567E-09
      20043.70c   1.90412E-09
      20044.70c   2.94222E-08
      20046.70c   5.64184E-11
      20048.70c   2.63756E-09
      6000.70c   1.49663E-04
      8016.70c   1.40983E-05
      8017.70c   3.43423E-08
      7014.70c   2.41258E-05
      7015.70c   8.91107E-08   $ Total   4.82894E-02
C Pins for Central Section
m15   92234.70c   4.76114E-04
      92235.70c   4.47979E-02
      92236.70c   2.03000E-04
      92238.70c   2.57262E-03
      13027.70c   2.09531E-06
      14028.70c   4.45567E-05
```

```
      14029.70c   2.26248E-06
      14030.70c   1.49144E-06
      25055.70c   3.80095E-06
      28058.70c   4.32527E-06
      28060.70c   1.66608E-06
      28061.70c   7.24236E-08
      28062.70c   2.30918E-07
      28064.70c   5.88080E-08
      24050.70c   2.18120E-08
      24052.70c   4.20622E-07
      24053.70c   4.76952E-08
      24054.70c   1.18723E-08
      29063.70c   1.01472E-06
      29065.70c   4.52275E-07
      5010.70c   6.24384E-08
      5011.70c   2.51322E-07
      6000.70c   1.58152E-04
      8016.70c   1.40998E-05
      8017.70c   3.43460E-08
      7014.70c   2.41284E-05
      7015.70c   8.91203E-08   $ Total   4.83090E-02
C  Upper Polar Cp
m16   92234.70c   4.76347E-04
      92235.70c   4.49115E-02
      92236.70c   1.72387E-05
      92238.70c   2.74489E-03
      4009.70c   6.28568E-09
      3006.70c   1.23889E-08
      3007.70c   1.50838E-07
      13027.70c   2.51941E-06
      14028.70c   2.97640E-05
      14029.70c   1.51135E-06
      14030.70c   9.96290E-07
      25055.70c   5.22143E-06
      28058.70c   5.94169E-06
      28060.70c   2.28873E-06
      28061.70c   9.94894E-08
      28062.70c   3.17216E-07
      28064.70c   8.07855E-08
      24050.70c   2.99635E-08
      24052.70c   5.77816E-07
      24053.70c   6.55197E-08
      24054.70c   1.63092E-08
      29063.70c   1.39394E-06
      29065.70c   6.21297E-07
      5010.70c   1.04273E-07
      5011.70c   4.19710E-07
      27059.70c   9.61221E-08
      20040.70c   1.37020E-06
      20042.70c   9.14495E-09
      20043.70c   1.90814E-09
      20044.70c   2.94843E-08
      20046.70c   5.65376E-11
      20048.70c   2.64313E-09
      6000.70c   1.90540E-04
      8016.70c   1.41281E-05
      8017.70c   3.44148E-08
      7014.70c   2.41767E-05
      7015.70c   8.92990E-08   $ Total   4.84326E-02
C  Plug for Target hole/Thermocouple Groove
m17   92234.70c   4.80653E-04
      92235.70c   4.47907E-02
      92236.70c   2.15927E-04
      92238.70c   2.56246E-03
      13027.70c   2.09531E-06
      14028.70c   4.45567E-05
      14029.70c   2.26248E-06
      14030.70c   1.49144E-06
      25055.70c   3.80095E-06
      28058.70c   4.32527E-06
      28060.70c   1.66608E-06
      28061.70c   7.24236E-08
```

```
      28062.70c   2.30918E-07
      28064.70c   5.88080E-08
      24050.70c   2.18120E-08
      24052.70c   4.20622E-07
      24053.70c   4.76952E-08
      24054.70c   1.18723E-08
      29063.70c   1.01472E-06
      29065.70c   4.52275E-07
      5010.70c   6.24384E-08
      5011.70c   2.51322E-07
      6000.70c   1.58152E-04
      8016.70c   1.40998E-05
      8017.70c   3.43460E-08
      7014.70c   2.41284E-05
      7015.70c   8.91203E-08   $ Total   4.83091E-02
C   Diametral Pin, AVG Density
m18   92234.70c   4.77378E-04
      92235.70c   4.44855E-02
      92236.70c   2.14455E-04
      92238.70c   2.54500E-03
      13027.70c   2.08103E-06
      14028.70c   4.42531E-05
      14029.70c   2.24706E-06
      14030.70c   1.48128E-06
      25055.70c   3.77505E-06
      28058.70c   4.29579E-06
      28060.70c   1.65473E-06
      28061.70c   7.19300E-08
      28062.70c   2.29344E-07
      28064.70c   5.84073E-08
      24050.70c   2.16633E-08
      24052.70c   4.17756E-07
      24053.70c   4.73702E-08
      24054.70c   1.17914E-08
      29063.70c   1.00781E-06
      29065.70c   4.49193E-07
      5010.70c   6.20129E-08
      5011.70c   2.49610E-07
      6000.70c   1.57074E-04
      8016.70c   1.40037E-05
      8017.70c   3.41119E-08
      7014.70c   2.39639E-05
      7015.70c   8.85130E-08   $ Total   4.79799E-02
C   SS304 at Typical Density
m20   26054.70c   3.49480E-03
      26056.70c   5.48609E-02
      26057.70c   1.26698E-03
      26058.70c   1.68612E-04
      6000.70c   1.59038E-04
      25055.70c   8.69257E-04
      14028.70c   7.84115E-04
      14029.70c   3.98155E-05
      14030.70c   2.62466E-05
      24050.70c   7.58219E-04
      24052.70c   1.46215E-02
      24053.70c   1.65796E-03
      24054.70c   4.12701E-04
      28058.70c   5.26236E-03
      28060.70c   2.02705E-03
      28061.70c   8.81145E-05
      28062.70c   2.80948E-04
      28064.70c   7.15491E-05
      15031.70c   3.46904E-05
      16032.70c   2.12040E-05
      16033.70c   1.69757E-07
      16034.70c   9.58232E-07
      16034.70c   4.46728E-09   $ tot   8.69072E-02
C   Brass for LPC Bolt
m21   29063.70c   5.19162E-02
      29065.70c   2.31397E-02
      30000.70c   8.10437E-03   $ Total   8.31603E-02
kcode  500000 1 150 2650
```

```
sdef    pos 0 0 0 rad=d1 erg=d3
si1       0 3.4665
sp1      -21 2
sp3     -3 0.988 2.249
*tr1   0 0 .00351038
        -.0231340494 90 90.0231340494 90 0 90 89.9768659506 90 -.0231340494
C  rand  seed=7065399757867  $ r2
C  rand  seed=5724484131590  $ r3
C  rand  seed=417647895433   $ r4
C  rand  seed=8132049697893  $ r5
C  rand  seed=8663498807872  $ r6
C  rand  seed=7447087897166  $ r7
lost 30 30
```

MCNP5 Input Detailed Model, Case 2, Table 4-1.

<u>*Case 2*</u>

```
HEU-COMP-FAST-100-Case 2-Detailed Model/ DIVA Sphere
C
C
C   Cell Cards
C
C   ************************************************************************
C   Lower Polar Cap-LPC
C   ************************************************************************
100    10 4.82470E-02 -101 102 -104  150 151 152 153 154 155 156 157
        160 161 162 163 164 165 166 167 103 110 111 112   imp:n=1
C    Support Rod Hole
101    21 8.31603E-02  -105  imp:n=1 $Brass Bolt
102    0  -103 105  imp:n=1 $ Support Hole
103    0 -101 -102 103     imp:n=1 $ Spot Face
C    Pins
104    12 4.82415E-02 -110 -104 166   imp:n=1
105    12 4.82415E-02 -111 -104   imp:n=1
107    12 4.82415E-02 -112 -104   imp:n=1
C    Mass Adjustment Button Recesses
110   0 -150 160 -101   imp:n=1
111   0 -151 161 -101   imp:n=1
112   0 -152 162 -101   imp:n=1
113   0 -153 163 -101   imp:n=1
114   0 -154 164 -101   imp:n=1
115   0 -155 165 -101   imp:n=1
116   0 -156 166 -101   imp:n=1
117   0 -157 167 -101   imp:n=1
120   0 -160 -101    imp:n=1
121   0 -161 -101   imp:n=1
122   0 -162 -101   imp:n=1
123   0 -163 -101   imp:n=1
124   0 -164 -101   imp:n=1
125   0 -165 -101   imp:n=1
126   0 -166 -101   imp:n=1
127   0 -167 -101   imp:n=1
C
130   0 101 -104 -900 103  imp:n=1
C
C   ************************************************************************
C   Lower Plate
C   ************************************************************************
208    11 4.82207E-02 -201 204 -205 210 211 212 213 214 imp:n=1
209    11 4.82207E-02 -206 imp:n=1 $Alignment Cone
210    0 201 204 -205 -900 imp:n=1
C    Pins
214    12 4.82415E-02 -210 204  imp:n=1
215    12 4.82415E-02 -211 204 imp:n=1
216    0              -213 204 imp:n=1
217    12 4.82415E-02 -212 204 imp:n=1
218    0              -214 204 imp:n=1
C
C   ************************************************************************
C   Central Plate
C   ************************************************************************
300   13 4.84393E-02 (-301 305 -306) 323 324 325
        310 311 312 313 307 308 410 411 412  u=1 imp:n=1
302   0 -307  u=1 imp:n=1
303   0 (-301  -308 309)  u=1 imp:n=1
304   17 4.84213E-02 -323 -301 308  u=1 imp:n=1   $Target Hole Plug
306   17 4.84213E-02 -324 -301  u=1 imp:n=1   $Thermocouple
307   17 4.84213E-02 -325 -301  u=1 imp:n=1   $Thermocouple
308   18 4.79799E-02 -309   u=1 imp:n=1   $Diametral Pin
C   Support Screw Holes
310   0  -310   u=1 imp:n=1
311   0  -311   u=1 imp:n=1
312   0  -312   u=1 imp:n=1
313   0  -313   u=1 imp:n=1
C  Pins
```

```
320   15 4.84213E-02 -410 308 -306  u=1 imp:n=1
321   15 4.84213E-02 -411 308 -306  u=1 imp:n=1
322   15 4.84213E-02 -412 308 -306  u=1 imp:n=1
331   0 -305 u=1 imp:n=1
332   0 (301 305 -306 309 310 311 312 313) u=1 imp:n=1
C
C   ************************************************************************
C   Upper Plate
C   ************************************************************************
406   14 4.84016E-02 -401 406 -407 410 411 412 u=1  imp:n=1
407   14 4.84016E-02 -408 u=1  imp:n=1
408   0  401 406 -407  u=1  imp:n=1
430   15 4.84213E-02 -410 308 406 -407 u=1  imp:n=1
431   15 4.84213E-02 -411 308 406 -407 u=1  imp:n=1
432   15 4.84213E-02 -412 308 406 -407 u=1  imp:n=1
C
C   ************************************************************************
C  Upper Polar Cap
C   ************************************************************************
500   16 4.83657E-02 -500 501 503 508 750 751 752 753 754 755 756 757
                         760 761 762 763 764 765 766 767 u=1  imp:n=1
501   0   -503 408 u=1  imp:n=1
C  Mass Adjustment Button Recesses
560   0 -750 760 -500 u=1  imp:n=1
561   0 -751 761 -500 u=1  imp:n=1
562   0 -752 762 -500 u=1  imp:n=1
563   0 -753 763 -500 u=1  imp:n=1
564   0 -754 764 -500 u=1  imp:n=1
565   0 -755 765 -500 u=1  imp:n=1
566   0 -756 766 -500 u=1  imp:n=1
567   0 -757 767 -500 u=1  imp:n=1
570   0 -760 -500 u=1  imp:n=1
571   0 -761 -500 u=1  imp:n=1
572   0 -762 -500 u=1  imp:n=1
573   0 -763 -500 u=1  imp:n=1
574   0 -764 -500 u=1  imp:n=1
575   0 -765 -500 u=1  imp:n=1
576   0 -766 -500 u=1  imp:n=1
577   0 -767 -500 u=1  imp:n=1
590   0 500 501 508  u=1  imp:n=1
591   0 -508  u=1 imp:n=1
C   ************************************************************************
C   ************************************************************************
905   0  205 206 210 -900 fill=1 imp:n=1
910  0  900 imp:n=0

C   Surface Cards
C
C   ************************************************************************
C   ****Lower Polar Cap- LPC**************************************************
C   ************************************************************************
101  sq 74.3031329 74.3031329 74.2764775 0 0 0 -5681.5712581 0 0 .05055
102     pz   -8.602701  $Spot Face
103 rcc 0 0 -7.811007 0 0 -1 0.747903 $Support Hole
104     pz   -4.06629  $ Top of polar cap
105 rcc 0 0 -7.811007 0 0 -0.76962 0.747903 $Support Hole
C   Pins
110 rcc -6.35 0 -5.177536 0 0 3.747262 0.57531
111 rcc 3.175 5.49926 -5.177536 0 0 3.747262 0.57531
112 rcc 3.175 -5.49926 -5.177536 0 0 3.748532 0.57531
C   LPC Mass Adjustment Button Recesses
150 rcc 0.00000 5.66256 -5.66256 0.00000 0.56345 -0.56345 0.17526
151 rcc 4.00403 4.00403 -5.66256 0.39843 0.39843 -0.56345 0.17526
152 rcc 5.66256 0.00000 -5.66256 0.56345 0 -0.56345 0.17526
153 rcc 4.00403 -4.00403 -5.66256 0.39843 -0.39843 -0.56345 0.17526
154 rcc 0.00000 -5.66256 -5.66256 0.00000 -0.56345 -0.56345 0.17526
155 rcc -4.00403 -4.00403 -5.66256 -0.39843 -0.39843 -0.56345 0.17526
156 rcc -5.66256 0.00000 -5.66256 -0.56345 0 -0.56345 0.17526
157 rcc -4.00403 4.00403 -5.66256 -0.39843 0.39843 -0.56345 0.17526
160 rcc 0.00000 6.1439 -6.1439 0.00000 0.08211 -0.08211 1.11125
161 rcc 4.34439 4.34439 -6.1439 0.05807 0.05807 -0.08211 1.11125
162 rcc 6.1439 0.00000 -6.1439 0.08211 0.00000 -0.08211 1.11125
```

```
163 rcc 4.34439 -4.34439 -6.1439 0.05807 -0.05807 -0.08211 1.11125
164 rcc 0.00000 -6.1439 -6.1439 0.00000 -0.08211 -0.08211 1.11125
165 rcc -4.34439 -4.34439 -6.1439 -0.05807 -0.05807 -0.08211 1.11125
166 rcc -6.1439 0.00000 -6.1439 -0.08211 0.00000 -0.08211 1.11125
167 rcc -4.34439 4.34439 -6.1439 -0.05807 0.05807 -0.08211 1.11125
C
C   ************************************************************************
C   ****Lower Plate- LP*****************************************************
C   ************************************************************************
201  sq 74.3031329 74.3031329 74.2764775 0 0 0 -5681.5712581 0 0 .05055
204     pz   -4.06629  $Bottom of LP
205     pz   -1.429004  $ Top of lower plate
206  trc 0 0 -1.429004 0 0 0.55372 0.635 0.315309609 $ LP Alignment cone
C  Lower Section Pins
210 rcc -6.35 0 -4.066286 0 0 2.636012 0.57531
211 rcc 3.175 5.49926 -4.066286 0 0 2.636012 0.57531
212 rcc 3.175 -5.49926 -4.066286 0 0 2.637282 0.57531
213 rcc 3.175 5.49926 -1.430274 0 0 0.001270 0.57531
214 rcc -6.35 0 -1.430274 0 0 0.001270 0.57531
C
C   ************************************************************************
C   ****Central Plate- CP***************************************************
C   ************************************************************************
301 sq 9.3495986 9.3495986 9.2963311 0 0 0 -713.5264512 0 0 0
305 pz -1.429004  $bottom of Central Plate
306 pz 1.429004  $Top of Central Plate
307  trc 0 0 -1.429004 0 0 0.5715 0.63627 0.306314321 $ CP Alignment Hole
308  cx  0.17272  $Diametral Hole
309 rcc  -8.914765 0 0   17.82953 0 0 0.164211 $ Diametral Pin
323 rcc 0.888238 0 0 8.80491 0 0 1.27 $ Target Hole Plug
324 rpp -0.0889 0.0889 -0.9525 4.1275 1.281684 1.429004 $Thermocouple
325 rpp -0.0889 0.0889 4.1275 8.80491 1.134364 1.429004 $Thermocouple
C    Support Rod Holes in CP
310 rcc 5.74467 5.74467 0 0.43734 0.43734 0 0.351028
311 rcc 5.74467 -5.74467 0 0.43734 -0.43734 0 0.351028
312 rcc -5.74467 -5.74467 0 -0.43734 -0.43734 0 0.351028
313 rcc -5.74467 5.74467 0 -0.43734 0.43734 0 0.351028
C
C   ************************************************************************
C   ****Upper Plate- UP*****************************************************
C   ************************************************************************
401 sq 9.3495986 9.3495986 9.2963311 0 0 0 -713.5264512 0 0 0
406 pz 1.429004 $Bottom of Upper Plate
407 pz 3.375152 $Top Of upper Plate
408 trc 0 0 3.375152 0 0 0.55372 0.635 0.315309609 $ UP Alignment Cone
C  Central Section Pins
410 rcc -6.35 -0.00063 -1.429004 0 0 4.804156 0.57531
411 rcc 3.17445 5.49958 -1.429004 0 0 4.804156 0.57531
412 rcc 3.17555 -5.49894 -1.429004 0 0 4.804156 0.57531
C
C   ************************************************************************
C   ****Upper Polar Cap- UPC************************************************
C   ************************************************************************
500 sq 65.4299300 65.4299300 65.3544096 0 0 0 -5000.2641811 0 0 0.046482
501 pz 3.375152 $Bottom of UPC
508 rcc 0 0 7.806182 0 0 1.11125 1.211072 $top support hole
503 trc 0 0 3.375152 0 0 0.5715 0.63627 0.306314321 $ UPC Alignment Hole
504 trc 0 0 3.375152 0 0 0.56261 0.635635 0.310811965 $Cone for modeling
C   UPC Mass Adjustment Button Recesses
750 rcc 0.00000 5.66256 5.66256 0.00000 0.56345 0.56345 0.17526
751 rcc 4.00403 4.00403 5.66256 0.39843 0.39843 0.56345 0.17526
752 rcc 5.66256 0 5.66256 0.56345 0 0.56345 0.17526
753 rcc 4.00403 -4.00403 5.66256 0.39843 -0.39843 0.56345 0.17526
754 rcc 0.00000 -5.66256 5.66256 0.00000 -0.56345 0.56345 0.17526
755 rcc -4.00403 -4.00403 5.66256 -0.39843 -0.39843 0.56345 0.17526
756 rcc -5.66256 0 5.66256 -0.56345 0 0.56345 0.17526
757 rcc -4.00403 4.00403 5.66256 -0.39843 0.39843 0.56345 0.17526
760 rcc 0.00000 6.1439 6.1439 0.00000 0.08211 0.08211 1.11125
761 rcc 4.34439 4.34439 6.1439 0.05807 0.05807 0.08211 1.11125
762 rcc 6.14390 0 6.1439 0.08211 0 0.08211 1.11125
763 rcc 4.34439 -4.34439 6.1439 0.05807 -0.05807 0.08211 1.11125
764 rcc 0.00000 -6.1439 6.1439 0.00000 -0.08211 0.08211 1.11125
```

```
765 rcc -4.34439 -4.34439 6.1439 -0.05807 -0.05807 0.08211 1.11125
766 rcc -6.14390 0 6.1439 -0.08211 0 0.08211 1.11125
767 rcc -4.34439 4.34439 6.1439 -0.05807 0.05807 0.08211 1.11125
C   **********************************************************************
C   ****Upper Socket******************************************************
C   **********************************************************************
600 sz 7.80542 1.105408 $Socket Sphere
601 rcc 0 0 8.654669 0 0 0.976376 0.714375 $Socket Cylinder
602 trc 0 0 9.631045 0 0 0.079375 0.714375 0.79375 $Flair at top of Socket
611   rcc   0   0   8.91667   0   0   0.15875   1.11125
612   rhp   0   0   9.07542   0   0   0.635   0.9525 0 0
C
C
900 rpp -356.616 713.232 -682.752 387.096 -280.416 629.7168 $Inside Walls

C   Data Cards
C     Lower Polar Cap
m10   92234.70c   4.74524E-04
      92235.70c   4.47388E-02
      92236.70c   1.71732E-05
      92238.70c   2.74959E-03
      4009.70c   6.26660E-09
      3006.70c   1.23513E-08
      3007.70c   1.50380E-07
      13027.70c   2.09313E-06
      14028.70c   3.70921E-05
      14029.70c   1.88345E-06
      14030.70c   1.24158E-06
      25055.70c   5.08310E-06
      28058.70c   5.78427E-06
      28060.70c   2.22809E-06
      28061.70c   9.68536E-08
      28062.70c   3.08812E-07
      28064.70c   7.86452E-08
      24050.70c   2.91696E-08
      24052.70c   5.62507E-07
      24053.70c   6.37838E-08
      24054.70c   1.58771E-08
      29063.70c   1.35701E-06
      29065.70c   6.04837E-07
      5010.70c   2.07912E-08
      5011.70c   8.36873E-08
      27059.70c   9.58303E-08
      20040.70c   1.36604E-06
      20042.70c   9.11719E-09
      20043.70c   1.90235E-09
      20044.70c   2.93948E-08
      20046.70c   5.63659E-11
      20048.70c   2.63511E-09
      6000.70c   1.68332E-04
      8016.70c   1.40852E-05
      8017.70c   3.43104E-08
      7014.70c   2.41033E-05
      7015.70c   8.90279E-08   $ Total   4.82470E-02
C    Lower Plate
m11   92234.70c   4.74733E-04
      92235.70c   4.47596E-02
      92236.70c   1.71786E-05
      92238.70c   2.73052E-03
      4009.70c   6.26450E-09
      3006.70c   1.23472E-08
      3007.70c   1.50329E-07
      13027.70c   3.34789E-06
      14028.70c   4.63496E-05
      14029.70c   2.35352E-06
      14030.70c   1.55146E-06
      25055.70c   3.48963E-06
      28058.70c   3.97100E-06
      28060.70c   1.52962E-06
      28061.70c   6.64916E-08
      28062.70c   2.12004E-07
      28064.70c   5.39913E-08
```

```
      24050.70c   2.00254E-08
      24052.70c   3.86171E-07
      24053.70c   4.37887E-08
      24054.70c   1.08999E-08
      29063.70c   9.31609E-07
      29065.70c   4.15231E-07
      5010.70c   1.03921E-07
      5011.70c   4.18296E-07
      27059.70c   9.57982E-08
      20040.70c   1.36558E-06
      20042.70c   9.11413E-09
      20043.70c   1.90171E-09
      20044.70c   2.93850E-08
      20046.70c   5.63470E-11
      20048.70c   2.63422E-09
      6000.70c   1.33492E-04
      8016.70c   1.40805E-05
      8017.70c   3.42989E-08
      7014.70c   2.40952E-05
      7015.70c   8.89980E-08   $ Total   4.82207E-02
C    Pins for Lower Part
m12   92234.70c   4.79981E-04
      92235.70c   4.47281E-02
      92236.70c   2.15625E-04
      92238.70c   2.55888E-03
      13027.70c   2.09237E-06
      14028.70c   4.44944E-05
      14029.70c   2.25932E-06
      14030.70c   1.48936E-06
      25055.70c   3.79563E-06
      28058.70c   4.31922E-06
      28060.70c   1.66375E-06
      28061.70c   7.23222E-08
      28062.70c   2.30595E-07
      28064.70c   5.87257E-08
      24050.70c   2.17815E-08
      24052.70c   4.20034E-07
      24053.70c   4.76285E-08
      24054.70c   1.18557E-08
      29063.70c   1.01330E-06
      29065.70c   4.51642E-07
      5010.70c   6.23511E-08
      5011.70c   2.50971E-07
      6000.70c   1.57930E-04
      8016.70c   1.40801E-05
      8017.70c   3.42979E-08
      7014.70c   2.40946E-05
      7015.70c   8.89956E-08   $ Total   4.82415E-02
C    Central Plate
m13   92234.70c   4.76368E-04
      92235.70c   4.49131E-02
      92236.70c   1.72364E-05
      92238.70c   2.75010E-03
      4009.70c   6.28627E-09
      3006.70c   1.23901E-08
      3007.70c   1.50852E-07
      13027.70c   1.67976E-06
      14028.70c   7.44171E-05
      14029.70c   3.77872E-06
      14030.70c   2.49096E-06
      25055.70c   3.07172E-06
      28058.70c   3.49544E-06
      28060.70c   1.34644E-06
      28061.70c   5.85287E-08
      28062.70c   1.86615E-07
      28064.70c   4.75254E-08
      24050.70c   1.76272E-08
      24052.70c   3.39924E-07
      24053.70c   3.85446E-08
      24054.70c   9.59457E-09
      29063.70c   8.20042E-07
      29065.70c   3.65504E-07
```

```
      5010.70c   4.17130E-08
      5011.70c   1.67900E-07
      27059.70c   9.61312E-08
      20040.70c   1.37033E-06
      20042.70c   9.14582E-09
      20043.70c   1.90832E-09
      20044.70c   2.94871E-08
      20046.70c   5.65429E-11
      20048.70c   2.64338E-09
      6000.70c   1.49993E-04
      8016.70c   1.41294E-05
      8017.70c   3.44181E-08
      7014.70c   2.41790E-05
      7015.70c   8.93074E-08   $ Total   4.84393E-02
C   Upper Plate
m14   92234.70c   4.76471E-04
      92235.70c   4.49232E-02
      92236.70c   1.72432E-05
      92238.70c   2.74561E-03
      4009.70c   6.28700E-09
      3006.70c   1.23915E-08
      3007.70c   1.50869E-07
      13027.70c   1.67996E-06
      14028.70c   3.72129E-05
      14029.70c   1.88958E-06
      14030.70c   1.24562E-06
      25055.70c   2.08901E-06
      28058.70c   2.37718E-06
      28060.70c   9.15684E-07
      28061.70c   3.98041E-08
      28062.70c   1.26913E-07
      28064.70c   3.23210E-08
      24050.70c   1.19879E-08
      24052.70c   2.31175E-07
      24053.70c   2.62134E-08
      24054.70c   6.52506E-09
      29063.70c   5.57693E-07
      29065.70c   2.48571E-07
      5010.70c   6.25767E-08
      5011.70c   2.51879E-07
      27059.70c   9.61423E-08
      20040.70c   1.37049E-06
      20042.70c   9.14688E-09
      20043.70c   1.90854E-09
      20044.70c   2.94905E-08
      20046.70c   5.65495E-11
      20048.70c   2.64369E-09
      6000.70c   1.50011E-04
      8016.70c   1.41310E-05
      8017.70c   3.44221E-08
      7014.70c   2.41818E-05
      7015.70c   8.93177E-08   $ Total   4.84016E-02
C Pins for Central Section
m15   92234.70c   4.77221E-04
      92235.70c   4.49020E-02
      92236.70c   2.03472E-04
      92238.70c   2.57860E-03
      13027.70c   2.10017E-06
      14028.70c   4.46602E-05
      14029.70c   2.26774E-06
      14030.70c   1.49491E-06
      25055.70c   3.80978E-06
      28058.70c   4.33532E-06
      28060.70c   1.66996E-06
      28061.70c   7.25918E-08
      28062.70c   2.31455E-07
      28064.70c   5.89446E-08
      24050.70c   2.18627E-08
      24052.70c   4.21600E-07
      24053.70c   4.78060E-08
      24054.70c   1.18999E-08
      29063.70c   1.01708E-06
```

```
      29065.70c   4.53326E-07
      5010.70c   6.25835E-08
      5011.70c   2.51906E-07
      6000.70c   1.58519E-04
      8016.70c   1.41326E-05
      8017.70c   3.44258E-08
      7014.70c   2.41844E-05
      7015.70c   8.93274E-08   $ Total   4.84213E-02
C  Upper Polar Cp
m16   92234.70c   4.75689E-04
      92235.70c   4.48495E-02
      92236.70c   1.72149E-05
      92238.70c   2.74110E-03
      4009.70c   6.27700E-09
      3006.70c   1.23718E-08
      3007.70c   1.50630E-07
      13027.70c   2.51593E-06
      14028.70c   2.97229E-05
      14029.70c   1.50926E-06
      14030.70c   9.94914E-07
      25055.70c   5.21422E-06
      28058.70c   5.93349E-06
      28060.70c   2.28557E-06
      28061.70c   9.93521E-08
      28062.70c   3.16778E-07
      28064.70c   8.06740E-08
      24050.70c   2.99221E-08
      24052.70c   5.77018E-07
      24053.70c   6.54292E-08
      24054.70c   1.62867E-08
      29063.70c   1.39201E-06
      29065.70c   6.20440E-07
      5010.70c   1.04129E-07
      5011.70c   4.19131E-07
      27059.70c   9.59894E-08
      20040.70c   1.36831E-06
      20042.70c   9.13233E-09
      20043.70c   1.90551E-09
      20044.70c   2.94436E-08
      20046.70c   5.64595E-11
      20048.70c   2.63948E-09
      6000.70c   1.90277E-04
      8016.70c   1.41086E-05
      8017.70c   3.43673E-08
      7014.70c   2.41433E-05
      7015.70c   8.91757E-08   $ Total   4.83657E-02
C  Plug for Target hole/Thermocouple Groove
m17   92234.70c   4.81770E-04
      92235.70c   4.48948E-02
      92236.70c   2.16429E-04
      92238.70c   2.56841E-03
      13027.70c   2.10017E-06
      14028.70c   4.46602E-05
      14029.70c   2.26774E-06
      14030.70c   1.49491E-06
      25055.70c   3.80978E-06
      28058.70c   4.33532E-06
      28060.70c   1.66996E-06
      28061.70c   7.25918E-08
      28062.70c   2.31455E-07
      28064.70c   5.89446E-08
      24050.70c   2.18627E-08
      24052.70c   4.21600E-07
      24053.70c   4.78060E-08
      24054.70c   1.18999E-08
      29063.70c   1.01708E-06
      29065.70c   4.53326E-07
      5010.70c   6.25835E-08
      5011.70c   2.51906E-07
      6000.70c   1.58519E-04
      8016.70c   1.41326E-05
      8017.70c   3.44258E-08
```

```
      7014.70c   2.41844E-05
      7015.70c   8.93274E-08   $ Total   4.84213E-02
C   Diametral Pin, AVG Density
m18   92234.70c   4.77378E-04
      92235.70c   4.44855E-02
      92236.70c   2.14455E-04
      92238.70c   2.54500E-03
      13027.70c   2.08103E-06
      14028.70c   4.42531E-05
      14029.70c   2.24706E-06
      14030.70c   1.48128E-06
      25055.70c   3.77505E-06
      28058.70c   4.29579E-06
      28060.70c   1.65473E-06
      28061.70c   7.19300E-08
      28062.70c   2.29344E-07
      28064.70c   5.84073E-08
      24050.70c   2.16633E-08
      24052.70c   4.17756E-07
      24053.70c   4.73702E-08
      24054.70c   1.17914E-08
      29063.70c   1.00781E-06
      29065.70c   4.49193E-07
      5010.70c   6.20129E-08
      5011.70c   2.49610E-07
      6000.70c   1.57074E-04
      8016.70c   1.40037E-05
      8017.70c   3.41119E-08
      7014.70c   2.39639E-05
      7015.70c   8.85130E-08   $ Total   4.79799E-02
C   SS304 at Typical Density
m20   26054.70c   3.49480E-03
      26056.70c   5.48609E-02
      26057.70c   1.26698E-03
      26058.70c   1.68612E-04
      6000.70c   1.59038E-04
      25055.70c   8.69257E-04
      14028.70c   7.84115E-04
      14029.70c   3.98155E-05
      14030.70c   2.62466E-05
      24050.70c   7.58219E-04
      24052.70c   1.46215E-02
      24053.70c   1.65796E-03
      24054.70c   4.12701E-04
      28058.70c   5.26236E-03
      28060.70c   2.02705E-03
      28061.70c   8.81145E-05
      28062.70c   2.80948E-04
      28064.70c   7.15491E-05
      15031.70c   3.46904E-05
      16032.70c   2.12040E-05
      16033.70c   1.69757E-07
      16034.70c   9.58232E-07
      16034.70c   4.46728E-09   $ tot   8.69072E-02
C   Brass for LPC Bolt
m21   29063.70c   5.19162E-02
      29065.70c   2.31397E-02
      30000.70c   8.10437E-03   $ Total   8.31603E-02
kcode  500000 1 150 2650
sdef    pos 0 0 0 rad=d1 erg=d3
si1       0 3.4665
sp1      -21 2
sp3     -3 0.988 2.249
*tr1   0 0 .005715  -.03768862 90 90.03768862 90 0 90 89.962311 90 -.03768862
C  rand  seed=7065399757867  $ r2
C  rand  seed=5724484131590  $ r3
C  rand  seed=417647895433   $ r4
C  rand  seed=8132049697893  $ r5
C  rand  seed=8663498807872  $ r6
C  rand  seed=7447087897166  $ r7
```

MCNP5 Input for Simple Model, Case 1, Table 4-2.

Case 1

```
HEU-COMP-FAST-100- Case 1-Simple Model/ ORSphere
C
C
C   Cell Cards
C
1      1 4.83068E-02 -1  imp:n=1
2      0         1  -900 imp:n=1
910    0             900 imp:n=0

C   Surface Cards
C
1   so 8.79068305
C
900  rpp -100 100 -100 100 -100 100

C   Data Cards
m1   92234.70c   4.75903E-04
      92235.70c   4.48592E-02
      92236.70c   2.18724E-05
      92238.70c   2.74041E-03
      14028.70c   4.58501E-05
      14029.70c   2.32816E-06
      14030.70c   1.53474E-06
      5010.70c   6.81721E-08
      5011.70c   2.74401E-07
      6000.70c   1.59286E-04   $ Total   4.83068E-02
kcode  500000 1 150 2650
sdef    pos 0 0 0 rad=d1 erg=d3
si1       0 3.4665
sp1      -21 2
sp3     -3 0.988 2.249
```

MCNP5 Input for Simple Model, Case 2, Table 4-2.

Case 2

```
HEU-COMP-FAST-100-Case 2-Simple Model/ ORSphere
C
C
C   Cell Cards
C
1     1 4.82842E-02 -1  imp:n=1
2     0         1  -900 imp:n=1
910   0             900 imp:n=0

C   Surface Cards
C
1   so 8.72995881
900  rpp -100 100 -100 100 -100 100

C   Data Cards
m1   92234.70c   4.75683E-04
      92235.70c   4.48383E-02
      92236.70c   2.19397E-05
      92238.70c   2.73900E-03
      14028.70c   4.58803E-05
      14029.70c   2.32969E-06
      14030.70c   1.53575E-06
      5010.70c   6.83700E-08
      5011.70c   2.75198E-07
      6000.70c   1.59200E-04   $ Total   4.82842E-02
kcode  500000 1 150 2650
sdef    pos 0 0 0 rad=d1 erg=d3
si1       0 3.4665
sp1      -21 2
sp3     -3 0.988 2.249
```

A.2 KENO Input Listing

KENO Input for Detailed Model, Case 1, Table 4-1.

Case 1

```
'Input generated by GeeWiz SCALE 6.1 Compiled on Tue Sep  6 15:23:32 2011
=csas6
detailed orsphere case 1
ce_v7_endf
read composition
 u-234       1 0 0.00047588 293   end
 u-235       1 0 0.044867 293   end
 u-236       1 0 1.7222e-05 293   end
 u-238       1 0 0.0027575 293   end
 be          1 0 6.2845e-09 293   end
 li          1 0 1.632e-07 293   end
 al          1 0 2.0991e-06 293   end
 si          1 0 4.0332e-05 293   end
 mn          1 0 5.0977e-06 293   end
 ni          1 0 8.521e-06 293   end
 cr          1 0 6.7326e-07 293   end
 cu          1 0 1.9675e-06 293   end
 b           1 0 1.0478e-07 293   end
 co          1 0 9.6105e-08 293   end
 ca          1 0 1.4132e-06 293   end
 c           1 0 0.00016881 293   end
 o           1 0 1.416e-05 293   end
 n           1 0 2.4262e-05 293   end
 u-234       2 0 0.00047609 293   end
 u-235       2 0 0.044888 293   end
 u-236       2 0 1.7228e-05 293   end
 u-238       2 0 0.0027383 293   end
 be          2 0 6.2824e-09 293   end
 li          2 0 1.6314e-07 293   end
 al          2 0 3.3575e-06 293   end
 si          2 0 5.0398e-05 293   end
 mn          2 0 3.4996e-06 293   end
 ni          2 0 5.8498e-06 293   end
 cr          2 0 4.622e-07 293   end
 cu          2 0 1.3507e-06 293   end
 b           2 0 5.2371e-07 293   end
 co          2 0 9.6073e-08 293   end
 ca          2 0 1.4127e-06 293   end
 c           2 0 0.00013387 293   end
 o           2 0 1.4155e-05 293   end
 n           2 0 2.4254e-05 293   end
 u-234       3 0 0.00048136 293   end
 u-235       3 0 0.044856 293   end
 u-236       3 0 0.00021624 293   end
 u-238       3 0 0.0025662 293   end
 al          3 0 2.0984e-06 293   end
 si          3 0 4.8381e-05 293   end
 mn          3 0 3.8065e-06 293   end
 ni          3 0 6.3628e-06 293   end
 cr          3 0 5.0274e-07 293   end
 cu          3 0 1.4691e-06 293   end
 b           3 0 3.1422e-07 293   end
 c           3 0 0.00015838 293   end
 o           3 0 1.4155e-05 293   end
 n           3 0 2.4253e-05 293   end
 u-234       5 0 0.00047526 293   end
 u-235       5 0 0.044809 293   end
 u-236       5 0 1.7196e-05 293   end
 u-238       5 0 0.0027437 293   end
 be          5 0 6.2717e-09 293   end
 li          5 0 1.6286e-07 293   end
 al          5 0 1.6759e-06 293   end
 si          5 0 8.05e-05 293   end
 mn          5 0 3.0646e-06 293   end
 ni          5 0 5.1226e-06 293   end
```

```
cr          5 0 4.0475e-07 293   end
cu          5 0 1.1828e-06 293   end
b           5 0 2.0913e-07 293   end
co          5 0 9.5908e-08 293   end
ca          5 0 1.4103e-06 293   end
c           5 0 0.00014965 293   end
o           5 0 1.4131e-05 293   end
n           5 0 2.4212e-05 293   end
u-234       6 0 0.00047537 293   end
u-235       6 0 0.044819 293   end
u-236       6 0 1.7203e-05 293   end
u-238       6 0 0.0027392 293   end
be          6 0 6.2724e-09 293   end
li          6 0 1.6288e-07 293   end
al          6 0 1.6761e-06 293   end
si          6 0 4.0255e-05 293   end
mn          6 0 2.0842e-06 293   end
ni          6 0 3.4838e-06 293   end
cr          6 0 2.7526e-07 293   end
cu          6 0 8.044e-07 293   end
b           6 0 3.1373e-07 293   end
co          6 0 9.5919e-08 293   end
ca          6 0 1.4105e-06 293   end
c           6 0 0.00014966 293   end
o           6 0 1.4133e-05 293   end
n           6 0 2.4215e-05 293   end
u-234       7 0 0.00047611 293   end
u-235       7 0 0.044798 293   end
u-236       7 0 0.000203 293   end
u-238       7 0 0.0025726 293   end
al          7 0 2.0953e-06 293   end
si          7 0 4.8311e-05 293   end
mn          7 0 3.801e-06 293   end
ni          7 0 6.3535e-06 293   end
cr          7 0 5.02e-07 293   end
cu          7 0 1.467e-06 293   end
b           7 0 3.1376e-07 293   end
c           7 0 0.00015815 293   end
o           7 0 1.4134e-05 293   end
n           7 0 2.4217e-05 293   end
u-234       8 0 0.00048065 293   end
u-235       8 0 0.044791 293   end
u-236       8 0 0.00021593 293   end
u-238       8 0 0.0025625 293   end
al          8 0 2.0953e-06 293   end
si          8 0 4.8311e-05 293   end
mn          8 0 3.801e-06 293   end
ni          8 0 6.3535e-06 293   end
cr          8 0 5.02e-07 293   end
cu          8 0 1.467e-06 293   end
b           8 0 3.1376e-07 293   end
c           8 0 0.00015815 293   end
o           8 0 1.4134e-05 293   end
n           8 0 2.4217e-05 293   end
u-234       10 0 0.00047635 293   end
u-235       10 0 0.044911 293   end
u-236       10 0 1.7239e-05 293   end
u-238       10 0 0.0027449 293   end
be          10 0 6.2857e-09 293   end
li          10 0 1.6323e-07 293   end
al          10 0 2.5194e-06 293   end
si          10 0 3.2272e-05 293   end
mn          10 0 5.2214e-06 293   end
ni          10 0 8.7279e-06 293   end
cr          10 0 6.8961e-07 293   end
cu          10 0 2.0152e-06 293   end
b           10 0 5.2398e-07 293   end
co          10 0 9.6122e-08 293   end
ca          10 0 1.4134e-06 293   end
c           10 0 0.00019054 293   end
o           10 0 1.4162e-05 293   end
n           10 0 2.4266e-05 293   end
```

```
 u-234       12 0 0.00047738 293   end
 u-235       12 0 0.044485 293   end
 u-236       12 0 0.00021446 293   end
 u-238       12 0 0.002545 293   end
 al          12 0 2.081e-06 293   end
 si          12 0 4.7981e-05 293   end
 mn          12 0 3.7751e-06 293   end
 ni          12 0 6.3102e-06 293   end
 cr          12 0 4.9858e-07 293   end
 cu          12 0 1.457e-06 293   end
 b           12 0 3.1162e-07 293   end
 c           12 0 0.00015707 293   end
 o           12 0 1.4038e-05 293   end
 n           12 0 2.4052e-05 293   end
 cu          15 0 0.075056 293   end
 zn          15 0 0.0081044 293   end
end composition
read parameter
 gen=2650
 npg=500000
 nsk=150
 htm=no
end parameter
read geometry
global unit 1
com="orcef sphere bottom section"
 sphere 1       10
 ellipsoid 2  8.799239  8.799239  8.804402  chord -z=-4.06146  chord +z=-8.712326   origin  x=0 y=0
z=-0.00483
 ellipsoid 3  8.802591  8.802591  8.813478  chord -z=-1.429  chord +z=-4.06629
 cylinder 8  0.57531  -1.423162  -5.17754   origin  x=-6.35 y=0 z=0
 cylinder 9  0.57531  -1.430274  -5.17754   origin  x=3.175 y=5.49926 z=0
 cylinder 10  0.57531   -1.429  -5.17754   origin  x=3.175 y=-5.49926 z=0
 cylinder 11  0.57531   -1.429  -5.17754   origin  x=3.175 y=5.49926 z=0
 cylinder 12  0.747903  -7.811008  -8.623808
 cone 13   0.3153  0.55372    0.635        0   origin  x=0 y=0 z=-1.429
 cylinder 14  0.17526  -8.00807  -8.809228   rotate  a1=0 a2=45 a3=0
 cylinder 15  0.17526  -8.00807  -8.809228   rotate  a1=0 a2=-45 a3=0
 cylinder 16  0.17526  -8.00807  -8.809228   rotate  a1=90 a2=45 a3=0
 cylinder 17  0.17526  -8.00807  -8.809228   rotate  a1=90 a2=-45 a3=0
 cylinder 18  0.17526  -8.00807  -8.809228   rotate  a1=45 a2=45 a3=0
 cylinder 19  0.17526  -8.00807  -8.809228   rotate  a1=45 a2=-45 a3=0
 cylinder 20  0.17526  -8.00807  -8.809228   rotate  a1=-45 a2=45 a3=0
 cylinder 21  0.17526  -8.00807  -8.809228   rotate  a1=-45 a2=-45 a3=0
 cylinder 22  1.11125  -8.688787  -8.809228   rotate  a1=0 a2=45 a3=0
 cylinder 23  1.11125  -8.688787  -8.809228   rotate  a1=0 a2=-45 a3=0
 cylinder 24  1.11125  -8.688787  -8.809228   rotate  a1=90 a2=45 a3=0
 cylinder 25  1.11125  -8.688787  -8.809228   rotate  a1=90 a2=-45 a3=0
 cylinder 26  1.11125  -8.688787  -8.809228   rotate  a1=45 a2=45 a3=0
 cylinder 27  1.11125  -8.688787  -8.809228   rotate  a1=45 a2=-45 a3=0
 cylinder 28  1.11125  -8.688787  -8.809228   rotate  a1=-45 a2=45 a3=0
 cylinder 29  1.11125  -8.688787  -8.809228   rotate  a1=-45 a2=-45 a3=0
 cylinder 68  0.747903  -7.811008     -8.9
 hole 2   origin  x=0 y=0 z=0.00351038   rotate  a1=-90 a2=-0.02313405 a3=90
 media 1 1 2 -8 -10 -11 -14 -15 -16 -17 -18 -19 -20 -21 -22 -23 -24 -25 -26 -27 -28 -29 -68
 media 2 1 3 -8 -10 -11
 media 2 1 13
 media 3 1 8
 media 3 1 9
 media 3 1 10
 media 0 1 -9 11
 media 15 1 12
 media 0 1 2 68 -12
 media 0 1 14 -22 2
 media 0 1 15 -23 2
 media 0 1 16 -24 2
 media 0 1 17 -25 2
 media 0 1 18 -26 2
 media 0 1 19 -27 2
 media 0 1 20 -28 2
 media 0 1 21 -29 2
 media 0 1 22 2
```

```
 media 0 1 23 2
 media 0 1 24 2
 media 0 1 25 2
 media 0 1 26 2
 media 0 1 27 2
 media 0 1 28 2
 media 0 1 29 2
 media 0 1 1 -2 -3 -8 -13
 boundary 1
unit 2
com="tilted upper portion of sphere"
 sphere 1        9  chord +z=-1.429
 ellipsoid 4  8.803387  8.803387  8.76508  chord -z=0  chord +z=-1.429
 ellipsoid 5  8.803387  8.803387  8.842202  chord -z=1.429  chord +z=0
 ellipsoid 6  8.801926  8.801926  8.818815  chord -z=3.37515  chord +z=1.429
 ellipsoid 7  8.806101  8.806101  8.80491  chord +z=3.37566   origin  x=0 y=0 z=-0.000508
 cone 13   0.3153  0.55372    0.635        0   origin  x=0 y=0 z=-1.434715   rotate  a1=-90
a2=0.03768862 a3=90
 cone 36   0.3063   0.5715    0.635        0   origin  x=0 y=0 z=-1.429
 cylinder 37  0.57531  3.37515   -1.429   origin  x=-6.35 y=0 z=0
 cylinder 38  0.57531  3.37515   -1.429   origin  x=3.175 y=-5.49926 z=0
 cylinder 39  0.57531  3.37515   -1.429   origin  x=3.175 y=5.49926 z=0
 xcylinder 40     1.27      8.9  0.888238
 xcylinder 41  0.17272      8.9     -8.9
 xcylinder 42  0.164211  8.914765  -8.914765
 xcylinder 43  0.351028      8.9  8.12419   rotate  a1=45 a2=0 a3=0
 xcylinder 44  0.351028      8.9  8.12419   rotate  a1=-45 a2=0 a3=0
 xcylinder 45  0.351028      8.9  8.12419   rotate  a1=135 a2=0 a3=0
 xcylinder 46  0.351028      8.9  8.12419   rotate  a1=-135 a2=0 a3=0
 cuboid 47   0.0889  -0.0889   4.1275  -0.9525    1.429  1.281684
 cuboid 48   0.0889  -0.0889      8.9   4.1275    1.429  1.134364
 cone 49   0.3153  0.55372    0.635        0   origin  x=0 y=0 z=3.37515
 cone 50   0.3063   0.5715  0.63627        0   origin  x=0 y=0 z=3.37515
 cylinder 51  0.17526  8.809228  8.00807   rotate  a1=0 a2=45 a3=0
 cylinder 52  0.17526  8.809228  8.00807   rotate  a1=0 a2=-45 a3=0
 cylinder 53  0.17526  8.809228  8.00807   rotate  a1=90 a2=45 a3=0
 cylinder 54  0.17526  8.809228  8.00807   rotate  a1=90 a2=-45 a3=0
 cylinder 55  0.17526  8.809228  8.00807   rotate  a1=45 a2=45 a3=0
 cylinder 56  0.17526  8.809228  8.00807   rotate  a1=45 a2=-45 a3=0
 cylinder 57  0.17526  8.809228  8.00807   rotate  a1=-45 a2=45 a3=0
 cylinder 58  0.17526  8.809228  8.00807   rotate  a1=-45 a2=-45 a3=0
 cylinder 59  1.11125  8.809228  8.688787   rotate  a1=0 a2=45 a3=0
 cylinder 60  1.11125  8.809228  8.688787   rotate  a1=0 a2=-45 a3=0
 cylinder 61  1.11125  8.809228  8.688787   rotate  a1=90 a2=45 a3=0
 cylinder 62  1.11125  8.809228  8.688787   rotate  a1=90 a2=-45 a3=0
 cylinder 63  1.11125  8.809228  8.688787   rotate  a1=45 a2=45 a3=0
 cylinder 64  1.11125  8.809228  8.688787   rotate  a1=45 a2=-45 a3=0
 cylinder 65  1.11125  8.809228  8.688787   rotate  a1=-45 a2=45 a3=0
 cylinder 66  1.11125  8.809228  8.688787   rotate  a1=-45 a2=-45 a3=0
 cylinder 67  1.211072  9.806182  7.806182
 media 5 1 4 -36 -37 -38 -39 -40 -41 -43 -44 -45 -46
 media 5 1 5 -37 -38 -39 -40 -41 -43 -44 -45 -46 -47 -48
 media 6 1 6 -37 -38 -39
 media 10 1 7 -50 -51 -52 -53 -54 -55 -56 -57 -58 -59 -60 -61 -62 -63 -64 -65 -66 -67
 media 2 1 13
 media 0 1 1 -4 -5 -6 -7 -13 -36 -42 -49 -50
 media 0 1 36 -13
 media 7 1 37 -41
 media 7 1 38
 media 7 1 39
 media 8 1 40 4 -41
 media 8 1 40 5 -41
 media 0 1 41 -42 4
 media 0 1 41 -42 5
 media 12 1 42
 media 0 1 43 4
 media 0 1 44 4
 media 0 1 45 4
 media 0 1 46 4
 media 0 1 43 5
 media 0 1 44 5
 media 0 1 45 5
```

```
 media 0 1 46 5
 media 8 1 47
 media 8 1 48 5
 media 6 1 49
 media 0 1 -49 50
 media 0 1 51 -59 7
 media 0 1 52 -60 7
 media 0 1 53 -61 7
 media 0 1 54 -62 7
 media 0 1 55 -63 7
 media 0 1 56 -64 7
 media 0 1 57 -65 7
 media 0 1 58 -66 7
 media 0 1 59 7
 media 0 1 60 7
 media 0 1 61 7
 media 0 1 62 7
 media 0 1 63 7
 media 0 1 64 7
 media 0 1 65 7
 media 0 1 66 7
 media 0 1 67 7
 boundary 1
end geometry
end data
end
```

KENO Input for Detailed Model, Case 2, Table 4-1.

Case 2

```
'Input generated by GeeWiz SCALE 6.1 Compiled on Tue Sep  6 15:23:32 2011
=csas6
detailed orsphere case 2
ce_v7_endf
read composition
 u-234       1 0 0.00047452 293   end
 u-235       1 0 0.044739 293   end
 u-236       1 0 1.7173e-05 293   end
 u-238       1 0 0.0027496 293   end
 be          1 0 6.2666e-09 293   end
 li          1 0 1.6273e-07 293   end
 al          1 0 2.0931e-06 293   end
 si          1 0 4.0217e-05 293   end
 mn          1 0 5.0831e-06 293   end
 ni          1 0 8.4967e-06 293   end
 cr          1 0 6.7134e-07 293   end
 cu          1 0 1.9618e-06 293   end
 b           1 0 1.0448e-07 293   end
 co          1 0 9.583e-08 293   end
 ca          1 0 1.4091e-06 293   end
 c           1 0 0.00016833 293   end
 o           1 0 1.4119e-05 293   end
 n           1 0 2.4192e-05 293   end
 u-234       2 0 0.00047473 293   end
 u-235       2 0 0.04476 293   end
 u-236       2 0 1.7179e-05 293   end
 u-238       2 0 0.0027305 293   end
 be          2 0 6.2645e-09 293   end
 li          2 0 1.6268e-07 293   end
 al          2 0 3.3479e-06 293   end
 si          2 0 5.0255e-05 293   end
 mn          2 0 3.4896e-06 293   end
 ni          2 0 5.8331e-06 293   end
 cr          2 0 4.6088e-07 293   end
 cu          2 0 1.3468e-06 293   end
 b           2 0 5.2222e-07 293   end
 co          2 0 9.5798e-08 293   end
 ca          2 0 1.4087e-06 293   end
 c           2 0 0.00013349 293   end
 o           2 0 1.4115e-05 293   end
 n           2 0 2.4184e-05 293   end
 u-234       3 0 0.00047998 293   end
 u-235       3 0 0.044728 293   end
 u-236       3 0 0.00021562 293   end
 u-238       3 0 0.0025589 293   end
 al          3 0 2.0924e-06 293   end
 si          3 0 4.8243e-05 293   end
 mn          3 0 3.7956e-06 293   end
 ni          3 0 6.3446e-06 293   end
 cr          3 0 5.013e-07 293   end
 cu          3 0 1.4649e-06 293   end
 b           3 0 3.1332e-07 293   end
 c           3 0 0.00015793 293   end
 o           3 0 1.4114e-05 293   end
 n           3 0 2.4184e-05 293   end
 u-234       5 0 0.00047637 293   end
 u-235       5 0 0.044913 293   end
 u-236       5 0 1.7236e-05 293   end
 u-238       5 0 0.0027501 293   end
 be          5 0 6.2863e-09 293   end
 li          5 0 1.6324e-07 293   end
 al          5 0 1.6798e-06 293   end
 si          5 0 8.0687e-05 293   end
 mn          5 0 3.0717e-06 293   end
 ni          5 0 5.1345e-06 293   end
 cr          5 0 4.0569e-07 293   end
 cu          5 0 1.1855e-06 293   end
```

```
b           5 0 2.0961e-07 293   end
co          5 0 9.6131e-08 293   end
ca          5 0 1.4136e-06 293   end
c           5 0 0.00014999 293   end
o           5 0 1.4164e-05 293   end
n           5 0 2.4268e-05 293   end
u-234       6 0 0.00047647 293   end
u-235       6 0 0.044923 293   end
u-236       6 0 1.7243e-05 293   end
u-238       6 0 0.0027456 293   end
be          6 0 6.287e-09 293   end
li          6 0 1.6326e-07 293   end
al          6 0 1.68e-06 293   end
si          6 0 4.0348e-05 293   end
mn          6 0 2.089e-06 293   end
ni          6 0 3.4919e-06 293   end
cr          6 0 2.759e-07 293   end
cu          6 0 8.0626e-07 293   end
b           6 0 3.1446e-07 293   end
co          6 0 9.6142e-08 293   end
ca          6 0 1.4137e-06 293   end
c           6 0 0.00015001 293   end
o           6 0 1.4165e-05 293   end
n           6 0 2.4271e-05 293   end
u-234       7 0 0.00047722 293   end
u-235       7 0 0.044902 293   end
u-236       7 0 0.00020347 293   end
u-238       7 0 0.0025786 293   end
al          7 0 2.1002e-06 293   end
si          7 0 4.8423e-05 293   end
mn          7 0 3.8098e-06 293   end
ni          7 0 6.3683e-06 293   end
cr          7 0 5.0317e-07 293   end
cu          7 0 1.4704e-06 293   end
b           7 0 3.1449e-07 293   end
c           7 0 0.00015852 293   end
o           7 0 1.4167e-05 293   end
n           7 0 2.4274e-05 293   end
u-234       8 0 0.00048177 293   end
u-235       8 0 0.044895 293   end
u-236       8 0 0.00021643 293   end
u-238       8 0 0.0025684 293   end
al          8 0 2.1002e-06 293   end
si          8 0 4.8423e-05 293   end
mn          8 0 3.8098e-06 293   end
ni          8 0 6.3683e-06 293   end
cr          8 0 5.0317e-07 293   end
cu          8 0 1.4704e-06 293   end
b           8 0 3.1449e-07 293   end
c           8 0 0.00015852 293   end
o           8 0 1.4167e-05 293   end
n           8 0 2.4274e-05 293   end
u-234       10 0 0.00047569 293   end
u-235       10 0 0.044849 293   end
u-236       10 0 1.7215e-05 293   end
u-238       10 0 0.0027411 293   end
be          10 0 6.277e-09 293   end
li          10 0 1.63e-07 293   end
al          10 0 2.5159e-06 293   end
si          10 0 3.2227e-05 293   end
mn          10 0 5.2142e-06 293   end
ni          10 0 8.7159e-06 293   end
cr          10 0 6.8866e-07 293   end
cu          10 0 2.0125e-06 293   end
b           10 0 5.2326e-07 293   end
co          10 0 9.5989e-08 293   end
ca          10 0 1.4115e-06 293   end
c           10 0 0.00019028 293   end
o           10 0 1.4143e-05 293   end
n           10 0 2.4233e-05 293   end
u-234       12 0 0.00047738 293   end
u-235       12 0 0.044485 293   end
```

```
 u-236       12 0 0.00021446 293   end
 u-238       12 0 0.002545 293   end
 al          12 0 2.081e-06 293   end
 si          12 0 4.7981e-05 293   end
 mn          12 0 3.7751e-06 293   end
 ni          12 0 6.3102e-06 293   end
 cr          12 0 4.9858e-07 293   end
 cu          12 0 1.457e-06 293   end
 b           12 0 3.1162e-07 293   end
 c           12 0 0.00015707 293   end
 o           12 0 1.4038e-05 293   end
 n           12 0 2.4052e-05 293   end
 cu          15 0 0.075056 293   end
 cu          15 0 0.0081044 293   end
end composition
read parameter
 gen=2650
 npg=500000
 nsk=150
 htm=no
end parameter
read geometry
global unit 1
com="orcef sphere"
 sphere 1        9
 ellipsoid 2  8.744413  8.744413  8.745982  chord -z=-4.11683  chord +z=-8.653251   origin  x=0 y=0
z=0.050546
 ellipsoid 3  8.744413  8.744413  8.745982  chord -z=-1.429  chord +z=-4.06629
 ellipsoid 4  8.735917  8.735917  8.760911  chord -z=0  chord +z=-1.429
 ellipsoid 5  8.735917  8.735917  8.760911  chord -z=1.429  chord +z=0
 ellipsoid 6  8.735917  8.735917  8.760911  chord -z=3.37515  chord +z=1.429
 ellipsoid 7  8.741951  8.741951    8.747  chord +z=3.328669   origin  x=0 y=0 z=0.046482
 cylinder 8  0.57531  -1.430274  -5.17754   origin  x=-6.35 y=0 z=0
 cylinder 9  0.57531  -1.430274  -5.17754   origin  x=3.175 y=5.49926 z=0
 cylinder 10  0.57531   -1.429  -5.17754   origin  x=3.175 y=-5.49926 z=0
 cylinder 11  0.57531   -1.429  -5.17754   origin  x=3.175 y=5.49926 z=0
 cylinder 12  0.747903  -7.811008  -8.580628
 cone 13   0.3153  0.55372    0.635        0   origin  x=0 y=0 z=-1.429
 cylinder 14  0.17526  -8.00807  -8.809228   rotate  a1=0 a2=45 a3=0
 cylinder 15  0.17526  -8.00807  -8.809228   rotate  a1=0 a2=-45 a3=0
 cylinder 16  0.17526  -8.00807  -8.809228   rotate  a1=90 a2=45 a3=0
 cylinder 17  0.17526  -8.00807  -8.809228   rotate  a1=90 a2=-45 a3=0
 cylinder 18  0.17526  -8.00807  -8.809228   rotate  a1=45 a2=45 a3=0
 cylinder 19  0.17526  -8.00807  -8.809228   rotate  a1=45 a2=-45 a3=0
 cylinder 20  0.17526  -8.00807  -8.809228   rotate  a1=-45 a2=45 a3=0
 cylinder 21  0.17526  -8.00807  -8.809228   rotate  a1=-45 a2=-45 a3=0
 cylinder 22  1.11125  -8.688787  -8.809228   rotate  a1=0 a2=45 a3=0
 cylinder 23  1.11125  -8.688787  -8.809228   rotate  a1=0 a2=-45 a3=0
 cylinder 24  1.11125  -8.688787  -8.809228   rotate  a1=90 a2=45 a3=0
 cylinder 25  1.11125  -8.688787  -8.809228   rotate  a1=90 a2=-45 a3=0
 cylinder 26  1.11125  -8.688787  -8.809228   rotate  a1=45 a2=45 a3=0
 cylinder 27  1.11125  -8.688787  -8.809228   rotate  a1=45 a2=-45 a3=0
 cylinder 28  1.11125  -8.688787  -8.809228   rotate  a1=-45 a2=45 a3=0
 cylinder 29  1.11125  -8.688787  -8.809228   rotate  a1=-45 a2=-45 a3=0
 cone 36   0.3063   0.5715    0.635        0   origin  x=0 y=0 z=-1.429
 cylinder 37  0.57531  3.37515   -1.429   origin  x=-6.35 y=0 z=0
 cylinder 38  0.57531  3.37515   -1.429   origin  x=3.175 y=-5.49926 z=0
 cylinder 39  0.57531  3.37515   -1.429   origin  x=3.175 y=5.49926 z=0
 xcylinder 40     1.27      8.9  0.888238
 xcylinder 41  0.17272      8.9     -8.9
 xcylinder 42  0.164211  8.914765  -8.914765
 xcylinder 43  0.351028      8.9  8.12419   rotate  a1=45 a2=0 a3=0
 xcylinder 44  0.351028      8.9  8.12419   rotate  a1=-45 a2=0 a3=0
 xcylinder 45  0.351028      8.9  8.12419   rotate  a1=135 a2=0 a3=0
 xcylinder 46  0.351028      8.9  8.12419   rotate  a1=-135 a2=0 a3=0
 cuboid 47   0.0889  -0.0889   4.1275  -0.9525    1.429  1.281684
 cuboid 48   0.0889  -0.0889      8.9   4.1275    1.429  1.134364
 cone 49   0.3153  0.55372    0.635        0   origin  x=0 y=0 z=3.37515
 cone 50   0.3063   0.5715  0.63627        0   origin  x=0 y=0 z=3.37515
 cylinder 51  0.17526  8.809228  8.00807   rotate  a1=0 a2=45 a3=0
 cylinder 52  0.17526  8.809228  8.00807   rotate  a1=0 a2=-45 a3=0
 cylinder 53  0.17526  8.809228  8.00807   rotate  a1=90 a2=45 a3=0
```

```
cylinder 54  0.17526  8.809228  8.00807   rotate  a1=90 a2=-45 a3=0
cylinder 55  0.17526  8.809228  8.00807   rotate  a1=45 a2=45 a3=0
cylinder 56  0.17526  8.809228  8.00807   rotate  a1=45 a2=-45 a3=0
cylinder 57  0.17526  8.809228  8.00807   rotate  a1=-45 a2=45 a3=0
cylinder 58  0.17526  8.809228  8.00807   rotate  a1=-45 a2=-45 a3=0
cylinder 59  1.11125  8.809228  8.688787   rotate  a1=0 a2=45 a3=0
cylinder 60  1.11125  8.809228  8.688787   rotate  a1=0 a2=-45 a3=0
cylinder 61  1.11125  8.809228  8.688787   rotate  a1=90 a2=45 a3=0
cylinder 62  1.11125  8.809228  8.688787   rotate  a1=90 a2=-45 a3=0
cylinder 63  1.11125  8.809228  8.688787   rotate  a1=45 a2=45 a3=0
cylinder 64  1.11125  8.809228  8.688787   rotate  a1=45 a2=-45 a3=0
cylinder 65  1.11125  8.809228  8.688787   rotate  a1=-45 a2=45 a3=0
cylinder 66  1.11125  8.809228  8.688787   rotate  a1=-45 a2=-45 a3=0
cylinder 67  1.211072  9.806182  7.806182
cylinder 68  0.747903  -7.811008     -8.9
cylinder 69  0.57531   -1.429  -5.17754   origin  x=-6.35 y=0 z=0
media 1 1 2 -69 -10 -11 -14 -15 -16 -17 -18 -19 -20 -21 -22 -23 -24 -25 -26 -27 -28 -29 -68 -3
media 2 1 3 -69 -10 -11
media 5 1 4 -36 -37 -38 -39 -40 -41 -43 -44 -45 -46
media 5 1 5 -37 -38 -39 -40 -41 -43 -44 -45 -46 -47 -48
media 6 1 6 -37 -38 -39
media 10 1 7 -50 -51 -52 -53 -54 -55 -56 -57 -58 -59 -60 -61 -62 -63 -64 -65 -66 -67
media 3 1 8
media 3 1 9
media 3 1 10
media 0 1 -9 11
media 0 1 -8 69
media 15 1 12
media 2 1 13
media 0 1 14 -22 2
media 0 1 15 -23 2
media 0 1 16 -24 2
media 0 1 17 -25 2
media 0 1 18 -26 2
media 0 1 19 -27 2
media 0 1 20 -28 2
media 0 1 21 -29 2
media 0 1 22 2
media 0 1 23 2
media 0 1 24 2
media 0 1 25 2
media 0 1 26 2
media 0 1 27 2
media 0 1 28 2
media 0 1 29 2
media 0 1 1 -2 -3 -4 -5 -6 -7 -13 -36 -42 -49 -50
media 0 1 -13 36
media 7 1 37 -41
media 7 1 38
media 7 1 39
media 8 1 40 4 -41
media 8 1 40 5 -41
media 0 1 41 -42 4
media 0 1 41 -42 5
media 12 1 42
media 0 1 43 4
media 0 1 44 4
media 0 1 45 4
media 0 1 46 4
media 0 1 43 5
media 0 1 44 5
media 0 1 45 5
media 0 1 46 5
media 8 1 47
media 8 1 48 5
media 6 1 49
media 0 1 -49 50
media 0 1 51 -59 7
media 0 1 52 -60 7
media 0 1 53 -61 7
media 0 1 54 -62 7
media 0 1 55 -63 7
```

```
 media 0 1 56 -64 7
 media 0 1 57 -65 7
 media 0 1 58 -66 7
 media 0 1 59 7
 media 0 1 60 7
 media 0 1 61 7
 media 0 1 62 7
 media 0 1 63 7
 media 0 1 64 7
 media 0 1 65 7
 media 0 1 66 7
 media 0 1 67 7
 media 0 1 2 68 -12
 boundary 1
end geometry
end data
end
```

KENO Input for Simple Model, Case 1, Table 4-2.

Case 1

```
'Input generated by GeeWiz SCALE 6.1 Compiled on Tue Sep  6 15:23:32 2011
=csas5
orsphere case 1
ce_v7_endf
read composition
 u-234       1 0 0.0004759 293   end
 u-235       1 0 0.044859 293   end
 u-236       1 0 2.1871e-05 293   end
 u-238       1 0 0.0027404 293   end
 si          1 0 4.9713e-05 293   end
 b           1 0 3.4257e-07 293   end
 c           1 0 0.00015929 293   end
end composition
read parameter
 gen=2650
 npg=500000
 nsk=150
 htm=no
end parameter
read geometry
global unit 1
com="sphere"
 sphere 1 1 8.790683
end geometry
end data
end
```

KENO Input for Simple Model, Case 2, Table 4-2.

Case 2

```
'Input generated by GeeWiz SCALE 6.1 Compiled on Tue Sep  6 15:23:32 2011
=csas5
orsphere case 2
ce_v7_endf
read composition
 u-234       1 0 0.00047568 293   end
 u-235       1 0 0.044838 293   end
 u-236       1 0 2.1938e-05 293   end
 u-238       1 0 0.002739 293   end
 si          1 0 4.9746e-05 293   end
 b           1 0 3.4357e-07 293   end
 c           1 0 0.0001592 293   end
end composition
read parameter
 gen=2650
 npg=500000
 nsk=150
 htm=no
end parameter
read geometry
global unit 1
com="sphere"
 sphere 1 1 8.729959
end geometry
end data
end
```

A.3 MONK Input Listing

MONK Input for Detailed Model, Case 1, Table 4-1.

Case 1

```
*HMF100 (ORCEF HEU sphere) detailed BM model - case 1
begin material specification
numden material 1       !lower polar cap
U234  4.7588E-04
U235  4.4867E-02
U236  1.7222E-05
U238  2.7575E-03
Be    6.2845E-09
Li    1.6320E-07
Al    2.0991E-06
Si    4.0332E-05
Mn    5.0977E-06
Ni    8.5210E-06
Cr    6.7326E-07
Cu    1.9675E-06
B     1.0478E-07
Co    9.6105E-08
Ca    1.4132E-06
CFREE 1.6881E-04
O     1.4160E-05
N      2.4262E-05

numden material 2 !lower plate
U234  4.7609E-04
U235  4.4888E-02
U236  1.7228E-05
U238  2.7383E-03
Be    6.2824E-09
Li    1.6314E-07
Al    3.3575E-06
Si    5.0398E-05
Mn    3.4996E-06
Ni    5.8498E-06
Cr    4.6220E-07
Cu    1.3507E-06
B     5.2371E-07
Co    9.6073E-08
Ca    1.4127E-06
CFREE 1.3387E-04
O     1.4155E-05
N      2.4254E-05

numden material 3       !lower section pins
U234   4.8136E-04
U235  4.4856E-02
U236  2.1624E-04
U238  2.5662E-03
Al    2.0984E-06
Si    4.8381E-05
Mn    3.8065E-06
Ni    6.3628E-06
Cr    5.0274E-07
Cu    1.4691E-06
B     3.1422E-07
CFREE 1.5838E-04
O     1.4155E-05
N      2.4253E-05

numden material 4       !central plate
U234  4.7526E-04
U235  4.4809E-02
U236  1.7196E-05
U238  2.7437E-03
Be    6.2717E-09
Li    1.6286E-07
Al    1.6759E-06
```

```
Si    8.0500E-05
Mn    3.0646E-06
Ni    5.1226E-06
Cr    4.0475E-07
Cu    1.1828E-06
B     2.0913E-07
Co    9.5908E-08
Ca    1.4103E-06
CFREE 1.4965E-04
O     1.4131E-05
N     2.4212E-05

numden material 5       !upper plate
U234  4.7537E-04
U235  4.4819E-02
U236  1.7203E-05
U238  2.7392E-03
Be    6.2724E-09
Li    1.6288E-07
Al    1.6761E-06
Si    4.0255E-05
Mn    2.0842E-06
Ni    3.4838E-06
Cr    2.7526E-07
Cu    8.0440E-07
B     3.1373E-07
Co    9.5919E-08
Ca    1.4105E-06
CFREE 1.4966E-04
O     1.4133E-05
N     2.4215E-05

numden material 6       !pins for centre section
U234  4.7611E-04
U235  4.4798E-02
U236  2.0300E-04
U238  2.5726E-03
Al    2.0953E-06
Si    4.8311E-05
Mn    3.8010E-06
Ni    6.3535E-06
Cr    5.0200E-07
Cu    1.4670E-06
B     3.1376E-07
CFREE 1.5815E-04
O     1.4134E-05
N     2.4217E-05

numden material 7       !plug for target & thermocouple
U234  4.8065E-04
U235  4.4791E-02
U236  2.1593E-04
U238  2.5625E-03
Al    2.0953E-06
Si    4.8311E-05
Mn    3.8010E-06
Ni    6.3535E-06
Cr    5.0200E-07
Cu    1.4670E-06
B     3.1376E-07
CFREE 1.5815E-04
O     1.4134E-05
N     2.4217E-05

numden material 8       !upper polar cap
U234  4.7635E-04
U235  4.4911E-02
U236  1.7239E-05
U238  2.7449E-03
Be    6.2857E-09
Li    1.6323E-07
Al    2.5194E-06
```

```
Si    3.2272E-05
Mn    5.2214E-06
Ni    8.7279E-06
Cr    6.8961E-07
Cu    2.0152E-06
B     5.2398E-07
Co    9.6122E-08
Ca    1.4134E-06
CFREE 1.9054E-04
O     1.4162E-05
N     2.4266E-05

numden material 9       !diametral filler rod
U234  4.7738E-04
U235  4.4485E-02
U236  2.1446E-04
U238  2.5450E-03
Al    2.0810E-06
Si    4.7981E-05
Mn    3.7751E-06
Ni    6.3102E-06
Cr    4.9858E-07
Cu    1.4570E-06
B     3.1162E-07
CFREE 1.5707E-04
O     1.4038E-05
N     2.4052E-05

numden material 10 !brass
Cu    7.5056E-02
Zn    8.1044E-03
end

begin material geometry
part 1 nest                    !alignment nub lower plate
zcone m2 0 0 0 0.635 0.3153 0.55372
zcone m0 0 0 0 0.63627 0.3063 0.5715

part 2 nest                    !brass bolt
zrod m10 0 0 0 0.747903 0.81280
zrod m0  0 0 [0.81280-0.99822] 0.747903 0.99822

part 3 nest                    !lower pin 1
zrod m3 0 0 0 0.57531 [1.11125+2.637282+5.842E-03]

part 4 nest                    !lower pin 2
zrod m3 0 0 0 0.57531 [1.11125+2.637282-1.27E-03]

part 5 nest                    !lower pin 3
zrod m3 0 0 0 0.57531 [1.11125+2.637282]

part 6 nest                    !MAB wide cyl
zrod m0 0 0 0 1.11125 [0.4572]

part 7 nest                    !MAB narrow cyl
zrod m0 0 0 0 0.17526 0.68072

part 8 nest                    !diametral hole & filler rod
xrod m9 0 0 0 0.164211 [17.82953 ]
xrod m0 0 0 0 0.17272  [17.82953 ]

part 9 nest                    !centre pin 1 (upper plate only)
zrod m6 0 0 0 0.57531 [1.946148+5.842E-03]

part 10 nest            !centre pins 2 and 3
zrod m6 0 0 0 0.57531 [1.429004*2+1.946148]

part 11 nest            !alignment nub upper plate
zcone m5 0 0 0 0.635 0.3153 0.55372
zcone m0 0 0 0 0.63627 0.3063 0.5715

part 12 nest            !hole in upper polar cap
```

```
zrod m0 0 0 0 1.211072 1.5

part 13 nest           !centre plate screw hole
yrod m0 0 0 0 0.351028 0.68072

part 14 cluster               !assemble all parts
zrod p2 0 0 -8.809228 0.747903 0.99822              !brass bolt
zcone p1 0 0 -1.429004 0.63627 0.3063 0.5715 !alignment nub lower plate
zrod p3 -6.35 0 [-4.066286-1.11125]
0.57531 [1.11125+2.637282+5.842E-03]        !lower pin 1
zrod p4 3.175 -5.49926 [-4.066286-1.11125]
0.57531 [1.11125+2.637282-1.27E-03]                !lower pin 2
zrod p5 3.175 5.49926 [-4.066286-1.11125]
0.57531 [1.11125+2.637282]                         !lower pin 3

!lower mass adjustment buttons
zrod p7 6.14390 0 -6.1439 0.17526 0.68072                  yrot 45
zrod p6 [6.14390+0.4572*cos(45)] 0 [-6.14390-0.4572*cos(45)]
1.11125 [0.4572]                                                  yrot 45
zrod p7 -6.14390 0 -6.1439 0.17526 0.68072          yrot -45
zrod p6 [-6.14390-0.4572*cos(45)] 0 [-6.14390-0.4572*cos(45)]
1.11125 [0.4572]                                                  yrot -45
zrod p7 0 -6.14390 -6.1439 0.17526 0.68072          xrot 45
zrod p6 0 [-6.14390-0.4572*cos(45)] [-6.14390-0.4572*cos(45)]
1.11125 [0.4572]                                                  xrot 45
zrod p7 0 6.14390 -6.1439 0.17526 0.68072                  xrot -45
zrod p6 0 [6.14390+0.4572*cos(45)] [-6.14390-0.4572*cos(45)]
1.11125 [0.4572]                                           xrot -45
zrod p7 4.34439 -4.34439 -6.1439 0.17526 0.68072
vx cos120 cos60 cos135 vz cos120 cos60 cos45
zrod p6 [4.34439+0.4572*cos(60)] [-4.34439-0.4572*cos(60)]
[-6.14390-0.4572*cos(45)]  1.11125 [0.4572]
vx cos120 cos60 cos135 vz cos120 cos60 cos45
zrod p7 -4.34439 -4.34439 -6.1439 0.17526 0.68072
vx cos60 cos60 cos135 vz cos60 cos60 cos45
zrod p6 [-4.34439-0.4572*cos(60)] [-4.34439-0.4572*cos(60)]
[-6.14390-0.4572*cos(45)]  1.11125 [0.4572]
vx cos60 cos60 cos135 vz cos60 cos60 cos45
zrod p7 4.34439 4.34439 -6.1439 0.17526 0.68072
vx cos120 cos120 cos135 vz cos120 cos120 cos45
zrod p6 [4.34439+0.4572*cos(60)] [4.34439+0.4572*cos(60)]
[-6.14390-0.4572*cos(45)]  1.11125 [0.4572]
vx cos120 cos120 cos135 vz cos120 cos120 cos45
zrod p7 -4.34439 4.34439 -6.1439 0.17526 0.68072
vx cos60 cos120 cos135 vz cos60 cos120 cos45
zrod p6 [-4.34439-0.4572*cos(60)] [4.34439+0.4572*cos(60)]
[-6.14390-0.4572*cos(45)]  1.11125 [0.4572]
vx cos60 cos120 cos135 vz cos60 cos120 cos45

!upper mass adjustment buttons
zrod p7 -5.66256 0 5.66256 0.17526 0.68072          yrot 45
zrod p6 [-5.66256-0.68072*cos(45)] 0 6.1439
1.11125 [0.4572]                                                  yrot 45
zrod p7 5.66256 0 5.66256 0.17526 0.68072                  yrot -45
zrod p6 [5.66256+0.68072*cos(45)] 0 6.1439
1.11125 [0.4572]                                                  yrot -45
zrod p7 0 5.66256 5.66256 0.17526 0.68072                  xrot 45
zrod p6 0 [5.66256+0.68072*cos(45)] 6.1439
1.11125 [0.4572]                                                  xrot 45
zrod p7 0 -5.66256 5.66256 0.17526 0.68072          xrot -45
zrod p6 0 [-5.66256-0.68072*cos(45)] 6.1439
1.11125 [0.4572]                                                  xrot -45
zrod p7 [4.34439-0.68072*cos(60)] [4.34439-0.68072*cos(60)] [5.66256]
0.17526 0.68072
vx cos60 cos60 cos135 vz cos60 cos60 cos45
zrod p6 4.34439 4.34439 6.14390 1.11125 [0.4572]
vx cos60 cos60 cos135 vz cos60 cos60 cos45
zrod p7 [-4.34439+0.68072*cos(60)] [-4.34439+0.68072*cos(60)] 5.66256
0.17526 0.68072
vx cos120 cos120 cos135 vz cos120 cos120 cos45
zrod p6 [-4.34439] [-4.34439] 6.14390 1.11125 [0.4572]
vx cos120 cos120 cos135 vz cos120 cos120 cos45
```

```
zrod p7 [4.34439-0.68072*cos(60)] [-4.34439+0.68072*cos(60)] 5.66256
0.17526 0.68072
vx cos60 cos120 cos135 vz cos60 cos120 cos45
zrod p6 [4.34439] [-4.34439] 6.14390  1.11125 [0.4572]
vx cos60 cos120 cos135 vz cos60 cos120 cos45
zrod p7 [-4.34439+0.68072*cos(60)] [4.34439-0.68072*cos(60)] 5.66256
0.17526 0.68072
vx cos120 cos60 cos135 vz cos120 cos60 cos45
zrod p6 [-4.34439] [4.34439] 6.14390  1.11125 [0.4572]
vx cos120 cos60 cos135 vz cos120 cos60 cos45

xrod p8 -8.803386 0 0 0.17272 [17.82953 ]
yrot -0.0231340494                                ! diametral hole & filler rod
zrod p9 -6.35 0 1.429004 0.57531 [1.946148+5.842E-03]
yrot -0.0231340494                                ! upper pin 1
zrod p10 3.175 -5.49926 -1.429004 0.57531 [1.429004*2+1.946148]
yrot -0.0231340494                                ! upper pin 2
zrod p10 3.175 5.49926 [-1.429004+5.842E-03]  0.57531
[1.429004*2+1.946148]  yrot -0.0231340494   ! upper pin 3
zcone p11 0 0 [1.429004+1.946148] 0.63627 0.3063 0.5715
yrot -0.0231340494                                ! alignment nub upper plate
zrod p12 0 0 7.806182 1.211072 1.5
yrot -0.0231340494                                ! hole in upper polar cap
yrod p13 5.74467 5.74467 0 0.351028 0.68072
zrot 45                                           ! centre plate screw holes
yrod p13 -5.74467 5.74467 0 0.351028 0.68072 zrot -45
yrod p13  -5.74467 -5.74467 0 0.351028 0.68072 zrot -135
yrod p13  5.74467 -5.74467 0 0.351028 0.68072 zrot 135
box m7 [-0.1778/2] -0.9525 [1.429004-0.14732] 0.1778 [4.1275+0.9525] 0.14732 yrot -0.0231340494
box m7 [-0.1778/2] 4.1275 [1.429004-0.29464] 0.1778 [8.685601-4.1275] 0.29464 yrot -0.0231340494
sphere h1 0 0 0 12.0
end

begin hole geometry
hole 1 plate                  ! divide by section (not tilted)
0 0 1
3
[-8.809228+0.092072339] h2    ! lower polar cap
-4.066286 h3                  ! lower plate
-1.429004 h10                 ! lower / central plate gap
m0

ghole 2 quadric                       ! lower polar cap
0 0 -0.00483
normal
[(61.02204)^2]  [61.02204*60.95049] [61.02204*60.95049] 0
1
m1 [(4724.72940)/8.80491]
m0

ghole 3 quadric                       ! lower plate
0 0 0
normal
[(14.49263)^2]  [14.49263*14.45685] [14.49263*14.45685] 0
1
m2 [(1122.97037/8.80491)]
m0

ghole 4 quadric                       ! central plate
yrot -0.0231340494
0 0 0
normal
[(2.042052)^2]  [2.042052*2.05994] [2.042052*2.05994] 0
1
h8 [(158.2586/8.80491)]
m0

ghole 5 quadric                       ! upper plate
yrot -0.0231340494
0 0 0
normal
[(9.349599)^2]  [9.349599*9.313822] [9.349599*9.313822] 0
```

```
1
m5 [(724.34990/8.80491)]
m0

ghole 6 quadric                       ! upper polar cap
yrot -0.0231340494
0 0 -0.000508
normal
[(66.13136)^2]  [66.13136*66.14925] [66.13136*66.14925] 0
1
m8 [(5128.31605/8.80491)]
m0

ghole 7 globe                 ! pin through central plate
origin -6.35 0 0
yrot -0.0231340494
1 0.57531 m6 h4

ghole 8 plate                 ! define target hole limit
yrot -0.0231340494
1 0 0
1
0.888238 h9
m4

ghole 9 globe                 ! target hole
yrot [90-0.0231340494]
1 1.27 m7
m4

ghole 10 plate                ! tilted sections
yrot -0.0231340494
0 0 1
3
[-1.429004+5.842E-03] h7      ! central plate
1.429004 h5                          ! upper plate
[1.429004+1.946148] h6        ! upper polar cap
m0
end

begin control data
stages -30 6000 1000
stdv 0.0001
end

begin source geometry
zonemat all / material 1 2 3 4 5 6 7 8 9
end
```

MONK Input for Detailed Model, Case 2, Table 4-1.

Case 2

```
*HMF100 (ORCEF HEU sphere) detailed BM model - case 2
begin material specification
numden material 1       !lower polar cap
U234   4.7452E-04
U235   4.4739E-02
U236   1.7173E-05
U238   2.7496E-03
Be     6.2666E-09
Li     1.6273E-07
Al     2.0931E-06
Si     4.0217E-05
Mn     5.0831E-06
Ni     8.4967E-06
Cr     6.7134E-07
Cu     1.9618E-06
B      1.0448E-07
Co     9.5830E-08
Ca     1.4091E-06
CFREE  1.6833E-04
O      1.4119E-05
N      2.4192E-05

numden material 2 !lower plate
U234   4.7473E-04
U235   4.4760E-02
U236   1.7179E-05
U238   2.7305E-03
Be     6.2645E-09
Li     1.6268E-07
Al     3.3479E-06
Si     5.0255E-05
Mn     3.4896E-06
Ni     5.8331E-06
Cr     4.6088E-07
Cu     1.3468E-06
B      5.2222E-07
Co     9.5798E-08
Ca     1.4087E-06
CFREE  1.3349E-04
O      1.4115E-05
N      2.4184E-05

numden material 3       !lower section pins
U234   4.7998E-04
U235   4.4728E-02
U236   2.1562E-04
U238   2.5589E-03
Al     2.0924E-06
Si     4.8243E-05
Mn     3.7956E-06
Ni     6.3446E-06
Cr     5.0130E-07
Cu     1.4649E-06
B      3.1332E-07
CFREE  1.5793E-04
O      1.4114E-05
N      2.4184E-05

numden material 4       !central plate
U234   4.7637E-04
U235   4.4913E-02
U236   1.7236E-05
U238   2.7501E-03
Be     6.2863E-09
Li     1.6324E-07
Al     1.6798E-06
Si     8.0687E-05
Mn     3.0717E-06
Ni     5.1345E-06
```

```
Cr     4.0569E-07
Cu     1.1855E-06
B      2.0961E-07
Co     9.6131E-08
Ca     1.4136E-06
CFREE  1.4999E-04
O      1.4164E-05
N      2.4268E-05

numden material 5       !upper plate
U234   4.7647E-04
U235   4.4923E-02
U236   1.7243E-05
U238   2.7456E-03
Be     6.2870E-09
Li     1.6326E-07
Al     1.6800E-06
Si     4.0348E-05
Mn     2.0890E-06
Ni     3.4919E-06
Cr     2.7590E-07
Cu     8.0626E-07
B      3.1446E-07
Co     9.6142E-08
Ca     1.4137E-06
CFREE  1.5001E-04
O      1.4165E-05
N      2.4271E-05

numden material 6       !pins for centre section
U234   4.7722E-04
U235   4.4902E-02
U236   2.0347E-04
U238   2.5786E-03
Al     2.1002E-06
Si     4.8423E-05
Mn     3.8098E-06
Ni     6.3683E-06
Cr     5.0317E-07
Cu     1.4704E-06
B      3.1449E-07
CFREE  1.5852E-04
O      1.4167E-05
N      2.4274E-05

numden material 7       !plug for target & thermocouple
U234   4.8177E-04
U235   4.4895E-02
U236   2.1643E-04
U238   2.5684E-03
Al     2.1002E-06
Si     4.8423E-05
Mn     3.8098E-06
Ni     6.3683E-06
Cr     5.0317E-07
Cu     1.4704E-06
B      3.1449E-07
CFREE  1.5852E-04
O      1.4167E-05
N      2.4274E-05

numden material 8       !upper polar cap
U234   4.7569E-04
U235   4.4849E-02
U236   1.7215E-05
U238   2.7411E-03
Be     6.2770E-09
Li     1.6300E-07
Al     2.5159E-06
Si     3.2227E-05
Mn     5.2142E-06
Ni     8.7159E-06
```

```
Cr     6.8866E-07
Cu     2.0125E-06
B      5.2326E-07
Co     9.5989E-08
Ca     1.4115E-06
CFREE  1.9028E-04
O      1.4143E-05
N      2.4233E-05

numden material 9       !diametral filler rod
U234   4.7738E-04
U235   4.4485E-02
U236   2.1446E-04
U238   2.5450E-03
Al     2.0810E-06
Si     4.7981E-05
Mn     3.7751E-06
Ni     6.3102E-06
Cr     4.9858E-07
Cu     1.4570E-06
B      3.1162E-07
CFREE  1.5707E-04
O      1.4038E-05
N      2.4052E-05

numden material 10 !brass
Cu     7.5056E-02
Zn     8.1044E-03
end

begin material geometry
part 1 nest                                 !alignment nub lower plate
zcone m2 0 0 0 0.635 0.3153 0.55372
zcone m0 0 0 0 0.63627 0.3063 0.5715

part 2 nest                                 !brass bolt
zrod m10 0 0 0 0.747903 0.76962
zrod m0  0 0 -0.0927347 0.747903 [0.76962+0.0927347]

part 3 nest                                 !lower pin 1
zrod m3 0 0 0 0.57531 [1.11125+2.637282]

part 4 nest                                 !lower pin 2
zrod m3 0 0 0 0.57531 [1.11125+2.637282-1.27E-03]

part 5 nest                                 !lower pin 3
zrod m3 0 0 0 0.57531 [1.11125+2.637282-1.27E-03]

part 6 nest                                 !MAB wide cyl
zrod m0 0 0 0 1.11125 [0.4572]

part 7 nest                                 !MAB narrow cyl
zrod m0 0 0 0 0.17526 0.68072

part 8 nest                                 !diametral hole & filler rod
xrod m9 0 0 0 0.164211 [17.82953 ]
xrod m0 0 0 0 0.17272  [17.82953 ]

part 9 nest                                 !centre pin 1 (upper plate only)
zrod m6 0 0 0 0.57531 [1.946148]

part 10 nest                        !centre pins 2 and 3
zrod m6 0 0 0 0.57531 [1.429004*2+1.946148]

part 11 nest                        !alignment nub upper plate
zcone m5 0 0 0 0.635 0.3153 0.55372
zcone m0 0 0 0 0.63627 0.3063 0.5715

part 12 nest                        !hole in upper polar cap
zrod m0 0 0 0 1.211072 1.5

part 13 nest                        !centre plate screw hole
```

```
yrod m0 0 0 0 0.351028 0.68072

part 14 cluster                              !assemble all parts
zrod p2 0 0 [-7.811008-0.76962-0.0927347]
0.747903 [0.76962+0.0927347]         !brass bolt
zcone p1 0 0 -1.429004 0.63627
0.3063 0.5715                        !alignment nub lower plate
zrod p3 -6.35 0 [-4.066286-1.11125]
0.57531 [1.11125+2.637282]           !lower pin 1
zrod p4 3.175 -5.49926 [-4.066286-1.11125]
0.57531 [1.11125+2.637282-1.27E-03]  !lower pin 2
zrod p5 3.175 5.49926 [-4.066286-1.11125]
0.57531 [1.11125+2.637282-1.27E-03]  !lower pin 3

!lower mass adjustment buttons
zrod p7 6.14390 0 -6.1439 0.17526 0.68072                  yrot 45
zrod p6 [6.14390+0.4572*cos(45)] 0 [-6.14390-0.4572*cos(45)]
1.11125 [0.4572]                                                          yrot 45
zrod p7 -6.14390 0 -6.1439 0.17526 0.68072                 yrot -45
zrod p6 [-6.14390-0.4572*cos(45)] 0 [-6.14390-0.4572*cos(45)]
1.11125 [0.4572]                                                          yrot -45
zrod p7 0 -6.14390 -6.1439 0.17526 0.68072                 xrot 45
zrod p6 0 [-6.14390-0.4572*cos(45)] [-6.14390-0.4572*cos(45)]
1.11125 [0.4572]                                                          xrot 45
zrod p7 0 6.14390 -6.1439 0.17526 0.68072                         xrot -45
zrod p6 0 [6.14390+0.4572*cos(45)] [-6.14390-0.4572*cos(45)]
1.11125 [0.4572]                                                  xrot -45
zrod p7 4.34439 -4.34439 -6.1439 0.17526 0.68072
vx cos120 cos60 cos135 vz cos120 cos60 cos45
zrod p6 [4.34439+0.4572*cos(60)] [-4.34439-0.4572*cos(60)]
[-6.14390-0.4572*cos(45)]  1.11125 [0.4572]
vx cos120 cos60 cos135 vz cos120 cos60 cos45
zrod p7 -4.34439 -4.34439 -6.1439 0.17526 0.68072
vx cos60 cos60 cos135 vz cos60 cos60 cos45
zrod p6 [-4.34439-0.4572*cos(60)] [-4.34439-0.4572*cos(60)]
[-6.14390-0.4572*cos(45)]  1.11125 [0.4572]
vx cos60 cos60 cos135 vz cos60 cos60 cos45
zrod p7 4.34439 4.34439 -6.1439 0.17526 0.68072
vx cos120 cos120 cos135 vz cos120 cos120 cos45
zrod p6 [4.34439+0.4572*cos(60)] [4.34439+0.4572*cos(60)]
[-6.14390-0.4572*cos(45)]  1.11125 [0.4572]
vx cos120 cos120 cos135 vz cos120 cos120 cos45
zrod p7 -4.34439 4.34439 -6.1439 0.17526 0.68072
vx cos60 cos120 cos135 vz cos60 cos120 cos45
zrod p6 [-4.34439-0.4572*cos(60)] [4.34439+0.4572*cos(60)]
[-6.14390-0.4572*cos(45)]  1.11125 [0.4572]
vx cos60 cos120 cos135 vz cos60 cos120 cos45

!upper mass adjustment buttons
zrod p7 -5.66256 0 5.66256 0.17526 0.68072                 yrot 45
zrod p6 [-5.66256-0.68072*cos(45)] 0 6.1439
1.11125 [0.4572]                                                          yrot 45
zrod p7 5.66256 0 5.66256 0.17526 0.68072                         yrot -45
zrod p6 [5.66256+0.68072*cos(45)] 0 6.1439
1.11125 [0.4572]                                                          yrot -45
zrod p7 0 5.66256 5.66256 0.17526 0.68072                         xrot 45
zrod p6 0 [5.66256+0.68072*cos(45)] 6.1439
1.11125 [0.4572]                                                          xrot 45
zrod p7 0 -5.66256 5.66256 0.17526 0.68072                 xrot -45
zrod p6 0 [-5.66256-0.68072*cos(45)] 6.1439
1.11125 [0.4572]                                                          xrot -45
zrod p7 [4.34439-0.68072*cos(60)] [4.34439-0.68072*cos(60)] [5.66256]
0.17526 0.68072
vx cos60 cos60 cos135 vz cos60 cos60 cos45
zrod p6 4.34439 4.34439 6.14390 1.11125 [0.4572]
vx cos60 cos60 cos135 vz cos60 cos60 cos45
zrod p7 [-4.34439+0.68072*cos(60)] [-4.34439+0.68072*cos(60)] 5.66256
0.17526 0.68072
vx cos120 cos120 cos135 vz cos120 cos120 cos45
zrod p6 [-4.34439] [-4.34439] 6.14390 1.11125 [0.4572]
vx cos120 cos120 cos135 vz cos120 cos120 cos45
zrod p7 [4.34439-0.68072*cos(60)] [-4.34439+0.68072*cos(60)] 5.66256
```

```
0.17526 0.68072
vx cos60 cos120 cos135 vz cos60 cos120 cos45
zrod p6 [4.34439] [-4.34439] 6.14390  1.11125 [0.4572]
vx cos60 cos120 cos135 vz cos60 cos120 cos45
zrod p7 [-4.34439+0.68072*cos(60)] [4.34439-0.68072*cos(60)] 5.66256
0.17526 0.68072
vx cos120 cos60 cos135 vz cos120 cos60 cos45
zrod p6 [-4.34439] [4.34439] 6.14390  1.11125 [0.4572]
vx cos120 cos60 cos135 vz cos120 cos60 cos45

xrod p8 -8.74395 0 0 0.17272 [17.82953 ]              ! diametral hole & filler
zrod p9 -6.35 0 1.429004 0.57531 [1.946148]   ! upper pin 1
zrod p10 3.175 -5.49926 -1.429004 0.57531
[1.429004*2+1.946148]                                 ! upper pin 2
zrod p10 3.175 5.49926 [-1.429004]  0.57531
[1.429004*2+1.946148]                                ! upper pin 3
zcone p11 0 0 [1.429004+1.946148] 0.63627 0.3063
0.5715                                               ! alignment nub upper plate
zrod p12 0 0 7.806182 1.211072 1.5                   ! hole in upper polar cap
yrod p13 5.74467 5.74467 0 0.351028 0.68072
zrot 45                                              ! centre plate screw holes
yrod p13 -5.74467 5.74467 0 0.351028 0.68072 zrot -45
yrod p13  -5.74467 -5.74467 0 0.351028 0.68072 zrot -135
yrod p13  5.74467 -5.74467 0 0.351028 0.68072 zrot 135
box m7 [-0.1778/2] -0.9525 [1.429004-0.14732] 0.1778
[4.1275+0.9525] 0.14732                              ! narrow thermocouple section
box m7 [-0.1778/2] 4.1275 [1.429004-0.29464] 0.1778
[8.618924-4.1275] 0.29464                            ! thick thermocouple section
sphere h1 0 0 0 12.0
end

begin hole geometry
hole 1 plate                  ! divide by section
0 0 1
5
[-8.69544+0.0927347] h2       ! lower polar cap
-4.066286 h3                  ! lower plate
-1.429004 h7                  ! central plate
1.429004 h5                           ! upper plate
[1.429004+1.946148] h6        ! upper polar cap
m0

ghole 2 quadric                       ! lower polar cap
0 0 0.050546
normal
[(74.30313)^2]  [74.30313*74.27648] [74.30313*74.27648] 0
1
m1 [(5681.57126)/8.74395]
m0

ghole 3 quadric                       ! lower plate
0 0 0.050546
normal
[(74.30313)^2]  [74.30313*74.27648] [74.30313*74.27648] 0
1
m2 [(5681.57126)/8.74395]
m0

ghole 4 quadric                       ! central plate
0 0 0
normal
[(9.3496)^2]  [9.3496*9.29633] [9.3496*9.29633] 0
1
h8 [(713.52645)/8.74395]
m0

ghole 5 quadric                       ! upper plate
0 0 0
normal
[(9.3496)^2]  [9.3496*9.29633] [9.3496*9.29633] 0
1
m5 [(713.52645)/8.74395]
```

```
m0

ghole 6 quadric                        ! upper polar cap
0 0 0.046482
normal
[(65.4299)^2]  [65.4299*65.3544] [65.4299*65.3544] 0
1
m8 [(5000.26418/8.74395)]
m0

ghole 7 globe                  ! pin through central plate
origin -6.35 0 0
1 0.57531 m6 h4

ghole 8 plate                  ! define target hole limit
1 0 0
1
0.888238 h9
m4

ghole 9 globe                  ! target hole
yrot 90
1 1.27 m7
m4
end

begin control data
stages -30 6000 1000
stdv 0.0001
end

begin source geometry
zonemat all / material 1 2 3 4 5 6 7 8 9
end
```

MONK Input for Simple Model, Case 1, Table 4-2.

Case 1

```
*HMF100 (ORCEF sphere) Simple BM model - Case 1
begin material specification
numden material 1       ! Uranium (93.2)
U234  4.7590E-04
U235  4.4859E-02
U236  2.1871E-05
U238  2.7404E-03
Si    4.9713E-05
B     3.4257E-07
CFREE 1.5929E-04
end

begin material geometry
part 1 nest
sphere m1 0 0 0 8.79068305
end

begin control data
stages -30 6000 1000
stdv 0.0001
end

begin source geometry
zonemat all / material 1
end
```

MONK Input for Simple Model, Case 2, Table 4-2.

Case 2

```
*HMF100 (ORCEF sphere) Simple BM model - Case 2
begin material specification
numden material 1      ! Uranium (93.2)
U234  4.7568E-04
U235  4.4838E-02
U236  2.1938E-05
U238  2.7390E-03
Si    4.9746E-05
B     3.4357E-07
CFREE 1.5920E-04
end

begin material geometry
part 1 nest
sphere m1 0 0 0 8.72995881
end

begin control data
stages -30 6000 1000
stdv 0.0001
end

begin source geometry
zonemat all / material 1
end
```

A.4 XSDRN Input Listing

XSDRN Input for Simple Model, Case 1, Table 4-2.

Case 1

```
'Input generated by GeeWiz SCALE 6.1 Compiled on Tue Sep  6 15:23:32 2011
=csas1
orsphere case 1
v7-238
read composition
 u-234       1 0 0.0004759 293   end
 u-235       1 0 0.044859 293   end
 u-236       1 0 2.1871e-05 293   end
 u-238       1 0 0.0027404 293   end
 si          1 0 4.9713e-05 293   end
 b           1 0 3.4257e-07 293   end
 c           1 0 0.00015929 293   end
end composition
read celldata
  multiregion spherical left_bdy=reflected right_bdy=vacuum end
           1      8.790683
      end zone
end celldata
end
```

XSDRN Input for Simple Model, Case 2, Table 4-2.

Case 2

```
'Input generated by GeeWiz SCALE 6.1 Compiled on Tue Sep  6 15:23:32 2011
=csas1
orsphere case 2
v7-238
read composition
 u-234       1 0 0.00047568 293   end
 u-235       1 0 0.044838 293   end
 u-236       1 0 2.1938e-05 293   end
 u-238       1 0 0.002739 293   end
 si          1 0 4.9746e-05 293   end
 b           1 0 3.4357e-07 293   end
 c           1 0 0.0001592 293   end
end composition
read celldata
  multiregion spherical left_bdy=reflected right_bdy=vacuum end
           1      8.729959
      end zone
end celldata
end
```

A.4 COG11.1 Input Listing

Models were creating using COG11.1 and ENDF/B-VII.1 neutron cross section libraries. Models were run for 2500 active cycles (150 inactive cycles) with 500,000 histories per cycle. Input decks were created and run by David P. Heinrichs from LLNL.

COG11.1 Input for Detailed Model, Case 1, Table 4-1.

Case 1

```
HMF100-1: ORSPHERE with 3.4665 inch average radius
basic
  neutron delayedn CM URRPT
criticality
  npart=50000 nbatch=5050 sdt=0.00001 nfirst=51 norm=1. nsource=1 0 0 0
assign-mc
  1 orange 2 pink 3 red 4 lime 5 sky 6 green 7 blue 8 black 9 yellow
mix nlib=ENDFB7R1 ptlib=PT.ENDFB7R1.BNL sablib=T.ENDFB7R1
  mat=1  bunches u234 4.7588-4 u235 4.4867-2 u236 1.7222-5 u238 2.7575-3 be 6.2845-9 li 1.6320-7 al
2.0991-6  si 4.0332-5 mn 5.0977-6 $ HEU,
                  ni 8.5210-6   cr 6.7326-7   cu 1.9675-6    b 1.0478-7 co 9.6105-8 ca 1.4132-6  c
1.6881-4 o16 1.4160-5  n 2.4262-5 $  Lower Cap
  mat=2  bunches u234 4.7609-4 u235 4.4888-2 u236 1.7228-5 u238 2.7383-3 be 6.2824-9 li 1.6314-7 al
3.3575-6  si 5.0398-5 mn 3.4996-6 $ HEU,
                  ni 5.8498-6   cr 4.6220-7   cu 1.3507-6    b 5.2371-7 co 9.6073-8 ca 1.4127-6  c
1.3387-4 o16 1.4155-5  n 2.4254-5 $  Lower Plate
  mat=3  bunches u234 4.8136-4 u235 4.4856-2 u236 2.1624-4 u238 2.5662-3                          al
2.0984-6  si 4.8381-5 mn 3.8065-6 $ HEU,
                  ni 6.3628-6   cr 5.0274-7   cu 1.4691-6    b 3.1422-7                           c
1.5838-4 o16 1.4155-5  n 2.4253-5 $  Lower Pins
  mat=4  bunches u234 4.7526-4 u235 4.4809-2 u236 1.7196-5 u238 2.7437-3 be 6.2717-9 li 1.6286-7 al
1.6759-6  si 8.0500-5 mn 3.0646-6 $ HEU,
                  ni 5.1226-6   cr 4.0475-7   cu 1.1828-6    b 2.0913-7 co 9.5908-8 ca 1.4103-6  c
1.4965-4 o16 1.4131-5  n 2.4212-5 $  Center Plate
  mat=5  bunches u234 4.7611-4 u235 4.4798-2 u236 2.0300-4 u238 2.5726-3                          al
2.0953-6  si 4.8311-5 mn 3.8010-6 $ HEU,
                  ni 6.3535-6   cr 5.0200-7   cu 1.4670-6    b 3.1376-7                           c
1.5815-4 o16 1.4134-5  n 2.4217-5 $  Center Pins
  mat=6  bunches u234 4.8065-4 u235 4.4791-2 u236 2.1593-4 u238 2.5625-3                          al
2.0953-6  si 4.8311-5 mn 3.8010-6 $ HEU,
                  ni 6.3535-6   cr 5.0200-7   cu 1.4670-6    b 3.1376-7                           c
1.5815-4 o16 1.4134-5  n 2.4217-5 $  Plugs
  mat=7  bunches u234 4.7738-4 u235 4.4485-2 u236 2.1446-4 u238 2.5450-3                          al
2.0810-6  si 4.7981-5 mn 3.7751-6 $ HEU, Diametral
                   ni 6.3102-6   cr 4.9858-7   cu 1.4570-6    b 3.1162-7                           c
1.5707-4 o16 1.4038-5  n 2.4052-5 $  Filler Rod
  mat=8  bunches u234 4.7537-4 u235 4.4819-2 u236 1.7203-5 u238 2.7392-3 be 6.2724-9 li 1.6288-7 al
1.6761-6  si 4.0255-5 mn 2.0842-6 $ HEU,
                  ni 3.4838-6   cr 2.7526-7   cu 8.0440-7    b 3.1373-7 co 9.5919-8 ca 1.4105-6  c
1.4966-4 o16 1.4133-5  n 2.4215-5 $  Upper Plate
  mat=9  bunches u234 4.7635-4 u235 4.4911-2 u236 1.7239-5 u238 2.7449-3 be 6.2857-9 li 1.6323-7 al
2.5194-6  si 3.2272-5 mn 5.2214-6 $ HEU,
                  ni 8.7279-6   cr 6.8961-7   cu 2.0152-6    b 5.2398-7 co 9.6122-8 ca 1.4134-6  c
1.9054-4 o16 1.4162-5  n 2.4266-5 $  Upper Cap
  mat=10 bunches   cu 7.5056-2   zn 8.1044-3
$ Brass Bolt
geometry
  unit    1 LA        -51 -100                                              $ Lower Assembly
  unit    1 LA    -42  51 -100                                              $ Lower Assembly, male
  unit    1 LA    -34  51 -100                                              $ Lower Assembly, tall
pin
  unit    2 UA  34 42  51 -100 tr 0 0 0.00351038 8.80338528 0 -0.000046213    $ Upper Assembly,
0.00351038 cm verticle shift, tilted 0.0231340494 degrees
define unit 1 $ Lower assembly
  sector  1 HEU    11 -12 -13  20  21  22  23  24  25  26  27  28  31  32  33 $ Lower Polar Cap
  sector 10 Brass -20  29                                                   $ Brass Bolt
  sector  2 HEU    12  31  32  33 -40 -41                                   $ Lower Plate
  sector  2 HEU    40 -42                                                   $ Lower Plate, male
```

```
  sector  3 HEU   -31 -34                                                  $ Lower Pin, Tall
  sector  3 HEU   -32 -40                                                  $ Lower Pin, Flush
  sector  3 HEU   -33 -35                                                  $ Lower Pin, Short
define unit 2 $ Upper assembly
  sector  4 HEU    51 -52 -54  56  58  59  61  62  63  64          71  72  73 $ Center Plate, Lower
Half
  sector  4 HEU    52 -53 -55      58  59  61  62  63  64  65  66  71  72  73 $ Center Plate, Upper
Half
  sector  5 HEU   -71                                                      $ Center Pin
  sector  5 HEU   -72                                                      $ Center Pin
  sector  5 HEU   -73                                                      $ Center Pin
  sector  6 HEU    51 -52 -54  58 -59                                      $ Plug for Target
Hole, Lower Half
  sector  6 HEU    52 -53 -54  58 -59                                      $ Plug for Target
Hole, Upper Half
  sector  6 HEU    52 -53 -55 -65                                          $ Plug for T/C, Deep
  sector  6 HEU    52 -53 -55  65 -66                                      $ Plug for T/C,
Shallow
  sector  7 HEU   -57  71                                                  $ Diametral Filler Rod
  sector  8 HEU    53 -80 -81  71  72  73                                  $ Upper Plate
  sector  8 HEU    80 -82                                                  $ Upper Plate
  sector  9 HEU    80 -86  87  88  91  92  93  94  95  96  97  98          $ Upper Polar Cap
$ --- Pictures ----------------------------------------------------------------------------------
------------------------------------------
  picture cs material color res 5000 -10   0    10   -10    0    -10    10   0    -10   title="axial
view, plane through tall  pin"
  picture cs material color res 1000  -5  -8.66 10    -5   -8.66 -10     5   8.66 -10   title="axial
view, plane through flush pin"
  picture cs material color res 1000  -5   8.66 10    -5    8.66 -10     5  -8.66 -10   title="axial
view, plane through short pin"
  picture cs material color           -8   8    10    -8    8    -10     8  -8    -10   title="axial
view at -45 degrees"
  picture cs material color            0 -10    10     0  -10    -10     0  10    -10   title="axial
view, y/z plane"
  picture cs material color            8   8    10     8    8    -10    -8  -8    -10   title="axial
view at +45 degrees"
  picture cs material color          -10  10    -6   -10  -10     -6    10 -10     -6   title="plane
view through pin holes"
  picture cs material color          -10  10    -3   -10  -10     -3    10 -10     -3   title="plane
view through button holes"
  picture cs material color          -10  10     0   -10  -10      0    10 -10      0   title="plane
view through center plate"
  picture cs material color          -10  10     1.4 -10  -10      1.4  10 -10      1.4 title="plane
view through pin holes"
volume
  material -15 -15 -17  15 -15 -17 -15  15 -17  30 30 35
surfaces $ All dimensions are in CENTIMETERS
$ -----------------------------------------------------------------------------------------------
------------------------------------------------
$ ---- Lower Polar Cap and Brass Bolt.  Note that 8.008069 = 5.66256*SQRT(2) and 8.6887867 =
6.1439*SQRT(2)
$ -----------------------------------------------------------------------------------------------
------------------------------------------------
   11 plane z -8.717156                                  $ Lower Polar Cap, lower
   12 plane z -4.066286                                  $ Lower Polar Cap, upper (Lower Plate,
lower)
   13 ellipsoid 8.799239 8.799239 8.804402 tr 0 0 -0.004826 $ Polar Cap, outer
   20 cylinder z 0.747903 -9.0 -7.811008                 $ Hole for brass bolt
   21 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0  9
0        -9 $ Button hole
   22 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0
6.3639610 -6.3639610 -9 $ Button hole
   23 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0  0
-9        -9 $ Button hole
   24 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0 -
6.3639610 -6.3639610 -9 $ Button hole
   25 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0 -9
0        -9 $ Button hole
   26 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0 -
6.3639610  6.3639610 -9 $ Button hole
   27 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0  0
9        -9 $ Button hole
```

```
   28 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0
6.3639610  6.3639610 -9 $ Button hole
   29 plane z -8.623808
$ Brass bolt
$ ----------------------------------------------------------------------------------------------------
--------------------------------------------------
$ ---- 3 Pin Holes and Pins in Lower Polar Cap and Lower Plate
$ ----------------------------------------------------------------------------------------------------
--------------------------------------------------
   31 cylinder z 0.57531 -5.177536 -1 tr -6.350  0       0 $ Hole for pin
   32 cylinder z 0.57531 -5.177536 -1 tr  3.175  5.49926 0 $ Hole for pin
   33 cylinder z 0.57531 -5.177536 -1 tr  3.175 -5.49926 0 $ Hole for pin
   34 plane z -1.423162 $ Lower Pin, tall
   35 plane z -1.430274 $ Lower Pin, short
$ ----------------------------------------------------------------------------------------------------
--------------------------------------------------
$ ---- Lower Plate
$ ----------------------------------------------------------------------------------------------------
--------------------------------------------------
   40 plane z -1.429004                                          $ Lower Plate, upper
   41 ellipsoid 8.802591 8.802591 8.813478 tr 0 0 0              $ Lower Plate, outer
   42 revolution 2 -1.429004 0.635 -0.875284 0.3153 tr 0 0 0 0 0 1 $ Lower Plate, male
$ ----------------------------------------------------------------------------------------------------
--------------------------------------------------
$ ---- Center Plate
$ ----------------------------------------------------------------------------------------------------
--------------------------------------------------
   51 plane z -1.429004                                           $ Center Plate, bottom
   52 plane z  0.0                                                $ Center Plate, center
   53 plane z  1.429004                                           $ Center Plate, top (Upper
Plate, lower)
   54 ellipsoid 8.803387 8.803387 8.765080                        $ Center Plate, lower half
   55 ellipsoid 8.803387 8.803387 8.842202                        $ Center Plate, upper half
   56 revolution 2 -1.429004 0.63627 -0.85740 0.3063 tr 0 0 0 0 0 1 $ Center Plate, female
   57 cylinder x 0.164211 -8.914765 8.914765                      $ Diametral filler rod
   58 cylinder x 0.172720                                         $ Diametral hole
   59 cylinder x 1.27      0.888238 9.0                           $ HEU in target hole
   61 cylinder   0.351028  8.12419  9.0 tr 0 0 0  9  9 0          $ Hole
   62 cylinder   0.351028  8.12419  9.0 tr 0 0 0 -9  9 0          $ Hole
   63 cylinder   0.351028  8.12419  9.0 tr 0 0 0 -9 -9 0          $ Hole
   64 cylinder   0.351028  8.12419  9.0 tr 0 0 0  9 -9 0          $ Hole
   65 box 0.1778 10.00 0.58928 tr 0 9.1275 1.429004               $ T/C, deep
   66 box 0.1778  5.08 0.29464 tr 0 1.5875 1.429004               $ T/C, shallow
$ ----------------------------------------------------------------------------------------------------
--------------------------------------------------
$ ---- 3 Pin Holes and Pins in Center Plate and Upper Plate
$ ----------------------------------------------------------------------------------------------------
--------------------------------------------------
   71 cylinder z 0.57531 -1.429004  3.375172 tr -6.350  0       0   $ Hole for pin
   72 cylinder z 0.57531 -1.429004  3.375172 tr  3.175  5.49926 0   $ Hole for pin
   73 cylinder z 0.57531 -1.429004  3.375172 tr  3.175 -5.49926 0   $ Hole for pin
$ ----------------------------------------------------------------------------------------------------
--------------------------------------------------
$ ---- Upper Plate
$ ----------------------------------------------------------------------------------------------------
--------------------------------------------------
   80 plane z 3.375152                                           $ Upper Plate, upper (Upper Polar
Cap, lower)
   81 ellipsoid 8.801926 8.801926 8.818815 tr 0 0 0              $ Upper Plate, outer
   82 revolution 2  3.375152 0.635  3.928872 0.3153 tr 0 0 0 0 0 1 $ Upper Plate, male
$ ----------------------------------------------------------------------------------------------------
--------------------------------------------------
$ ---- Upper Polar Cap
$ ----------------------------------------------------------------------------------------------------
--------------------------------------------------
   86 ellipsoid 8.806101 8.806101 8.804910 tr 0 0 -0.000508        $ Upper Plate, outer
   87 revolution 2 3.375152 0.63627 3.946652 0.3063 tr 0 0 0 0 0 1 $ Upper Plate, female
   88 cylinder z 1.211072 7.806182 9.0                           $ Large hole
   91 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0  9
0          9 $ Button hole
   92 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0
6.3639610 -6.3639610  9 $ Button hole
```

```
   93 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0  0
-9          9 $ Button hole
   94 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0 -
6.3639610 -6.3639610  9 $ Button hole
   95 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0 -9
0          9 $ Button hole
   96 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0 -
6.3639610  6.3639610  9 $ Button hole
   97 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0  0
9          9 $ Button hole
   98 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 1.1125 9.0 1.1125 tr 0 0 0
6.3639610  6.3639610  9 $ Button hole
$ ---- Surfaces for units
  100 box 100. 100. 100. $ The big box bounding all geometry
end
```

COG11.1 Input for Detailed Model, Case 2, Table 4-1.

Case 2

```
HMF100-2: ORSPHERE with 3.4420 inch average radius
basic
  neutron delayedn CM URRPT
criticality
  npart=500000 nbatch=2650 sdt=0.00001 nfirst=151 norm=1. nsource=1 0 0 0
assign-mc
  1 orange 2 pink 3 red 4 lime 5 sky 6 green 7 blue 8 black 9 yellow
mix nlib=ENDFB7R1 ptlib=PT.ENDFB7R1.BNL
  mat=1  bunches u234 4.7452-4 u235 4.4739-2 u236 1.7173-5 u238 2.7496-3 be 6.2666-9 li 1.6273-7 al
2.0931-6  si 4.0217-5 mn 5.0831-6 $ HEU,
                    ni 8.4967-6   cr 6.7134-7   cu 1.9618-6    b 1.0448-7 co 9.5830-8 ca 1.4091-6  c
1.6833-4 o16 1.4119-5  n 2.4192-5 $  Lower Cap
  mat=2  bunches u234 4.7473-4 u235 4.4760-2 u236 1.7179-5 u238 2.7305-3 be 6.2645-9 li 1.6268-7 al
3.3479-6  si 5.0255-5 mn 3.4896-6 $ HEU,
                    ni 5.8331-6   cr 4.6088-7   cu 1.3468-6    b 5.2222-7 co 9.5798-8 ca 1.4087-6  c
1.3349-4 o16 1.4115-5  n 2.4184-5 $  Lower Plate
  mat=3  bunches u234 4.7998-4 u235 4.4728-2 u236 2.1562-4 u238 2.5589-3                          al
2.0924-6  si 4.8243-5 mn 3.7956-6 $ HEU,
                    ni 6.3446-6   cr 5.0130-7   cu 1.4649-6    b 3.1332-7                          c
1.5793-4 o16 1.4114-5  n 2.4184-5 $  Lower Pins
  mat=4  bunches u234 4.7637-4 u235 4.4913-2 u236 1.7236-5 u238 2.7501-3 be 6.2863-9 li 1.6324-7 al
1.6798-6  si 8.0687-5 mn 3.0717-6 $ HEU,
                    ni 5.1345-6   cr 4.0569-7   cu 1.1855-6    b 2.0961-7 co 9.6131-8 ca 1.4136-6  c
1.4999-4 o16 1.4164-5  n 2.4268-5 $  Center Plate
  mat=5  bunches u234 4.7722-4 u235 4.4902-2 u236 2.0347-4 u238 2.5786-3                          al
2.1002-6  si 4.8423-5 mn 3.8098-6 $ HEU,
                    ni 6.3683-6   cr 5.0317-7   cu 1.4704-6    b 3.1449-7                          c
1.5852-4 o16 1.4167-5  n 2.4274-5 $  Center Pins
  mat=6  bunches u234 4.8177-4 u235 4.4895-2 u236 2.1643-4 u238 2.5684-3                          al
2.1002-6  si 4.8423-5 mn 3.8098-6 $ HEU,
                    ni 6.3683-6   cr 5.0317-7   cu 1.4704-6    b 3.1449-7                          c
1.5852-4 o16 1.4167-5  n 2.4274-5 $  Plugs
  mat=7  bunches u234 4.7738-4 u235 4.4485-2 u236 2.1446-4 u238 2.5450-3                          al
2.0810-6  si 4.7981-5 mn 3.7751-6 $ HEU, Diametral
                    ni 6.3102-6   cr 4.9858-7   cu 1.4570-6    b 3.1162-7                          c
1.5707-4 o16 1.4038-5  n 2.4052-5 $  Filler Rod
  mat=8  bunches u234 4.7647-4 u235 4.4923-2 u236 1.7243-5 u238 2.7456-3 be 6.2870-9 li 1.6326-7 al
1.6800-6  si 4.0348-5 mn 2.0890-6 $ HEU,
                    ni 3.4919-6   cr 2.7590-7   cu 8.0626-7    b 3.1446-7 co 9.6142-8 ca 1.4137-6  c
1.5001-4 o16 1.4165-5  n 2.4271-5 $  Upper Plate
  mat=9  bunches u234 4.7569-4 u235 4.4849-2 u236 1.7215-5 u238 2.7411-3 be 6.2770-9 li 1.6300-7 al
2.5159-6  si 3.2227-5 mn 5.2142-6 $ HEU,
                    ni 8.7159-6   cr 6.8866-7   cu 2.0125-6    b 5.2326-7 co 9.5989-8 ca 1.4115-6  c
1.9028-4 o16 1.4143-5  n 2.4233-5 $  Upper Cap
  mat=10 bunches   cu 7.5056-2   zn 8.1044-3
$ Brass Bolt
geometry
$ --- Lower sphere
  sector  1 HEU   -10  11 -12  20  21  22  23  24  25  26  27  28  31  32  33 $ Lower Polar Cap
  sector 10 Brass -20  13                                                      $ Brass Bolt
  sector  2 HEU   -10  12 -14  31  32  33                                      $ Lower Plate
  sector  2 HEU    14 -30                                                      $ Lower Plate, male
  sector  3 HEU   -31 -34                                                      $ Lower Pin, Short
  sector  3 HEU   -32 -14                                                      $ Lower Pin, Flush
  sector  3 HEU   -33 -34                                                      $ Lower Pin, Short
 $ --- Center section
  sector  4 HEU    14 -40 -41  42  44  45  61  62  63  64  65  66  71  72  73 $ Center Plate
  sector  5 HEU   -71                                                          $ Center Pin
  sector  5 HEU   -72                                                          $ Center Pin
  sector  5 HEU   -73                                                          $ Center Pin
  sector  6 HEU   -40  44 -45                                                  $ Plug for Target Hole
  sector  6 HEU   -40 -41 -65  66                                              $ Plug for T/C, Deep
  sector  6 HEU   -40 -41  65 -66                                              $ Plug for T/C,
Shallow
  sector  7 HEU   -43                                                          $ Diametral Filler Rod
$ --- Top section
   sector  8 HEU    41 -80 -81  71  72  73                                     $ Upper Plate
   sector  8 HEU    41  80 -82                                                 $ Upper Plate, male
```

```
   sector  9 HEU    80 -81  87  88  91  92  93  94  95  96  97  98           $ Upper Polar Cap
$ --- Pictures -----------------------------------------------------------------------------------
-------------------------------------------------
  picture cs material color res 5000 -10   0    10   -10    0    -10    10   0    -10   title="axial
view, plane through tall  pin"
  picture cs material color res 1000  -5  -8.66 10    -5   -8.66 -10     5   8.66 -10   title="axial
view, plane through flush pin"
  picture cs material color res 1000  -5   8.66 10    -5    8.66 -10     5  -8.66 -10   title="axial
view, plane through short pin"
  picture cs material color           -8   8    10    -8    8    -10     8  -8    -10   title="axial
view at -45 degrees"
  picture cs material color            0 -10    10     0  -10    -10     0  10    -10   title="axial
view, y/z plane"
  picture cs material color            8   8    10     8    8    -10    -8  -8    -10   title="axial
view at +45 degrees"
  picture cs material color          -10  10    -6   -10  -10     -6    10 -10     -6   title="plane
view through pin holes"
  picture cs material color          -10  10    -3   -10  -10     -3    10 -10     -3   title="plane
view through button holes"
  picture cs material color          -10  10     0   -10  -10      0    10 -10      0   title="plane
view through center plate"
  picture cs material color          -10  10     1.4 -10  -10      1.4  10 -10      1.4 title="plane
view through pin holes and T/C grooves"
volume
  material -15 -15 -17  15 -15 -17 -15  15 -17  30 30 35
surfaces $ All dimensions are in CENTIMETERS
$ ------------------------------------------------------------------------------------------------
-------------------------------------------------
$ ---- Lower Polar Cap, Brass Bolt and Lower Plate.  Note that 8.008069 = 5.66256*SQRT(2) and
8.6887867 = 6.1439*SQRT(2)
$ ------------------------------------------------------------------------------------------------
-------------------------------------------------
   10 ellipsoid 8.744413 8.744413 8.745982 tr 0 0 0.050546 $ Lower Sphere (Polar Cap and Lower
Plate), outer
   11 plane z -8.602705                                    $ Lower Polar Cap, lower
   12 plane z -4.066286                                    $ Lower Polar Cap, upper; and Lower
Plate, lower
   13 plane z -8.580628                                    $ Brass bolt
   14 plane z -1.429004                                    $ Lower Plate, upper; and Center Plate,
bottom
   20 cylinder z 0.747903 -9.0 -7.811008                   $ Hole for brass bolt
   21 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0  9          0
-9 $ Button hole
   22 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0  6.3639610 -6.3639610
-9 $ Button hole
   23 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0  0         -9
-9 $ Button hole
   24 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0 -6.3639610 -6.3639610
-9 $ Button hole
   25 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0 -9          0
-9 $ Button hole
   26 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0 -6.3639610  6.3639610
-9 $ Button hole
   27 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0  0          9
-9 $ Button hole
   28 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0  6.3639610  6.3639610
-9 $ Button hole
   30 revolution 2 -1.429004 0.635 -0.875284 0.3153 tr 0 0 0 0 0 1 $ Lower Plate, male
$ ------------------------------------------------------------------------------------------------
-------------------------------------------------
$ ---- 3 Pin Holes and Pins in Lower Polar Cap and Lower Plate
$ ------------------------------------------------------------------------------------------------
-------------------------------------------------
   31 cylinder z 0.57531 -5.177536 -1 tr -6.350  0       0 $ Hole for pin
   32 cylinder z 0.57531 -5.177536 -1 tr  3.175  5.49926 0 $ Hole for pin
   33 cylinder z 0.57531 -5.177536 -1 tr  3.175 -5.49926 0 $ Hole for pin
   34 plane z -1.430274 $ Lower Pin, short
$ ------------------------------------------------------------------------------------------------
-------------------------------------------------
$ ---- Center Plate
$ ------------------------------------------------------------------------------------------------
-------------------------------------------------
```

```
   40 ellipsoid 8.735917 8.735917 8.760911                           $ Center Plate, outer
   41 plane z  1.429004                                              $ Center Plate, top; and Upper
Plate, lower
   42 revolution 2 -1.429004 0.63627 -0.85740 0.3063 tr 0 0 0 0 0 1 $ Center Plate, female
   43 cylinder x 0.164211 -8.914765 8.914765                         $ Diametral filler rod
   44 cylinder x 0.172720                                            $ Diametral hole
   45 cylinder x 1.27      0.888238 9.0                              $ HEU in target hole
   61 cylinder   0.351028  8.12419  9.0 tr 0 0 0  9  9 0             $ Hole
   62 cylinder   0.351028  8.12419  9.0 tr 0 0 0 -9  9 0             $ Hole
   63 cylinder   0.351028  8.12419  9.0 tr 0 0 0 -9 -9 0             $ Hole
   64 cylinder   0.351028  8.12419  9.0 tr 0 0 0  9 -9 0             $ Hole
   65 box 0.1778 10.00 0.58928 tr 0 9.1275 1.429004                  $ T/C, deep
   66 box 0.1778  5.08 0.29464 tr 0 1.5875 1.429004                  $ T/C, shallow
$ ----------------------------------------------------------------------------------------------------
-------------------------------------------------
$ ---- 3 Pin Holes and Pins in Center Plate and Upper Plate
$ ----------------------------------------------------------------------------------------------------
-------------------------------------------------
   71 cylinder z 0.57531 -1.429004  3.375172 tr -6.350  0       0   $ Hole for pin
   72 cylinder z 0.57531 -1.429004  3.375172 tr  3.175  5.49926 0   $ Hole for pin
   73 cylinder z 0.57531 -1.429004  3.375172 tr  3.175 -5.49926 0   $ Hole for pin
$ ----------------------------------------------------------------------------------------------------
-------------------------------------------------
$ ---- Upper Plate
$ ----------------------------------------------------------------------------------------------------
-------------------------------------------------
   80 plane z 3.375152                                              $ Upper Plate, upper; and Upper
Polar Cap, lower
   81 ellipsoid 8.741951 8.741951 8.746999 tr 0 0 0                 $ Upper Plate, outer; and Upper
Polar Cap, outer
   82 revolution 2  3.375152 0.635  3.928872 0.3153 tr 0 0 0 0 0 1 $ Upper Plate, male
$ ----------------------------------------------------------------------------------------------------
-------------------------------------------------
$ ---- Upper Polar Cap
$ ----------------------------------------------------------------------------------------------------
-------------------------------------------------
   87 revolution 2 3.375152 0.63627 3.946652 0.3063 tr 0 0 0 0 0 1 $ Upper Plate, female
   88 cylinder z 1.211072 7.806182 9.0                              $ Large hole
   91 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0  9          0
9 $ Button hole
   92 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0  6.3639610 -6.3639610
9 $ Button hole
   93 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0  0         -9
9 $ Button hole
   94 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0 -6.3639610 -6.3639610
9 $ Button hole
   95 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0 -9          0
9 $ Button hole
   96 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0 -6.3639610  6.3639610
9 $ Button hole
   97 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0  0          9
9 $ Button hole
   98 revolution 4 8.008069 0.17526 8.6887867 0.17526 8.6887867 9 9 9 tr 0 0 0  6.3639610  6.3639610
9 $ Button hole
end
```

COG11.1 Input for Simple Model, Case 1, Table 4-2.

Case 1

```
HMF100-1 Simplified Model: 53,475.983 gram ORSphere with 8.79068305 radius (Case 1)
basic
  neutron delayedn CM URRPT
criticality
  npart=500000 nbatch=2650 sdt=0.00001 nfirst=151 norm=1. nsource=1 0 0 0
assign-mc 1 orange
mix nlib=ENDFB7R1 ptlib=PT.ENDFB7R1.BNL sablib=T.ENDFB7R1
  mat=1 bunches u234 4.7590-4 u235 4.4859-2 u236 2.1871-5 u238 2.7404-3 si 4.9713-5 b 3.4257-7 c
1.5929-4
geometry
  sector 1 orsphr -1
  picture cs material color -9  0  9 -9  0 -9   9  0 -9  title="Simplified model for Case 1"
  volume material  -9 -9 -9  9 -9 -9 -9  9 -9  18 18 18
surfaces $ All dimensions are in CENTIMETERS
   1 sphere 8.79068305
end
```

COG11.1 Input for Simple Model, Case 2, Table 4-2.

Case 2

```
HMF100-2 Simplified Model: 52,350.943 gram ORSphere with 8.72995881 radius (Case 2)
basic
  neutron delayedn CM URRPT
criticality
  npart=500000 nbatch=2650 sdt=0.00001 nfirst=151 norm=1. nsource=1 0 0 0
assign-mc 1 orange
mix nlib=ENDFB7R1 ptlib=PT.ENDFB7R1.BNL sablib=T.ENDFB7R1
  mat=1 bunches u234 4.7568-4 u235 4.4838-2 u236 2.1938-5 u238 2.7390-3 si 4.9746-5 b 3.4357-7 c
1.5920-4
geometry
  sector 1 orsphr -1
  picture cs material color -9  0  9 -9  0 -9   9  0 -9  title="Simplified model for Case 2"
  volume material  -9 -9 -9  9 -9 -9 -9  9 -9  18 18 18
surfaces $ All dimensions are in CENTIMETERS
   1 sphere 8.72995881
end
```

APPENDIX B: DERIVATION OF ELLIPSOID EQUATION AND VOLUMES

Each section of sphere had a measured deviation from spherical for each plate (Case 1) or section (Case 2). Using a general ellipsoid equation, Equation B.1, an equation to describe each plate or section was developed and an equation to calculate the volume of each plate was derived. The deviation from spherical at the top and bottom of each plate or section is used. Using the deviation from spherical and the height of each plate x,y,z coordinates could be derived. It was assumed that x=y and the y=0 plane was used to derive the equations. Because the sum of the heights of the plates/sections does not equal the diameter of the sphere the center of the ellipsoid curve for the lower and upper polar cap for Case 1 and the bottom section and upper polar cap for Case 2 must be shifted. For the initial derivation the center of the ellipsoid is assumed to be at the origin ($\bar{x}, \bar{y}, \bar{z} = 0, 0, 0$). The actual center of the ellipsoids is derived later. The method is outlined and described below

Equation B.1	$A(x-\bar{x})^2 + B(y-\bar{y})^2 + C(z-\bar{z})^2 + G = 0$	-General ellipsoid equation
Equation B.2	$A(x-0)^2 + B(y-0)^2 + C(z-0)^2 + G = 0$	-Assume 0,0,0 origin
Equation B.3	$Ax^2 + B(0)^2 + Cz^2 + G = 0$	-Use y=0 plane
Equation B.4	$A{x_1}^2 + C{z_1}^2 + G = 0$	-Substitute in points at top and bottom of plate/section, x_1, 0, z_1 and x_2, 0, z_2
Equation B.5	$A{x_2}^2 + C{z_2}^2 + G = 0$	
Equation B.6	$A({x_1}^2 - {x_2}^2) + C({z_1}^2 - {z_2}^2) = 0$	-Subtract equations
Equation B.7	$A({x_1}^2 - {x_2}^2) = C({z_2}^2 - {z_1}^2)$	-Solve for A/C
Equation B.8	$A/C = ({z_2}^2 - {z_1}^2)/({x_1}^2 - {x_2}^2)$	
Equation B.9	$\frac{A}{C}(x^2 + y^2) + z^2 + \frac{G}{C} = 0$	-Divide Equation B.2 and B.4 by C. Equation B.9 uses symmetry and the fact that A=B.
Equation B.10	$\frac{A}{C}{x_1}^2 + {z_1}^2 + \frac{G}{C} = 0$	
Equation B.11	$\frac{G}{C} = -\frac{A}{C}{x_1}^2 - {z_1}^2$	-Solve for G/C
Equation B.12	$\frac{G}{C} = \frac{({z_1}^2 - {z_2}^2)}{({x_1}^2 - {x_2}^2)}{x_1}^2 - {z_1}^2$	-Plug Equation B.8 into B.11 (distribution of negative sign switches order of numerator)
Equation B.13	$({z_2}^2 - {z_1}^2)/({x_1}^2 - {x_2}^2)(x^2 + y^2) + z^2 + \frac{({z_1}^2 - {z_2}^2)}{({x_1}^2 - {x_2}^2)}{x_1}^2 - {z_1}^2 = 0$	-Plug Equation B.8 and B.12 into Equation B.9
Equation B.14	$({z_2}^2 - {z_1}^2)(x^2 + y^2) + ({x_1}^2 - {x_2}^2)z^2 + ({z_1}^2 - {z_2}^2){x_1}^2 - ({x_1}^2 - {x_2}^2){z_1}^2 = 0$	-Multiply by $({x_1}^2 - {x_2}^2)$
Equations B.15 B.16 B.17	$A = B = ({z_2}^2 - {z_1}^2)$ $C = ({x_1}^2 - {x_2}^2)$ $G = ({z_1}^2 - {z_2}^2){x_1}^2 - ({x_1}^2 - {x_2}^2){z_1}^2$	-Extract A,B,C, and G Coefficients from Equation B.14

Next, an equation for the volume of each plate/section is derived. This required simplifying the three dimension ellipsoid equation to a one dimensional ellipse equation in the y=0 plane and then rotating the curve around the z axis. The resulting solid of revolution is identical to the ellipsoid and has equal volume. To begin Equation B.3 is solved for x (Equation B.17); this is the equation of the ellipse that is plugged into the solid of revolution equation given as Equation B.18.

Equation B.18	$f(z) = x = \sqrt{-\frac{G}{A} - \frac{C}{A}z^2}$	-Equation B.3 is solved for x. Only the positive half of the ellipse is used.
Equation B.19	$V = \pi \int_{z_1}^{z_2} f(z)^2 dz$	-Volume equation for a solid of revolution.
Equation B.20	$V = \pi \int_{z_1}^{z_2} \sqrt{-\frac{G}{A} - \frac{C}{A}z^2}^{\,2} dz = \pi \int_{z_1}^{z_2} \left(-\frac{G}{A} - \frac{C}{A}z^2\right) dz$	-Substitute Equation B.17 into Equation B.18
Equation B.21	$V = \pi \left[\left(-\frac{G}{A}z - \frac{C}{A}\frac{1}{3}z^3\right)\right]_{z_1}^{z_2}$	-Integrate
Equation B.22	$V = \pi \left[\left(-\frac{G}{A}z_2 - \frac{1}{3}\frac{C}{A}{z_2}^3\right) - \left(-\frac{G}{A}z_1 - \frac{1}{3}\frac{C}{A}{z_1}^3\right)\right]$	-Plug in limits of integration.

Finally, the shift of the sphere was calculated by taking the difference between the $z_1$and $z_2$used for the equation derivation and volume calculation and the actual height of the bottom and top of the plates/sections with relation to the center of the model. The center of the model was the center of the diametral hole which was the center of the sphere for Case 1 and 0.0508 cm below the center of the sphere for Case 2. Table B-1 and B-2 gives the x_1, z_1, x_2, and z_2 values used in the equation derivations. These values were based on the heights of the plates and polar caps, the nominal radius, and the deviation from spherical. A radius of 3.4665 in. (8.80491 cm) was used for Case 1 and 3.4425 in. (8.74395 cm) for Case 2. Table B-1 and B-2 also give the ellipsoid coefficients for each section of sphere. This format was used because it is often used in neutron codes. The general mathematical format for an ellipsoid equation is given as Equation B.24 and the relation between the coefficients for the two equations is given as Equation B.25.

Equation B.23	$Ax^2 + By^2 + C(z - \bar{z})^2 + G = 0$
Equation B.24	$\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1$
Equation B.25	$a^2 = -{}^{G}/_{A}$ $b^2 = -{}^{G}/_{B}$ $c^2 = -{}^{G}/_{C}$

Table B-1. Derivation of Ellipsoid Equations and Volumes, Case 1.[(a)]

Variable	Lower Polar Cap	Lower Plate	Center Plate Lower Half[(b)]	Center Plate Upper Half[(b)]	Upper Plate	Upper Polar Cap
Deviation at Top (in./cm)	-1.8E-03/ -4.57E-03	-8.0E-04/ -2.03E-03	-6.0E-04/ -1.52E-03	-2.0E-04/ -5.08E-04	-2.0E-04/ -5.08E-04	0.0/ 0.0
Deviation at Bottom (in./cm)	-2.0E-04/ -5.08E-04	0.0/ 0.0	-1.0E-03/ -2.54E-03	-6.0E-04/ -1.52E-03	-1.0E-03/ -2.54E-03	4.0E-04/ 1.02E-03
R at Top (cm)[(c)]	8.800338	8.802878	8.803386	8.804402	8.804402	8.80491
R at Bottom (cm)[(c)]	8.804402	8.80491	8.80237	8.803386	8.80237	8.805926
Height of Top, z_1(cm)[(d)]	-4.06146	-1.429004	0	1.429004	3.375152	8.8049100
x_1(cm)[(e)]	7.807080	8.686116	8.803386	8.687660	8.131780	0
Height of bottom, z_2(cm)[(d)]	-8.804402	-4.066286	-1.429004	0	1.429004	3.375660
x_2(cm)[(e)]	0	7.809722	8.685601	8.803386	8.685601	8.133219
Actual Height of Top[(f)]	-4.066286	-1.429004	0	1.429004	3.375152	8.8044020
$\bar{z}$[(g)]	-0.004826	0	0	0	0	-0.000508
A=B[(h)]	61.02204	14.49263	2.04205	2.04205	9.34960	66.13136
C[(h)]	60.95049	14.45685	2.05994	2.02416	9.31382	66.14925
G[(h)]	-4724.72940	-1122.97037	-158.25826	-158.25826	-724.34990	-5128.31605
V (cm^3)	509.89289	574.80300	344.84014	344.89368	436.61075	647.95477

(a) Values were not rounded until the end of the calculations. A truncated number of digits are shown in this table.
(b) The Center Plate had to be modeled as two parts.
(c) This value is 8.80491 cm plus the deviation from spherical.
(d) These heights are in relation to the center of the ellipsoid if it were at 0, 0, 0. For the lower polar cap and upper polar cap these do not equal the heights in relation to the center of the model. This is due to the fact that the sum of the heights of the plates is larger than the radius of the curve.
(e) $x = \sqrt{R^2 - z^2}$
(f) This is the height of the top of the plate or polar cap in relation to the center of the model which is the center of the sphere for Case 1. It is the sum of the heights of the plates. These heights are shown in Figure 3-2, 3-4, 3-5, 3-6, and 3-9.
(g) This is the shift of the ellipsoid for the lower and upper polar caps so that the tops and bottoms of all the plates and polar caps align. It is the difference between the Actual Height of Top and z_1.
(h) Due to the method of derivation, for surfaces above the z=0 plane these coefficients must be multiplied by -1 to get them into standard MCNP format.

Table B-2. Derivation of Ellipsoid Equations and Volumes, Case 2.[(a)]

Variable	Bottom Section[(b)]	Center Section[(b)]	Upper Polar Cap
Deviation at Top (in./cm)	2.0E-04/5.08E-04	-1.70E-03/-4.32E-03	1.2E-03/3.05E-03
Deviation at Bottom (in./cm)	8.0E-04/2.03E-03	-2.9E-03/-7.37E-03	-5.0E-04/-1.27E-03
R at Top (cm)[(c)]	8.744458	8.739632	8.746998
R at Bottom (cm) [(c)]	8.745982	8.736584	8.74268
Height of Top, z_1(cm)[(d)]	-1.4795500	3.3751520	8.7469980
x_1(cm)[(e)]	8.618380	8.061608	0
Height of bottom, z_2(cm)[(d)]	-8.745982	-1.429004	3.328670
x_2(cm)[(e]	0	8.618924	8.084207
Actual Height of Top [(f)]	-1.4290040	3.3751520	8.7934800
$\bar{z}$[(g)]	0.050546	0	0.046482
A=B[(h)]	74.30313	9.34960	65.42993
C[(h)]	74.27648	9.29633	65.35441
G[(h)]	-5681.57126	-713.52645	-5000.26418
V (cm^3)	1048.61776	1108.74634	639.43142

(a) Values were not rounded until the end of the calculations. A truncated number of digits were preserved in this table.
(b) For Case 2 the lower polar cap and lower plate are treated as one section and the center plate and upper plate are treated as one section.
(c) This value is 8.74395 cm plus the deviation from spherical
(d) These heights are in relation to the center of the ellipsoid if it were at 0, 0, 0. For the lower polar cap and upper polar cap these do not equal the heights in relation to the center of the model.
(e) $x = \sqrt{R^2 - z^2}$
(f) This is the height of the top of the plate or polar cap in relation to the center of the model which is the center of the diametral hole and 0.0508 cm below the center of the sphere for Case 2. It is the sum of the heights of the plates. These heights are shown in Figure 3-3, 3-7, and 3-10.
(g) This is the shift of the ellipsoid for the lower and upper polar caps so that the tops and bottoms of all the plates and polar caps align. It is the difference between the Actual Height of Top and z_1.
(h) Due to the method of derivation, for surfaces above the z=0 plane these coefficients must be multiplied by -1 to get them into standard format.

APPENDIX C: METHOD TO CALCULATE VOLUMES AND DENSITIES

In order to calculate the total volume of each plate or section for the detailed benchmark model and the average enrichment for the simple benchmark model the volume of each void or penetration must be calculated.

First, the volume of the button recesses was calculated. For Case 1 the calculation was straight forward. The volume was split into the dome section, the cylindrical bore hole and the screw hole. The following method was used to calculate the total volume

Table C-1. Calculation of Button Recesses Volume, Case 1.

Screw Hole Dia.	D_{screw}	=0.138 in./0.35052 cm	-Given
Screw Hole Depth	h_{screw}	=0.268 in./0.68072 cm	-Given
Cylinder Height	h_{bore}	=0.018 in./0.04572 cm	-Given
Recess Dia.	D_{bore}	=0.875 in./2.2225 cm	-Given
Dome Height	$h_{dome} = R - \sqrt{R^2 - \left({D_{bore}}/{2}\right)^2}$	=0.0704 cm	-R is radius surface. Assumed to be average radius of 8.80491 cm.
Dome Volume	$V_{dome} = 1/3\,\pi h_{dome}{}^2(3R - h_{dome})$	=0.13675 cm^3	-Equation for dome volume
Recess Volume	$V_{bore} = \frac{\pi}{4} D_{bore}{}^2 h_{bore}$	=0.17737 cm^3	-Equation for cylinder volume
Screw Hole Vol.	$V_{screw} \frac{\pi}{4} D_{screw}{}^2 h_{screw}$	=0.06569 cm^3	-Equation for cylinder volume
Total Volume	$V = 8(V_{dome} + V_{bore} + V_{screw})$	=3.038473 cm^3	-Assume all eight cylinders have equal volume.

For Case 2 only a flat spot was left of the bottom section when the sphere was re-machined. The new radius of the flat spot on the lower polar cap was not given and thus the dome height of the flat spot had to be calculated. The mass adjustment button recess on the y=0 plane was used to perform these calculations. The center line of the mass adjustment button recesses sat on the x=z line when the origin is at the center of the diametral hole. The point at which this line intersected the curve of the ellipsoid of the polar cap was calculated. The coordinates of the bottom of the screw hole and the bottom of the recess was also calculated and, using the distance formula, the depth of the mass adjustment button recesses after re-machining was calculated. Table C-2 outlines this calculation for the lower polar cap mass adjustment button as well as the total volume calculation.

Table C-2. Calculation of Lower Polar Cap Button Recesses Depth, Case 2.

Ellipsoid Equation	$74.30313(x)^2 + 74.30313(y)^2$ $+74.27648(z - 0.050546)^2 - 5681.57126 = 0$		-Derived in Appendix B
Intersection of curve and x=z in y=0 plane	$74.30313(z)^2 + 74.30313(0)^2$ $+74.27648(z - 0.050546)^2$ $-5681.57126 = 0$ $z = 6.20901, -6.158470$	$z_1 = x_1 =$ $-6.15847\ cm$	-The negative value is used for the lower polar cap.
Coordinates of bottom of screw hole.[(a)] Calculated using Case 1 values and remain constant for Case 2. Results for only the y=0 or $\theta = \pi$ plane are given here.	$x = \rho sin\varphi cos\theta, y = \rho sin\varphi sin\theta, z = \rho cos\varphi$ $\rho = R^{case1} - (h_{screw} + h_{bore} + h_{dome})^{case1}$ $\varphi = \frac{3\pi}{4}$ $\theta = 0, \frac{\pi}{4}, \frac{\pi}{2}, \frac{3\pi}{4}, \pi, \frac{5\pi}{4}, \frac{3\pi}{2}, \frac{7\pi}{4}$	$\rho = 8.00806\ cm$ $\varphi = \frac{3\pi}{4}$ $\theta = \pi$ $x_2 = -5.6626\ cm$ $z_2 = -5.6626\ cm$ $y = 0$	-Screw hole location is easily defined with spherical coordinates and can then be transformed into Cartesian coordinates.
Total Depth	$h_{tot} = \sqrt{(x_2 - x_1)^2 + (z_2 - z_1)^2}$	=0.70132 cm	-Distance formula
Depth of Dome	$h_{dome} = h_{tot} - h_{screw}$	=0.0206 cm	-Calculate dome height
Total Volume	$V = 8(V_{dome} + V_{screw})$	=0.61867 cm	-The bore section of the button recess has been removed and only the dome section and screw hole remain.

(a) The same method is used to calculate the coordinates of the bottom of the bore hole except ρ= $R^{case1} - (h_{bore} + h_{dome})^{case1}$=8.6888.

For Case 2 the height of the mass adjustment button bore hole was reduced in the upper polar cap. The new depth was not given and was calculated in a manner similar to that used to calculate the button recess depth for the lower polar cap. The new dome height for the 2.2225-cm diameter button recess also had to be calculated in order to calculate the new bore hole depth. Table C-3 outlines this calculation for the upper polar cap mass adjustment buttons.

Table C-3. Calculation of Upper Polar Cap Button Recess Depth, Case 2.

Ellipsoid Equation	$65.4299(x)^2 + 65.4299(y)^2$ $+65.3544(z - 0.046482)^2 - 5000.26418 = 0$		-Derived in Appendix B
Intersection of curve and x=z in y=0 plane	$65.4299(z)^2 + 65.4299(0)^2$ $+65.3544(z - 0.046482)^2$ $-5000.26418 = 0$ $z = 6.20646, -6.16001$	$z_1 = x_1$ $= 6.20646\ cm$	-The positive value is used for the upper polar cap.
Coordinates of bottom of screw hole. [(a)] Calculated using Case 1 values and remain constant for Case 2. Results for only the y=0 or $\theta = 0$ plane are given here.	$x = \rho sin\varphi cos\theta, y = \rho sin\varphi sin\theta, z = \rho cos\varphi$ $\rho = R^{case1} - (h_{screw} + h_{bore} + h_{dome})^{case1}$ $\varphi = \frac{\pi}{4}$ $\theta = 0, \frac{\pi}{4}, \frac{\pi}{2}, \frac{3\pi}{4}, \pi, \frac{5\pi}{4}, \frac{3\pi}{2}, \frac{7\pi}{4}$	$\rho = 8.00806\ cm$ $\varphi = \frac{\pi}{4}$ $\theta = 0$ $x_2 = 5.6626\ cm$ $z_2 = 5.6626\ cm$ $y = 0$	-Screw hole location is easily defined with spherical coordinates and can then be transformed into Cartesian coordinates.
Total Depth	$h_{tot} = \sqrt{(x_2 - x_1)^2 + (z_2 - z_1)^2}$	=0.76919 cm	-Distance formula
Dome Height	$h_{dome} = R - \sqrt{R^2 - \left({D_{bore}}/{2}\right)^2}$	=0.0709 cm	-R is radius surface. Assumed to be average radius of 8.74268 cm. The diameter of the recess was 2.2225.
Depth of Dome	$h_{bore} = h_{tot} - h_{screw} - h_{dome}$	=0.1756 cm	-Calculate dome height
Total Volume	$V = 8(V_{dome} + V_{bore} + V_{screw})$	=2.172346 cm^3	-The bore section of the button recess has been removed and only the dome section and screw hole remain.

(a) The same method is used to calculate the coordinates of the bottom of the bore recess except ρ= $R^{case1} - (h_{bore} + h_{dome})^{case1}$=8.6888.

All other volume calculations were more straightforward. Tables C-4 through C-9 summarize the volumes for each individual part, the total volume, and compares volume calculated by Christine E. White of INL using AutoCAD® 2012, (©2011 Autodesk,Inc.). Calculated volumes were used in the calculation of atom densities for this evaluation. Tables C-4 through C-9 also provide the total volume for each section, the section mass, and the resulting density.[a]

[a] Inconsistencies between Case 1 and Case 2 densities are addressed in Section 3.1.1.

Table C-4. ORSphere Volumes, Case 1.

	Calculated	AutoCAD®
Bottom Section Volume		
Lower Polar Cap Volume		
Total Ellipsoid Section Volume[(a)]	509.6592146	509.6557064
Support Hole	-1.592353171	-1.5923538
Pin Hole Volume (3)	-3.466464423	-3.4664644
Mass Adjustment Button Recesses (8)	-3.038473102	-3.047776
Total Lower Polar Cap Volume		
Lower Plate Volume		
Total Ellipsoid Section Volume	574.8029968	574.800623
Pin Hole (3)	-8.226811453	-8.231566
Cutoff Alignment Cone	0.407303759	0.4075603
Total Lower Plate Volume	566.98349	566.9888449
Additional Lower Section Volume		
Pins (3)	11.69803	--
Bottom Section Volume/Mass/Density[(b)]	1080.24344 cm^3/ 20310 g/ 18.80132 g/cm^3	

(a) Volume of Spot Face, 0.23368 cm^3, has already been removed.
(b) Calculated volumes were used in density calculations.

Table C-5. ORSphere Volumes, Case 2.

	Calculated	AutoCAD®
Bottom Section Volume		
Lower Polar Cap Volume		
Total Ellipsoid Section Volume[(a)]	484.50130	484.48419
Support Hole	-1.39123	-1.39122
Pin Hole Volume (3)	-3.46646	-3.46646
Mass Adjustment Button Recesses (8)	-0.61867	-0.61930
Total Lower Polar Cap Volume	479.02493	479.00720
Lower Plate Volume		
Total Ellipsoid Section Volume	563.88110	563.88023
Pin Hole (3)	-8.22681	-8.22682
Cutoff Alignment Cone	0.40756	0.40756
Total Lower Plate Volume	556.06185	556.06097
Additional Lower Section Volume		
Pins (3)	11.69063	--
Bottom Section Volume/Mass/Density[(b)]	1046.77742 cm^3/ 19624.59 g/ 18.74762 g/cm^3	

(a) Volume of Spot Face, 0.23536 cm^3, has already been removed.
(b) Calculated volumes were used in density calculations.

Table C-6. ORSphere Volumes, Case 1.

Center Section Volumes		
	Calculated	AutoCAD®
Center Plate Volume		
Total Ellipsoid Section Volume	689.73381	689.73484
Pin Holes (3)	-8.91535	-8.91535
Support Screw Holes (4)	-1.04863	-1.04863
Target Hole	-39.88151	-39.87369
Thermocouple Groove	-0.378098	-0.37312
Diametral Hole[(a)]	-0.80300	-0.80162
Cutoff Alignment Cone Hole	-0.415081	-0.41508
Total Center Plate Volume	638.292142	-638.30975
Upper Plate Volume		
Total Ellipsoid Section Volume	436.610750	436.60721
Pin Holes (3)	-6.070869	-6.07087
Cutoff Alignment Cone	0.407560	0.40756
Total Upper Plate Volume	430.947442	430.94633
Additional Center Section Volumes		
Pin Volume[(b)] (3)	14.88085	--
Target Plug[(c)]	39.13962	39.13200
Thermocouple	0.37810	0.37312
Center Section Volume/Mass/Density[(d)]	1123.63813 cm^3/ 21095.06 g/18.77389 g/cm^3	
Filler Rod Volume/Mass/Density[(d)]	1.510408 cm^3/ 28.163 g/ 18.64596 g/cm^3	

(a) Volume excludes volume already accounted for by pin hole and target plug hole volumes.
(b) Pin volume excludes 0.105369-cm^3 hole where diametral hole passes through one HEU pin.
(c) Target Plug volume excludes volume of diametral hole.
(d) Calculated volumes were used in density calculations.

Table C-7. ORSphere Volumes, Case 2.

Center Section Volumes		
	Calculated	AutoCAD®
Center Plate Volume		
Total Ellipsoid Section Volume	679.14379	679.14033
Pin Holes (3)	-8.91535	-8.91535
Support Screw Holes (4)	-0.95224	-0.94167
Target Hole	-39.56452	-39.53095
Thermocouple Groove	-0.37484	-0.36953
Diametral Hole[(a)]	-0.71394	-0.79529
Cutoff Alignment Cone Hole	-0.41508	-0.41508
Total Center Plate Volume	628.20783	628.17246
Upper Plate Volume		
Total Ellipsoid Section Volume	429.60255	429.59795
Pine Holes (3)	-6.07087	-6.07087
Cutoff Alignment Cone	0.40756	0.40756
Total Upper Plate Volume	423.93924	423.93464
Additional Center Section Volumes		
Pin Volume[(b)] (3)	14.88085	--
Target Plug[(c)]	38.74521	38.79495
Thermocouple	0.374838	0.36953
Center Section Volume/Mass/Density[(d)]	1106.14797 cm^3/ 20814.95 g/ 18.8175 g/cm^3	
Filler Rod Volume/Mass/Density[(d)]	1.510408 cm^3/ 28.163 g/ 18.64596 g/cm^3	

(a) Volume excludes volume already accounted for by pin hole and target plug hole volumes.
(b) Pin volume excludes 0.105369-cm^3 hole where diametral hole passes through one HEU pin.
(c) Target Plug volume excludes volume of diametral hole.
(d) Calculated volumes were used in density calculations.

Table C-8. ORSphere Volumes, Case 1.

Upper Section Volumes		
	Calculated	AutoCAD®
Upper Polar Cap Volume		
Total Ellipsoid Section Volume	647.9548	647.9334
Cutoff Alignment Cone Hole	-0.415081	-0.415081
Mass Adjustment Button Recesses (8)	-3.038473	-3.045819
Upper Socket Hole	-4.407062	-4.407059
Total Upper Polar Cap Volume	640.0942	640.0654
Upper Section Volume/Mass/Density[(a)]	640.09416 cm^3/ 12042.76 g/ 18.81404 g/cm^3	

(a) Calculated volumes were used in density calculations.

Table C-9. ORSphere Volumes, Case 2.

Upper Section Volumes		
	Calculated	AutoCAD®
Upper Polar Cap Volume		
Total Ellipsoid Section Volume	639.4314	639.4104
Cutoff Alignment Cone Hole	-0.41508	-0.41508
Mass Adjustment Button Recesses (8)	2.172345	2.172334
Upper Socket Hole	4.355357	4.355292
Total Upper Polar Cap Volume	632.4886	632.4676
Upper Section Volume/Mass/Density[(a)]	632.48864 cm^3/ 11883.24 g/ 18.788807 g/cm^3	

(a) Calculated volumes were used in density calculations.

APPENDIX D: DERIVATION OF SIMPLE BENCHMARK MODEL AVERAGE ISOTOPIC AND IMPURITY CONTENT

The average sphere enrichment and impurity content was calculated by taking a volume-weighted average for each sphere part in the bottom, middle, and top section, and then taking a mass weighted average of the three parts plus the diametral filler rod. The isotopic content for each part was given in Table 1-3 and are summarized in Tables D-1 through D-3. The uranium fraction and impurities given in Table 1-4 were normalized to a total mass fraction of one. Impurities besides silicon, boron and carbon were replaced with void which decreased the total mass fraction. The uranium fraction and impurity content are also summarized in Tables D-1 through D-3. Impurities besides silicon, boron and carbon are retained in the tables for reference since they are in the detailed benchmark model but were replaced with void in the simple benchmark model.

Table D-1. Material Data, Bottom Section, Case 1 and 2.

	Normalized Uranium Weight Fraction, Uranium Isotopic Distributions, and Impurity Content		
	Lower Polar Cap	Lower Plate	Pins
g U/g Total	9.99577E-01	9.99612E-01	9.99595E-01
^{234}U	*0.98410%*	*0.98450%*	*0.99540%*
^{235}U	*93.18000%*	*93.22000%*	*93.15600%*
^{236}U	*0.03592%*	*0.03593%*	*0.45100%*
^{238}U	*5.79998%*	*5.75957%*	*5.39760%*
Be, ppm	5.0023E-03	5.0006E-03	-
Li, ppm	1.0005E-01	1.0001E-01	-
Al, ppm	5.0023E+00	8.0010E+00	5.0005E+00
Si, ppm	1.0005E+02	1.2502E+02	1.2001E+02
Mn, ppm	2.4735E+01	1.6981E+01	1.8470E+01
Ni, ppm	4.4169E+01	3.0323E+01	3.2982E+01
Cr, ppm	3.0918E+00	2.1226E+00	2.3087E+00
Cu, ppm	1.1042E+01	7.5807E+00	8.2455E+00
B, ppm	1.0005E-01	5.0006E-01	3.0003E-01
Co, ppm	5.0023E-01	5.0006E-01	-
Ca, ppm	5.0023E+00	5.0006E+00	-
C, ppm	1.7908E+02	1.4202E+02	1.6802E+02
O, ppm	2.0009E+01	2.0002E+01	2.0002E+01
N, ppm	3.0014E+01	3.0004E+01	3.0003E+01

Table D-2. Material Data, Center Section, Case 1 and 2.

	Normalized Uranium Weight Fraction, Uranium Isotopic Distributions, and Impurity Content			
	Central Plate	Upper Plate	Pin	Target Hole Plug and Thermocouple Filler
g U/g Total	9.99531E-01	9.99647E-01	9.99595E-01	9.99595E-01
^{234}U	*0.98430%*	*0.98440%*	*0.98600%*	*0.99540%*
^{235}U	*93.20000%*	*93.21000%*	*93.17100%*	*93.15600%*
^{236}U	*0.03592%*	*0.03593%*	*0.42400%*	*0.45100%*
^{238}U	*5.77978%*	*5.76967%*	*5.41900%*	*5.39760%*
Be, ppm	4.9994E-03	4.9999E-03	-	-
Li, ppm	9.9987E-02	9.9999E-02	-	-
Al, ppm	3.9995E+00	3.9999E+00	5.0005E+00	5.0005E+00
Si, ppm	1.9997E+02	9.9999E+01	1.2001E+02	1.2001E+02
Mn, ppm	1.4892E+01	1.0128E+01	1.8470E+01	1.8470E+01
Ni, ppm	2.6592E+01	1.8085E+01	3.2982E+01	3.2982E+01
Cr, ppm	1.8615E+00	1.2659E+00	2.3087E+00	2.3087E+00
Cu, ppm	6.6481E+00	4.5212E+00	8.2455E+00	8.2455E+00
B, ppm	1.9997E-01	3.0000E-01	3.0003E-01	3.0003E-01
Co, ppm	4.9994E-01	4.9999E-01	-	-
Ca, ppm	4.9994E+00	4.9999E+00	-	-
C, ppm	1.5898E+02	1.5900E+02	1.6802E+02	1.6802E+02
O, ppm	1.9997E+01	2.0000E+01	2.0002E+01	2.0002E+01
N, ppm	2.9996E+01	3.0000E+01	3.0003E+01	3.0003E+01

Table D-3. Material Data, Top Section and Diametral Filler Rod, Case 1 and 2.

	Normalized Uranium Weight Fraction, Uranium Isotopic Distributions, and Impurity Content	
	Upper Polar Cap	Diametral Filler Rod
g U/g Total	9.99577E-01	9.99595E-01
^{234}U	*0.98410%*	*0.99540%*
^{235}U	*93.18000%*	*93.15600%*
^{236}U	*0.03592%*	*0.45100%*
^{238}U	*5.79998%*	*5.39760%*
Be, ppm	5.0023E-03	-
Li, ppm	1.0005E-01	-
Al, ppm	5.0023E+00	5.0005E+00
Si, ppm	1.0005E+02	1.2001E+02
Mn, ppm	2.4735E+01	1.8470E+01
Ni, ppm	4.4169E+01	3.2982E+01
Cr, ppm	3.0918E+00	2.3087E+00
Cu, ppm	1.1042E+01	8.2455E+00
B, ppm	1.0005E-01	3.0003E-01
Co, ppm	5.0023E-01	-
Ca, ppm	5.0023E+00	-
C, ppm	1.7908E+02	1.6802E+02
O, ppm	2.0009E+01	2.0002E+01
N, ppm	3.0014E+01	3.0003E+01

Next, the impurity content/isotopic distribution of each part was multiplied by the volume of that part within each section. These products for each individual part were summed together and then divided by the total volume of each part. An example of this process for the middle section of sphere for Case 1 is shown with the following equations. The impurity contents and isotopic distributions are taken from Table D-2 and the volumes are taken from Table C-6. This resulted in volume weighted averaged for the impurity content and isotopic distribution of each part. A volume weighted average had to be used because the mass of each individual part was not known.

$$x^j_{section} = \frac{\sum_{i=1}^{n} x^j_i V_i}{\sum_{i=1}^{n} V_i}$$
$$y^k_{section} = \frac{\sum_{i=1}^{n} y^k_i V_i}{\sum_{i=1}^{n} V_i}$$

-x^j_i= impurity content of j^{th} of part i
-V_i=volume of part i
-y^k_i=isotopic content of k^{th} isotopic of part i

$$x^{boron}_{center} = \frac{x^{boron}_{CP} \cdot V_{CP} + x^{boron}_{UP} \cdot V_{UP} + x^{boron}_{TP} \cdot V_{TP} + x^{boron}_{Pins} \cdot V_{Pin} + x^{boron}_{TG} \cdot V_{TG}}{V_{CP} + V_{UP} + V_{TP} + V_{Pins} + V_{TG}}$$

-CP-Center Plate
-UP-Upper Plate
-TP- Target Plug
-TG-Thermocouple Groove

$$x^{boron}_{center} = \frac{0.19997 \cdot 638.292142 + 0.3 \cdot 430.947442 + 0.30003 \cdot 39.13962 + 0.30003 \cdot 14.88085 + 0.30003 \cdot 0.37810}{638.292142 + 430.947442 + 39.13962 + 14.88085 + 0.37810}$$
$$x^{boron}_{center} = 0.243179\ ppm\ Boron$$[a]

Once the volume-weighted average has been calculated, see Table D-4 and D-5 for results for each section, the mass weighted average of the entire sphere was calculated. This was done by a similar method but with mass rather than volume, using the following general equations. The mass weighted average was taken over the bottom, middle, top sections of sphere and the diametral filler rod. Table D-4 and D-5 also has the results of this calculation.

$$x^j_{sphere} = \frac{\sum_{l=1}^{n} x^j_l m_l}{\sum_{l=1}^{n} m_l}$$
$$y^k_{sphere} = \frac{\sum_{l=1}^{n} y^k_l m_l}{\sum_{l=1}^{n} m_l}$$

-x^j_l= impurity content of j^{th} of section l
-m_l= mass of section l
-y^k_l=isotopic content of k^{th} isotopic of part l

[a] It should be noted that this calculation was completed without rounding the normalized impurity content or part volumes. When the rounded values presented here are used a different average impurity content is obtained (0.241527 ppm). The value calculated without rounding of normalized impurity content and volumes is used in the simple benchmark model.

Table D-4. Material Data, Simple Benchmark Model, Case 1.

	Mass (g)	Volume (cm^3)	Isotopic Distribution ^{234}U (wt.%)	^{235}U (wt.%)	^{236}U (wt.%)	^{238}U (wt.%)
Bottom[(a)]	20310	1080.24344	0.984432	93.20073	0.04042	5.77441
Center[(a)]	21095.06	1123.63813	0.984751	93.20190	0.05566	5.75768
Top[(b)]	12042.76	640.09416	0.984400	93.21000	0.03593	5.76967
Diametral Filler Rod[(b)]	28.163	1.51041	0.995400	93.15600	0.45100	5.39760
Simple Benchmark Model Value[(c,d)]	**53475.983**	**2845.486142**	**0.984557**	**93.20326**	**0.04564**	**5.76655**
	Mass (g)	**Volume (cm^3)**	**Impurity Content[(e)] U (gU/gTot)**	**Si (ppm)**	**B (ppm)**	**C (ppm)**
Bottom[(a)]	20310	1080.24344	0.999598	113.367867	0.312167	159.508403
Center[(a)]	21095.06	1123.63813	0.999579	157.759525	0.243179	159.424067
Top[(b)]	12042.76	640.09416	0.999571	79.996872	0.499980	201.992101
Diametral Filler Rod[(b)]	28.163	1.51041	0.999595	120.011365	0.300028	168.015911
Simple Benchmark Model Value[(c,d)]	**53475.983**	**2845.486142**	**0.999584**	**123.367738**	**0.327242**	**169.046919**

(a) These isotopic and impurity contents are the volume weighted average using the contents and volumes of each part within the section

(b) The volume weighted average did not need to be taken because only one part made up the entire section, i.e. there were not pins or plugs in this section.

(c) These isotopic and impurity contents are the mass weighted average using the volume weighted contents and masses of each section.

(d) Volume weighted average and normalized impurity contents were not rounded before calculating the mass weighted average of the simple benchmark model.

(e) The uranium fraction and impurity content do not sum to a value of one because impurities besides Si, B, and C were replaced with void, thus reducing the total weight fraction of the material, before an average was taken.

Table D-5. Material Data, Simple Benchmark Model, Case 2.

	Mass (g)	Volume (cm^3)	Isotopic Distribution ^{234}U (wt.%)	^{235}U (wt.%)	^{236}U (wt.%)	^{238}U (wt.%)
Bottom[(a)]	19624.59	1046.77742	0.984439	93.20098	0.04056	5.77402
Center[(a)]	20814.95	1106.14797	0.984754	93.20189	0.05582	5.75754
Top[(b)]	11883.24	632.48864	0.984400	93.21000	0.03593	5.76967
Diametral Filler Rod[(b)]	28.163	1.51041	0.995400	93.15600	0.45100	5.39760
Simple Benchmark Model Value[(c,d)]	**52350.943**	**2786.9244**	**0.984561**	**93.20336**	**0.04580**	**5.76628**
	Mass (g)	**Volume (cm^3)**	**Impurity Content[(e)] U (gU/gTot)**	**Si (ppm)**	**B (ppm)**	**C (ppm)**
Bottom[(a)]	19624.59	1046.77742	0.999598	113.533115	0.314774	159.269417
Center[(a)]	20814.95	1106.14797	0.999579	157.754196	0.243193	159.427731
Top[(b)]	11883.24	632.48864	0.999571	79.996872	0.499980	201.992101
Diametral Filler Rod[(b)]	28.163	1.51041	0.999595	120.011365	0.300028	168.015911
Simple Benchmark Model Value[(c,d)]	**52350.943**	**2786.9244**	**0.999584**	**123.506628**	**0.328345**	**169.034772**

(a) These isotopic and impurity contents are the volume weighted average using the contents and volumes of each part within the section
(b) The volume weighted average did not need to be taken because only one part made up the entire section, i.e. there were not pins or plugs in this section.
(c) These isotopic and impurity contents are the mass weighted average using the volume weighted contents and masses of each section.
(d) Volume weighted average and normalized impurity contents were not rounded before calculating the mass weighted average of the simple benchmark model.
(e) The uranium fraction and impurity content do not sum to a value of one because impurities besides Si, B, and C were replaced with void, thus reducing the total weight fraction of the material, before any average was done.

APPENDIX E: DERIVATION OF TILT ANGLE

When the bottom section was lifted to meet the center section of the sphere for Case 1 the pin which extended beyond the top surface of the lower plate caused the center plate to tilt. A gap of 0.01143 cm was present on the side of the sphere by the protruding pin and zero on the opposite side. The gap and dimensions are given in Figure 3-4. In order to determine the tilt angle of the center plate the gap and height of the protruding pin were used as well as the diameter of the plates at the upper and lower surfaces of the lower and center plates. These surfaces formed two triangles, a larger triangle with the gap and a smaller right triangle with the edge of the pin. Figure E.1 is a simplified, not-to-scale drawing of the plates to show the dimensions used to derive the tilt angle.

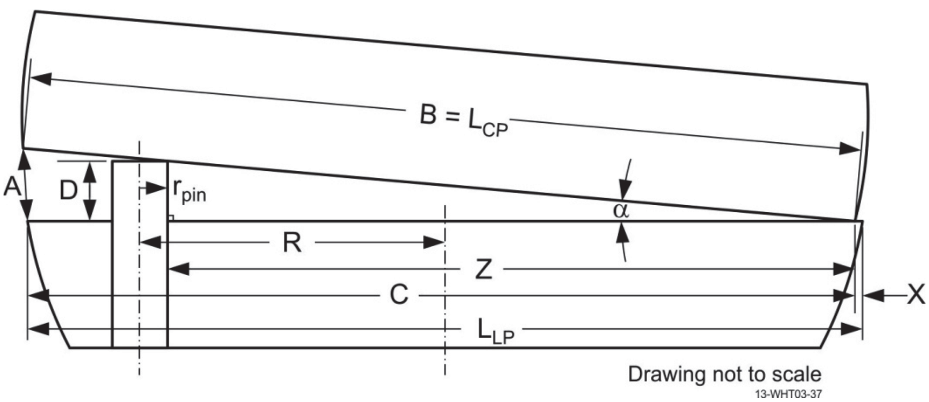

Figure E-1. Simplified, Not-to-Scale Sketch of Tilt Angle Between Lower and Center Plate, Case 1.

Given Dimensions

A	Gap between edges of lower and center plate Does not form a right angle with either plate $= 0.01143\ cm$
$B=L_{CP}$	Diameter of bottom surface of center plate $= 2 \cdot 8.685601 = 17.371202\ cm$
D	Height of pin protrusion $= 0.005842\ cm$
L_{LP}	Diameter of top surface of lower plate $= 2 \cdot 8.6861159 = 17.3722318\ cm$
R	Distance to center of pin from center of lower plate $= 6.35\ cm$
r_{pin}	Radius of pin $= 0.57531\ cm$

Derived Variables

X	Distance the edge of the center plate is shifted in from the edge of the lower plate due to the rotation of the plate.
C	Distance between edge of lower plate and point at which upper plate touches the lower plate.
Z	Distance between edge of pin and point at which upper plate touches the lower plate.
α	Angle between lower plate and center plate.

The large triangle formed by the plate surfaces and the measured gap between the edges of the plates is a non-right triangle that can be solved using the law of cosines, Equation E.1. Two variables, C and α, are unknown in Equation E.1. C can be related to X using Equation E.2. Using the smaller, right triangle, X can be solved for using the intermediate variable Z. This relationship is shown in Equations E.3 and E.4.

$$\mathrm{A}^2 = \mathrm{B}^2 + \mathrm{C}^2 - 2\mathrm{BC}\cos(\alpha) \qquad \text{Equation E.1}$$

$$\mathrm{C} = \mathrm{L_{LP}} - X \qquad \text{Equation E.2}$$

$$\tan(\alpha) = \frac{\mathrm{D}}{Z} \qquad \text{Equation E.3}$$

$$Z = \frac{L_{LP}}{2} - X + R - r_{pin} \qquad \text{Equation E.4}$$

If known variable are plugged into Equation E.4 and then Z is then plugged into Equation E.3, an equation for X in terms of α can then be obtained, Equation E.5. Next, X can be plugged into Equation E.2 and the resulting C can be plugged into Equation E.1 to obtain Equation E.6.

$$Z = 14.4608059 - X$$

$$\tan(\alpha) = \frac{\mathrm{D}}{14.6808059 - X}$$

$$X = 14.4608059 - \frac{0.005842}{\tan(\alpha)} \qquad \text{Equation E.5}$$

$$\mathrm{C} = 17.3722318 - \left(14.4608059 - \frac{0.005842}{\tan(\alpha)}\right)$$

$$\mathrm{C} = 2.9114259 + \frac{0.005842}{\tan(\alpha)}$$

$$0.01143^2 = 17.371202^2 + \left(2.9114259 + \frac{0.005842}{\tan(\alpha)}\right)^2 - 2 \cdot 17.371202 \cdot \left(2.9114259 + \frac{0.005842}{\tan(\alpha)}\right)\cos(\alpha) \qquad \text{Equation E.6}$$

Equation E.6 can then be solved to obtain a tilt angle of 0.0231340494°. If this angle is then used in Equation E.5 a value of -0.008 cm is obtained, implying the center plate overhangs the lower plate. The experimenter stated that this would not have happened. The discrepancy is attributed to not knowing the exact point of rotation for the center plate. If a vertical shift of 0.00351038 is used and the center plate is rotated about the center point, thus the centers of the lower and center plate remain perpendicular, the X value in Figure E-1 becomes +0.0005 cm. At the lower end the center plate would then sit ~3.4×10^{-6} cm above the lower plate. This distance is within the uncertainty in the gap between plates. The center plate would sit just on the corner of the HEU pin. The distance A, however, would only be ~0.007 cm rather than 0.01143 cm. The effect of the different gap is within the uncertainty in the tilt angle.

A vertical shift of 0.00351038 cm and an angle of rotation of 0.0231340494 degrees along the X-axis is used in the detailed benchmark model for Case 1.

APPENDIX F: APPROXIMATION OF SUPPORT STRUCTURE WORTH

A model to approximate the worth of the support structure was created. Because of a lack of dimension and material data some details of the structure had to be assumed. Photographs and drawings were consulted in the process of modeling and approximating the support structure. Some additional information was provided by the experimenter regarding the support structure. The support structure for the top section was a mechanical drive for the measurements of ORSphere. It was mounted off of a cross shape object spanning the 4 carbon steel posts of the assembly machine. The arms of the cross were 4x4 inch square aluminum pipes with a ¼-inch–thick wall. The arms extended diagonally between posts with a mechanical drive mounted in the center that had the upper support rod attached to it. The rods supporting the central section were stainless steel tubing.[a]

The experiment was supported by the vertical lift table's four posts on a 4 ft. (121.92 cm) square. Only the four posts of the vertical lift table were modeled. The posts were carbon steel but were modeled as stainless steel with an OD of 3 in. (3.81 cm OR) and 1/4 in. thick walls (3.175 cm IR). The four posts were modeled with an arbitrary height of 200 cm, extending from the bottom of the lower support structure to just above the upper cross beam support structure. The four posts can be seen in Figures F-1 and F-2.

According to the experimenter, the upper support cross beams were 4x4-in.-square-aluminum pipes with ¼-in.-thick walls and attached to the vertical posts using a fitting that surrounded the outer diameter of the post. The cross beams held the support rod and socket for the upper polar cap. The cross beams were modeled as being 4x4-in.(10.16x10.16-cm)-square-aluminum pipes with a 1/4 in. (0.635 cm) thick wall and extending between the four vertical posts; the fittings that mounted the cross beams to the posts were not modeled. Figures F-1 and F-2 show the cross beams.

The center support structure is also shown in Figures F-1 and F-2 and consisted of four fuel hangers which were pinned to the center plate using Type 304 stainless steel pins. Minimal definitive information is given for the center fuel plate hangers. Notes from the experimenter give the hanger OD as 0.5 in., ID as 0.375 in., and the length as approximately 31-1/2 in.; the hanger length was adjustable to ensure proper placement of the center fuel plate. The fuel hangers were stainless steel tubes with an IR of 0.47625 cm and an OR of 0.635 cm. The stainless steel pins had a radius of 0.351028 cm. The length of the pins was not given. The length of the pins was approximated and modeled as 0.975 cm.

[a] Personal email communication with J.T. Mihalczo, July 29, 2013.

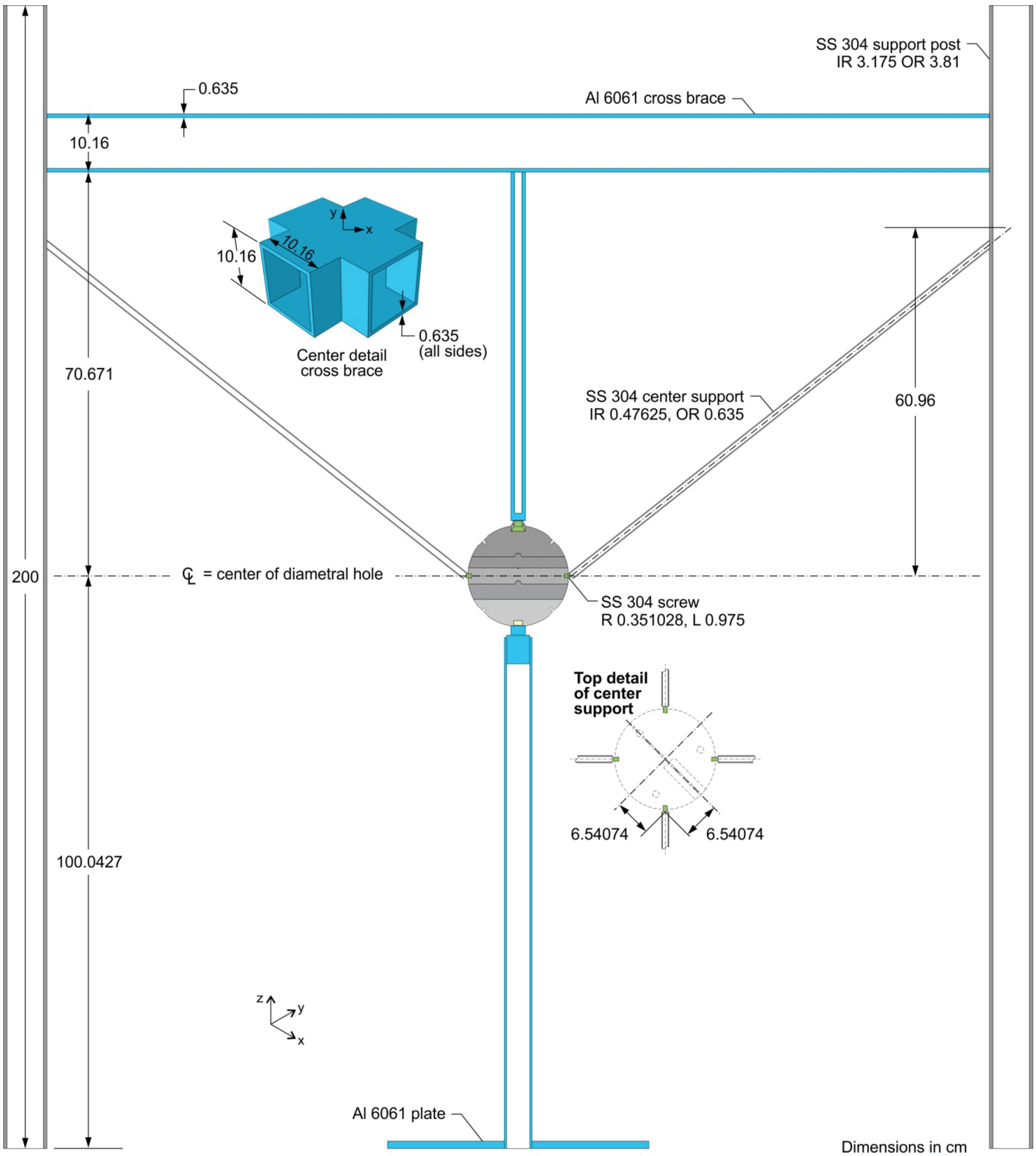

Figure F-1. Cross-Section View of Support Structure.

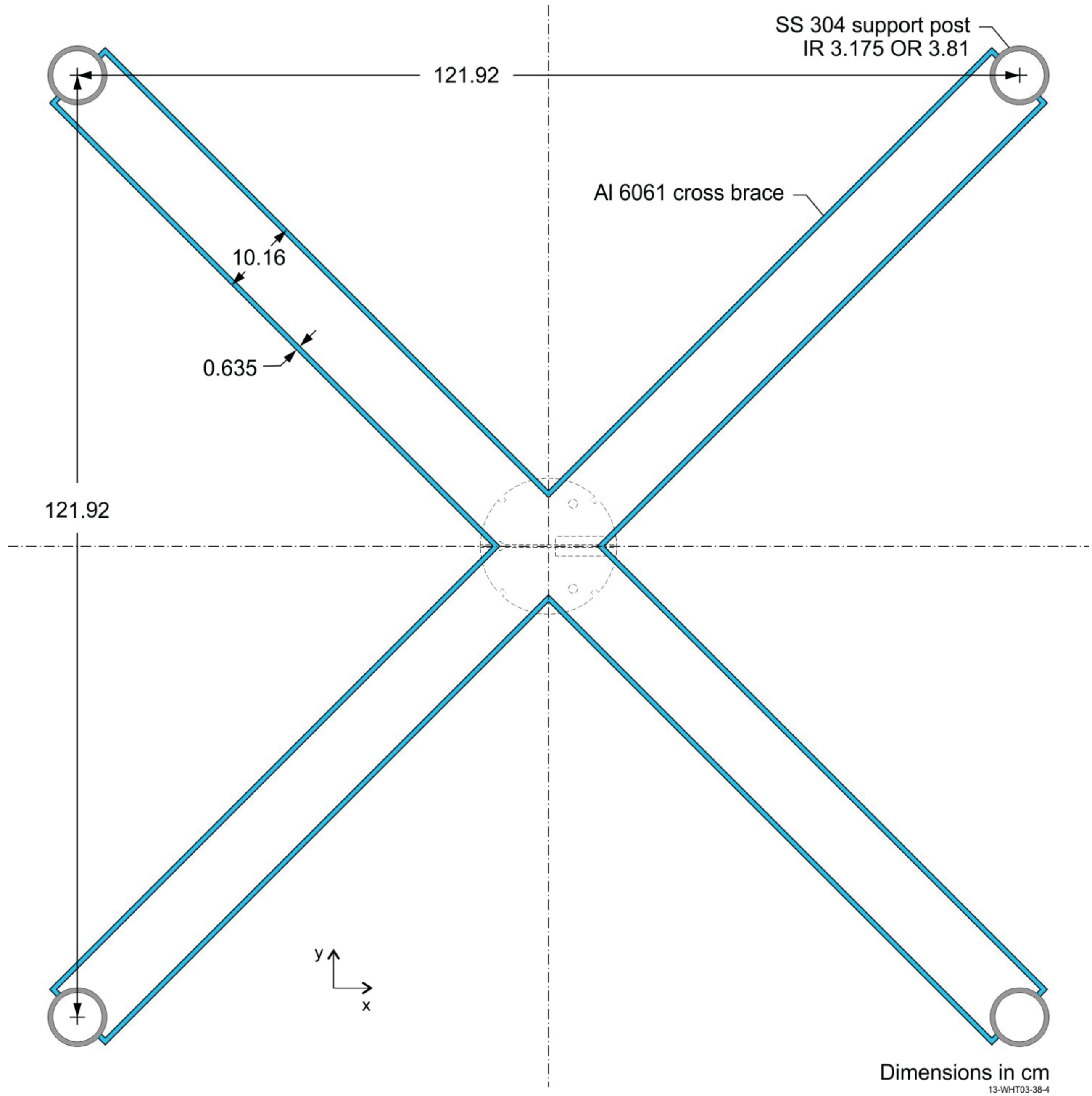

Figure F-2. Cross-Section View of Support Posts and Cross Beams.

The bottom support structure was aluminum 6061 and the dimensions are given in Figure 1-20. The bottom support structure was simplified in the structural support worth approximation models. The brass bolt was included in the benchmark model. The 2-5/8 in. tall, aluminum plug sat flush with the spot face on the lower polar cap. The smaller, 1 in. diameter section of plug had a height of 0.5 in. The larger diameter section of plug had a diameter of 1.610 in., the inner diameter of 1-1/2 IPS-SCH40. The transition between the two diameters had a 45^{o} angle. This corresponds to a transition height of 0.305 in. Rather than modeling the transition one half the height was added to the smaller diameter section of plug and one half was added to the larger diameter section of plug. This resulted in the smaller diameter section of plug having a height of 0.6525 in. (1.65735 cm) and the larger diameter section of plug having a height of 1.9725 in. (5.01015 cm). The main body of the support stand was modeled as a pipe with an OD of 1.9100 in. (2.413 cm OR), an ID of

1.610 in. (2.0447 cm IR), and a length of 34.695 in. (88.1253 cm). The plate at the bottom of the stand was 0.5 in. thick (1.27 cm) with a diameter of 18 in. (22.86 cm R). The total height from the top of the aluminum plug to the bottom of the aluminum plate was 36 in. (91.44 cm). Four fins steadied the aluminum stand. The fins were 30° right triangles with a base length of 20.447 cm, a height of 35.415 cm, and a thickness of 0.635 cm. The dimensions of the lower support structure are given in Figure F-3.

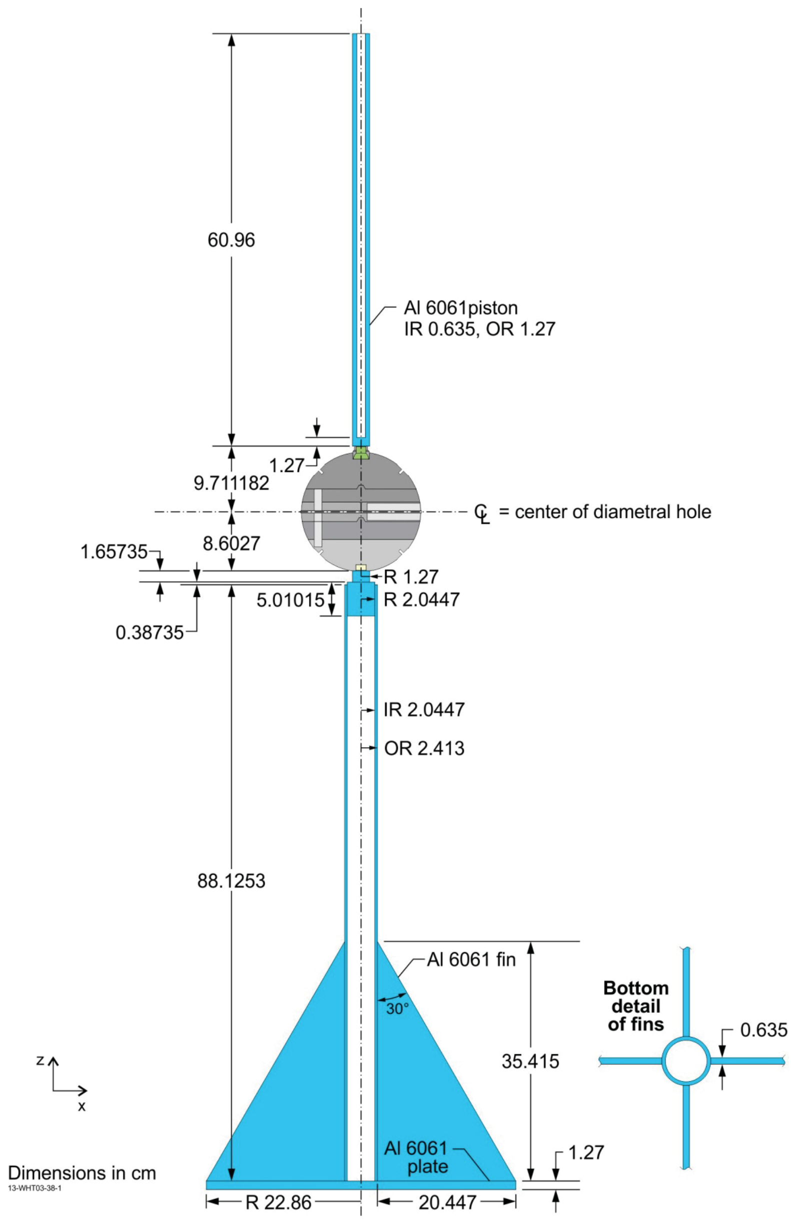

Figure F-3. Cross-Section View of Lower Support Stand and Support Rod.

The socket and support rod were not present in the benchmark model. The dimensions of the socket are given in Figure 1-16. No dimensions for the support rod were given. The mass of the stainless steel on the interior of the socket is not given but the mass of the uranium on the outside of the socket was 64 g. The height of the ball portion and cylindrical portion of the stainless steel was not given so dimensions were estimated based on the given dimensions, see Figure F-4 (dimensions are given in inches). When the density of the uranium in the upper socket was calculated the density was 18.9 g/cm^3, much higher than the 18.75 g/cm^3 density the experimenter gave (see Section 1.2.6). The density of the ball was varied until the density was 18.751 g/cm^3. The dimensions of the upper socket in the support structure approximation model are given in Figure F-5.

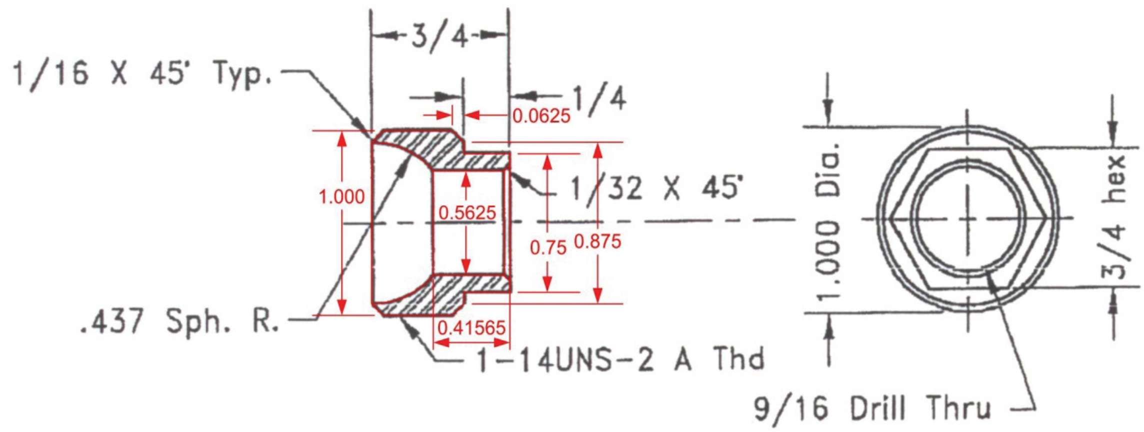

Figure F-4. Upper Socket Estimated Dimensions.[a]

As is seen in Figure F-5, the chamfer at the bottom of the socket was not modeled and the chamfer at the middle of the socket was modeled as a clean 90^o cutaway. These two simplifications have opposing effects and thus have no effect of the model. The diameter of the hole for the upper socket in the upper polar cap was 2.422144 cm (.9536 in.). This diameter disagrees with the 1.000-in. diameter given in Figure F-4. The 2.422144-cm diameter (1.211072-cm radius) was used because it accounts for the threads of the socket and socket hole and the undercut to thread root in the upper polar cap (see Figure 1-15). The support rod was model as a simple tube, flush with the top of the socket, with an OD of 1 in. (1.27 cm OR), an ID of 1/2 in. (0.635 cm IR), and a length of 2 ft. (60.96 cm). A solid 1.27 cm thick plug was modeled in the lower end of the aluminum tube.

This support structure model was an approximation. The calculation worth is -21.52 ± 1.2 ¢. Although slightly lower, this approximation verifies that the measured correction of 25.19 ± 1.76 ¢ is reasonable.

[a] Estimated dimensions are in red.

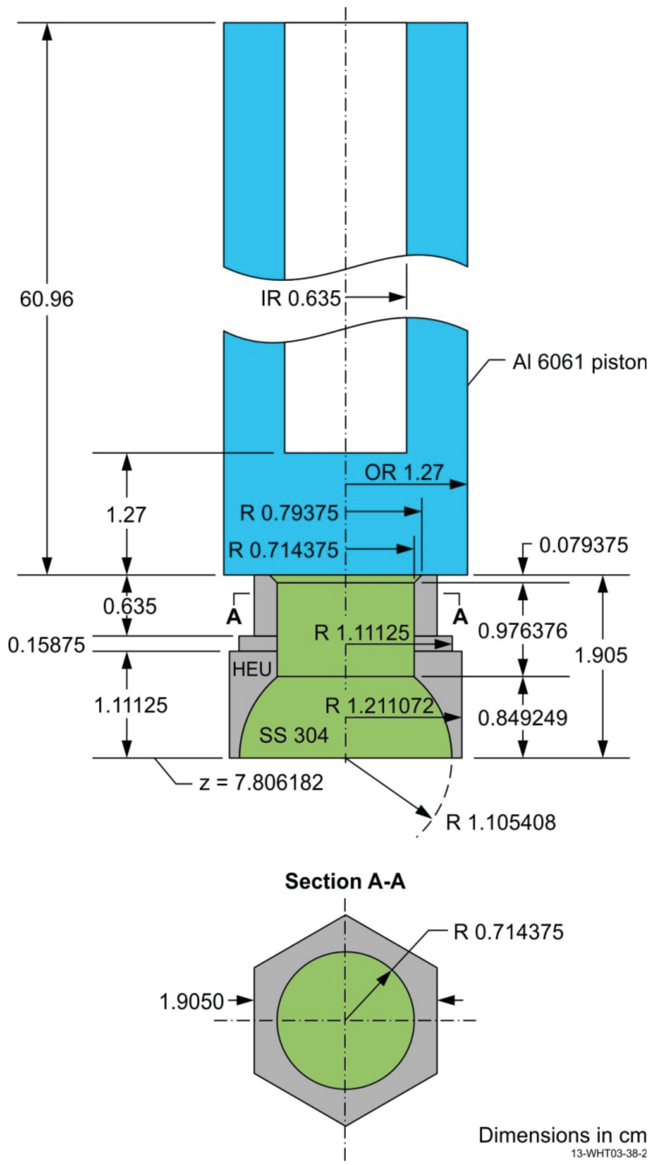

Figure F-5. Upper Socket Model Dimensions.