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Revison 1

ORSPHERE: PHYSICS MEASUREMENTS FOR BARE, HEU(93.2)-METAL SPHERE

Margaret A. Marshall
John D. Bess
J. Blair Briggs
Christine E. White
James P. Dyrda
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Idaho National Laboratory

Idaho Falls, Idaho 83415

http://www.inl.gov

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CRIT-REAC-COEF-KIN-RRATE

ORSPHERE: PHYSICS MEASUREMENTS FOR BARE, HEU(93.2)-METAL SPHERE

Evaluator

Margaret A. Marshall
Idaho National Laboratory

Internal Reviewers
John D. Bess
J. Blair Briggs
Christine E. White

Independent Reviewers

James P. Dyrda
Nigel P. Tancock
Atomic Weapons Establishment

Udo Wehmann
Under Subcontract to OECD NEA

John T. Mihalczo
Oak Ridge National Laboratory

Status of Compilation/Evaluation/Peer Review

Section 1	Compiled	Independent Review	Working Group Review	Approved
1.0 DETAILED DESCRIPTION				
1.1 Description of the Critical and/or Subcritical Configuration	YES	YES	YES	YES
1.2 Description of Buckling and Extrapolation-Length Measurements	NA	NA	NA	NA
1.3 Description of Spectral-Characteristics Measurements	NA	NA	NA	NA
1.4 Description of Reactivity-Effects Measurements	YES	YES	YES	YES
1.5 Description of Reactivity-Coefficient Measurements	YES	YES	YES	YES
1.6 Description of Kinetics Measurements	YES	YES	YES	YES
1.7 Description of Reaction-Rate Distribution Measurements	YES	YES	YES	YES
1.8 Description of Power-Distribution Measurements	NA	NA	NA	NA
1.9 Description of Isotopic Measurements	NA	NA	NA	NA
1.10 Description of Other Miscellaneous Types of Measurements	NA	NA	NA	NA
Section 2	**Evaluated**	**Independent Review**	**Working Group Review**	**Approved**
2.0 EVALUATION OF EXPERIMENTAL DATA				
2.1 Evaluation of Critical and/or Subcritical Configuration Data	YES	YES	YES	YES
2.2 Evaluation of Buckling and Extrapolation Length Data	NA	NA	NA	NA
2.3 Evaluation of Spectral-Characteristics Data	NA	NA	NA	NA
2.4 Evaluation of Reactivity-Effects Data	YES	YES	YES	YES
2.5 Evaluation of Reactivity-Coefficient Data	YES	YES	YES	YES
2.6 Evaluation of Kinetics-Measurements Data	YES	YES	YES	YES
2.7 Evaluation of Reaction-Rate Distributions	YES	YES	YES	YES
2.8 Evaluation of Power-Distribution Data	NA	NA	NA	NA
2.9 Evaluation of Isotopic Measurements	NA	NA	NA	NA
2.10 Evaluation of Other Miscellaneous Types of Measurements	NA	NA	NA	NA

Section 3	Compiled	Independent Review	Working Group Review	Approved
3.0 BENCHMARK SPECIFICATIONS				
3.1 Benchmark-Model Specifications for Critical and/or Subcritical Measurements	YES	YES	YES	YES
3.2 Benchmark-Model Specifications for Buckling and Extrapolation-length Measurements	NA	NA	NA	NA
3.3 Benchmark-Model Specifications for Spectral-Characteristics Measurements	NA	NA	NA	NA
3.4 Benchmark-Model Specifications for Reactivity-Effects Measurements	YES	YES	YES	YES
3.5 Benchmark-Model Specifications for Reactivity-Coefficient Measurements	YES	YES	YES	YES
3.6 Benchmark-Model Specifications for Kinetics Measurements	YES	YES	YES	YES
3.7 Benchmark-Model Specifications for Reaction-Rate Distribution Measurements	YES	YES	YES	YES
3.8 Benchmark-Model Specifications for Power-Distribution Measurements	NA	NA	NA	NA
3.9 Benchmark-Model Specifications for Isotopic Measurements	NA	NA	NA	NA
3.10 Benchmark-Model Specifications of Other Miscellaneous Types of Measurements	NA	NA	NA	NA
Section 4	**Compiled**	**Independent Review**	**Working Group Review**	**Approved**
4.0 RESULTS OF SAMPLE CALCULATIONS				
4.1 Results of Calculations of the Critical or Subcritical Configurations	YES	YES	YES	YES
4.2 Results of Buckling and Extrapolation Length Calculations	NA	NA	NA	NA
4.3 Results of Spectral-Characteristics Calculations	NA	NA	NA	NA
4.4 Results of Reactivity-Effect Calculations	YES	YES	YES	YES
4.5 Results of Reactivity-Coefficient Calculations	YES	YES	YES	YES
4.6 Results of Kinetics-Parameter Calculations	YES	YES	YES	YES
4.7 Results of Reaction-Rate Distribution	YES	YES	YES	YES
4.8 Results of Power-Distribution Calculations	NA	NA	NA	NA
4.9 Results of Isotopic Calculations	NA	NA	NA	NA
4.10 Results of Calculations of Other Miscellaneous Types of Measurements	NA	NA	NA	NA
Section 5	**Compiled**	**Independent Review**	**Working Group Review**	**Approved**
5.0 REFERENCES	YES	YES	YES	YES
Appendix A: Computer Codes, Cross Sections, and Typical Input Listings	YES	YES	YES	YES

ORSPHERE: PHYSICS MEASUREMENTS FOR BARE, HEU(93.2)-METAL SPHERE

IDENTIFICATION NUMBER: ORSPHERE-FUND-EXP-001
CRIT-REAC-COEF-KIN-RRATE

KEY WORDS: acceptable, bare, central void reactivity, critical experiment, delayed neutron fraction, fission density, highly enriched, metal, neutron importance, ORALLOY, ORCEF, prompt neutron decay constant, sphere, unmoderated, unreflected, uranium, uranium worth

SUMMARY INFORMATION

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 isotopic composition 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 inches), masses (±0.01 g), and material data. The experiment was also set up to minimize the amount of structural material in the sphere proximity. Two, correlated spheres were evaluated and judged to be acceptable as criticality benchmark experiments. This evaluation is given in HEU-MET-FAST-100. The second, smaller sphere was used for additional reactor physics measurements. Worth measurements (Reference 1, 2, 3 and 4), the delayed neutron fraction (Reference 3, 4 and 5) and surface material worth coefficient (Reference 1 and 2) are all measured and judged to be acceptable as benchmark data. The prompt neutron decay constant (Reference 6 and 7), relative fission density (Reference 8) and relative neutron importance (Reference 8) measurements are also evaluated and judged to be acceptable benchmark data..

Information for the evaluation was compiled from References 1 through 8, the experimental logbooks 8[a] and 9;[b] additional drawings and notes provided by the experimenter; and communication with the lead experimenter, John T. Mihalczo.

[a] Radiation Safety Information Computation Center (RSICC), The ORNL Critical Experiments Logbooks, Book 108r, http://rsicc.ornl.gov/RelatedLinks.aspx?t=criticallist.
[b] This logbook was scanned by the experimenter September 2012 and is not currently available on the RSICC website.

1.1 Description of the Critical and/or Subcritical Configuration

The criticality portion of this evaluation has been reviewed and approved by the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and has been published under the following identifier: HEU-MET-FAST-100.[a] A sketch and a photo of the assembly has been provided as Figure 1.1-1 and Figure 1.1-2 for reference.

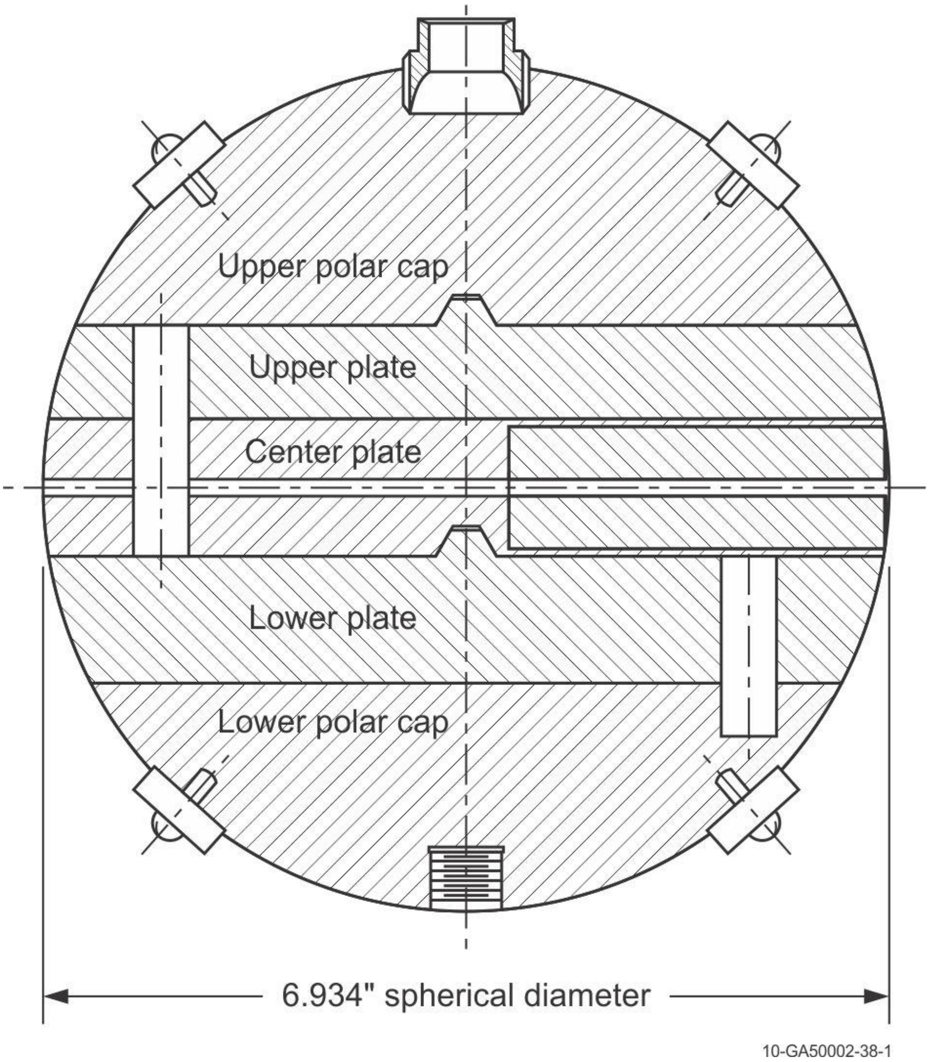


Figure 1.1-1. Sketch of the Assembled Five Sphere Parts.

[a] International Handbook of Evaluated Criticality Safety Benchmark Experiments, NEA/NSC/DOC(95)03, OECD-NEA, Paris (2013).

Figure 1.1-2. Photograph of the Disassembled Three Part Sphere.

1.2 Description of Buckling and Extrapolation Length Measurements

Buckling and extrapolation length measurements were not made.

1.3 Description of Spectral Characteristics Measurements

Spectral characteristics measurements were not made.

1.4 Description of Reactivity Effects Measurements

1.4.1 Overview of Experiment

Many reactivity measurements were performed on the critical spheres. These measurements were recorded in the logbooks. Because it is not always evident how logbook data should be interpreted, only worth measurements that are published or are summarized in tables provided by the experimenter are presented and evaluated in this benchmark report.

The worth of the mass adjustment buttons and diametral filler rod were measured using the critical sphere described as Case 2 in HEU-MET-FAST-100.[a] The mass adjustment buttons were made of ORALLOY, stainless steel, and aluminum and were of various thicknesses. The buttons were placed both on the surface of the sphere and the empty socket hole in the upper polar cap. Changes were made to the center plate of the 3.4420-inch-radius critical sphere for the central void worth measurement.

1.4.2 Geometry of the Experiment Configuration and Measurement Procedure

1.4.2.1 Central Void Reactivity

The central void reactivity[a] was measured and results were reported in Reference 3 and 4. The reactivity of the central void was measured by determining system reactivity for the 3.4420-inch-average-radius sphere with and without a 0.460-inch diameter uranium metal sphere present at the center of the sphere. This measurement required that the geometry of the central plate be varied from the central plate geometry used in the critical configuration (Section 1.1). No other section of the sphere was altered. A variable number of uranium buttons, placed on the outer surface of the 3.4420-cm-average-radius sphere, were used. The modified central plate of the central section is shown in Figure 1.4-1. The modification of the diametral hole allowed for a uranium plug to be inserted and removed from the sphere to create a 0.230-inch radius void at the center of the sphere. A 0.460-inch diameter uranium metal sphere (15.614 g) was used to fill the void region in order to simulate a solid sphere. The plug and sphere are shown in Figure 1.4-2 with manufacturing tolerances. By comparison of the sphere reactivity with and without the sphere present at the center of the ORSphere the worth of the central void was determined. All other holes in the center plate were filled with plugs when reactivity measurements were performed. The measurement process to obtain the stable reactor period is described in Reference 3 as follows:

> The system was assembled with the small central sphere in place to slightly above delayed criticality by use of a small removable reflector. When the power or fission rate reached the appropriate level, the small reflector was removed in ~0.2 s. The positive stable reactor period was obtained from the reaction rate as a function of time in seven external detectors containing BF_3 that were either neutron counters or neutron sensitive ionization chambers. For the four neutron counters, the count rate was measured as a function of time; for the three ionization chambers, the output current was recorded on strip-chart recorders as a function of time. All detectors were external to the sphere at distances from 6 to 15 feet and were surrounded by at least 2 inches of paraffin moderator (*see Figure 1.4-3*). The stable reactor periods were obtained graphically. The shorter reactor periods were measured over at least two decades of purely exponential change. The longer stable reactor periods were measured for at least a time period of 30 minutes of purely exponential change. The sphere was then disassembled by either raising the upper polar cap or lowering the lower section. The small, central uranium sphere was removed manually, and the system was reassembled with the small reflector in place to a power level from

[a] This worth is also called the central uranium reactivity. To be consistent with Reference 3 and 4, it is called central void worth or central void reactivity in this evaluation.

which the reactor period could again be measured after the small additional reflector was removed.

Multiple runs, 43, with a variable number of mass adjustment buttons were performed on ten separate days between May 19 and August 10, 1972. Once the stable reactor periods were obtained, the Inhour equation was used to determine the system reactivity in dollars. This required the use of delayed neutron parameters. The relative yield and decay constants from Keepin et al. for ^{235}U and ^{238}U were used.[a] The fraction of fission for ^{234}U and ^{236}U were split 50/50 between ^{235}U and ^{238}U. The fraction of fissions, obtained from neutron transport calculations, and Keepin data was provided in Reference 3 and is shown in Table 1.4-1at the end of Section 1.4.2. The system reactivity of the ORSphere with the small central sphere present, versus the reactivity with the small central sphere removed, yielded the worth of the small central sphere, or inversely, the worth of the central void region. The stable reactor periods are provided in Table 1.4-2 at the end of this section and a sample calculation of the central void region worth is given in Appendix B. A table is provided by the experimenter, Table 1.4-3, which gives the calculated reactivity for each detector of each run. The average central void region worth was 9.165 ± 0.023 ¢. This value is the variance weighted average of the daily averages and standard deviations.[b] The given error is the standard deviation of the mean of all measurements with all detectors. The distribution of the mean measurements is given in Figure 1.4-4.

[a] The Keepin et al. delayed neutron parameters were provided in Reference 3 and were obtained from: G.R. Keepin, T.F. Wimmett, and R.K. Zeigler, *Phys. Rev.*, **107**, 1044 (1975).

[b] Personal communication with J.T. Mihalczo, November 25, 2013.

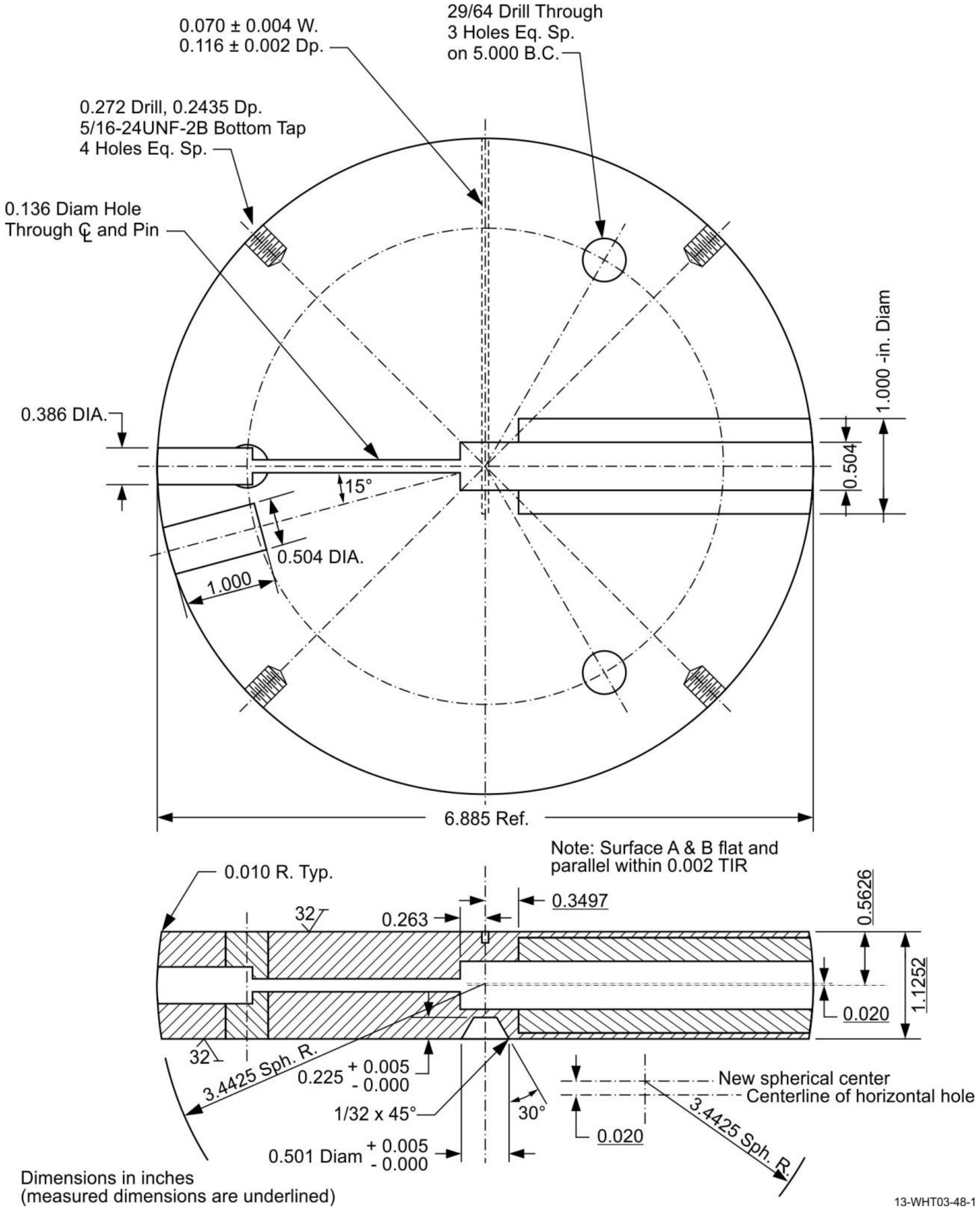


Figure 1.4-1. Modified Central Plate for Center Section of 3.4420-inch-average Radius Sphere.[a]

[a] This figure is based on the original drawing in Reference 3; however, the figure has been redrawn with changes to the drawing for improved clarity but no changes to the dimensions.

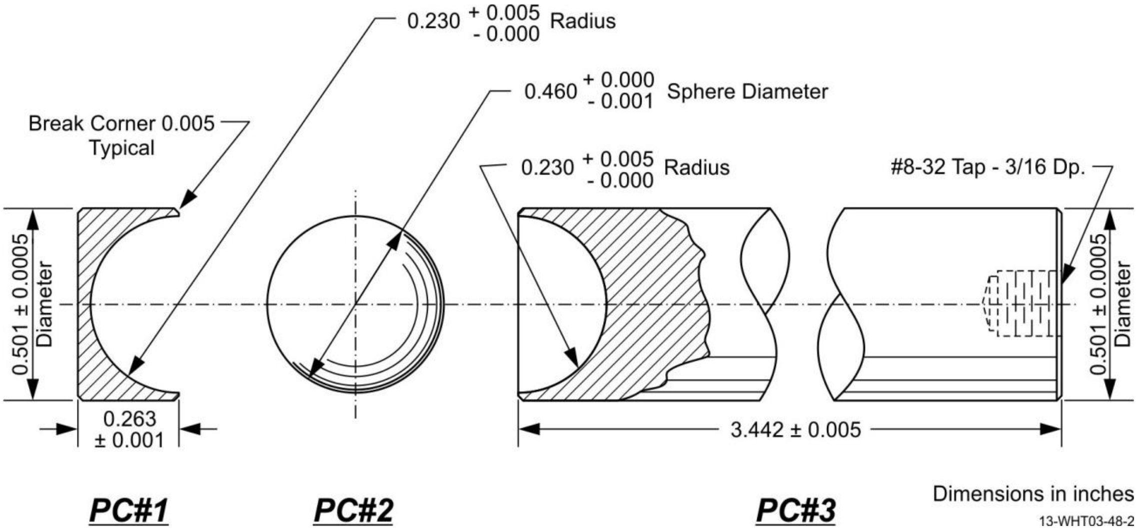
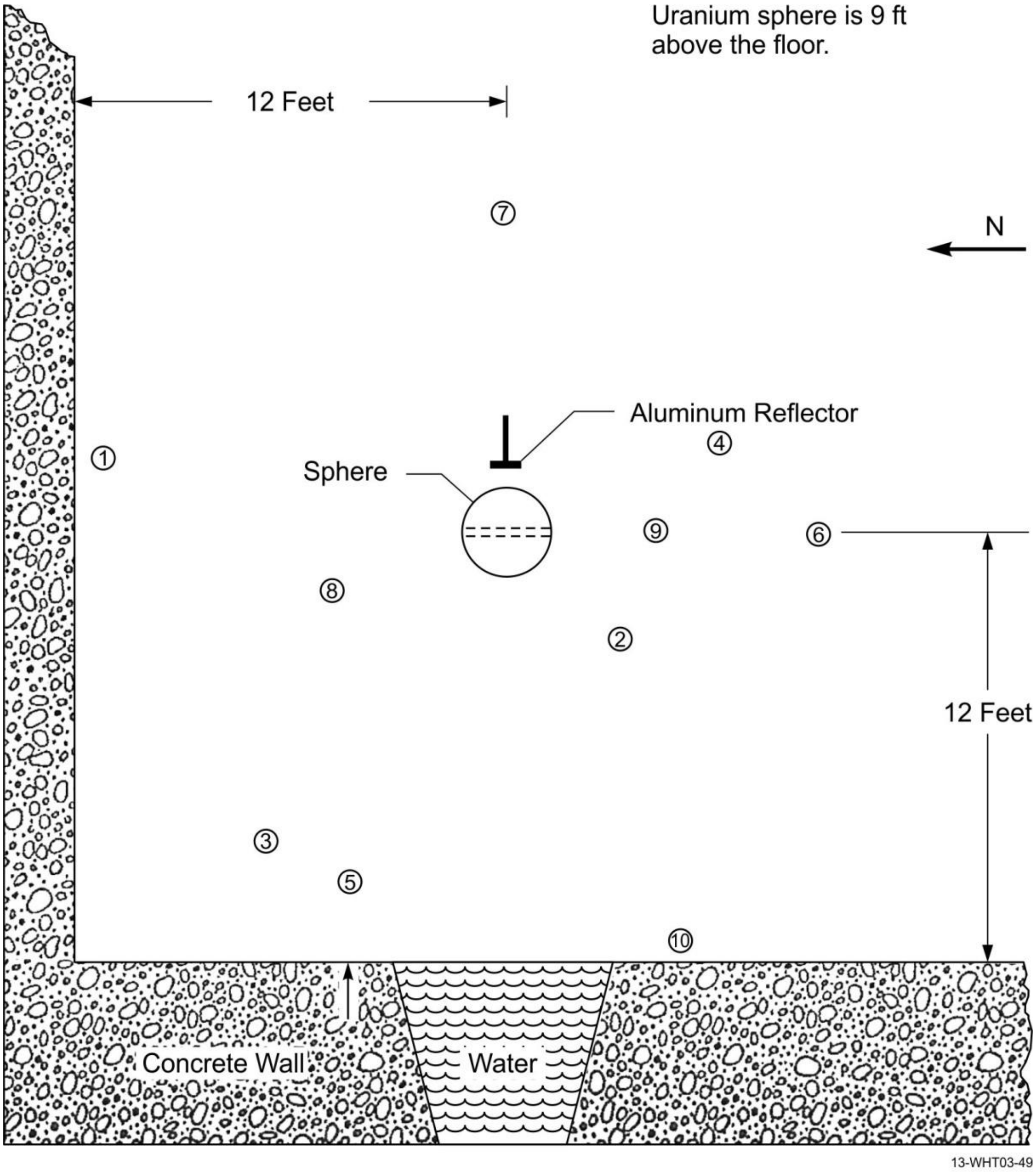


Figure 1.4-2. Dimensions and Manufacturing Tolerances of Plug and Sphere for Central Void Region Worth Measurement (Reference 3).



#	Detector	Distance from Sphere Horizontally	Distance from Sphere Vertically
1	A	12	+ 3
2	D	4	- 8
3	Ln	12	- 7
4	C	7	- 6
5	BF_3 #1	10	- 7
6	BF_3 #2	8	- 7
7	BF_3 #3	8	- 7
8	Rhoette	5	- 2
9	E	4	- 9
10	F	12	- 9

Figure 1.4-3. Plan View of Detector Location for ORSphere Experiments.[a]

[a] This drawing was provided by the experimenter. Locations are given in units of feet. The west wall has six water windows in it and is described in the safety analysis report for the ORCEF. (Personal email communication with J.T. Mihalczo, February 20, 2013)

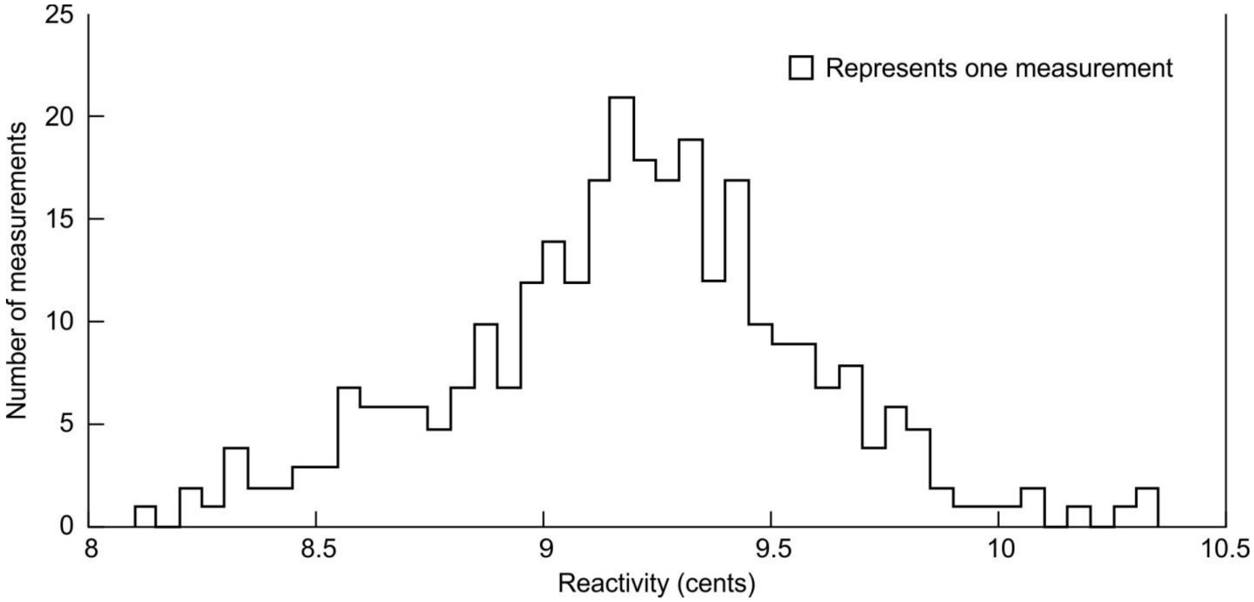


Figure 1.4-4. Distribution of Measured Central Void Region Worth Values.

1.4.2.2 Worth of Buttons on the Sphere Surface

Reactivity worths were measured for various types of surface mass adjustment buttons using system reactivity measurements. The system reactivity was determined by measuring the stable reactor period of the sphere both with and without the buttons. The Inhour equation was then used to convert the stable reactor period into system reactivity in dollars/cents. The delayed neutron parameters of uranium isotopes for fast fission of Keepin, Wimett, and Zeigler (1957) were used in the Inhour equation. The change in system reactivity when buttons are added or removed yields the worth of the buttons. A more thorough explanation of the measurements of the stable reactor period and the conversion to reactivity in dollars is given with the description of the central void reactivity and Appendix B.

The only published mass adjustment button worths are given in Reference 1. Adding 16, 0.250-inch-thick surface uranium mass adjustment buttons (43.9 g each) increased the reactivity of the 3.4420-inch-average-radius sphere, with diametral filler rod in place, from -23 ¢ to +12.4 ¢. The inner and outer diameter for all the buttons, regardless of material and thickness, was the same.[a] The button diameter was smaller than the diameter of the button recesses and had a diameter of 0.8720 inch and an inner diameter of 0.1770 inch.[b] Reference 3 gives the button diameter as 0.8750 inch which is actually the diameter of the button recess. All mass adjustment buttons placed on the outside of the sphere were held in place using No.8-55 stainless steel screws. The screws were each tightened so that the underside of the head was flush with the outer surface of the button.[c] When the buttons were present they were held in place by screws and when removed the screws were also removed.

The logbook provides worth results for four, 1/8-inch-thick uranium mass adjustment buttons on the surface of the sphere. These measurements were performed with the 3.4420-inch-average-radius sphere with 12, 1/8-inch-thick uranium mass adjustment buttons held in place with No.8-55 screws stainless steel (Type 304) screws . The worth was measured by determining the system reactivity for the sphere with and without four, 1/8-inch-thick uranium mass adjustment buttons placed in the four remaining mass adjustment button recesses. The exact location of the four added and removed mass adjustment buttons was not available; however, the measured buttons were probably split between the upper and lower polar caps.[d] The measured results were provided in the logbook[a] and in a typed table provided by

[a] Personal email communication with J.T. Mihalczo, August 13, 2013.
[b] Personal email communication with J.T. Mihalczo, September 6, 2013 and Reference 1.
[c] Personal email communication with J.T. Mihalczo, August 15 and October 8, 2013. The screw type is found in Reference 5 and 7, see Figure 1.6-2.
[d] Personal communication with J.T. Mihalczo, October 8, 2013.

the experimenter and are in Table 1.4-4 at the end of Section 1.4.2. The table states that "holding screws were not involved." However, in the logbook it is clear that the base case had 12, 1/8-inch-thick buttons with screws for four other buttons. Four buttons were then added to the sphere, thus filling the 16 available spaces. This method allowed the worth of 4 buttons to be measured without including the worth of the screws. The average worth for four, 1/8-inch-thick uranium mass adjustment buttons on the surface of the sphere was +6.1415 ± 0.0834 ¢.

The worth of one aluminum button on the surface of the sphere, including the holding screw, was measured. The aluminum buttons were aluminum Type 6061 and had the same dimensions as the uranium buttons.[b] For these measurements, the 3.4420-inch-average-radius sphere had 12 and 13, 1/8-inch-thick uranium mass adjustment buttons on the surface of the sphere. Four or three 1/8-inch-thick aluminum buttons were added to or removed from the sphere using the remaining mass adjustment button recesses and held in place using holding screws. The logbook gives the stable reactor period of these measurements. The reactor periods were converted into system reactivity and then the worth per aluminum button, including the holding screw was determined. The results are given in Table 1.4-5 at the end of Section 1.4.2.[c] The average worth per 1/8-inch-thick aluminum button with holding screw was 0.7058 ± 0.0104 ¢.

1.4.2.3 Worth of Buttons in Empty Socket Hole of Upper Polar Cap

Three uranium mass adjustment buttons were placed in the empty socket hole in the upper polar cap of the sphere. The three uranium buttons had a total mass of 65.2 g and each had a thickness of 0.1250 inch, an inner diameter of 0.1770 inch and an outer diameter of 0.8720 inches. The 3.4420-inch-average-radius sphere was used with 13, 1/8-inch-thick and one 1/16-inch-thick uranium buttons on the surface of the sphere and a 3/8 inch aluminum shim. According to the experimenter, the 3/8 inch aluminum shim was referring to the distance position of the aluminum reflector used to achieve exactly delayed critical.[d] Stable reactor period values for five runs from five detectors, measured with and without the buttons for each run, is recorded in the logbook along with the associated system reactivities.[e] Additionally, a typed table of the logbook results was provided by the experimenter with the worth for each detector measurement for each run as well as the average worth given. This table is recreated as Table 1.4-6 at the end of Section 1.4.2. The average worth of the three uranium mass adjustment buttons in the empty socket hole was 7.86 ± 0.04 ¢.

The logbook also gives a reactivity worth measurement for three 1/8-inch-thick aluminum buttons placed in the empty socket hole. The aluminum buttons were aluminum Type 6061 and had the same dimensions as the uranium buttons.[f] The sphere used for the aluminum button worth measurement had 15 1/8-inch-thick uranium mass adjustment buttons on the surface of the sphere and a 5/8 inch aluminum shim. According to the experimenter, the 5/8 inch aluminum shim refers to the distance to the aluminum reflector used to achieve exactly delayed critical.[g] Similar to the uranium button in the empty socket hole measurements, results were provided in the logbook as well as in a typed table provided by the experimenter. The results from the table are given as Table 1.4-7 at the end of Section 1.4.2.[h] The mass of the aluminum buttons was not provided. The average worth for the three, 1/8-inch-thick aluminum buttons in the empty socket hole of the upper polar cap was 3.1259 ± 0.0358 ¢.

The worth of three 1/8-inch-thick stainless steel buttons, with dimensions the same as the uranium mass adjustment buttons, in the empty socket hole was measured. The stainless steel buttons were stainless steel Type 304 and had the same dimensions as the uranium buttons.[i] The sphere used had 16 1/8-inch

[a] Logbook 8, page 129-130.
[b] Personal email communication with J.T. Mihalczo, August 13, 2013.
[c] Logbook 8, page 139-140.
[d] Personal email communication with J.T. Mihalczo, September 19, 2013.
[e] Logbook 8, page 143-144.
[f] Personal email communication with J.T. Mihalczo, August 13, 2013.
[g] Personal email communication with J.T. Mihalczo, September 19, 2013.
[h] Logbook 8, page 145-146.
[i] Personal email communication with J.T. Mihalczo, August 13, 2013.

uranium buttons on the surface of the 3.4420-inch-average radius sphere and a ¼-inch aluminum shim. According to the experimenter, the 1/4 inch aluminum shim was referring to the distance position of the aluminum reflector used to achieve exactly delayed critical.[a] The measurement and reporting methods were the same as for the aluminum button worth. The table of results is given in Table 1.4-8 at the end of Section 1.4.2.[b] The mass of the stainless steel buttons was not given. The average worth for the three 1/8-inch-thick stainless steel buttons was 4.7228 ± 0.0420 ¢.

1.4.2.4 Diametral Filler Rod Reactivity Worth

The uranium diametral filler rod was actually two sections of rods that were placed in the diametral hole of the sphere. The two rods were of 0.1293-inch diameter and 4.265- and 2.745-inch long (17.117 and 11.046 g, respectively). Dimensional certification reports give the rod lengths as 4.2650 inches and 2.7545 inches and the diameter as 0.1290/0.1295 inches, which averaged to 0.1293 inch. The length of the shorter filler rod did not agree between Reference 1 and the certification report, this discrepancy is discussed in Section 2.4.4. The masses on the dimensional certification report are the same as those given in Reference 1. The total length of two filler rods was slightly greater than the length of the diametral hole.[c] The worth of the diametral rod was found by measuring the stable reactor period for the 3.4420-inch-average-radius sphere with 16, 1/8-inch-thick uranium mass adjustment buttons with and without the diametral filler rods in place. The results are given in the logbook and in a typed table provided by the experimenter and are shown in Table 1.4-9 at the end of Section 1.4.2.[d] The published worth of the filler rod was given as +11.23 ± 0.07 ¢ (Reference 1 and 2); the experimenter's notes give the average worth as 11.2340±0.0717¢.

Table 1.4-1. Fission Fractions and Delayed Neutron Parameters (Reference 3).

Keepin Delayed Neutron Parameters[(a)]												
Group	Relative Yield ^{235}U			Decay Constant ^{235}U			Relative Yield ^{238}U			Decay Constant ^{238}U		
1	0.038	±	0.003	0.0127	±	0.0002	0.013	±	0.001	0.0132	±	0.0003
2	0.213	±	0.005	0.0317	±	0.0008	0.137	±	0.002	0.0321	±	0.0006
3	0.188	±	0.016	0.115	±	0.003	0.162	±	0.020	0.139	±	0.005
4	0.407	±	0.007	0.311	±	0.008	0.388	±	0.012	0.358	±	0.014
5	0.128	±	0.008	1.40	±	0.081	0.225	±	0.013	1.41	±	0.067
6	0.026	±	0.003	3.87	±	0.369	0.075	±	0.005	4.02	±	0.214
Fission Fraction[(b)]												
^{234}U 0.8241%			^{235}U 98.1922%			^{236}U 0.0123%			^{238}U 0.9714%			

(a) The delayed neutron parameters were provided in Reference 3 but they were originally published by Keepin et al.
(b) The fission fractions were "obtained from one-dimensional S_n neutron transport calculation with ENDF/B-VI cross sections for a delayed critical sphere" (Reference 3).

[a] Personal email communication with J.T. Mihalczo, September 19, 2013.
[b] Logbook 8, page 147-148.
[c] Personal communication with J.T. Mihalczo, April 15, 2013. The diametral filler rod was not machined to match the curve of the sphere.
[d] Logbook 8, page 134-135.

Table 1.4-2. Stable Reactor Period Values for Central Void Reactivity Measurements (Reference 3).

Run Number		Shutdown Method[(a)]	Number Of Mass Adjustment Buttons	Reactor Period (s) from						
				Ion Chambers			Neutron Counters[(b)]			
				A	D	Ln	1 (*BF #1*)	2 (*BF #2*)	3 (*BF #3*)	4 (*TMC*)
528	A	UPC	12[(c)]	94.9	103.3	99.3	97.7	-	97.7	99.3
	B			1750	2081	2314	2149	-	2149	2070
529	A	UPC	12[(c)]	86.7	99.1	97.7	96.4	-	91.9	98.5
	B			1002	1110	964	1244	-	1231	1164
530	A	UPC	12[(c)]	249	250	239	286	-	278	244
	B			60.4	63.1	61.4	61.9	-	63.2	62.7
531	A	UPC	9[(c)]	216	196	186	180	-	179	169
	B			-415	-456	-429	-438	-	-427	-416
532	A	UPC	9[(c)]	172	167	193	184	-	181	184
	B[(d)]			-507	-555	-523	-518	-	-533	-560
533	A	UPC	9[(c)]	-282	-278	-258	-261	-261	-261	-260
	B[(e)]			250	261	266	245	242	245	262
534	A	UPC	9[(c)]	-320	-305	-312	-305	-305	-298	-292
	B			231	243	253	255	256	254	247
535	A[(e)]	UPC	9[(c)]	241	248	246	240	254	245	249
	B			-277	-297	-302	-292	-287	-289	-289
536	A	UPC	9[(c)]	281	307	287	261	261	267	281
	B			-324[(f)]	-319	-289	-302	-293	-297	-317
537	A[(c)]	UPC	9[(c)]	-305	-300	-290	-289	-289	-287	-287
	B			320	350	332	322	317	324	331
538	A	LS	9[(c)]	293	294	295	304	300	298	311
	B			-327	-288	-302	-305	-313	-308	-326

Table 1.4-2 (cont'd.) Stable Reactor Period Values for Central Void Reactivity Measurements (Reference 3).

Run Number		Shutdown Method[(a)]	Number Of Mass Adjustment Buttons	Reactor Period (s) from						
				Ion Chambers			Neutron Counters[(b)]			
				A	D	Ln	1 (*BF #1*)	2 (*BF #2*)	3 (*BF #3*)	4 (*TMC*)
539	A	LS	9[(c)]	221	244	233	230	228	228	236
	B			-299	-316	-300	-295	-296	-295	-299
540	A	LS	10	-282	-303	-293	-300	-300	-302[(f)]	-284
	B			242	255	251	248	246	250	227[(f)]
541	A	LS	10	-299	-314	-304	-302	-316	-304	-301
	B			278	233	237	240	234	238	240
542	A	LS	10	254	260	260	241	248	248	286
	B			-286	-276	-258	-284	-283	-281	-291
543	A	LS	10	278	296	304	292	300	285	293
	B			-305	-270	-274	-283	-292	-287	-287
544	A	LS	10	-306	-290	-277	-287	-292	-280	-279
	B			241	291	279	274	270	266	279
545	A	LS	10	303	305	300	289	292	302	298
	B			-276	-290	-286	-280	-281	-278[(f)]	-286
546	A	LS	10	-297	-305	-271	-278	-284	-276	-287
	B			284	301	289	284	302	291	293
547	A	LS	10	300	288	310	302	302	302	302
	B			-265	-299	-297	-279	-292	-284	-287
548	A	LS	10	-282	-299	-305	-291	-295	-292	-288
	B			249	271	279	271	268	272	275
549	A	LS	10	273	280	278	272	272	274	274
	B			-322	-303	-296	-305	-308	-313	-303
550	A	LS	10	-291	-306	-274	-287	-281	-287	-287
	B			273	302	302	292	302	302	291
551	A	LS	10	283	279	282	266	266	276	273
	B			-281	-294	-315	-293	-285	-289	-284
552	A	LS	10	-286	-298	-310	-289	-285	-289	-286
	B			254	285	287	284	276	271	271
553	A	LS	10	279	285	286	284	279	284	278
	B			-286	-295	-281	-285	-287	-286	-288
554	A	LS	10	-310	-299	-304	-292	-289	-289	-286
	B			286	289	291	268	271	268	282
555	A	LS	10	292	300	307	285	285	292	285
	B			-281	-314	-286	-292	-287	-294	-290
556	A	LS	10	-282	-295	-298	-301	-300	-305	-283
	B			273	310	294	300	296	301	296[(f)]
557	A	LS	10	268	276	278	266	266	294	270
	B			-297	-299	-281	-294	-291	-294[(f)]	-287

Table 1.4-2 (cont'd.). Stable Reactor Period Values for Central Void Reactivity Measurements (Reference 3).

Run Number		Shutdown Method[(a)]	Number Of Mass Adjustment Buttons	Reactor Period (s) from						
				Ion Chambers			Neutron Counters[(b)]			
				A	D	Ln	1 (*BF #1*)	2 (*BF #2*)	3 (*BF #3*)	4 (*TMC*)
558	A	LS	10	-296	-299	-280	-296	-301	-296	-297
	B			257	273	268	266	268	262	264
559	A	LS	10	269	279	274	266	263	266	262
	B			-287	-306	-272	-292	-292	-305	-294
560	A	LS	10	-313	-300	-301	-296	-292	-294	-291
	B			221	239	250	242	240	238	241
561	A	LS	10	231	239	248	240	234	237	238
	B			-289	-291	-291	-288	-292	-287	-309
562	A	UPC	10	-282	-300	-297	-294	-294	-288	-292
	B			268	271	279	263[(f)]	262[(f)]	267[(f)]	270
563	A	UPC	10	316	332	339	328	326	320	335
	B			-296	-268	-278	-300	-304	-302	-300
564	A	UPC	10	-282	-296	-305	-294	-297	-297	-295
	B			252	256	259	254	249	249	251
565	A	UPC	10	247	255	250	248	249	249	248
	B			-289	-301	-294	-292	-291	-289	-290
566	A	UPC	10	-282	-296	-291	-284	-291	-292	-293
	B			247	269	274	268	272	270	269
569	A	UPC	10	302	284	304	272	274	266	282
	B			-276	-272	-278	-280	-279[(f)]	-282[(f)]	-277
570	A	UPC	10	-270	-275	-268	-280	-279	-280	-277
	B			277	297	299	291	299	277	279
571	A	UPC	10	286	301	284	270	272	274	275
	B			-272	-285	-290	-306	-309	-310[(f)]	-311
572	A	UPC	10	-263	-271	-265	-280	-277	-274	-276
	B			286	298	302	292	291	293	289

(a) UPC designates that the upper polar cap was raised to disassemble the system. LS designates that the lower section consisting of the lower polar cap and lower plate was removed to disassemble the system.
(b) In Reference 3 the neutron counters are labeled as 1, 2, 3, and 4. When comparing results with the logbook it can be determined which numbers correspond to which detector. The detector names have been included in this table. These numbers do not coincide with the detector numbers given in Figure 1.4-3.
(c) For these measurements a small aluminum reflector (worth a few cents) was present at various distances from the sphere. For all other measurements, this aluminum reflector was removed. Mass adjustment buttons were equally divided between upper and lower polar caps. For an odd number of buttons, the upper polar cap had one more button than the bottom.
(d) Central void region empty.
(e) Central void region filled with uranium metal
(f) *This value varied between Reference 3 and the logbook. The logbook value was used and recorded in this table rather than the Reference 3 value. The incorrect values in Reference 3 are typographical errors mostly associated with the omission of a minus sign. This is supported by the results in Appendix B.*

Table 1.4-3. Worth in Cents (¢) of a 0.460-inch-diameter ^{235}U Sphere in the Center of a 3.4420-inch-average-radius ^{235}U Sphere.[(a)]

Run Date	Run No.	A	D	Ln	TMC	BF_3 No. 1	BF_3 No. 2	BF_3 No. 3	Average Each Run
May 19, 1972	528	9.28	8.77	9.11	9.05	9.19	--	9.19	9.0983
	529	9.50	8.55	8.50	8.65	8.89	--	9.25	8.8900
	530	9.51	9.06	9.16	9.04	9.76	--	9.45	9.3300
	531	8.45	8.58	9.03	9.64	9.10	--	9.25	9.0083
	532	8.89	8.78	8.21	8.27	8.47	--	8.49	8.5183
									8.9690
May 30, 1972	533	9.71	9.64	10.06	10.06	10.30	10.35	10.30	10.0600
	534	9.32	9.37	9.08	9.55	9.18	9.16	9.32	9.2829
	535	9.97	9.44	9.37	9.58	9.67	9.54	9.64	9.6014
	536	8.49	8.27	9.05	8.60	9.14	9.32	9.15	8.8600
	537	8.37	8.18	8.54	8.61	8.66	8.71	8.68	8.5357
									9.2680
June 1, 1972	538	8.29	8.98	8.69	8.10	8.54	8.44	8.55	8.5129
	539	9.87	9.14	9.63	9.60	9.78	9.80	9.82	9.6629
	540	9.84	9.22	9.47	10.07	9.38	9.41	9.32	9.5300
	541	8.96	9.38	9.49	9.43	9.47	9.31	9.47	9.3586
									9.2661
June 26, 1972	542	9.56	9.69	10.15	9.02	9.82	9.73	9.77	9.6771
	543	8.85	9.37	9.19	9.01	9.12	8.83	9.11	9.0671
	544	9.38	8.98	9.41	9.37	9.25	9.21	9.51	9.3014
	545	9.14	8.82	8.95	8.98	9.21	9.16	9.11	9.0529
	546	8.92	8.57	9.42	9.01	9.32	8.98	9.29	9.0729
									9.2343
June 28, 1972	547	9.44	8.84	8.62	8.91	9.09	8.81	8.98	8.9557
	548	9.75	9.06	8.84	9.22	9.12	9.18	9.18	9.1929
	549	8.63	8.87	9.02	8.94	8.93	8.87	8.76	8.8600
	550	9.19	8.54	9.20	9.04	9.03	9.04	8.91	8.9929
									9.0004

Table 1.4-3 (cont'd.). Worth in Cents (¢) of a 0.460-inch-diameter ^{235}U Sphere in the Center of a 3.4420-inch-average-radius ^{235}U Sphere.[(a)]

Run Date	Run No.	A	D	Ln	TMC	BF_3 No. 1	BF_3 No. 2	BF_3 No. 3	Average Each Run
July 26, 1972	551	9.27	9.05	8.62	9.34	9.24	9.40	9.19	9.1586
	552	9.56	8.89	8.65	9.32	9.08	9.27	9.26	9.1471
	553	9.21	8.95	9.23	9.18	9.16	9.19	9.14	9.1514
	554	8.90	8.82	8.71	9.17	9.24	9.26	9.30	9.0571
									9.1286
July 28, 1972	555	9.16	8.42	8.88	9.05	9.01	9.11	8.89	8.9314
	556	9.38	8.66	8.78	9.07	8.65	8.72	8.57	8.8329
	557	9.14	8.99	9.33	9.31	9.22	9.28	8.87	9.1629
	558	9.32	9.03	9.49	9.19	9.18	9.06	9.24	9.2157
									9.0357
July 31, 1972	559	9.32	8.82	9.59	9.28	9.26	9.31	9.01	9.2271
	560	9.62	9.52	9.34	9.67	9.55	9.67	9.66	9.5757
	561	9.79	9.70	9.56	9.38	9.75	9.79	9.82	9.6843
	562	9.45	9.04	8.99	9.21	9.25	9.28	9.33	9.2214
									9.4272
August 1, 1972	563	8.58	9.04	8.74	8.31	8.38	8.33	8.42	8.5429
	564	9.68	9.33	9.12	9.43	9.40	9.44	9.44	9.4057
	565	9.61	9.25	9.48	9.58	9.54	9.56	9.60	9.5171
	566	9.76	9.14	9.17	9.20	9.41	9.18	9.21	9.2957
									9.1904
August 10, 1972	569	9.15	9.46	9.09	9.37	9.43	9.43	9.47	9.3429
	570	9.60	9.24	9.38	9.41	9.19	9.12	9.36	9.3286
	571	9.44	8.96	9.06	8.78	8.94	8.86	8.81	8.9786
	572	9.66	9.32	9.42	9.30	9.18	9.26	9.30	9.3486
									9.2497

(a) This table is recreated from a printed table provided by the experimenter. All averages and notes were provided by the experimenter.

Table 1.4-4. Stable Reactor Period and Worth in Cents (¢) for Four 1/8-inch Uranium Buttons on Surface of the Sphere.[(a)]

Run No.	Configuration	TMC		Log N		BF_3 No. 1		BF_3 No. 3		Temp. °C
		sec	cents	sec	cents	sec	cents	sec	cents	
203	Base	-528	-2.60	-429	-3.26	-599.3	-2.27	-584.2	-2.33	25.9
204	+ 4 U	278	4.08	297	3.84	275.7	4.11	277.5	4.08	25.8
	Worth		6.68		7.10		6.38		6.41	
205	Base	-702	-1.92	-685	-1.97	-661.9	-2.04	-659.2	-2.05	25.8
206	+ 4 U	306	3.74	305	3.75	301.7	3.79	301.7	3.79	25.2
	Worth		5.66		5.72		5.83		5.84	
207	Base	-657	-2.06	-674	-2.00	-644.9	-2.10	-641.0	-2.11	25.1
208	+ 4 U	292	3.90	269	4.20	266.3	4.24	265.2	4.26	25.0
	Worth		5.96		6.20		6.34		6.37	
209	Base	-730	-1.66	-728	-1.67	-674.9	-1.79	-687.9	-1.76	25.0
210	+ 4 U	275	4.11	286	3.98	273.6	4.14	273.6	4.14	24.8
	Worth		5.77		5.65		5.93		5.90	
211	Base	-672	-2.01	-648	-2.09	-660.5	-2.05	-667.1	-2.02	24.6
212	+ 4 U	274	4.13	262	4.30	266.3	4.24	265.8	4.25	24.8
	Worth		6.14		6.39		6.29		6.27	
	GRAND AVG. WORTH:		6.04		6.21		6.15		6.16	
	Holding screws not involved[(b)]							Average=		6.1415 ± 0.0834[(c)]
	Uranium button dimensions - 0.125" X 0.875"			22 gm each						

(a) This table is recreated from a printed table provided by the experimenter. All averages and notes were provided by the experimenter.
(b) In the logbook it clear that the base case has 12, 1/8-inch/thick buttons with screws for four other buttons. Four buttons were then added to the sphere, thus filling the 16 available spaces. This method allowed the worth of 4 buttons to be measured without including the worth of the screws.
(c) Standard deviation of the mean.

Table 1.4-5. Stable Reactor Period and Worth in Cents (¢) for one 1/8-inch-thick Aluminum Buttons on the Surface of the Sphere.[(a)]

Run No.	Configuration	TMC		Log N		BF_3 No. 1		BF_3 No. 2		BF_3 No. 3		Temp. °C
		sec	cents	sec	cents	sec	cents	sec	cents	sec	cents	
236	Base[1]	-481	-2.88	-445	-3.14	-485	-2.85	-463	-3.00	-477	-2.91	24.8
237	+ 4 Al	-27740	≅∞	∞	∞	150000	≅∞	∞	∞	∞	∞	24.9
	Worth per button		0.7200		0.7850		0.7125		0.7500		0.7275	
238	Base[2]	-1371	-0.96	-1082	-1.22	-1281	-1.03	-1325	-0.99	-1333	-1.00	25.0
239	+ 3 Al	1085	1.13	960	1.28	1082	114.00	1065	1.16	1030	1.19	25.0
	Worth per button		0.6967		0.8333		0.7233		0.7167		0.7300	
240	Base[2]	1192	1.04	1264	0.98	1264	0.98	1281	1.05	1212	1.02	24.8
241	+ 3 Al	-1408	-0.93	-1362	-0.96	-1508	-0.86	-1436	-0.81	-1468	-0.88	24.8
	Worth per button		0.6566		0.6467		0.6133		0.6200		0.6333	
242	Base[2]	--	--	-1194	-1.10	-1532	-0.85	-1567	-0.83	-1532	-0.85	24.7
243	+ 3 Al	1054	1.17	1295	0.96	1089	1.13	996	1.24	978	1.26	24.8
	Worth per button				0.6867		0.6600		0.6900		0.7033	
244	Base[2]	1026	1.19	945	1.29	996	1.24	996	1.24	952	1.29	24.7
245	+ 3 Al	-1406	-0.93	-1352	-0.97	-1435	-0.91	-1437	-0.91	-1411	-0.93	24.6
	Worth per button		0.7067		0.7533		0.7167		0.7167		0.7400	
GRAND AVG. WORTH per button			0.6950		0.7410		0.6852		0.6987		0.7068	
	Note 1:	There were 12 U-Buttons on Sphere surface (i.e., 4 A1 buttons measured).							Average=		0.7058 ± 0.00198[(b)]	
	Note 2:	There were 13 U-Buttons on Sphere surface (i.e., 3 A1 buttons measured).										

(a) This table is recreated from a printed table provided by the experimenter. All averages and notes were provided by the experimenter.
(b) Standard deviation of the mean.

Table 1.4-6. Stable Reactor Period and Worth in Cents (¢) for Three 1/8-inch-thick Uranium Buttons in Empty Socket Hole.[(a)]

Run No.	Configuration	TMC		Log N		BF_3 No. 1		BF_3 No. 2		BF_3 No. 3		Temp. °C
		sec	cents	sec	cents	sec	cents	sec	cents	sec	cents	
247A	Base	571	2.10	541	2.21	--	--	--	--	--	--	25.6
247B	- 3U	-261	-5.77	-257	-5.87	--	--	--	--	--	--	25.5
	Worth		7.87		8.08		--		--		--	
248A	Base	601	2.03	613	1.97	558	2.15	581	2.07	588	-2.05	25.5
248B	- 3U	-259	-5.82	-275	-5.42	-265	-5.66	-260	-5.79	-259	-5.82	25.5
	Worth		7.85		7.39		7.81		7.86		7.87	
249A	Base	580	-2.07	613	1.97	607	1.99	581	2.07	618	1.95	25.4
249B	- 3U	-260	-5.79	-260	-5.79	-252	-6.01	-250	-6.06	-251	-6.05	25.0
	Worth		7.86		7.76		8.00		8.13		8.00	
250A	Base	621	1.94	623	1.94	582	2.07	584	2.06	580	2.07	25.3
250B	- 3U	-261	-5.77	-260	-5.79		--		--		--	25.1
	Worth		7.71		7.73		--		--		--	
251A	Base	605	1.99	580	2.07	589	2.04	567	2.12	592	2.03	25.1
251B	- 3U	-259	-5.82	-266	-5.64	-258	-5.85	-254	-5.96	-256	-5.90	24.9
	Worth		7.81		7.71		7.89		8.08		7.93	
	GRAND AVG. WORTH:		7.82		7.73		7.90		8.02		7.93	
Note:	Base Conf. = Top Socket out, ℄ Pin in. 13 (1/8 in.) and 1 (1/16 in.) Uranium Buttons on surface Al shim @ 3/8 in. from the sphere 3 (1/8 in.) Uranium Buttons in Socket Hole									Average=	7.860 ± 0.0091[(b)]	

(a) This table is recreated from a printed table provided by the experimenter. All averages and notes were provided by the experimenter.
(b) Standard deviation of the mean.

Table 1.4-7. Stable Reactor Period and Worth in Cents (¢) for Three 1/8-inch-thick Aluminum Buttons in Empty Socket Hole.[(a)]

Run No.	Configuration	TMC		Log N		BF_3 No. 1		BF_3 No. 2		BF_3 No. 3		Temp. °C
		sec	cents	sec	cents	sec	cents	sec	cents	sec	cents	
252A	Base	-600	-2.27	-564	-2.42	-614	-2.21	-605	-2.25	-615	-2.21	25.4
252B	- 3 Al	-269	-5.56	-274	-5.44	-276	-5.40	-278	-5.35	-271	-5.51	25.5
	Worth		3.29		3.02		3.19		3.10		3.30	
253A	Base	-588	-2.32	-501	-2.75	-589	-2.31	-591	-2.31	-602	-2.61	25.3
253B	- 3 Al	-272	-5.49	-270	-5.38	-276	-5.40	-264	-5.69	-264	-5.69	25.2
	Worth		3.17		2.63		3.09		3.38		3.08	
254A	Base	-569	-2.40	-575	-2.38	-555	-2.47	-555	-2.47	-584	-2.34	25.0
254B	- 3 Al	-272	-5.49	-268	-5.59	--	--	-270	-5.53	-270	-5.53	25.0
	Worth		3.09		3.21		--		3.06		3.19	
255A	Base	-576	-2.37	-550	-2.49	--	--	-542	-2.53	-540	-2.54	25.3
255B	- 3 Al	-260	-5.79	-265	-5.66	--	--	-270	-5.53	-264	-5.68	25.3
	Worth		3.42		3.17		--		3.00		3.14	
256A	Base	-573	-2.38	-573	-2.38	--	--	-547	-2.51	-573	-2.38	25.2
256B	- 3 Al	-274	-5.44	-275	-5.42	--	--	-276	-5.40	-266	-5.63	25.0
	Worth		3.06		3.04		--		2.89		3.25	
	GRAND AVG. WORTH		3.21		3.01		3.14		3.09		3.19	
Note:	Base Configuration:	Top Socket Out, ℄ Pin in, 15 (1/8) ^{235}U-Buttons on Surface Al Shim @ 5/8 in., °C Measured between U-Button and Sphere Surface 3 (1/8 in.) Aluminum Button in Socket Hole.								Average=	3.1259 ± .0078[(b)]	

(a) This table is recreated from a printed table provided by the experimenter. All averages and notes were provided by the experimenter.
(b) Standard deviation of the mean.

Table 1.4-8. Stable Reactor Period and Worth in Cents (¢) for Three 1/8-inch-thick Stainless Steel Buttons in the Empty Socket Hole.[(a)]

Run No.	CONF.	TMC		Log N		BF_3 No. 1		BF_3 No. 2		BF_3 No. 3		Temp. °C
		sec	cents	sec	cents	sec	cents	sec	cents	sec	cents	
257A	Base	338	3.42	346	3.35	347	3.34	344	3.36	341	3.39	25.0
257B	- 3 SS	-964	-1.28	-855	-1.56	-900	-1.48	-844	-1.58	-961	-1.38	25.0
	Worth		4.70		4.91		4.82		4.94		4.77	
258A	Base	369	3.15	391	2.99	352	3.30	358	3.25	357	3.25	24.9
258B	- 3 SS	-925	-1.44	-800	-1.67	-944	-1.41	-952	-1.40	-944	-1.41	25.0
	Worth		4.59		4.66		4.71		4.65		4.66	
259A	Base	350	3.31	302	3.79	362	3.21	360	3.23	365	3.19	25.0
259B	- 3 SS	-717	-1.88	-870	-1.52	-889	-1.50	-902	-1.47	-960	-1.38	25.0
	Worth		5.19		5.31		4.71		4.70		4.57	
260A	Base	370	3.15	371	3.14	365	3.18	365	3.18	367	3.17	24.9
260B	- 3 SS	-921	-1.44	-702	-1.92	-937	-1.42	-943	-1.41	-982	-1.35	24.8
	Worth		4.59		5.06		4.60		4.59		4.52	
261A	Base	368	3.16	363	3.20	353	3.29	365	3.18	371	3.14	24.8
261B	- 3 SS	-986	-1.35	-931	-1.42	-1010	-1.30	-928	-1.43	-983	-1.35	24.7
	Worth		4.51		4.62		4.59		4.61		4.49	
	GRAND AVG. WORTH		4.72		4.91		4.69		4.70		4.60	
Note:	Base Conf:	Top Socket Out, ℄ Pin in, 16 (1/8) ^{235}U-Buttons on Surface Al Shim @ 1/4 in. from sphere surface 3 (1/8) Stainless Steel Buttons in Socket Hole.							Average=	4.7228 ± 0.0084[(b)]		

(a) This table is recreated from a printed table provided by the experimenter. All averages and notes were provided by the experimenter.
(b) Standard deviation of the mean.

Table 1.4-9. Stable Reactor Period and Reactivity Worth in Cents (¢) for The Diametral Filler Rod.[a]

Run No.	CONF.	TMC		Log N		BF_3 No. 1		BF_3 No. 2		BF_3 No. 3		Temp. °C
		sec	cents	sec	cents	sec	cents	sec	cents	sec	cents	
216	Base	-214	-7.36	-229	-6.76	-216	-7.28	-215.0	-7.32	-214	-7.36	25.9
217	+ Diametral Rod	291	3.92	286	3.98	282.7	4.02	280.1	4.05	278.7	4.07	25.5
	Worth		11.28		10.74		11.30		11.37		11.43	
218	Base	-220	-7.11	-231	-6.69	-224.1	-6.91	-221.5	-7.05	-221.8	-7.03	25.4
219	+ Diametral Rod	290	3.93	284	4.01	272.3	4.01	267.1	4.23	281.4	4.03	25.3
	Worth		11.04		10.70		10.92		11.28		11.06	
220	Base	-229	-6.76	-223	-6.99	-209.8	-7.55	-212.4	-7.43	-229.3	-6.75	25.1
221	+ Diametral Rod	280	4.05	287	3.96	286.6	3.97	289.2	3.94	278.8	4.07	24.9
	Worth		10.81		10.95		11.53		11.37		10.82	
222	Base	-215	-7.32	-214	-7.36	-207.2	-7.68	-206.5	-7.70	-209.1	-7.58	25.0
223	+ Diametral Rod	261	4.32	272	4.16	267.9	4.22	274.1	4.13	L271.2	4.17	25.0
	Worth		11.64		11.52		11.90		11.83		11.75	
224	Base	-224	-6.95	-235	-6.55	-222.8	-7.00	-218.6	-7.17	-217.6	-7.20	25.0
225	+ Diametral Rod	263	4.29	284	4.01	271.5	4.16	273.4	4.14	273.1	4.15	25.0
	Worth		11.24		10.56		11.16		11.31		11.35	
	GRAND AVG. WORTH		11.20		10.89		11.36		11.43		11.28	
										Average=	11.2340 ± .0717[b]	

(a) This table is recreated from a printed table provided by the experimenter. All averages and notes were provided by the experimenter.
(b) Standard deviation of the mean.

All measured reactivity worths are summarized in Table 1.4-10.

Table 1.4-10. Summary of Measured Reactivity Worths.

	Measured Worth with Standard Deviation(¢)
Central Void	9.165 ± 0.023
Sixteen, 0.635-cm-thick Uranium Buttons on Sphere Surface	From -23 ¢ to +12.4 ¢
Four, 0.3175-cm-thick Uranium Buttons on Sphere Surface	6.1415 ± 0.0834
One, 0.3175-cm-thick Aluminum Button on Sphere Surface	0.7058 ± 0.0104
Three, 0.3175-cm-thick Uranium Buttons in Socket Hole	7.86 ± 0.04
Three, 0.3175-cm-thick Stainless Steel Buttons in Socket Hole	4.7228 ± 0.0420
Three, 0.3175-cm-thick Aluminum Buttons in Socket Hole	3.1259 ± 0.0358
Diametral Filler Rod	11.2340 ± 0.0717

1.4.3 Material Data

The materials for the sphere are given in Section 1.3 of HEU-MET-FAST-100.

The small sphere and plug for the central void reactivity measurement was made such that the material was identical to the surrounding sphere. Impurity, isotopic composition or density data was not provided for the small sphere and plug. An isotopic composition for the "plugs for 0.500-in-diam holes" was given in Reference 2 and is presented in Table 1.4-11. It is not known if this isotopic composition applies to the plug in the 0.504-inch-diameter surface hole. However, the experimenter has access to month isotopic composition averages for the Y-12 plant. "The material used for the central worth measurements was fabricated in April 1972." The corresponding isotopic composition would be:[a]

^{234}U	0.985 wt.%
^{235}U	93.161 wt.%
^{236}U	0.442 wt.%
^{238}U	5.412 wt.%

The isotopic composition and impurity data for the uranium mass adjustment buttons is given in Reference 1 and presented in Table 1.4-11 and Table 1.4-12. The isotopic composition but not impurity data were given in Reference 1 for the diametral filler rods, see Table 1.4-11.

According to the experimenter, the aluminum buttons were aluminum Type 6061 and the steel buttons were stainless steel Type 304.[b] The screws used to hold the buttons in place were stainless steel Type 304.[c]

[a] Personal email communication with J.T. Mihalczo, September 6 and 10, 2013.
[b] Personal email communication with J.T. Mihalczo, August 13, 2013.
[c] Personal communication with J.T. Mihalczo, October 8, 2013.

Table 1.4-11. Isotopic Content of Uranium Metal Parts
(Reference 1 and 2, 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	93.20 [(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	0.9860	93.171	0.424	5.4190
Pins for lower part	0.9954	93.156	0.451	5.3976
Plugs for 0.500-in.-diam. holes (Ref. 2)[(b,c)]	0.988	93.164	0.4460	5.4020
Split Plugs (Ref. 2)[(c)]	0.985	93.154	0.460	5.3880
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 isotopic compositions were from the average monthly isotopic compositions 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 isotopic compositions 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 isotopic composition calculation could not be reproduced because the weight of the target hole filler and pins was not given.)*

(b) Measured and documented values. *Written as "*Measured and reported out,*" in Reference 2.*

(c) *The following is footnote (c) in Reference 2 although a reference to footnote (c) does not appear anywhere in the table. It is believed that it applies to the lines for the plugs for the 0.500-inch-diameter holes and the split plugs.*
Solid plugs were provided to fill all holes. Split filler plugs with inside diameters of 0.082 and 0.136 were provided to fit around the shafts of the various detectors and sources inserted into the 0.500 radial and 0.375-in.-diam surface holes.

Table 1.4-12. Impurity Content of Enriched Uranium Sphere Parts
(Reference 1 additions by the evaluator are *italic*).

ORNL Part #	Part Description	Gram U per gram of uranium metal[(a)] x100	Impurity Content (ppm) [(c,d)] 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. *This is the uranium weight fraction in the ORALLOY.*
(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.
(d) *Reference 1 gives an average impurity content 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.*

1.4.4 Temperature Data

Dimensional measurements of all parts were performed at the Y-12 plant at 70 ^oF (21.1 ^oC). Reference 1 gives the experimental temperature as 24.5 ^oC (76 ^oF). However in Table 1.4-4 through Table 1.4-9 various variable experimental temperatures are given.

The temperature coefficient for the ORSphere should be the same as the measured coefficient of about 1/3 ¢ per degree centigrade for GODIVA I,[a] as is typically used for other ORCEF bare HEU (ORALLOY) experiments.[b]

[a] R.E. Peterson and G.A. Newby, "An unreflected U-235 Critical Assembly," *Nucl. Sci. and Eng.*, **1**, 112-125 (1956).
[b] Personal email communication with J.T. Mihalczo, March 11, 2013

1.4.5 Additional Information Relevant to Reactivity Effects Measurements

Additional information was not identified.

1.5 Description of Reactivity Coefficient Measurements

1.5.1 Overview of Experiment

The reactivity per gram of surface material was evaluated using the change in reactivity between the 3.4665-inch-average-radius sphere and the 3.4420-inch-average-radius sphere.

1.5.2 Geometry of the Experiment Configuration and Measurement Procedure

The geometry of the 3.4665-inch- and 3.4420-inch-average radius spheres are described in Section 1.2 of HEU-MET-FAST-100.[a] The system reactivity for the larger sphere was 68.1 ± 2.0 ¢ and the smaller sphere had a worth of -23.4 ¢.[b] This 91.5 ¢ change in reactivity divided by the 1125 g of surface material which was removed yields a reactivity coefficient for surface material of 0.081 ± 0.001 ¢ per gram ORALLOY surface material.[c] However, this value has not been corrected to account for the tilt between the lower and center plate of the larger diameter sphere that is not present for the smaller diameter sphere.[d] The gap between the plates was 0.0045 inches on one side and zero on the other yielding an average gap of 2.25×10^{-3}inches. "Using a measured reactivity worth of the gap of 2.2 ± 0.1 cents per thousandths of an inch, this correction is 5.0 ± 0.2 cents and the resulting excess reactivity of the system corrected to no gap between the lower and central section is 73.1 ± 2.0 cents" (Reference 1).

1.5.3 Material Data

The material data for the sphere are given in Section 1.3 of HEU-MET-FAST-100.

1.5.4 Temperature Data

The temperature data for the sphere are given in Section 1.4 of HEU-MET-FAST-100.

1.5.5 Additional Information Relevant to Reactivity Coefficient Measurements

Additional information was not identified.

1.6 Description of Kinetics Measurements

1.6.1 Overview of Experiment

The effective delayed neutron fraction, β_{eff}, for the ORSphere was measured using time correlation measurements with californium-252 (Reference 5). It was also determined as the ratio of measured and calculated central void reactivities (Reference 3 and 4).

The prompt neutron decay constant for the ORSphere was determined using hundreds of Rossi-α and randomly pulsed neutron measurements with californium-252 (Reference 6 and 7).

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[a] International Handbook of Evaluated Criticality Safety Benchmark Experiments, NEA/NSC/DOC(95)03, OECD-NEA, Paris (2013).

[b] Reference 1 gives a reactivity of -23 ¢. The logbook, gives an average reactivity of -23.4 ¢.

[c] These values are rounded in Reference 1. In HEU-MET-FAST-100 the exact values are 91.1 ¢ reactivity change and 1125.04 g mass difference. The reactivity coefficient still rounds to 0.081 ¢/g ORALLOY surface material.

[d] Personal communication with J.T Mihalczo, September 3, 2013.

1.6.2 Geometry of the Experiment Configuration and Measurement Procedure

The kinetic parameter measurements were performed using the 3.4425-inch-nominal-radius/3.4420-inch-average-radius sphere. The central plate was machined as shown in Figure 1.6-2 to allow for necessary fission sources and detectors.

1.6.2.1 Delayed Neutron Fraction

The effective delayed neutron fraction was measured using a time correlation randomly pulsed neutron measurement and a Rossi-α measurement; this method has been shown to be incorrect and is briefly described here to preserve all experimental measurements.[a] The experimental setup is shown in Figure 1.6-1 and the geometry of the sphere is shown in Figure 1.6-2. More detailed descriptions of the geometry and the methods are given in Reference 5.The resulting β_{eff} value was 0.00602 ± 0.00008 which is much lower than the β_{eff} value from the central void reactivity measurements (0.00657 ± 0.00002, see end of Section 1.6.2.1) and the β_{eff} value measured for GODIVA I (0.0066). Reference 5 attributes the low value to possible "improper theoretical formulation for correcting point kinetics for spatial effects." The experimenter has stated that this value is clearly wrong and should not be used.[b]

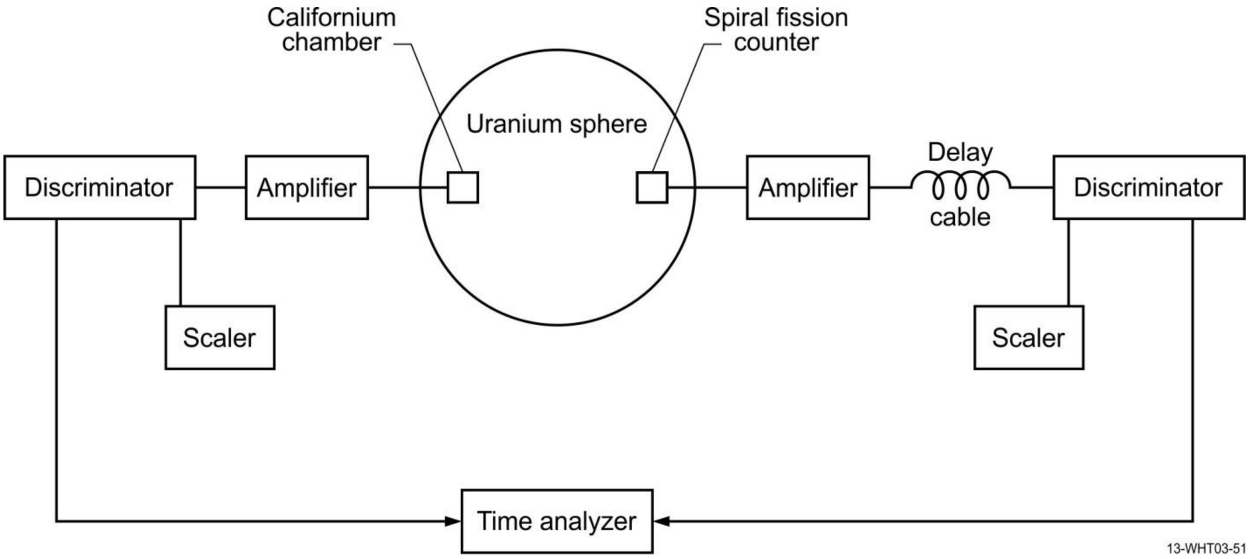

Figure 1.6-1. Block Diagram of Instrumentation for Time Correlation Measurements (Reference 5).

[a] "The theory for the analysis is not correct and gave an impossible value of the delayed neutron fraction which should not be used for even a reference. It was published to see if some bright theorist could come up with a better interpretation. Beta effective was 10% lower than beta which is impossible. Similar unpublished measurements for JEZEBEL and FLATOP with a Pu core and FLATTOP with a uranium core were also 10 % too low which is impossible!" Personal communication with J.T. Mihalczo, September 3, 2013.

[b] Personal email communication with J.T. Mihalczo, July 15, 2013.

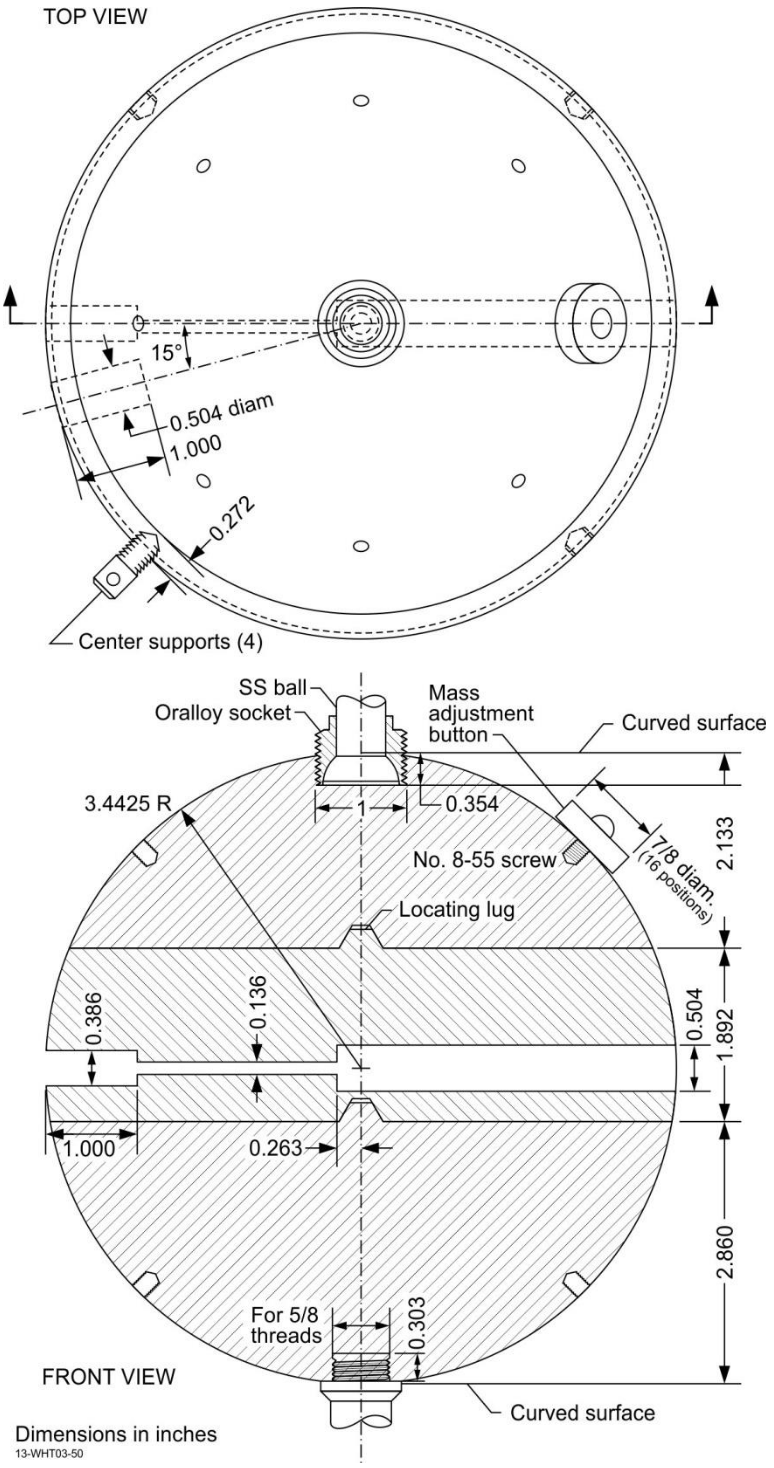

Figure 1.6-2. Sphere Geometry Time Correlation Measurements (Reference 5 and 7).

The effective delayed neutron fraction for the ORSphere was also determined using the central void reactivity. As described in Section 1.4, the reactivity was measured using the stable reactor period in units of dollars. The void worth was calculated in units of Δk using S_n transport theory, extrapolated to infinite order S_n, with a precision of at least 10^{-7} Δk. ONEDANT and XSDRNPM codes with Hansen-Roach and ENDF/B-VI cross section libraries were used. The average reactivity of the central void was $6.02 \pm 0.01 \times 10^{-4}$ Δk. According to Reference 3 this uncertainty "essentially includes all the variation in these calculated values (this choice is somewhat arbitrary but conservative)". This calculation is discussed in more depth in Reference 3 and 4. The ratio of the measured worth in dollars and the calculated worth in Δk yields the effective delayed neutron fraction, $\beta_{eff} = \rho(\Delta k)/\rho(\$)$. The resulting

β_{eff} value was 0.00657 ± 0.00002. This derived value agrees well with the delayed neutron fraction measured with GODIVA I (0.0066).

1.6.2.2 Prompt Neutron Decay Constant

Measurements of the prompt neutron decay constant, α, were performed in 1971, 1972, and 1975, but final results were not published until 2011 by the experimenter, J.T. Mihaclzo in Reference 6. The results were not originally published because the "neutron decay constant obtained by fitting the time decay for a single measurement had a larger uncertainty than previous measurements." The experimenter published the results many years later when it was realized that because of the large number of measurements the prompt neutron decay constant could be accurately obtained from measurements if the average for all measurements were used. Reference 6 and 7 both discuss this measurement. Reference 6 is a more recent re-analyzing of the experiment data using more data points. It also provides more detail and is thus considered the main reference.[a] All information and quotes regarding the prompt neutron decay constant measurements are taken from Reference 6 unless noted otherwise.

Rossi-α and randomly pulsed neutron measurements were performed to measure the prompt neutron decay constant. A ^{252}Cf source was used for the measurements. Less than 0.15 μg of ^{252}Cf "was electroplated on one electrode of a parallel plate or annular ionization chamber, and thus served as a time-tagged source of fission neutrons. There were three californium ionization chambers with spontaneous fission rates of ~25,000 to 86,000 fissions per second. One was a 0.5×0.5-inch-diameter right circular cylinder; one was a 0.375-inch-diameter, 0.5-inch-high cylindrical chamber; and the other has a diameter of 1.00 inch and a height of 1.00 inch". See Table 1.6-1 for more details for the chambers and for assigned chamber numbers. The 0.5-inch-diameter source ionization chambers had a 0.125-inch-diameter shaft to contain the voltage/signal cables. "The 0.375-inch-diameter source ionization chamber had a large-diameter shaft (0.25 inch)" for the same purpose.

The ORSphere had "two 1-inch-deep reentrant holes at the surface, one machined for a 0.5-inch-outside diameter, 0.5-inch-long chamber and one for the 0.375-inch-outside diameter, 1.0-inch-long chamber." These reentrant holes are shown in Figure 1.4-1 and Figure 1.6-2. The 1.000-inch-deep, 0.504-inch-diameter reentrant hole was called a surface hole (SH) and the other 1.000-inch deep reentrant hole was called the 0.386-inch-diameter portion of the diametric hole (DH). Split fissile plugs, which were uranium metal annuli split down the center-line of the sphere, of various lengths were used around the shafts of the detectors when they were interior to the sphere to reduce the amount of void introduced into the sphere.

A spiral fission counter (SFC) built by J. C. Hogterp of Los Alamos National Laboratory was used for neutron detection. The fission counter had 63.8 mg of ~93 wt.% ^{235}U metal and was a 0.5-inch-diameter, 0.5-inch-high right circular cylindrical counter with a 0.125-inch-diameter shaft. Split plugs were also used around the shaft of the SFC when they were inside the sphere.

The SFC, for single input, or a ^{252}Cf ionization chamber and the SFC, for double input, could be connected to the two-channel, shift-register time analyzer, made available by John Orndoff of Los Alamos National Laboratory. The analyzer "had 19 time bins with selectable width as short as 0.25 μs." The time analyzer is described in more detail in Section 2 of Reference 6.

When the prompt neutron decay constant measurements were performed the center plate geometry was the same as the geometry shown in Figure 1.4-1 and Figure 1.6-2. The geometries of all other sphere plates were the same as those given for the critical assembly sphere in HEU-MET-FAST-100. To achieve the desired reactivity, up to 16 mass adjustment buttons and a 70-g aluminum reflector worth approximately 2 ¢, which was remotely positioned, were used. The system was kept as close to exactly delayed critical as possible using a variable number of uranium buttons. For each measurement there were "at least two (usually more) verifications of delayed criticality each day" (Reference 7). In the logbook the system reactivity checks ranged from approximately -0.5 ¢ to +0.5 ¢.

[a] Personal email communication with J.T. Mihalczo, April 1, 2014.

A number of Rossi-α and randomly pulsed neutron experiments were performed at delayed critical. The placement of the ^{252}Cf source and the SFC varied between measurements. "[The] two different Cf sources could be located either at the surface of the sphere in holes especially sized to hold the two different diameter sources or at various radial locations in the diametral hole (DH) of the sphere, including the center. The spiral fission chamber detector was also located at different radii, including the center. The SFC also fit in the surface hole (SH) for the 0.5-inch-diameter Cf sources." The SFC and the ionization chambers were usually placed at opposite ends of the sphere so as much uranium was between the two as possible. Plugs were used so that as little void was introduced to the volume of the sphere as possible; this was done by filling unused holes with tight fitting plugs and using the split plugs around the shafts of the detectors and source ionization chambers.

Additionally, a "limited [number of] measurements were performed with NaI and ^{6}Li glass scintillation detectors adjacent to the surface of the sphere." These measurements are discussed further in Reference 6 but only limited details regarding the scintillators were given.

For the Rossi-α measurements the sphere was assembled continuously and for the randomly pulsed neutron measurements the sphere was typically cycled 25 times per prompt neutron decay measurements between assembled and disassembled "to reduce the background from fission chains initiated by delayed neutrons from previous fission that produced counts not correlated with the latest californium source fission." Runs were performed such that the random pulsed neutron measurements and Rossi-α measurements were back-to-back. An example of the plotted data is shown in Figure 1.6-3.

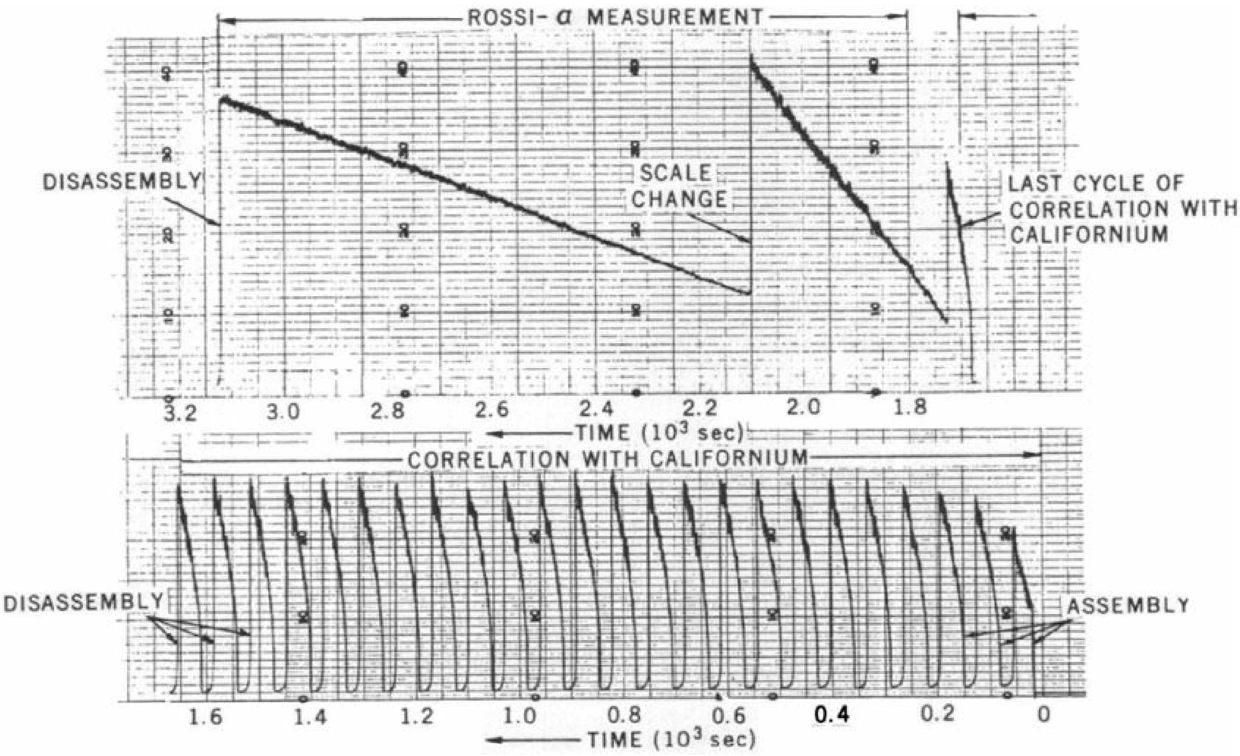

Figure 1.6-3. Fission Rate during Randomly Pulsed Neutron and Rossi-α Measurements.
(Note the time starts at zero at the bottom right of the randomly pulsed neutron measurements and increases until ~3125 s at the top left of the Rossi-α measurement.)

"The data from both types of measurements were fitted by nonlinear least-squares method to the function $D + E\exp(-\alpha t)$ to determine the prompt neutron decay constant (α) with the value of D fixed and obtained appropriately from the average count rate, the detected Cf fission rate, and the width of the time bins." Measured values were averaged using a variance weighted average. "All measurements were included in the average even though some were more than 3σ away from the average. Since these usually had larger statistical uncertainty, they did not significantly affect the average value." For more information regarding the derivation of the prompt neutron decay constant see Reference 6. An example of typical count results is shown in Figure 1.6-4 and average results are summarized in Table 1.6-1.

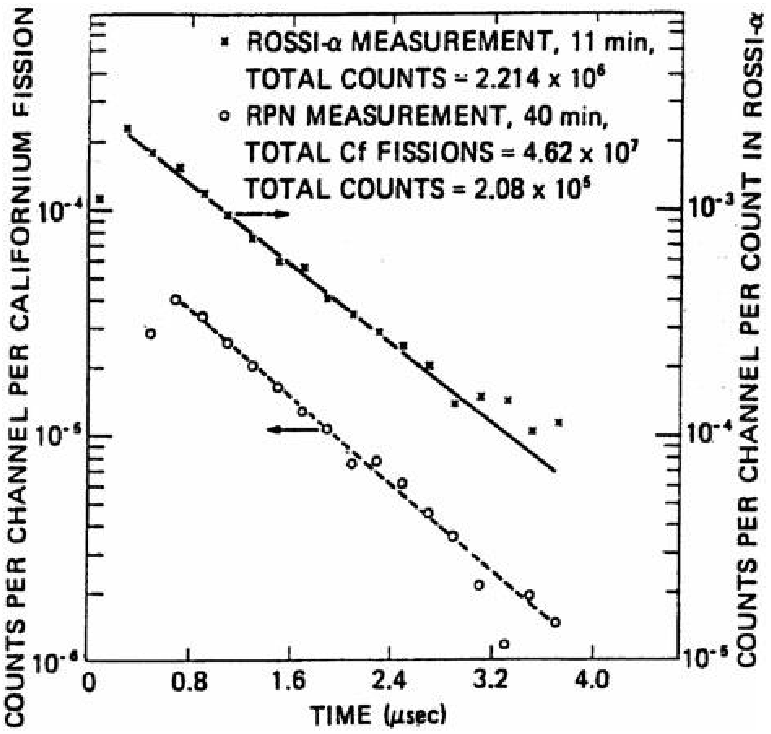

Figure 1.6-4. Typical Results of Rossi-α and Randomly Pulsed Neutron Measurements.

Table 1.6-1. Average of Prompt Neutron Decay Constant Measurements (Reference 6).

Cf Chamber[(a)]			Spiral Fission Chamber[(b)]		Prompt Neutron Decay Constant (μs^{-1})			
Number	Location	Radius (inch)	Location	Radius (inch)	Rossi-Alpha	Randomly Pulsed Neutron	All Values[(c)]	
59	DH	2.717	DH	1.678	1.1172 ± 0.0035	1.1089 ± 0.0050	1.1145 ± 0.0028	(107)
59	DH	2.717	DH	0	1.1061 ± 0.0016	1.1157 ± 0.0030	1.1082 ± 0.0014	(152)
2	Surface	3.512	DH	0	1.1075 ± 0.0022	1.1226 ± 0.0070	1.1089 ± 0.0021	(81)
61	DH	0.102	SH	2.693	1.1476 ± 0.0097	0.9478 ± 0.0880	1.1451 ± 0.0097	(14)
61	DH	1.78	SH	2.693	1.0965 ± 0.0059	1.0817 ± 0.0077	1.0919 ± 0.004	(44)
61	DH	2.472	DH	0	1.0907 ± 0.0027	1.0925 ± 0.0046	1.0904 ± 0.0024	(94)
61	DH	0.012	Scintillator at surface[(d)]		1.1046 ± 0.0075	1.1102 ± 0.0066	1.1078 ± 0.005	(46)
Average of All Values							1.1061 ± 0.0009	(538)

(a) Chamber 61 (0.500-inch-diameter; 8.6×10^4 fissions/second) could be at any radius in the DH and in the 0.504-inch-diameter SH. Chamber 59 (0.375-inch-diameter; 2.6×10^4 fissions/second) could be located only at one end of the DH, and chamber 2 (1.000-inch-diameter; 5.6×10^4 fissions/second) only adjacent to the outer surface. The radial location given in the location of the Cf deposit in the ionization chamber.
(b) The 0.50-inch-diameter, 0.500-inch-long SFC could be placed at any radius in the diametral hole or in the 0.5-in.-diameter SH. The radial location given is for the center of the SFC.
(c) The values in parentheses are the numbers of both types of measurements that were performed.
(d) The scintillator was adjacent to the outer surface of the sphere. The scintillators were shielded with 0.25-inch-thick lead, and this lead shielding actually was in contact with the sphere surface.

The average of all measurements of the prompt neutron decay constant is 1.1061 ± 0.0009 μs^{-1}.

1.6.2.3 Mean Neutron Generation Time

The mean neutron generation time, Λ, was not reported by the experimenter, but it can be derived from the independently measured delayed neutron fraction, β_{eff}, and the prompt neutron decay constant, α, see Section 2.6.3.

1.6.3 Material Data

The uranium metal of the sphere is described for the Case 2 sphere in Section 1.3 of HEU-MET-FAST-100.

The material for the plugs was uranium metal but it is not explicitly stated that the material is the same composition and isotopic composition as the surrounding sphere. The isotopic composition for the split plugs is given in Table 1.4-11.

The sources used were ^{252}Cf sources with less than 0.15 μg of ^{252}Cf. No additional material data were given for the ionization chambers.

The spiral fission chamber contained 63.8 mg of ~93 wt.% ^{235}U metal. No additional material data were given for the spiral fission chamber.

1.6.4 Temperature Data

The temperature data for the sphere are given in Section 1.4 of HEU-MET-FAST-100.

1.6.5 Additional Information Relevant to Kinetics Measurements

Additional information was not identified.

1.7 Description of Reaction-Rate Distribution Measurements

1.7.1 Overview of Experiment

The relative neutron importance and relative fission density along the center line of the sphere were measured. The critical sphere described as Case 2 in HEU-MET-FAST-100 was used but with a modified center plate, as described in Section 1.4.2. The purpose of the measurements was to "properly account for spatial effects in the point reactor kinetics description of Rossi-α measurements" (Reference 8).

1.7.2 Geometry of the Experiment Configuration and Measurement Procedure

1.7.2.1 Relative Neutron Importance

The idea of the relative neutron importance measurements was to determine the radial dependence of the effect, or importance, of neutrons born inside the sphere at different radial positions on the neutron population within and external to the sphere. To measure this, a ^{252}Cf neutron source was passed through a 0.345-cm-diametral hole in the ORSphere. "The count rates of BF_3 proportional counters external to the sphere were observed and the relative count rate was assumed to be proportional to the relative importance of fission neutrons from ^{252}Cf (Maxwellian neutron spectrum with a temperature of 1.4 MeV)" (Reference 8). The source "was a solid Cf source made especially for the purpose of these measurements."[a] The diametral hole of varying diameter in the center plate, as shown in Figure 1.4-1 and Figure 1.6-2, was plugged with filler plugs of 1.270- and 0.965-cm outer diameter and 0.345-cm inner

[a] Personal email communication with J.T. Mihalczo, January 26, 2015.

diameter. This created a diametral hole of constant diameter for the source to pass through. The source was a ^{252}Cf neutron source "contained in a 0.315-cm-diameter × 0.961-cm-long welded stainless-steel cylinder positioned remotely with a 0.330-cm-diameter solid uranium metal push rod by a small electric-motor-powered screw drive. The hole [in front of the source] was filled with 0.330-cm-diameter uranium metal cylinders, either 1.270- or 0.635-cm long. The total reactivity effect associated with the source motion was <0.3 cents" (Reference 8).

The small 70-gram aluminum reflector was used to compensate for the change in reactivity as the source moved through the diametral hole. The required position of the aluminum reflector was determined by moving an empty source container through the sphere and adjusting the reflector to maintain the system at delayed critical. The aluminum reflector was oriented such that it did not have an effect on the relative neutron importance measurement.[a] "The surface mass-adjustment buttons (44 and 22 g of uranium each) that were required to achieve criticality were removed for the importance function measurement for which the sphere reactivity was -20 cents" (Reference 8).

The effect of sphere position and room return on the neutron importance function was experimentally investigated. The position of the sphere and the three BF_3 detectors in the experimental room is shown in Figure 1.7-1. It was found that the orientation of the sphere and the detector location had no measureable effect on neutron importance. The effect of the walls was determined by placing a 279 × 173 ×15.9-cm polyethylene slab 170 cm from the sphere; the short dimension was parallel to the floor. The neutron importance was found to be independent of the slab. The effect of the source centering in its container was evaluated and found to have the largest effect near the outer surface of the sphere but the effect was still much less than 1%.

The relative neutron importance measurements were normalized to one at the center of the sphere and results are given in Table 1.7-1 and shown in Figure 1.7-2.

[a] Personal email communication with J.T. Mihalczo, January 19, 2015.

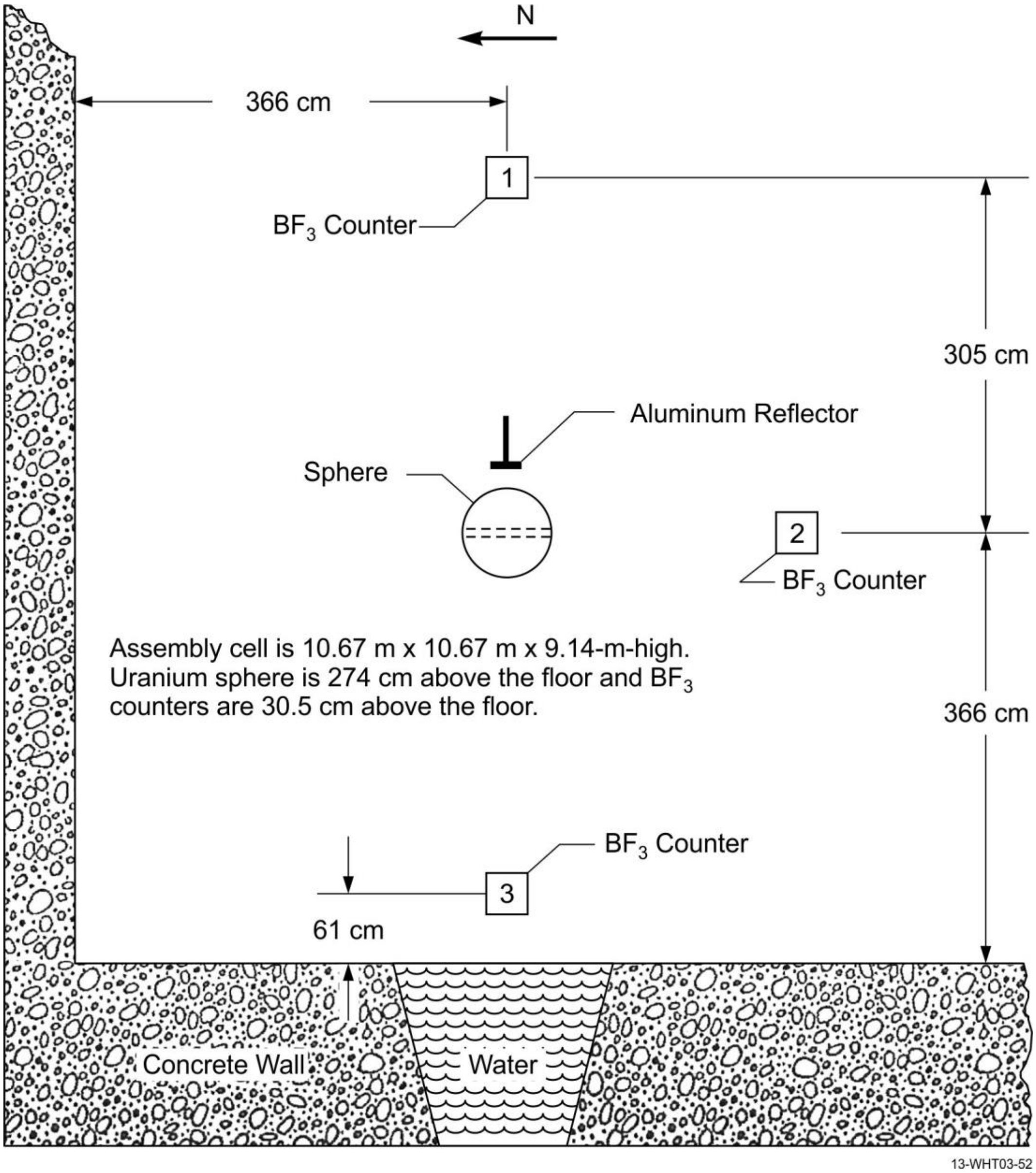

Figure 1.7-1. Plan View of BF_3 Detector Location for Neutron Importance Measurements.[a]

[a] This drawing was provided in Reference 8. The west wall has six water windows in it and is described in the safety analysis report for the ORCEF. (Personal email communication with J.T. Mihalczo, February 20, 2013.)

Table 1.7-1. Relative Importance of Neutrons as a Function of Radius.

Radius[(a)] (cm)	Average Relative Neutron Importance	Radius[(a,d)] (cm)	Average Relative Neutron Importance
-8.138	0.278 ± 0.003[(b)]	-0.470	0.992 ± 0.002[(b)]
-8.105[(c)]	0.267 ± 0.002	0.660[(c)]	0.986 ± 0.001
-8.100	0.289 ± 0.001	0.805[(e)]	0.985 ± 0.002
-8.004	0.299 ± 0.001	0.904	0.992 ± 0.001
-7.480[(e)]	0.379 ± 0.002	1.905[(c)]	0.951 ± 0.002
-6.833[(e)]	0.464 ± 0.002	2.024	0.956 ± 0.001
-6.825	0.458 ± 0.003	2.078[(e)]	0.932 ± 0.002
-6.759[(c)]	0.425 ± 0.002	3.175[(c)]	0.864 ± 0.001
-6.731	0.468 ± 0.003	3.449	0.848 ± 0.090
-5.730[(c)]	0.578 ± 0.002	4.445[(c)]	0.750 ± 0.001
-5.583	0.620 ± 0.002	4.646[(e)]	0.716 ± 0.001
-5.484	0.624 ± 0.002	4.722	0.737 ± 0.001
-5.428	0.633 ± 0.003	5.712[(c)]	0.608 ± 0.001
-4.392[(c)]	0.729 ± 0.003	5.895[(e)]	0.576 ± 0.001
-4.288[(e)]	0.759 ± 0.001	5.994	0.589 ± 0.001
-4.221	0.770 ± 0.002	7.216	0.418 ± 0.001
-4.166	0.761 ± 0.002	7.419[(e)]	0.414 ± 0.002
-3.208	0.860 ± 0.001	7.650[(c)]	0.364 ± 0.001
-3.170[(c)]	0.849 ± 0.001	8.273[(c)]	0.277 ± 0.001
-3.012[(e)]	0.875 ± 0.001	8.400	0.264 ± 0.001
-2.891	0.886 ± 0.002	8.443[(e)]	0.243 ± 0.001
-1.900[(c)]	0.936 ± 0.001	8.590[(e)]	0.230 ± 0.001
-1.740[(e)]	0.956 ± 0.003	8.618	0.224 ± 0.001
-1.618	0.958 ± 0.002	8.745[(c)]	0.204 ± 0.002
-0.632[(c)]	0.987 ± 0.001	9.091[(f)]	0.165 ± 0.001

(a) Minus sign refers to values measured on the east or south half of the sphere.
(b) Errors in measure values given in this and subsequent tables are precision based on repeated measurement.
(c) Importance given for these radii is the average of measurements performed (i) with the sphere oriented so that the diametral hole was in the east-west direction, (ii) with the sphere oriented so that the diametral hole was in the north-south direction, (iii) with the sphere oriented so that the diametral hole was in the north-south direction and with a 279- × 173- ×15.9-cm polyethylene slab placed 170 cm north of the sphere center. For each orientation three counters were used and 2 to 4 measurements were made which 10^6 counts were obtained in each counter.
(d) At radii not called out by a footnote value given are for measurements with the sphere oriented so that the diametral hole was in the east-west direction only.
(e) Measurements made with the sphere oriented so that the diametral hole was in the north-south direction only.
(f) External to the sphere.

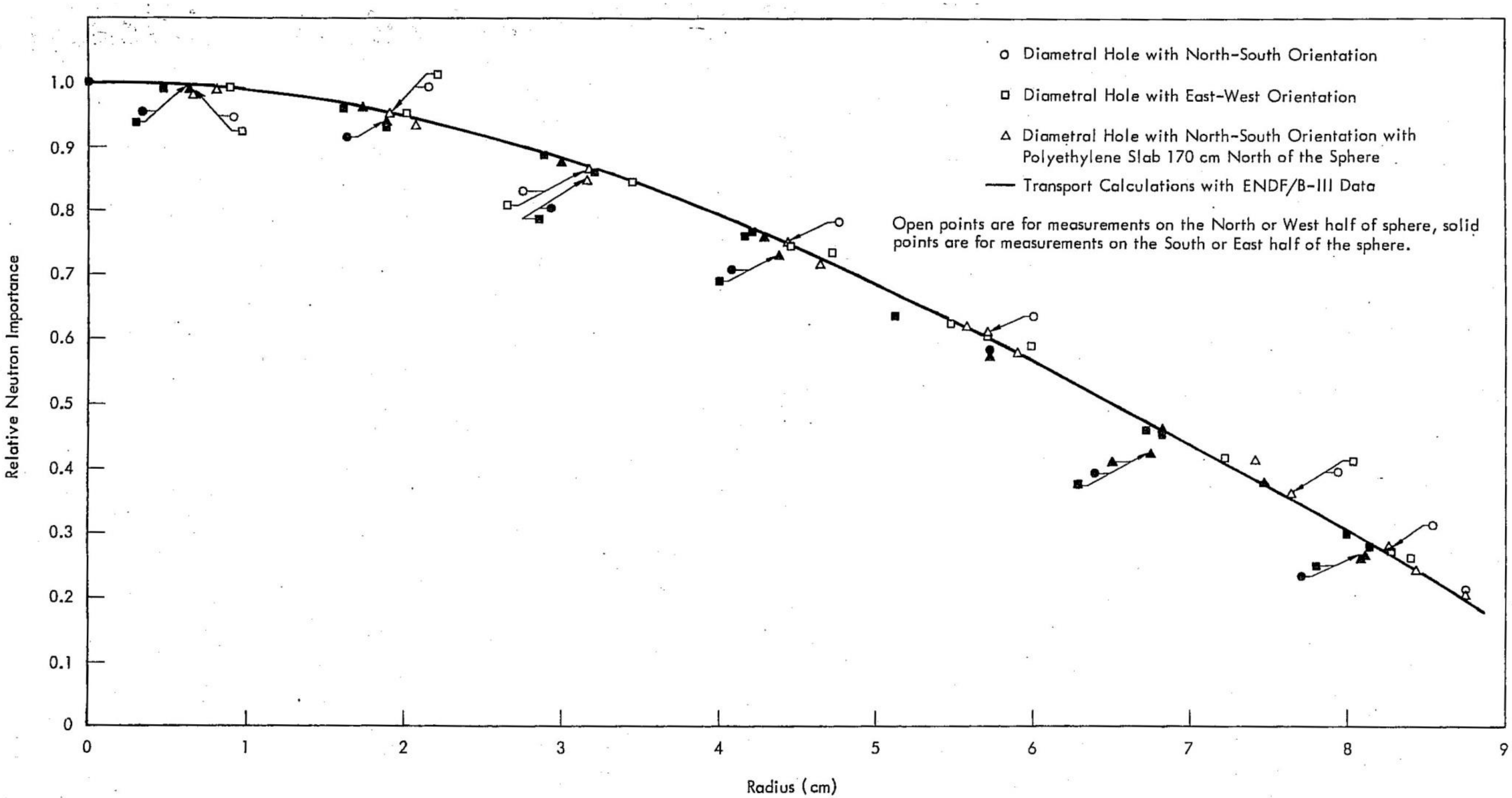

Figure 1.7-2. Relative Neutron Importance (Reference 8).

1.7.2.2 Relative Fission Density

The measurement of the relative fission density in the ORSphere is described in Reference 8:

> The relative spatial distribution of the fission density was measured by activating 0.330-cm-diameter uranium cylinders placed in the diametral hole and observing their resulting fission product gamma-ray activity with a pair of NaI scintillation detection systems. The cylinders were 0.635 or 0.318 cm long. The two detection systems were adjusted to have the same response with standard sources. Each activated cylinder was always counted simultaneously with a normalizing cylinder activated in the same irradiation at the center of the sphere. To minimize the effects of slow drifts in the response of the scintillation systems over the counting period, each pair of activated cylinders was counted in each detector and the average ratio of responses calculated.

As with the neutron importance measurements, the orientation effect and room return effect, simulated using a polyethylene slab, were evaluated and it was determined that the "the measured fission density distribution [is] independent of the orientation of the sphere or the presence of the polyethylene slab" (Reference 8). The results of the relative spatial distribution of the fission density measurements are given in Table 1.7-2 and shown in Figure 1.7-3.

Table 1.7-2. Relative Radial Fission Density (Reference 8).

Radius[(a)] (cm)	Average Relative Fission Density [(b)]	Radius (cm)	Average Relative Fission Density
-8.265	0.261 ± 0.001	0.635	0.996 ± 0.001
-7.633	0.354 ± 0.001	1.272	0.978 ± 0.002
-6.995	0.440 ± 0.001	1.908	0.956 ± 0.003
-6.355	0.519 ± 0.001	2.543	0.910 ± 0.002
-5.725	0.603 ± 0.002	3.180	0.872 ± 0.003
-5.088	0.672 ± 0.003	3.815	0.810 ± 0.001
-4.450	0.746 ± 0.001	4.450	0.742 ± 0.002
-3.815	0.810 ± 0.003	5.088	0.675 ± 0.002
-3.180	0.871 ± 0.002	5.725	0.600 ± 0.001
-2.54	0.910 ± 0.003	6.355	0.518 ± 0.005
-1.908	0.951 ± 0.002	6.995	0.438 ± 0.002
-1.272	0.978 ± 0.002	7.633	0.351 ± 0.001
-0.635	1.001 ± 0.004	8.265	0.257 ± 0.002
0.0	1.000		

(a) Minus sign refers to values measured on the east or south half of the sphere.
(b) Average of all values for any radius [values averaged from measurements (i) with the sphere oriented so that the diametral hole was in the east-west direction, (ii) with the sphere oriented so that the diametral hole was in the east-west direction and with a 279- × 173- ×15.9-cm polyethylene slab placed 170 cm east of the sphere center, and (iii) with the sphere oriented so that the diametral hole was in the north-south direction]. Error in values is precision based on repeated measurements.

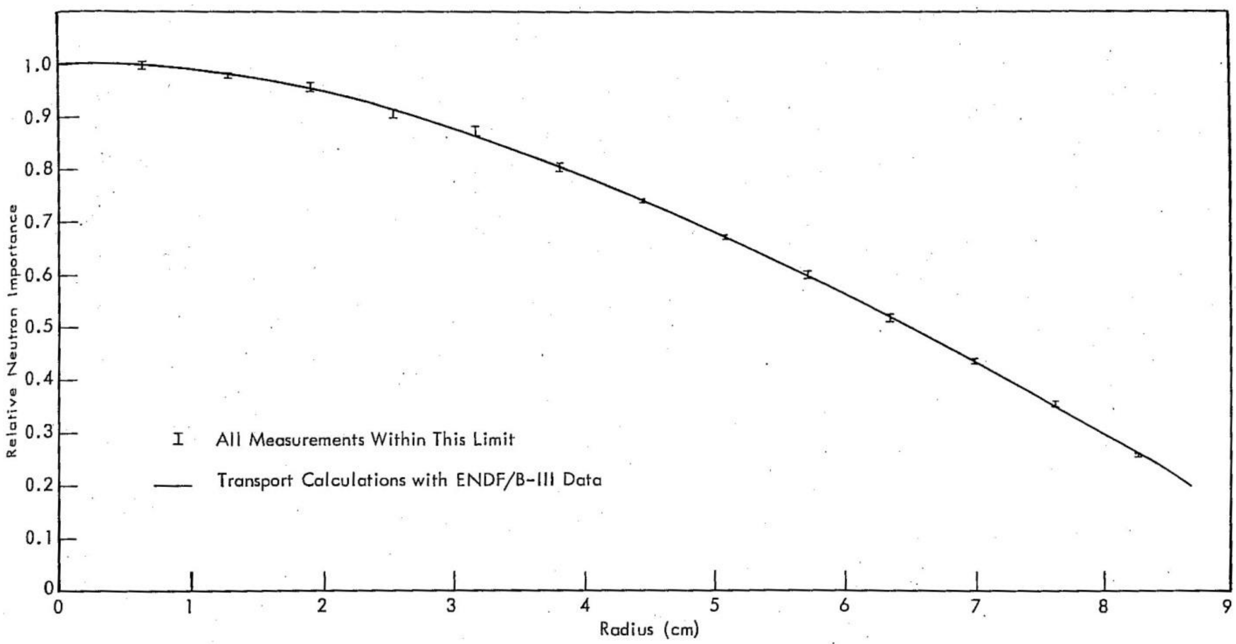

Figure 1.7-3. Relative Radial Fission Density (Reference 8).

1.7.3 Material Data

The uranium metal of the sphere is described in Section 1.3 of HEU-MET-FAST-100.

The material for the plugs and the activated cylinders was uranium metal, but the material would have been similar to that of the surrounding sphere.[a]

The source for the neutron importance measurements was a ^{252}Cf neutron source in a welded stainless steel cylinder. The source was a ^{252}Cf source, with a Maxwellian neutron spectrum and a temperature of 1.4 MeV.[b] No further information regarding the source or the container was given.

1.7.4 Temperature Data

The temperature data for the sphere are given in Section 1.4 of HEU-MET-FAST-100.

1.7.5 Additional Information Relevant to Reaction-Rate Distribution Measurements

Additional information is not available.

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[a] Personal email communication with J.T. Mihalczo, October 8. 2013.

[b] L. Green, J.A. Mitchell, and N.M. Steen, “The Californium-252 Fission Neutron Spectrum from 0.5 to 13 MeV,” *Nucl. Sci. Eng.*, **50**, 257, (1973).

1.8 Description of Power Distribution Measurements

The power distribution is related to the relative fission density (Section 1.7).

1.9 Description of Isotopic Measurements

Isotopic measurements were not performed.

1.10 Description of Other Miscellaneous Types of Measurements

There were no additional miscellaneous measurements performed.

2.0 EVALUATION OF EXPERIMENTAL DATA

The measurements were evaluated using Monte Carlo N-Particle (MCNP) Version 5-1.60[a] and ENDF/B-VII.0[b] neutron cross section libraries. All models were calculated such that the statistical uncertainty in k_{eff}, σ_{MC}, is less than or equal to ±0.00002.

2.1 Evaluation of Critical and/or Subcritical Configuration Data

The criticality portion of this evaluation has been reviewed and approved by the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and has been published under the following identifier: HEU-MET-FAST-100.[c]

2.2 Evaluation of Buckling and Extrapolation Length Data

Buckling and extrapolation-length measurements were not performed.

2.3 Evaluation of Spectral Characteristics Data

Spectral characteristics measurements were not performed.

2.4 Evaluation of Reactivity Effects Data

Various worth measurements were performed, including central void reactivity measurement, button worth measurements, and diametral filler rod worth measurements. The system reactivity was calculated from the system stable reactor period. The Inhour equation was used along with the delayed neutron parameters to convert the stable reactor period to reactivity in dollars. The reactivity of the system in two states, i.e. with and without the piece of material that is being evaluated, is compared to obtain a worth. These worth measurements were evaluated and judged to be acceptable benchmark data.

The geometry and material parameters were evaluated for the central void worth and the worth of the four, 1/8"-thick-uranium-buttons on the surface by perturbing the benchmark models. The uncertainty in an individual MCNP run was ±0.00002 k_{eff}. Two MCNP runs were required for a calculated worth measurement ($\rho = \frac{k_2 - k_1}{k_2 k_1}$, where the worth is in units of Δk_{eff}). The statistical uncertainty corresponds to a statistical uncertainty in a worth of ±0.00003 Δk_{eff} or ±0.43 ¢; the statistical uncertainty in each k_{eff} is propagated appropriately. The effects of uncertainty in the evaluated geometry and material parameters of the central void reactivity and the worth of the surface buttons were found to be within the statistical uncertainty in the Monte Carlo calculation, $\pm 0.43\sqrt{2}$ ¢ for a one-sided uncertainty perturbation. The $\sqrt{2}$ factor is because the effect on the worth is a comparison of two worths, perturbed and unperturbed, each with a Monte Carlo statistical uncertainty of 0.43 ¢.

An analysis of the effect of scaling and perturbing the isotopic abundances in the small central sphere was performed. The effect on the central sphere was chosen since the worth of mass, and thus also the effect of the uncertainties, is larger at the center of the sphere than the surface of the sphere. The uncertainty in the isotopic abundances are believed to have the largest effect on the worth measurements;

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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] International Handbook of Evaluated Criticality Safety Benchmark Experiments, NEA/NSC/DOC(95)03, OECD-NEA, Paris (2013).

thus, the isotopics were perturbed for this analysis. Table 2.4-1 summarizes the results of this analysis. These results show that, even with a scaling factor of 300, the effects on worth, due to uncertainty in ^{234}U and ^{236}U (when scaled to 1σ) was approximately 0.001 ± 0.001 Δ¢ each, which is still within the scaled statistical uncertainty of the Monte Carlo calculations. The effect on worth of perturbing the ^{235}U enrichment was approximately 0.002 ± 0.001 Δ¢ (when scaled to 1σ); this is just above the noise of the Monte Carlo calculation.[a] Based on this analysis, an uncertainty of ±0.002 ¢ was applied to all worth measurements to represent the uncertainty in the ^{235}U enrichment. Since the effects of uncertainty in impurity, mass, and dimensions are considered to be less than the calculated values for isotopic abundance of ^{236}U and ^{234}U of 0.001 ¢, an effect of ±0.001 ¢ was applied to all worth measurements for uncertainty in each of those parameters.

Table 2.4-1. Analysis of Effect of Scaling and Perturbing on Calculated Uncertainty Effects.[(a)]

Deviation	Δρ (¢)	±	σ_{MC}	Scaling Factor	1σ	Δρ (¢)	±	$\sigma_{statistical}$
$^{234}U^{(b)}$								
+0.395 wt.%	-0.15	±	0.43	40	1%	-0.004	±	0.011
+0.593 wt.%	0.61	±	0.43	60	1%	0.010	±	0.007
+0.790 wt.%	0.15	±	0.43	80	1%	0.002	±	0.005
+0.988 wt.%	0.61	±	0.43	100	1%	0.006	±	0.004
+1.186 wt.%	0.76	±	0.43	120	1%	0.006	±	0.004
+2.964 wt.%	0.31	±	0.43	300	1%	0.001	±	0.001
$^{235}U^{(c)}$								
±0.708 wt.%	-0.46	±	0.43	40	0.0177 wt.%	-0.011	±	0.011
±1.062 wt.%	0.38	±	0.43	60	0.0177 wt.%	0.006	±	0.007
±1.416 wt.%	0.00	±	0.43	80	0.0177 wt.%	0.000	±	0.005
±1.770 wt.%	-0.15	±	0.43	100	0.0177 wt.%	-0.002	±	0.004
±2.124 wt.%	-0.15	±	0.43	120	0.0177 wt.%	-0.001	±	0.004
±5.310 wt.%	0.69	±	0.22	300	0.0177 wt.%	0.002	±	0.001
$^{236}U^{(b)}$								
+0.520 wt.%	0.46	±	0.43	40	0.0130 wt.%	0.011	±	0.011
+0.780 wt.%	0.15	±	0.43	60	0.0130 wt.%	0.003	±	0.007
+1.040 wt.%	0.61	±	0.43	80	0.0130 wt.%	0.008	±	0.005
+1.300 wt.%	0.31	±	0.43	100	0.0130 wt.%	0.003	±	0.004
+1.560 wt.%	0.46	±	0.43	120	0.0130 wt.%	0.004	±	0.004
+3.900 wt.%	0.00	±	0.43	300	0.0130 wt.%	0.000	±	0.001

(a) This analysis was performed by John D. Bess of Idaho National Laboratory.
(b) The perturbation for ^{234}U and ^{236}U was a one-sided, positive perturbation. This allowed for a larger scaling factor to be used.
(c) The perturbation for ^{235}U was two-sided. The ^{238}U content, which was varied to maintain unity, was the limiting factor for the scaling factor.

[a] This analysis was performed by John D. Bess of Idaho National Laboratory on September 10, 2013.

2.4.1 Delayed Neutron Parameters and Fission Fraction

The delayed neutron parameters of Keepin et al. were used to convert stable reactor periods to system reactivity in dollars/cents. Fission fractions were also required and were originally "obtained from one-dimensional S_n neutron transport calculation with ENDF/B-VI cross sections for a delayed critical sphere" (see Table 1.4-1).

There is a given uncertainty in the Keepin delayed neutron parameters (Table 1.4-1). This uncertainty is judged to represent a random component of the overall uncertainty in the delayed neutron parameters. The systematic component of the uncertainty in the delayed neutron parameters is evaluated using an independent data set.

The effect of the random uncertainty in the Keepin delayed neutron parameters (Table 1.4-1) was evaluated by propagating the uncertainty in the Keepin data and a 5% uncertainty on stable reactor period through the Inhour equation calculation. For many of the worth measurements it was found that the calculated propagated uncertainty is within the given measurement uncertainty. For a few of the worth measurements, the calculated uncertainty was found to be larger than the given measurement uncertainty; in those cases the calculated uncertainty is used. This convention is further discussed in Sections 2.4.2 through 2.4.4. In Table 2.4-5, Table 2.4-8, Table 2.4-9, and Table 2.4-10 the random component of the uncertainty is included in the experiment method uncertainty.

The systematic component of the overall uncertainty in the delayed neutron parameters was evaluated by repeating the Inhour equation calculation, for all worth measurements, using the delayed neutron parameters provided in the ABBN cross section library[a] that are derived from the delayed neutron parameters recommended by Spriggs, Campbell and Piksaikin.[b] The values are given in Table 2.4-2. The change in the worth using ABBN delayed neutron parameters versus the Keepin delayed neutron parameters is judged to be a bounding, systematic uncertainty effect due to uncertainty in the delayed neutron parameters. The average, 1σ effect of using the ABBN delayed neutron parameters was an increase of 1.32% in the worth. This value is used for each worth measurement; see Table 2.4-5, Table 2.4-8, Table 2.4-9, and Table 2.4-10.

Table 2.4-2. Delayed Neutron Parameters.

ABBN Delayed Neutron Parameters[(a)]					
Group	Decay Constant	Relative Yield			
		^{234}U	^{235}U	^{236}U	^{238}U
1	0.0124667	0.05485	0.03278	0.02449	0.0084
2	0.0282917	0.1566	0.15391	0.09797	0.104
3	0.0425244	0.10476	0.09135	0.10797	0.0375
4	0.133042	0.1823	0.19688	0.12696	0.137
5	0.2924672	0.35475	0.33079	0.40988	0.294
6	0.6664877	0.083	0.09025	0.13696	0.198
7	1.634781	0.04618	0.08115	0.08747	0.128
8	3.5546	0.01756	0.02289	0.0083	0.0931

(a) These values are based on the ABBN cross section library and were provided by Yevgeniy Rozhikhin (IPPE).

[a] Values provided by Yevgeniy Rozhikhin, December 6, 2013.
[b] G.D. Spriggs, J.M. Campbell, and V.M. Piksaikin, "An 8-Group Delayed Neutron Model Based on a Consistent Set of Half Lives," *Progress in Nuclear Energy*, **41**, No. 1-4, 223-251 (2002).

Additional method uncertainty in the determination of system reactivity is the uncertainty in the fission fraction. The fission fractions given in Table 1.4-1 were calculated using ENDF/B-VI cross section data. The benchmark model for the central void reactivity measurement was used to calculate the fission fraction per isotope from ENDF/B-VII.0 cross section libraries using MCNP5.1-60. The fission fraction obtained for ENDF/B-VII.0 cross section libraries is given in Table 2.4-3. The effect the change in fission fraction has on the calculated average for the central void reactivity is 0.0010 Δ¢. It was found the effect was smaller for all other worth measurements thus ±0.0010 Δ¢ was applied to all worth measurement uncertainties to account for the effect of the fission fraction value.

Table 2.4-3. Fission Fraction Values.

Delayed Neutron Parameters[a]		
Isotope	Fission Fractions ENDF/B-VI[b]	Fission Fractions ENDF/B-VII.0[c]
^{234}U	0.8241%	0.7876%
^{235}U	98.1922%	98.2357%
^{236}U	0.0123%	0.0166%
^{238}U	0.9714%	0.9601%
Average Calculated Central Void Reactivity[a]	9.1512 ¢	9.1522 ¢
Effect of Fission Fraction Value (1σ)		0.0010 Δ¢

(a) Because Keepin data for the delayed neutron parameters is only given for ^{235}U and ^{238}U 50% of the ^{234}U fission fraction and 50% of the ^{236}U were added to the ^{235}U and the other half were in ^{238}U for the Inhour calculations.
(b) The ENDF/B-VI fission fraction values were provided by the experimenter in Reference 3.
(c) The ENDF/B-VII fission fraction values were calculated with MCNP5 using the central void reactivity benchmark model. The fraction of weight gained by fission in each isotope was used to compute the fission fractions.

There is also an uncertainty in the treatment of the ^{234}U and ^{236}U isotopes. Because Keepin data for the delayed neutron parameters is only given for ^{235}U and ^{238}U "half the ^{234}U fissions and half the ^{236}U were [added to] ^{235}U and the other half were in ^{238}U" (Reference 3). The uncertainty effect of this assumption is evaluated by attributing 100% of the ^{234}U and ^{236}U fissions to first ^{235}U and then to ^{236}U. This yields a change in the average calculated central void reactivity of 0.0306 Δ¢. This perturbation of the fission fractions bounds the true uncertainty thus a scaling factor of $2\sqrt{3}$ is used. This uncertainty is 0.0088 Δ¢ and is given in Table 2.4-4. The effect was found to be smaller on all other worth measurements thus an uncertainty of ±0.0088 Δ¢ was applied to all worth measurement uncertainties to account for the effect of the fission fraction value.

Table 2.4-4. Uncertainty in Treatment of ^{234}U and ^{236}U.

Delayed Neutron Parameters				
Isotope	Fission Fractions	Fission Fraction used in Calculation of Benchmark Reactivity	100% ^{234}U and ^{236}U Fissions Attributed to ^{235}U	100% ^{234}U and ^{236}U Fissions Attributed to ^{238}U
^{234}U	0.8241%	-	-	-
^{235}U	98.1922%	98.6104%	99.0286%	98.1922%
^{236}U	0.0123%	-	-	-
^{238}U	0.9714%	1.3896%	0.9714%	1.8078%
Average Calculated Central Void Reactivity		9.1512 ¢	9.1666 ¢	9.1359 ¢
Change in Average Central Void Reactivity			0.0306 Δ¢	
Effect of 1σ Uncertainty in Treatment of Fission Fraction			0.0306 Δ¢ / $2\sqrt{3}$ = 0.0088 Δ¢	

2.4.2 Central Void Reactivity Measurement

Material Properties The isotopic abundances for the central sphere for the central void reactivity measurement were not explicitly given but is given as being the same as for the surrounding sphere. There are four sections of plugs needed for the central reactivity measurements (see Figure 1.4-1): (1) A long plug for the 0.504-inch (1.28016-cm)-diameter diametral hole which surrounds the 0.460-inch (1.1684-cm)-diameter sphere, (2) a plug to fit the 0.136-inch (0.34544-cm)-diameter section of the diametral hole, (3) a plug to fit the 0.386-inch (0.98044-cm)-diameter surface hole along the diametral hole, and (4) a plug to fit the 0.504-inch (1.28016-cm)-diameter surface hole. The experimenter provided the monthly average isotopic compositions for the Y-12 plant the month in which the parts were fabricated. Reference 2 provides an isotopic composition for "plugs for 0.500-inch-diameter holes" (Table 1.4-11). The plugs for the 0.98044-cm- and 1.28016-cm-diameter surfaces holes and the 1.28016-cm-diameter diametral hole, including the 1.1684-cm-diameter sphere, would most likely have been fabricated at the same time. The isotopic abundances for the "plugs for the 0.500-inch [1.27-cm]-diameter holes" are believed to apply to these three plugs and the small sphere. The plug for the 0.34544-cm-diameter hole would have been a section of the diametral filler rod used in the critical assemblies (HEU-MET-FAST-100).

The uncertainty in the isotopic abundances would be the same as for the critical sphere (HEU-MET-FAST-100); the ^{238}U content is adjusted to maintain unity:

^{234}U	1	%[a]
^{235}U	0.0177	wt.%
^{236}U	0.0130	wt.%

The impurities for the material used for the central void reactivity was not provided. The average impurity content provided in Reference 1 (see Table 1.4-12 footnotes) was used for the small central sphere and all the other plugs used. This is the same average impurity content that is used for the diametral filler rod. 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.

Because the calculated effects of uncertainties in isotope abundance and impurities was within the statistical noise of the Monte Carlo calculations, even when using scaling factors, an uncertainty of

[a] It should be noted that the uncertainty for ^{234}U is 1% of the given weight percent. The uncertainty for ^{235}U and ^{236}U are given in units of weight percent.

[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).

±0.002 ¢ was applied for the ^{235}U enrichment uncertainty and ±0.001 ¢ was applied for the isotopic abundance of ^{234}U and ^{236}U uncertainties. This is discussed in Section 2.4.0.

Geometry and Mass The dimensions and manufacturing tolerances for the long uranium plug and sphere placed in the 1.28016-cm-diameter diametral hole used for the central void reactivity measurement are given in Figure 1.4-2. The mass of the small uranium sphere was 15.614 g. The uncertainty in the other dimensions for the long plug for the diametral hole would have negligible effect on the worth of the central void because they would remain constant when the small central sphere is added to and removed from the system.

All other holes are plugged for the central void reactivity measurements. The dimensions of these plugs are not given. The plugs for the 0.504-inch (1.28016-cm)- and 0.386-inch (0.98044-cm)-diameter surface holes were modeled as cylinders having a length of 1.000 inch (2.54 cm), to match the depth of the holes. The diameter of each plug was modeled such that the gap around the plug equaled the gap around the long plug in the diametral hole ($[0.504 - 0.501]/2$ inch, 0.00381 cm). This yielded plug diameters of 1.27254 cm and 0.97282 cm. The plug for the small, 0.136-inch (0.34544-cm)-diameter hole linking the 0.98044-cm -diameter surface hole to the 1.28016-cm -diameter diametral hole was most likely identical in diameter and composition to the diametral hole filler rod used in HEU-MET-FAST-100 since the hole diameters are the same. Thus, the diameter for the plug was 0.328422 cm. The dimensions of these plugs have a negligible effect on the worth measurements because they remain constant when the small central sphere is added to and removed from the system.

Because the calculated effects of the uncertainties in the small sphere diameter and mass were within the statistical noise of the Monte Carlo calculations and are considered to be less than the effect of the uncertainty in ^{234}U and ^{236}U, which is scaled to a value of ±0.001 ¢, a value of ±0.001 ¢ was also applied for both the uncertainty in the small sphere diameter and mass.

Central Void Reactivity The central void reactivity was measured by comparing the system reactivity with and without a small sphere present at the center of the larger sphere. The average worth was obtained from 43 worth measurements between May 19, 1972 and August 10, 1972. The given worth in Reference 3 is 9.165 ±0.023 ¢. If the variance weighted average of the daily averages and standard deviations for the values in Table 1.4-3 is recalculated a value of 9.16898 ± 0.018 ¢ is obtained which is close to the published average. The published value is used for this evaluation.

If the Inhour equation results are re-calculated for the stable reactor periods in Table 1.4-2 the resulting average worth is 9.1434 ± 0.018 ¢; the differences are believed to be due to rounding and both values are within 1σ of each other. The given uncertainty of ±0.023 ¢ is used as the method uncertainty. Because multiple runs were performed, this uncertainty includes the effect of uncertainty in temperature, measurement technique, and reproducibility. The total uncertainty is summarized in Table 2.4-5.

Table 2.4-5. Central Void Reactivity Total Uncertainty.

Uncertainty	¢	Uncertainty	¢
Experiment Method	± 0.0230	^{234}U Abundance	± 0.0010
Fission Fraction Values	± 0.0010	^{235}U Abundance	± 0.0020
Treatment of ^{234}U and ^{236}U	± 0.0088	^{236}U Abundance	± 0.0010
Delayed Neutron Parameter [(a)]	± 0.1210	Small Sphere Diameter	± 0.0010
Small Sphere Mass	± 0.0010		
Total	**± 0.123 ¢**		

(a) This is the systematic component of the delayed neutron parameter uncertainty. The random component is included in the experiment method uncertainty (see Section 2.4.1).

2.4.3 Button Worth Measurements

Material Properties The uranium isotopic abundances for the buttons were given in Reference 1 and 2 (Table 1.4-11). The uncertainty in the abundances would be the same as for the critical sphere which is given above in Section 2.4.2.

The impurities for the uranium buttons was provided in Table 1.4-12. 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.[a] These were assumed to be bounding uncertainties.

Because the calculated effects of the isotopic and impurity uncertainties for the uranium buttons were within the statistical noise of the Monte Carlo calculations, and are considered to be less than the effect of the uranium uncertainties at the center of the sphere, a value of ±0.002 ¢ was applied for the ^{235}U enrichment uncertainty and ±0.001 ¢ was applied for the isotopic abundance of ^{234}U and ^{236}U uncertainties.

The screws holding the buttons in place were stainless steel type 304 number 8-55 screws. The effect of the screw material on the worth of the buttons was evaluated but was within the statistical noise of the Monte Carlo calculation. The worth of one screw was approximated using the worth of the stainless steel button on the empty socket hole of the upper polar cap. Three stainless steel Type 304 buttons were worth 4.7228 ¢ in the socket hole. Using the given button dimensions the worth per volume for the stainless steel was determined, 1.342 ¢ per cubic centimeter. The volume of one screw was approximately 0.121 cm^3 for the 0.635-cm-thick buttons and 0.090 cm^3 for the 0.3175-cm-thick buttons. This corresponds to a worth per screw of 0.16 ¢ and 0.12 ¢ for the 0.635 and 0.3175 cm thick buttons, respectively. These values are assigned as bounding uncertainties for the screw material; the 1σ uncertainties are ±0.09 ¢ for the 0.635-cm-thick buttons and ±0.07 ¢ for the 0.3175-cm-thick buttons. This uncertainty is not applied to the 4, 0.3175-cm-thick uranium buttons placed on the surface of the sphere. Because the worth of the four buttons was measured independently of the screws the uncertainty due to the screw material is negligible.

The aluminum buttons were aluminum Type 6061 and the steel buttons were stainless steel Type 304. The aluminum and stainless steel compositions are given in Table 2.4-6 and Table 2.4-7; ‘other’ elements listed in Table 2.4-6 were not included in the model composition. The effect of replacing the aluminum Type 6061 with pure aluminum and switching the stainless steel Type 304 for stainless steel Type 316 is within the statistical uncertainty of the Monte Carlo calculation thus a ±0.001 ¢ uncertainty was

[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).

arbitrarily applied for the material uncertainty, including both composition and impurity uncertainties, for the aluminum and stainless steel buttons.

Table 2.4-6. Type 6061 Aluminum Composition.

Element	Standard Composition[(a)(b)]	Model Composition
Silicon	0.40-0.80 wt.%	0.6 wt.%
Iron	< 0.7 wt.%	0.35 wt.%
Copper	0.15-0.40 wt.%	0.275 wt.%
Manganese	< 0.15 wt.%	0.075 wt.%
Magnesium	0.8-1.2 wt.%	1 wt.%
Chromium	0.04-0.35 wt.%	0.195 wt.%
Zinc	< 0.25 wt.%	0.125 wt.%
Titanium	< 0.15 wt.%	0.075 wt.%
Other Elements Each	< 0.05 wt.%	--
Total	< 0.15 wt.%	--
Aluminum	Remainder	97.305 wt.%
Density (g/cm^3)	2.70	2.70

(a) Where single units are shown, these indicate the maximum amounts permitted.
(b) ASTM Standard B308M, 2010, "Standard Specification for Aluminum-Alloy 6061-T6 Standard Structural Profiles," ASTM International, West Conshohocken, PA, 2010.

Table 2.4-7. Type 304 Stainless Steel Composition.

Element	Standard Composition[(a)(b)]	Model Composition
Iron, Fe	Balance	69.9225 wt.%
Carbon, C	0.08 wt.%	0.04 wt.%
Manganese, Mn	2.00 wt.%	1.00 wt.%
Silicon, Si	1.00 wt.%	0.50 wt.%
Chromium, Cr	18.0-20.0 wt.%	19.00 wt.%
Nickel, Ni	8.0-11.0 wt.%	9.50 wt.%
Phosphorus, P	0.045 wt.%	0.0225 wt.%
Sulfur, S	0.03 wt.%	0.015 wt.%
Density (g/cm^3)	8.00	8.00

(a) ASTM Standard A 312/A 312M-09.
(b) Single values are maximum values.

Geometry and Mass The experimenter has stated that all buttons had the same diameters, smaller than the diameter of the button recesses, and varying thicknesses. In Reference 1 the diameter is given as 0.8720 inch and the experimenter has confirmed this as the correct diameter. Reference 3 gives the button diameter as 0.8750 inch but it is believed that this is an accidental swap of the button diameter with the button recess diameter. The outer diameter of the buttons is 0.872 ± 0.001 inch (2.21488 ± 0.00254 cm) in the benchmark model. The inner diameter was 0.1770 inches (0.44958 cm). No uncertainty for the inner diameter was given but an uncertainty of 0.00254 cm was applied. The thicknesses of the buttons were 1/8 inch, 0.3175 cm, and 1/4 inch, 0.635 cm. The masses of the uranium buttons were 43.9 grams each for the 0.635-cm-thick uranium buttons and 65.2 grams for three 0.3175-cm-thick uranium buttons. The uncertainty in these masses would have been 0.1 g; this is the uncertainty in mass as discussed in HEU-MET-FAST-100. The aluminum Type 6061 and stainless steel Type 304 buttons were modeled at nominal densities (see Table 2.4-6 and Table 2.4-7).

The placement of buttons on the surface of the sphere was not explicitly given; however, the experimenter has stated that the perturbed buttons were distributed between the upper and lower polar caps. The effect of button placement on worth was calculated by determining button worth if all buttons are placed close together on the upper polar cap and then buttons are placed at maximum spacing on the upper and lower polar caps. This applies only to the worth of the four uranium buttons and the worth per aluminum buttons measurements. The effect of button placement is within the statistical noise of the Monte Carlo and is judged to be negligible.

The holding screws for the surface buttons were modeled as having a radius to match the screw holes in the critical sphere, 0.175247 cm. The geometry of the head of the screws is not known. The screws were modeled to be flush with the outer surface of the buttons, 1.25349-cm and 0.93599-cm long for the 0.635-cm-thick and 0.3175-cm-thick buttons, respectively. The effect of varying the dimensions of the screws was within the statistical uncertainty of the Monte Carlo calculations. It is judged that the uncertainty in the dimensions and density of the screws is within the ±0.09 ¢ and ±0.06 ¢ uncertainties derived in the above section for material properties.

Because the effect of the geometric uncertainties was within the statistical noise of the Monte Carlo calculations, even when using scaling factors where possible, an uncertainty of ±0.001 ¢ was applied for the dimensional and mass uncertainties for the buttons.

Worth of Buttons on the Sphere Surface When 16, 0.635-cm-thick uranium buttons are added to the 3.4220-inch-average-radius sphere (Case 2 in HEU-MET-FAST-100) the system reactivity is increased from -23 ¢ to +12.4 ¢. It is not known if these reactivities were obtained from a single run or from multiple runs or if the two reactivity measurements were performed on the same day or many days apart. In HEU-MET-FAST-100 an uncertainty of ±2.0 ¢ is applied to system reactivities which includes "assembly reproducibility, reactor period measurements uncertainty, and uncertainties in the delayed neutron parameters" (Reference 1). This uncertainty is applied to system reactivity for the sphere without any buttons, -23 ± 2.0 ¢, and the sphere with 16 uranium buttons, 12.4 ± 2 ¢. This yields a worth for 16, 0.635-cm-thick uranium buttons of 35.4 ± 2.828 ¢ ($\pm 2.0\sqrt{2}$ ¢). The total uncertainty is summarized in Table 2.4-8.

The worth of four 0.3175-cm-thick mass adjustment buttons is given as 6.1415 ± 0.0834 ¢. This is measured with 12 mass adjustment buttons plus an extra 4 holding screws on the reference sphere. Four uranium buttons are added to the sphere and, by comparing the reactivity, the worth of the four uranium mass adjustment buttons, without holding screws, is obtained. The worth was measured five times. If the Inhour results are re-calculated the resulting average is 6.1492 ± 0.0403 ¢; the differences are believed to be due to rounding and both values are within 1σ of each other. The given uncertainty of ±0.0834 ¢ is used as the method uncertainty. Because multiple runs were performed this uncertainty includes the effect of uncertainty in temperature, measurement technique, and reproducibility. The multiple reactivity measurements used to obtain the worth were all performed one after another and the changes made to the sphere, i.e. the addition of buttons, were small. This meant that when the difference between reactivities was taken to obtain the worth, many of the systematic uncertainties that contributed to the larger uncertainty on the 16, 0.635-cm-thick uranium buttons worth were negligible. The total uncertainty is summarized in Table 2.4-8.

The worth of one 0.3175-cm-thick aluminum button, including the holding screw, on the surface of the sphere was measured as being 0.7058 ± 0.0104 ¢. The worth per button was measured for five experimental runs with either three or four aluminum buttons added to the sphere with 12 or 13 uranium buttons placed in the remaining mass adjustment button recesses. If the Inhour results are re-calculated the resulting average is 0.7017 ± 0.0046 ¢ per aluminum button; the differences are believed to be due to rounding and both values are within 1σ of each other. The given uncertainty of ±0.0104 ¢ is used as the method uncertainty. Because multiple runs were performed, this uncertainty includes the effect of uncertainty in temperature, measurement technique, and reproducibility. The total uncertainty is summarized in Table 2.4-8.

Table 2.4-8. Uncertainty in Worth of Button(s) on Surface of Sphere.

Sixteen 0.635-cm-thick Uranium Buttons[(a)]					
Uncertainty		¢	Uncertainty		¢
Experiment Method	±	2.8284	Button Dimensions	±	0.0010
Fission Fraction Values	±	0.0010	^{234}U Abundance	±	0.0010
Treatment of ^{234}U and ^{236}U	±	0.0088	^{235}U Abundance	±	0.0020
Delayed Neutron Parameter [(b)]	±	0.4673	^{236}U Abundance	±	0.0010
Button Mass	±	0.0010	Holding Screws[(c)]	±	0.0900
		Total	**± 2.8682 ¢**		
Four 0.3175-cm-thick Uranium Buttons[(d)]					
Uncertainty		¢	Uncertainty		¢
Experiment Method	±	0.0834	^{234}U Abundance	±	0.0010
Fission Fraction Values	±	0.0010	^{235}U Abundance	±	0.0020
Treatment of ^{234}U and ^{236}U	±	0.0088	^{236}U Abundance	±	0.0010
Delayed Neutron Parameter [(b)]	±	0.0811	Button Dimensions	±	0.0010
Button Mass	±	0.0010			
		Total	**± 0.1167 ¢**		
One 0.3175-cm-thick Aluminum Button[(a)]					
Uncertainty		¢	Uncertainty		¢
Experiment Method	±	0.0104	Aluminum Composition	±	0.0010
Fission Fraction Values	±	0.0010	Button Density	±	0.0010
Treatment of ^{234}U and ^{236}U	±	0.0088	Button Dimensions	±	0.0010
Delayed Neutron Parameter [(b)]	±	0.0093	Holding Screws[(c)]	±	0.0600
		Total	**± 0.0623 ¢**		

(a) The worth of these buttons includes the worth of the holding screws.
(b) This is the systematic component of the delayed neutron parameter uncertainty. The random component is included in the experiment method uncertainty (see Section 2.4.1).
(c) This uncertainty includes that material, dimensions, and density of the holding screws.
(d) The worth of these buttons was measured independent of the holding screws.

Worth of Buttons in Empty Socket Hole of Upper Polar Cap Three 0.3175-cm-thick uranium buttons with a total mass of 65.2 grams were placed in the empty socket hole of the upper polar cap. The measured reactivity worth of these three uranium buttons is 7.86 ± 0.04 ¢. Five experimental runs in which the system reactivity was determined with the buttons in place and then again with the buttons removed were performed to get the average worth. If the Inhour results are re-calculated, the resulting average is 7.81 ± 0.0734 ¢. This calculated average is lower than the given average by 0.05 ¢, which is within the calculated uncertainty in the value. It is not known why the calculated average deviates from the given average by more than the other worth measurements. The uncertainty in the calculated average (±0.0734 ¢), since it is larger than the given uncertainty, is used as the method uncertainty. Because multiple runs were performed, this uncertainty includes the effect of uncertainty in temperature, measurement technique, and reproducibility. The total uncertainty is summarized in Table 2.4-9.

Three 0.3175-cm-thick stainless steel Type 304 buttons had a worth of 4.7228 ± 0.0420 ¢ when placed in the empty socket hole of the upper polar cap. Five experimental runs were performed. If the Inhour results are re-calculated, the resulting average is 4.7032 ± 0.0246 ¢; the differences are believed to be due to rounding and both values are within 1σ of each other. The given uncertainty of ±0.0420 ¢ is used as the method uncertainty. Because multiple runs were performed, this uncertainty includes the effect of uncertainty in temperature, measurement technique, and reproducibility. The total uncertainty is summarized in Table 2.4-9.

Three 0.3175-cm-thick aluminum Type 6061 buttons, modeled at nominal density, placed in the empty socket hole of the upper polar cap had a measured worth of 3.1259 ± 0.0358 ¢. If the Inhour results are re-calculated, the resulting average is 3.1266 ± 0.0608 ¢; the differences between the given and calculated averages are believed to be due to rounding and both values are within 1σ of each other. The uncertainty in the calculated average (±0.0608 ¢), since it is larger than the given uncertainty, is used as the method uncertainty. Because multiple runs were performed, this uncertainty includes the effect of uncertainty in temperature, measurement technique, and reproducibility. The total uncertainty is summarized in Table 2.4-9.

Table 2.4-9. Uncertainty in Worth of Button in the Empty Socket Hole.

Three 0.3175-cm-thick Uranium Buttons					
Uncertainty		¢	Uncertainty		¢
Experiment Method	±	0.0734	^{234}U Abundance	±	0.0010
Fission Fraction Values	±	0.0010	^{235}U Abundance	±	0.0020
Treatment of ^{234}U and ^{236}U	±	0.0088	^{236}U Abundance	±	0.0010
Delayed Neutron Parameter [(a)]	±	0.1038	Button Dimensions	±	0.0010
Button Mass	±	0.001			
		Total	**± 0.1274 ¢**		
Three 0.3175-cm-thick Stainless Steel Buttons					
Uncertainty		¢	Uncertainty		¢
Experiment Method	±	0.0420	Steel Composition	±	0.0010
Fission Fraction Values	±	0.0010	Button Density	±	0.0010
Treatment of ^{234}U and ^{236}U	±	0.0088	Button Dimensions	±	0.0010
Delayed Neutron Parameter [(a)]	±	0.0623			
		Total	**± 0.0757 ¢**		
Three 0.3175-cm-thick Aluminum Buttons					
Uncertainty		¢	Uncertainty		¢
Experiment Method	±	0.0608	Aluminum Composition	±	0.0010
Fission Fraction Values	±	0.0010	Button Density	±	0.0010
Treatment of ^{234}U and ^{236}U	±	0.0088	Button Dimensions	±	0.0010
Delayed Neutron Parameter [(a)]	±	0.0413			
		Total	**± 0.0741 ¢**		

(a) This is the systematic component of the delayed neutron parameter uncertainty. The random component is included in the experiment method uncertainty (see Section 2.4.1).

2.4.4 Diametral Filler Rod Measurements

Material Properties The isotopic abundances for the diametral filler rod are given in Table 1.4-11). The uncertainty in the abundances is the same as for the critical sphere (HEU-MET-FAST-100); values are given in Section 2.4.2.

The impurity data for the diametral filler rod was not provided. The average impurity content provided in Reference 1 (see Table 1.4-12 footnotes) was used for the diametral filler rod. 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.[a] These were assumed to be bounding uncertainties.

The effect of perturbing the isotopic abundances and impurities in the diametral filler rod was within the statistical noise of the Monte Carlo calculations, even when using scaling factors; an uncertainty of ±0.002 ¢ was applied for the ^{235}U uncertainty and ±0.001 ¢ was applied for the ^{234}U and ^{236}U uncertainties. This is discussed in Section 2.4.0.

[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).

Geometry and Mass The geometry and mass for the diametral filler rod is the same as for the diametral filler rod for the critical sphere (HEU-MET-FAST-100). The diametral filler rod was modeled as one 28.163 gram uranium metal rod with a diameter of 0.328442 cm and a length of 17.82953 cm. The uncertainty in the mass and dimensions of the diametral filler rod were evaluated for the critical sphere and found to have a negligible effect.[a]

Diametral Filler Rod Worth The diametral filler rod has a measured worth of 11.2340 ± 0.0717 ¢. The value of 11.23 ± 0.07 ¢ given in Reference 1 and 2 has been rounded from the values given in the experimenter's notes. The non-rounded value is used for the benchmark model. The worth is an average of five runs with and without the diametral filler rod present in the diametral hole of the critical sphere. If the Inhour results are re-calculated, the resulting average is 11.173 ± 0.078 ¢; the differences are believed to be due to rounding and both values are within 1σ of each other. The uncertainty in the calculated average (±0.078 ¢), since it is larger than the given uncertainty, is used as the method uncertainty. Because multiple runs were performed, this uncertainty includes the effect of uncertainty in temperature, measurement technique, and reproducibility. The total uncertainty is summarized in Table 2.4-10.

Table 2.4-10. Diametral Filler Rod Uncertainty.

Uncertainty		¢	Uncertainty		¢
Experiment Method	±	0.0780	^{234}U Abundance	±	0.0010
Fission Fraction Values	±	0.0010	^{235}U Abundance	±	0.0020
Treatment of ^{234}U and ^{236}U	±	0.0088	^{236}U Abundance	±	0.0010
Delayed Neutron Parameter [(a)]	±	0.1483	Diametral Filler Rod Dimensions[(a)]	±	NEG
Diametral Filler Rod Mass[(a)]	±	NEG			
		Total	**± 0.1678 ¢**		

(a) These uncertainties were evaluated in HEU-MET-FAST-100.

2.5 Evaluation of Reactivity Coefficient Data

The worth per gram of uranium on the surface of the sphere was determined using the system reactivity change between the two critical spheres described in HEU-MET-FAST-100. Because the two spheres are nearly identical the uncertainties in the two spheres evaluated in HEU-MET-FAST-100 are highly correlated. While the material and dimensional uncertainties have an effect upon individual system reactivities, they have a negligible effect on the surface mass worth because the worth is a change in system reactivity of two highly correlated spheres. Thus, only the uncertainty of the reactivity measurement of 2.0¢ is applicable; the uncertainty of the reactivity measurement includes assembly reproducibility (±0.3 ¢), reactor period measurements uncertainties, and uncertainties in the delayed neutron parameter.

The given change in system reactivity, as shown in Table 2.5-1, is used to derive the worth per gram of surface material. The system reactivity corrected for the tilt in the larger sphere is used. The mass of each sphere is also given in Table 2.5-1. The uncertainty in the mass is the uncertainty in mass for each section added together in quadrature. The uncertainty in the center section and upper polar cap were ±0.01 g for each sphere. The uncertainty in the mass of the diametral filler rod was ±0.014 g for each sphere. The uncertainty in the mass of the bottom section of sphere was ±1 g for the 8.80491-cm-average-radius sphere and ±0.01 g for the 8.74268-cm-average-radius sphere. To obtain the uncertainty

[a] This determination was completed in HEU-MET-FAST-100. The effect of the uncertainty in the diametral filler rod was determined using the effect on k_{eff} and negligibility was set at less than 0.00001 Δk_{eff}.

in the worth per gram of surface material the measurement uncertainty in the system reactivity, ±2.0 ¢, and the uncertainty in the masses are propagated to get a ±0.003 ¢ per gram uncertainty.

Table 2.5-1. Worth per Gram of Surface Material

	System Reactivity			Mass		
8.80491-cm-Average-Radius Sphere	73.1	±	2.6 ¢[(a)]	53,475.983	±	1.017 g
8.74268-cm-Average-Radius Sphere	-23.4	±	2.0 ¢	52,350.943	±	0.210 g
Change	96.5	±	2.83 ¢	1,125.04	±	1.038 g
Worth per Gram of Surface Material	**0.086**	**±**	**0.003**	**¢ per gram**		

(a) This uncertainty includes a 1.67¢ uncertainty in the tilt angle between the center and lower plates. This tilt is not present in the 8.74268-cm-average-radius sphere.

2.6 Evaluation of Kinetics Measurements Data

2.6.1 Delayed Neutron Fraction

Two methods of measuring the effective delayed neutron fraction, β_{eff}, were tested with ORSphere. The first used the central void reactivity and the second used time correlation measurements with californium-252 yielding β_{eff} values of 0.00657 ± 0.00002 and 0.00602 ± 0.00008, respectively. The 0.00602 ± 0.00008 value from the time correlation measurements is rejected due to the "improper theoretical formulation for correcting point kinetics for spatial effects" that is cited in Reference 5.

The 0.00657 ± 0.00002 β_{eff} value is the ratio of the calculated worth of the central void, $6.02 \pm 0.01\times10^{-4}$ Δk, and the measured central void worth, 9.165 ± 0.023 ¢. This method is similar to methods used by Gordon Hansen to determine β_{eff} at Los Alamos National Laboratory.[a,b] The 0.0066 β_{eff} value for Godiva given by the experimenter is believed to have been obtained by measuring the "increment between delayed and prompt critical" for surface mass of the sphere.[c]

It should be noted that the uncertainty in the central void worth was evaluated in Section 2.4.2 and the uncertainty in the value was found to be ±0.123 ¢. The uncertainty accounts for uncertainty in the fission fraction values, uncertainty in the delayed neutron parameters, treatment of the ^{234}U and ^{236}U in the Inhour equations, and the sphere geometry, mass, and material properties in addition to the experimental method uncertainty. This uncertainty in the measured central void worth is the driving uncertainty in the β_{eff} value. The increase in the worth uncertainty increases the β_{eff} uncertainty from 0.000016 to 0.000089.

Hansen's method is highly dependent on the calculated Δk reactivity of the central void. The calculated worth of the central void in units of Δk was obtained by the experimenter using S_n transport theory, extrapolated to infinite order S_n, with a precision of less than 10^{-7} Δk. ONEDANT and XSDRNPM codes with Hansen-Roach and ENDF/B-VI cross section libraries were used. This method is only valid for worth measurements that can be very accurately measured and very accurately modeled. There also must be uniformity in the composition such that deficiencies in the nuclear data will cancel when the reactivity is calculated by taking the difference between the reference and perturbed models. To determine the accuracy of the calculated reactivity the benchmark model for the central void measurement (see Section 3.4) and the Case 2 simple benchmark model for HEU-MET-FAST-100 were used to recalculate the reactivity in units of Δk. The models with and without the 0.5482-cm-radius

[a] Personal phone communication with J.T. Mihalczo, November 14, 2013.

[b] G.E. Hansen, C. Maier, "Material Replacement Experiments: Theory and Measurements for the Lady Godiva Assembly," LA-1525 (1953). It should be noted that this report gives a β_{eff} value of 0.0068.

[c] G.E. Hansen, "Status of Computational and Experimental Correlations for Los Alamos Fast-Neutron Critical Assemblies," *Physics of Fast and Intermediate Reactors*, Proc. Of a Seminar, Vol. 1, p. 453, IAEA, (1962).

sphere at the center of the main sphere yielding the system k_{eff} with, k_1, and without, k_2, the sphere present. The reactivity of the sphere was then calculated, $\rho(\Delta k) = {(k_1 - k_2)}/{k_1 \cdot k_2}$. β_{eff} was then calculated using the benchmark central void worth of 9.165 ± 0.123¢ (see Section 2.4.2). Table 2.6-1 shows the results for the calculations using various codes and cross sections. From these results it can be seen that regardless of code and cross section used to calculate the reactivity of the central void in units of Δk the resulting β_{eff} is the same within the uncertainty. However, it can also be seen that in order to determine β_{eff} with a reasonable uncertainty the worth measurement must be of a material volume whose reactivity can be calculated with a small uncertainty.

Using deterministic methods the worth is re-calculated using ENDF/B-V.0, ENDF/B-VI.0 and ENDF.B-VII.0. The average re-calculated worth is 6.06×10^{-4} Δk which is 0.4 pcm above the given calculated worth of $6.02 \pm 0.01\times10^{-4}$. The 0.4 pcm difference is used as the bounding uncertainty in the calculated central void reactivity (0.23 pcm 1σ uncertainty). According to expert judgment[a] the uncertainties in nuclear data could contribute approximately 0.5% to the relative reactivity uncertainty for fast high enriched non-reflected uranium systems. It is the judgment of the evaluator that by re-calculating using the three ENDF/B libraries the spread in the calculated reactivity due to discrepancies in nuclear data is accounted for and 0.23 pcm uncertainty in the calculated central void reactivity accounts for nuclear data sensitivities. The increase in the uncertainty in the calculated central void reactivity increases the β_{eff} uncertainty to 0.000092.

[a] Personal email communication with E. Ivanov, February 3, 2015.

Table 2.6-1. Calculation of β_{eff} using Various Method to Calculate the Void Reactivity Effect.

Code	Cross Section	$\rho(\Delta k)$			β_{eff} [(e)]			$\frac{\beta_{eff}-\beta_{eff}^{given}}{\sigma_\beta+\sigma_\beta^{given}}$ [(g)]
Given (Ref. 3)		0.000602	±	0.000002[(f)]	0.00657	±	0.00009	-
MCNP5[(a)]	ENDF/B-VII.0	0.000618	±	0.000011	0.00675	±	0.00015	0.75
MCNP5[(b)]	JEFF-3.1	0.00065	±	0.00003	0.00706	±	0.00033	1.17
MCNP5[(b)]	JENDL-3.3	0.00058	±	0.00003	0.00632	±	0.00032	-0.61
MONK[(c)]	JEFF-3.1	0.00056	±	0.00009	0.00611	±	0.00099	-0.43
MONK[(c)]	ENDF/B-VII.0	0.00053	±	0.00009	0.00578	±	0.00099	-0.73
XSDRNPM[(d)]	ENDF/B-VII.0-238g	0.000605	±	10^{-8}	0.00661	±	0.00009	0.22
XSDRNPM[(d)]	ENDF/B-VI.0-238g	0.000608	±	10^{-8}	0.00664	±	0.00009	0.39
XSDRNPM[(d)]	ENDF/B-V.0-238g	0.000605	±	10^{-8}	0.00660	±	0.00009	0.17

(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 20000 normal stages, 1000 super histories per stage and 10 generations per super-history.
(d) Results provided by John D. Bess from Idaho National Laboratory (S_N=512, convergence=10^{-9}). Standard SCALE settings were used.
(e) β_{eff} was calculated using the benchmark central void worth of 9.165 ± 0.123¢.For the Monte Carlo calculations of reactivity, the dominant uncertainty in β_{eff} is the uncertainty in the calculated reactivity. For the deterministic calculations of the reactivity, the dominant uncertainty in β_{eff} is the uncertainty in the benchmark central void worth measurement (see Section 2.4.2 for the contributions to that uncertainty).
(f) The given uncertainty in the calculated reactivity of 0.000001 is increased to 0.000002 to account for additional uncertainty in the calculation.
(g) This ratio of the difference of the calculated β_{eff} from the given β_{eff} over the sum of the two uncertainties gives an idea of the agreement between the two β_{eff} values.

Because β_{eff} is a property of the system as a whole this method can be applied to any worth measurement taken for the system. This method is repeated for the uranium button worth measurements. Results are given in Table 2.6-2. Although there is a large variation in the β_{eff}, they are the same to within the 3σ uncertainty. These worth measurements were not as precisely measured and the worth cannot be as accurately calculated.

Table 2.6-2. Calculation of β_{eff} using Various Surface Worth Measurements.

	β_{eff}^{given} = 0.00657 ± 0.00009(a)			$\frac{\beta_{eff}-\beta_{eff}^{given}}{\sigma_\beta+\sigma_\beta^{given}}$ (b)
	Given Worth (¢)	$\rho(\Delta k)$(c) 10^3	β_{eff} 10^3	
16, 0.635-cm-thick Uranium Buttons on Sphere Surface	35.4 ± 2.868	2.862 ± 0.0028	8.085 ± 0.66	2.02
4, 0.3175-cm-thick Uranium Buttons on Sphere Surface	6.1415 ± 0.1167	0.43 ± 0.0028	7.005 ± 0.48	0.76
3, 0.3175-cm-thick Uranium Buttons in Socket Hole	7.86 ± 0.1274	0.54 ± 0.0028	6.89 ± 0.38	0.69
Surface Material Worth	96.5 ± 2.83	5.89 ± 0.028	6.10 ± 0.18	-2.34

(a) It should be noted that this value is derived using a small void region at the center of the core.
(b) This ratio of the difference of the calculated β_{eff} from the given β_{eff} over the sum of the two uncertainties gives an idea of the agreement between the two β_{eff} values.
(c) Change in reactivity was calculated using MCNP5 and ENDF/B-VII.0 neutron cross section libraries.

Based on these two studies it can be determined that this method is valid, although, it should be limited to use for worth measurements that are very accurately measured, with a uniform composition, and whose worth can also be calculated very accurately.

The final experimental uncertainty in the delayed neutron fraction was increased from 0.00002 to 0.00009 to account for increase in the uncertainty in the central void reactitivy from ±0.023 ¢ to ±0.123 ¢, and additional uncertainty in the calculated reactivity, increased from ±0.1 pcm to ±0.23 pcm.

2.6.2 Prompt Neutron Decay Constant[a]

The prompt neutron decay constant, α, is the asymptotic inverse reactor period or the logarithmic rate of change of the neutron population as is written in Equation 2.6.1.

Equation 2.6.1

$$\alpha = \frac{1}{n(t)}\frac{dn}{dt}$$

The value of α is reported as 1.1061 ± 0.0009 μsec^{-1}. The value is reported in Table 1.6-1 as a positive value but the prompt neutron decay constant is negative for systems below prompt critical.[b] The given uncertainty is from the statistics of the 538 measurements performed. It is much lower than the uncertainty given for GODIVA, 1.10 ± 0.01 μsec^{-1} (Reference 6 and 7). However, many of the 538 measurements were correlated and taking the deviation of the variance weighted average fails to account for possible systematic uncertainties. To account for this the ±0.0009 μsec^{-1} uncertainty was increased by the square root of the number of measurements and then divided by the square root of the number of independent source/detector configurations($\pm 0.0009 \cdot \sqrt{538}/\sqrt{7}$). This yields a final experimental uncertainty of ±0.0079 μsec^{-1} for the prompt neutron decay constant, α.

2.6.3 Mean Neutron Generation Time

Although the mean neutron generation time, Λ, was not reported by the experimenter, it can be derived from the independently measured delayed neutron fraction, β_{eff}, and the prompt neutron decay constant,

[a] Special thanks to Dr. Brian C. Kiedrowski of Los Alamos National Laboratory whose advice and input was integral to the formulation of the prompt neutron decay constant evaluation.
[b] J.D. Orndoff, "Prompt Neutron Periods of Metal Critical Assemblies," *Nucl. Sci. and Eng.*, **2**, 450 (1957).

α. Using the point kinetics Equation 2.6.2. and Equation 2.6.1, α can be approximated as Equation 2.6.3 when delayed neutrons can be neglected.

Equation 2.6.2
$$\frac{dn(t)}{dt} = \frac{\rho(t)-\beta_{eff}}{\Lambda} n(t) + \sum_{i=1}^{6} \lambda_i c_i(t),$$
$$\frac{dc_i(t)}{dt} = \frac{\beta_i}{\Lambda} n(t) - \lambda_i c_i(t), \quad i = 1, \ldots, 6$$

Equation 2.6.3
$$\alpha = \frac{\rho - \beta_{eff}}{\Lambda}$$

Where n is the neutron density; β_i, λ_i, and c_i are related to the delayed neutron precursor groups and are not a factor in this formulation; ρ is the reactivity of the system in units of Δk; β_{eff} is the effective delayed neutron fraction; and Λ is the mean generation time or neutron reproduction time. Equation 2.6.3 can be used to derive the mean generation time.

Equation 2.6.4
$$\Lambda = l = \frac{\rho - \beta_{eff}}{\alpha}$$

In Equation 2.6.4 the mean generation time is equal to the prompt neutron lifetime[a], l, and the reactivity, ρ, is zero because the system is at delayed critical. The three terms affecting the mean generation time are each independently measured:

$$\beta_{eff} = 0.00657 \pm 0.00009$$
$$\rho = 0 \pm 2\ ¢$$
$$\alpha = -1.1061 \pm 0.0079\ \mu sec^{-1}.$$

These values yield a value for Λ of 0.00594 μsec or 5.94 nanosec. The uncertainties can be propagated using Equation 2.6.4 to obtain an uncertainty of ±0.15 nanosec.

2.7 Evaluation of Reaction-Rate Distributions

2.7.1 Relative Neutron Importance

The radial distribution of the relative neutron importance was measured by the changes in count rate in external BF_3 counters as a source is passed through the diametral hole of the sphere normalized to the count rate when the source is at the center of the sphere. The 8.74268-cm-average-radius sphere was used (Case 2 in HEU-MET-FAST-100). Three BF_3 counters were used at locations shown in Figure 1.7-1. The source was a ^{252}Cf source, with a Maxwellian neutron spectrum and a temperature of 1.4 MeV.

It should be noted that the experimental setup is measuring count rate using BF_3 detectors which use a (n,α) reaction and not total flux. Because the system was a fast system, spectrum changes as the Cf source was passed through the diametral hole would have been minimal and the BF_3 count rate measurements would be proportional to the total flux and thus it is judged that the relative neutron importance is not biased by the use of BF_3 detectors. However, to be more precise what the experimenter calls the relative neutron importance will now be called relative neutron importance for BF_3 detector response and a Cf source.

The experimenter evaluated the effect of sphere position and orientation, room return, detector location, and source centering in the container. The effect of all these was found to be negligible. The uncertainties given in Table 1.7-1 are "precision[s] based on repeated measurement" (Reference 8). These uncertainties are taken to be the measurement uncertainties.

[a] J.J. Dudersstadt, "Nuclear Reactor Analysis," John, Wiley & Sons, reprinting of (1976) edition.

A rounding uncertainty of one in the last significant digit was applied to all relative neutron importance for BF_3 detector response and a Cf source measurements. This uncertainty was taken to be a bounding uncertainty with a uniform distribution. The 1σ rounding uncertainty was ±0.001/√3 or 0.00057.

The effect of sphere radius, uranium isotopic composition, sphere mass, and source position were evaluated using MCNP5.1.60 and ENDF/B-VII.0 neutron cross section library and the simple benchmark model. The uranium isotopic composition uncertainty effect was non-negligible; the sphere radius and mass and source position uncertainty effects were negligible. An uncertainty was judged to be negligible if the 1σ effect was less than the rounding uncertainty (±0.00057).

The uncertainty in the sphere radius was the same as for the critical benchmark model, 2.54 $\times 10^{-4}$ cm (1σ) (HEU-MET-FAST-100). The effect was evaluated by perturbing the sphere radius by 10σ above and below the benchmark sphere radius using the simple benchmark model. The difference between the high and low radius perturbed models over two yields the 10σ uncertainty effect. The effect is then scaled to the 1σ effect. The sphere mass was conserved when the sphere radius was adjusted. The effect of the uncertainty in the sphere radius on the relative neutron importance for BF_3 detector response and a Cf source was negligible.

The uncertainty in the uranium isotopic composition was the same as for the critical benchmark model (HEU-MET-FAST-100). The effect of the ^{235}U uncertainty was evaluated and the maximum uncertainty effect was 0.15%. It was judged that because this uncertainty was sufficiently small and because the uncertainty effect on the critical benchmark model of the ^{234}U and ^{236}U content was smaller than the effect of the ^{235}U enrichment that the effect of the ^{234}U and ^{236}U content would be negligible for the relative neutron importance for BF_3 detector response and a Cf source. The uncertainty in ^{235}U enrichment was ±0.0177 wt.% (1σ). The effect was evaluated using a similar approach to that used for the sphere radius. The ^{238}U content was adjusted to maintain unity. The maximum uncertainty effect of 0.15% was applied to all measurement points.

The uncertainty in the sphere mass was the same as for the total mass uncertainty for the 8.74268-cm-average-radius sphere of the surface worth coefficient measurements, 0.21 g (Table 2.5-1). The effect was evaluated using a similar approach to that used for the sphere radius. When the sphere mass was adjusted the sphere radius was held constant. The effect of the uncertainty in the sphere mass on the relative neutron importance for BF_3 detector response and a Cf source was negligible.

The uncertainty in the source position was taken to be ± 0.001 cm, which is one in the last significant digit of the given source location. The source position was perturbed by 3σ in the simple benchmark model. However, the results of the calculation were meaningless because they were not larger than the statistical uncertainty. Rather than increasing the scaling factor the slope of the relative neutron importance for BF_3 detector response and a Cf source was used. The slope of each measurement point, n_i, was determined using the following equation:

Equation 2.7.1

$$n_i = \frac{y_{i+1} - y_{i-1}}{x_{i+1} - x_{i-1}} \cdot \sigma_x$$

where y_i is the measured relative neutron importance for BF_3 detector response and a Cf source, x_i is the measured source location, and σ_x is the position uncertainty. This method does not yield a value for the end point measurements. The effect of the source position uncertainty was negligible. This agrees with the experimental findings that the source position in the source container has a negligible effect.

An additional uncertainty to account for the normalization was also included. Because the measured count rates were normalized to the count rate when the source was at the center of the sphere, the uncertainty in all points is multiplied by $\sqrt{2}$. Since the same uncertainty value is applied to all measurement points this simplified approach is justified. There is no uncertainty associated with the normalization point.

The uncertainties in the relative neutron importance for BF_3 detector response and a Cf source are summarized in Table 2.7-1. The total uncertainty is given in Table 2.7-2.

It should be noted that these measurements are the relative neutron importance for BF_3 detector response and a Cf source. The results are only a trend in the data and are not absolute. This is why the uncertainty effects are very small or negligible; the effect washes out when the normalization is performed.

Table 2.7-1. Summary of Experimental Uncertainty in Relative Neutron Importance for BF_3 Detector Response and a Cf Source.

Uncertainty		Effect
Sphere Radius	±	NEG
Uranium Isotopic composition	±	0.15%
Sphere Mass	±	NEG
Source Position	±	NEG
Total	±	0.15%√2[(a)]
Rounding	±	0.001/√3

(a) The √2 accounts for the added uncertainty from the normalization.

Table 2.7-2. Relative Neutron Importance for BF_3 Detector Response and a Cf Source Experimental Uncertainty.

Radius (cm)	Relative Neutron Importance	Radius (cm)	Relative Neutron Importance
-8.138	0.278 ± 0.0031	0	1 --[(a)]
-8.105	0.267 ± 0.0022	0.660	0.986 ± 0.0024
-8.100	0.289 ± 0.0013	0.805	0.985 ± 0.0029
-8.004	0.299 ± 0.0013	0.904	0.992 ± 0.0024
-7.480	0.379 ± 0.0022	1.905	0.951 ± 0.0029
-6.833	0.464 ± 0.0023	2.024	0.956 ± 0.0023
-6.825	0.458 ± 0.0032	2.078	0.932 ± 0.0029
-6.759	0.425 ± 0.0023	3.175	0.864 ± 0.0022
-6.731	0.468 ± 0.0032	3.449	0.848 ± 0.0900
-5.730	0.578 ± 0.0024	4.445	0.750 ± 0.0020
-5.583	0.620 ± 0.0025	4.646	0.716 ± 0.0019
-5.484	0.624 ± 0.0025	4.722	0.737 ± 0.0019
-5.428	0.633 ± 0.0033	5.712	0.608 ± 0.0017
-4.392	0.729 ± 0.0034	5.895	0.576 ± 0.0017
-4.288	0.759 ± 0.0020	5.994	0.589 ± 0.0017
-4.221	0.770 ± 0.0026	7.216	0.418 ± 0.0015
-4.166	0.761 ± 0.0026	7.419	0.414 ± 0.0023
-3.208	0.860 ± 0.0022	7.650	0.364 ± 0.0014
-3.170	0.849 ± 0.0021	8.273	0.277 ± 0.0013
-3.012	0.875 ± 0.0022	8.400	0.264 ± 0.0013
-2.891	0.886 ± 0.0028	8.443	0.243 ± 0.0013
-1.900	0.936 ± 0.0023	8.590	0.230 ± 0.0013
-1.740	0.956 ± 0.0037	8.618	0.224 ± 0.0012
-1.618	0.958 ± 0.0029	8.745	0.204 ± 0.0021
-0.632	0.987 ± 0.0024	9.091	0.165 ± 0.0012
-0.470	0.992 ± 0.0022		

(a) There is no uncertainty associated with the normalization point.

2.7.2 Relative Fission Density

The relative fission density measurement was the activation of uranium cylinders inserted through the diametral hole of the sphere normalized to a corresponding activation of a cylinder at the center of the sphere. The uranium activation cylinders were 0.330 cm in diameter and 0.635 or 0.318 cm long. The 8.74268-cm-average-radius sphere was used (Case 2 in HEU-MET-FAST-100). The experimenter evaluated the effect of the sphere orientation and room return on the relative fission density measurements. It was found that the effect of both is negligible. The uncertainties given in Table 1.7-2 are based on multiple measurements and are taken to be the measurement uncertainties.

A rounding uncertainty of one in the last significant digit was applied to all relative fission densities. This uncertainty was taken to be a bounding uncertainty with a uniform distribution. The 1σ rounding uncertainty was $\pm 0.001/\sqrt{3}$ or 0.00057.

The effect of the uranium activation cylinder position, diameter, and length, the uranium isotopic composition, and the uranium mass were evaluated using MCNP5.1.60 and ENDF/B-VII.0 neutron cross section library and the simple benchmark model. The effect of all these uncertainties was negligible except for the cylinder position which was 0.40%. An uncertainty was judged to be negligible if the 1σ effect was less than the rounding uncertainty (±0.00057).

The uncertainty in the cylinder position was taken to be ±0.01 cm. Most of the cylinder positions were given to three decimals; however, for two measurements the position was only given to two. Because the uncertainty in position was taken to be one in the last significant digit, the larger 0.01 cm value was applied to all data points. The method of evaluation was the same as for the position uncertainty for the relative neutron importance for BF_3 detector response and a Cf source (Section 2.7.1). The maximum effect of ± 0.41% was applied to all measurement points.

The cylinder length was given as being either 0.635 or 0.318 cm long. It is not specified what length of cylinder was used for each measurement point. For the benchmark model a length of 0.318 cm was used. The uncertainty in cylinder length was evaluated by using a 0.635 cm cylinder. The effect of cylinder length on the relative fission density is negligible.

The diameter of the cylinder was given as 0.330 cm. The effect was evaluated by perturbing the diameter cylinder by 10σ above and below the benchmark value using the detailed benchmark model. The difference between the high and low perturbed models divided by two yields the 10σ uncertainty effect. The effect is then scaled to the 1σ effect. The effect of the uncertainty in the cylinder diameter on the relative fission density was negligible.

The uranium isotopic composition was evaluated in the same manner as for the relative neutron importance for BF_3 detector response and a Cf source (Section 2.7.1). The effect of the uncertainty in ^{235}U enrichment on the relative fission density was negligible.

The effect of the mass of the sphere was evaluated in the same manner as for the relative neutron importance for BF_3 detector response and a Cf source (Section 2.7.1). The effect of the uncertainty in the sphere mass on the relative fission density was negligible.

An additional uncertainty to account for the normalization was also included. Because the measured activations were normalized to the activation at the center of the sphere, the uncertainty in all points is multiplied by $\sqrt{2}$. Since the same uncertainty value is applied to all measurement points this simplified approach is justified. There is no uncertainty associated with the normalization point.

The uncertainties in the relative fission density are summarized in Table 2.7-3. The total uncertainties are given in Table 2.7-4.

It should be noted that these measurements are the relative fission density. The results are only a trend in the data and are not absolute. This is why the uncertainty effects are very small or negligible; the effect washes out when the normalization is done.

Table 2.7-3. Summary of Experimental Uncertainty in Fission Density.

Uncertainty		Effect
Cylinder Position	±	0.40%
Cylinder Diameter	±	NEG
Cylinder Length	±	NEG
Uranium Isotopic composition	±	NEG
Sphere Mass	±	NEG
Source Position	±	NEG
Total	±	0.40%√2[(a)]
Rounding	±	0.001/√3

(a) The √2 accounts for the added uncertainty from the normalization.

Table 2.7-4. Relative Radial Fission Density Uncertainty.

Radius (cm)	Relative Fission Density	Radius (cm)	Relative Fission Density
-8.265	0.261 ± 0.0019	0.635	0.996 ± 0.0058
-7.633	0.354 ± 0.0023	1.272	0.978 ± 0.0059
-6.995	0.440 ± 0.0027	1.908	0.956 ± 0.0062
-6.355	0.519 ± 0.0032	2.543	0.910 ± 0.0056
-5.725	0.603 ± 0.0040	3.180	0.872 ± 0.0058
-5.088	0.672 ± 0.0049	3.815	0.810 ± 0.0047
-4.450	0.746 ± 0.0044	4.450	0.742 ± 0.0047
-3.815	0.810 ± 0.0055	5.088	0.675 ± 0.0043
-3.180	0.871 ± 0.0053	5.725	0.600 ± 0.0036
-2.54	0.910 ± 0.0060	6.355	0.518 ± 0.0058
-1.908	0.951 ± 0.0058	6.995	0.438 ± 0.0032
-1.272	0.978 ± 0.0059	7.633	0.351 ± 0.0023
-0.635	1.001 ± 0.0070	8.265	0.257 ± 0.0025
0	1 --[(a)]		

(a) There is no uncertainty associated with the normalization point.

2.8 Evaluation of Power Distribution Data

Power distribution measurements were not performed.

2.9 Evaluation of Isotopic Measurements

Isotopic measurements were not performed.

2.10 Evaluation of Other Miscellaneous Types of Measurements

Other miscellaneous types of measurements were not performed.

3.0 BENCHMARK SPECIFICATIONS

Models of the experiments were created using MCNP5 with ENDF/B-VII.0 neutron cross section libraries. Models were run in MCNP5 such that the statistical uncertainty (1σ) of k_{eff} was not more than 0.00002.

3.1 Benchmark-Model Specifications for Critical and/or Subcritical Measurements

The criticality portion of this evaluation has been reviewed and approved by the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and has been published under the following identifier: HEU-MET-FAST-100.[a]

3.2 Benchmark-Model Specifications for Buckling and Extrapolation-Length Measurements

Buckling and extrapolation-length measurements were not performed.

3.3 Benchmark-Model Specifications for Spectral Characteristics Measurements

Spectral characteristic measurements were not performed.

3.4 Benchmark-Model Specifications for Reactivity Effects Measurements

3.4.1 Description of the Benchmark Model Simplifications

The as-built model and the detailed model of the 8.74268-cm-average-radius sphere (Case 2) were used as the base model for the worth measurements. Changes made to the base model for each worth measurement are described in Section 3.4.2 and 3.4.3. The simplification biases and corrections applied to obtain the base detailed model are (1) the room return and air bias, (2) the effect of removing the stainless steel table of the vertical lift machine, (3) the measured correction for the upper support structure, (5) the measured correction for the support rod and upper socket, (6) the measured correction for the center and lower support structure, and (7) the measured temperature correction. These simplifications are described in more detail in HEU-MET-FAST-100. A worth measurement is a result of a change in the system reactivity. It is judged that the aforementioned simplifications have negligible effects on the worth measurements because the structure, which is removed in the base detailed benchmark model, is constant and is not changed when changes are made to the system.

The benchmark model for the worth measurements of the three buttons in the empty socket hole did not include the mass adjustment buttons on the surface of the sphere. This simplification was within the statistical noise of the Monte Carlo calculation. The simplification bias introduced by not including the mass adjustment buttons on the surface of the sphere in the benchmark models was judged to be negligible because the buttons were on the surface of the sphere and were present both when the three buttons were added to and removed from the empty socket hole of the upper polar cap.

There were no additional simplification biases for the worth measurements.

[a] International Handbook of Evaluated Criticality Safety Benchmark Experiments, NEA/NSC/DOC(95)03, OECD-NEA, Paris (2013).

3.4.2 Dimensions

The benchmark models for the worth measurement are based on the detailed critical benchmark model for the 8.742395-cm-average-radius sphere (detailed Case 2 benchmark model in HEU-MET-FAST-100). The dimensions for this model are given in Figure 3.4-1, Figure 3.4-2, and Figure 3.4-3. These figures are provided for reference; HEU-MET-FAST-100 should be referenced for a full description. Changes to each section of sphere for individual measurements are described in Section 3.4.2.1 through 3.4.2.3.

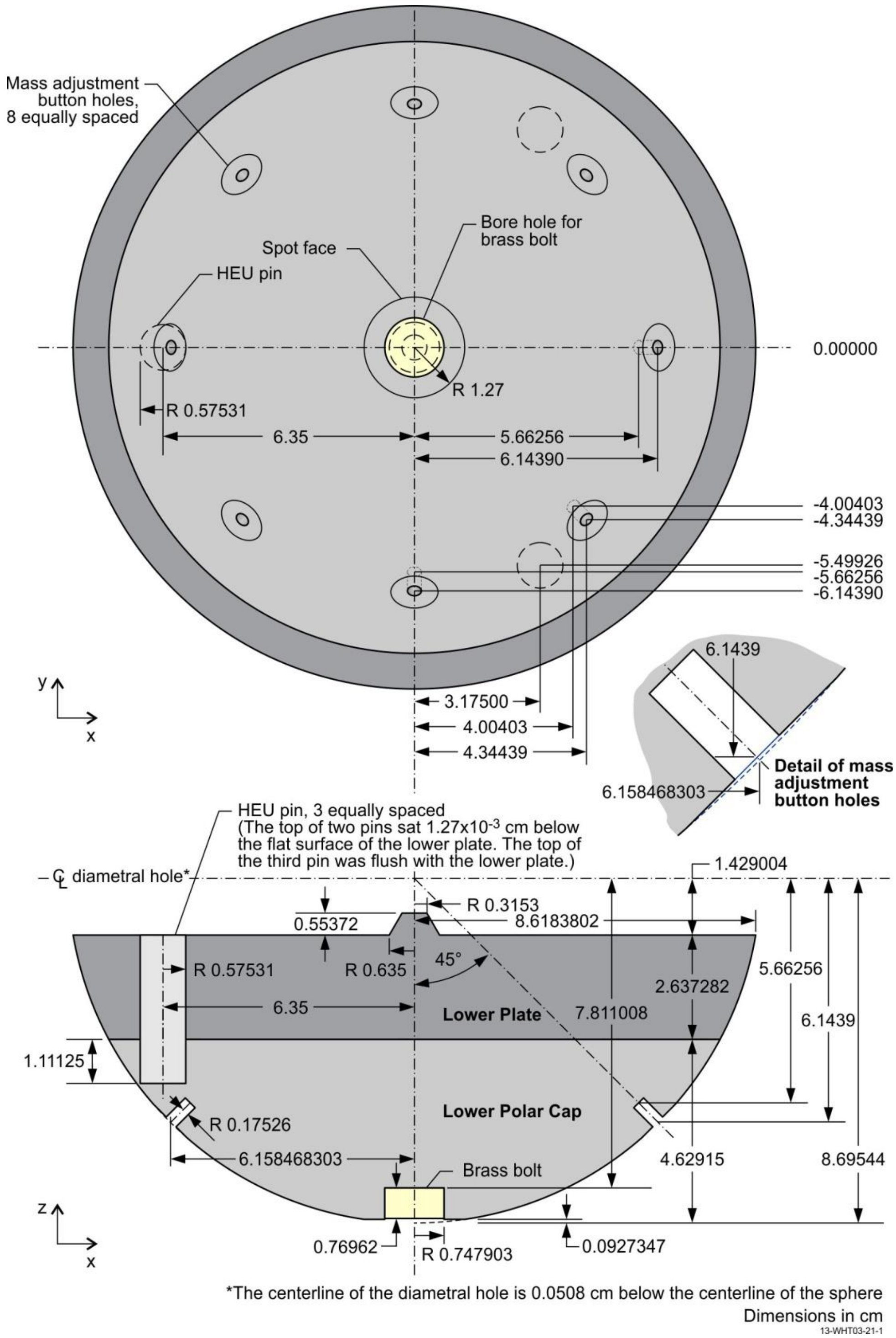

Figure 3.4-1. Bottom Section of Sphere for Base Model for Worth Measurements.

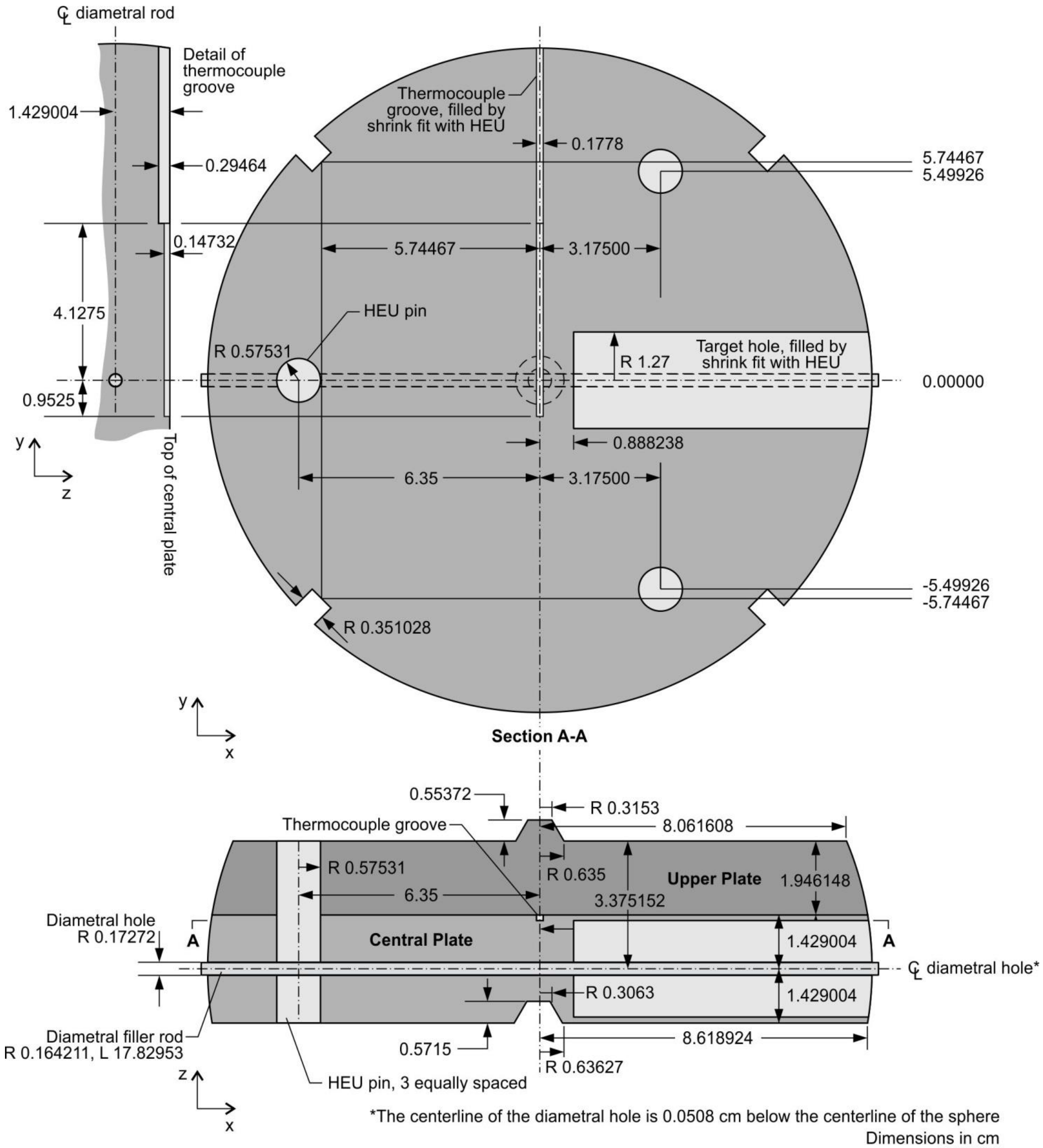

Figure 3.4-2. Center Section of Sphere for Base Model for Worth Measurements.

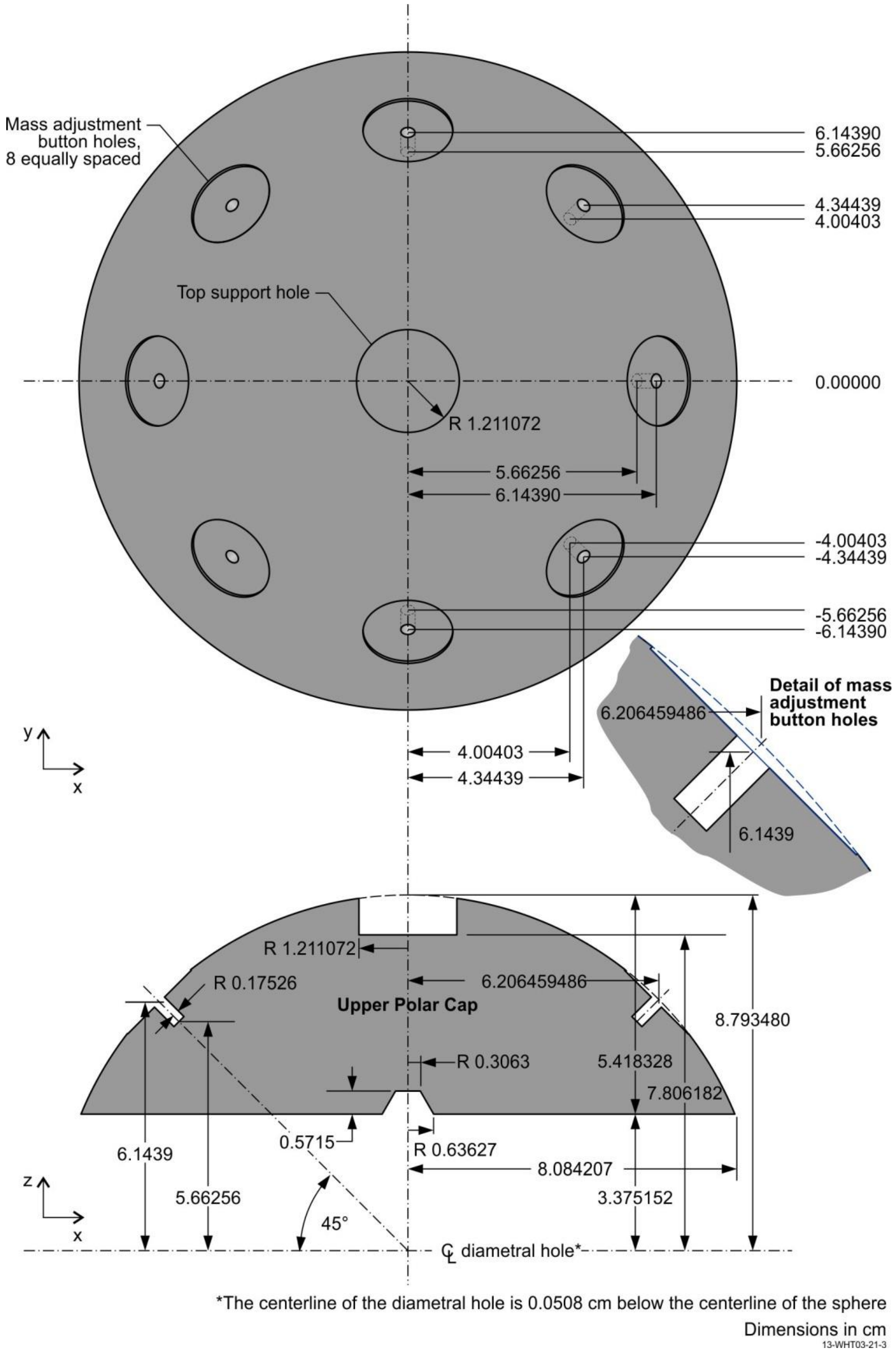

Figure 3.4-3. Upper Polar Cap for Base Model for Worth Measurements.

3.4.2.1 Central Void Reactivity

For the central void reactivity measurements, the center plate of the Case 2 core was modified. Sections of the diametral hole were drilled to a larger diameter and a surface hole was added. These holes are plugged in the benchmark model for the central void reactivity. A 0.5842-cm-radius sphere at the center of the larger sphere is added to and removed from the benchmark model to determine the central void reactivity. The modified central plate and plugs used for the central void reactivity benchmark model are shown in Figure 3.4-4. The bottom section and upper polar cap are the same as for the critical benchmark model, Figure 3.4-1 and Figure 3.4-3.

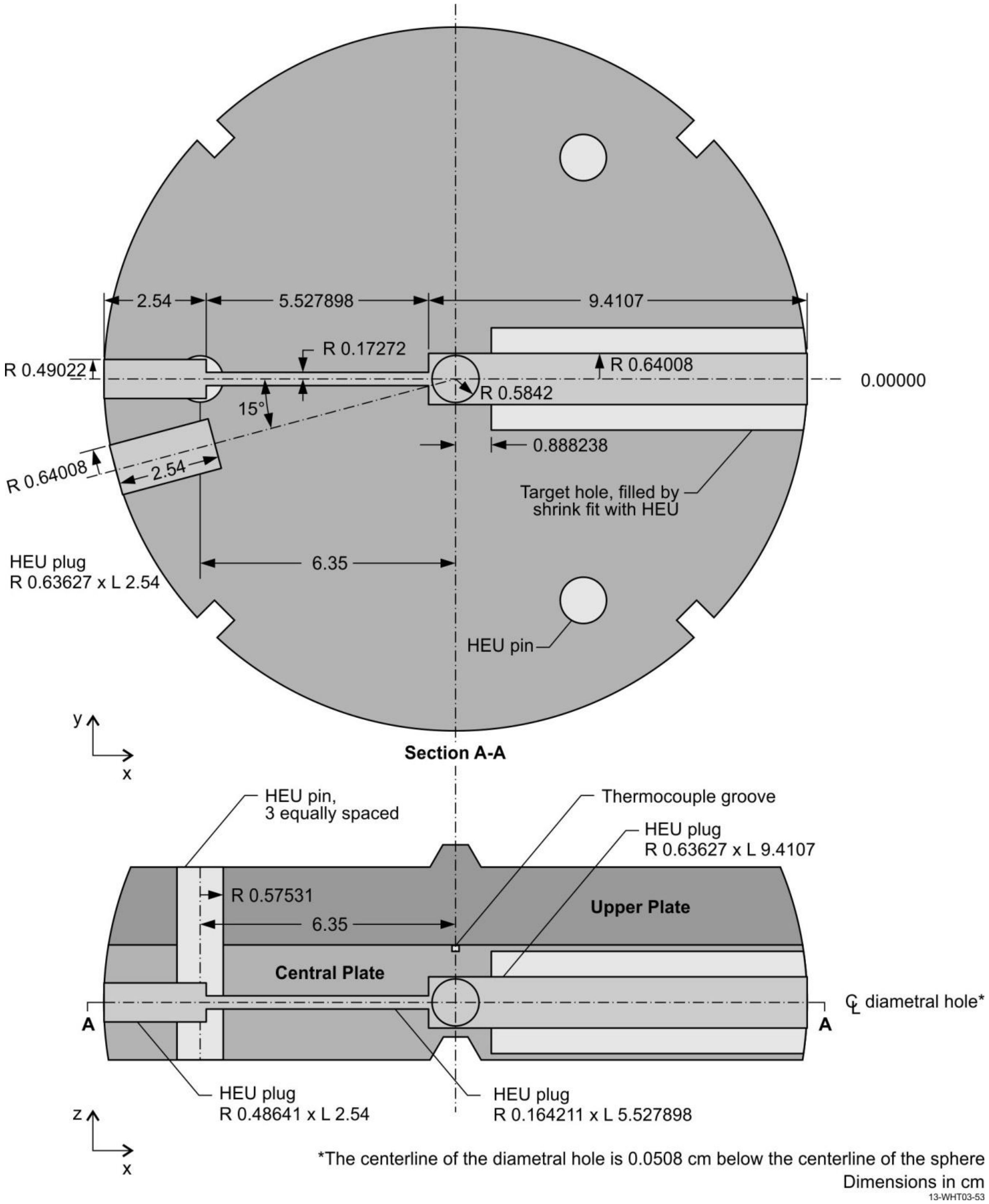

Figure 3.4-4. Modified Center Plate and HEU Plugs for the Central Void Reactivity Measurement.

3.4.2.2 Button Worth Measurements

The benchmark models for the button worth measurements are shown in Figure 3.4-1, Figure 3.4-2, and Figure 3.4-3. For the benchmark models for the button worth measurements, mass adjustment buttons are added to the surface of the sphere, as shown in Figure 3.4-5 and Figure 3.4-6, and placed in the empty socket hole of the upper polar cap, as shown in Figure 3.4-7.

For the worth of the 16, 0.635-cm-thick mass adjustment buttons, no buttons or screws are present for the reference benchmark model. The reference benchmark model is identical to the critical detailed benchmark model for Case 2 of HEU-MET-FAST-100. For the perturbed benchmark model 16, 0.635-cm-thick × 1.10744-cm-OR × 0.22479-cm-IR buttons are added to the 16 mass adjustment recesses with 16, 0.175247-cm-radius × 1.25349-cm-long screws. The difference between the reactivity of the reference and perturbed benchmark model yields the worth of 16, 0.635-cm-thick uranium buttons with holding screws.

For the worth of the 4, 0.3175-cm-thick uranium mass adjustment buttons the reference benchmark model has 12, 0.3175-cm-thick × 1.10744-cm-OR × 0.22479-cm-IR uranium mass adjustment buttons and 16, 0.175247-cm-radius × 0.93599-cm-long holding screws on the mass adjustment button recesses. The mass adjustment button recesses B1 and B5 in Figure 3.4-5 and T3 and T7 in Figure 3.4-6 did not have uranium buttons but did have holding screws in the reference benchmark model; all other mass adjustment button recesses held a uranium button. For the perturbed benchmark model the 0.3175-cm-thick uranium buttons are added to the four empty mass adjustment button recesses. The difference between the reactivity of the base and perturbed benchmark model yields the worth of 4, 0.3175-cm-thick uranium buttons independent of the holding screws.

The worth of one 0.3175-cm-thick aluminum button was measured by: determining the worth of three and four aluminum buttons, including the worth of the holding screws; dividing by the number of aluminum buttons, yielding multiple worth per aluminum button values: and then averaging the results to get an average worth per aluminum buttons. The reference benchmark models had 12 and 13, 0.3175-cm-thick × 1.10744-cm-OR × 0.22479-cm-IR uranium buttons with 12 and 13 0.175247-cm-radius × 0.93599-cm-long holding screws. For the perturbed benchmark model three or four 0.3175-cm-thick × 1.10744-cm-OR × 0.22479-cm-IR aluminum buttons with 0.175247-cm-radius × 0.93599-cm-long holding screws are placed in the empty mass adjustment button recesses. The aluminum buttons are placed in location B1, T3, and T7 for the three buttons and B1, B5, T3, and T7 for the four buttons, see Figure 3.4-5 and Figure 3.4-6. The difference between the reactivity of the reference and perturbed benchmark models yields the worth of 3 and 4, 0.3175-cm-thick aluminum buttons including the holding screws. The worth is then divided by the number of buttons, yielding two worth per aluminum button values, and the results are averaged to determine the benchmark worth per aluminum button.

For the worth of 3 mass adjustment buttons in the empty socket hole of the upper polar cap the reference benchmark model is identical to the Case 2 critical sphere detailed benchmark model of HEU-MET-FAST-100, shown for reference in Figure 3.4-1, Figure 3.4-2, and Figure 3.4-3. Three buttons were stacked in the socket hole of the upper polar cap for the perturbed benchmark model as shown in Figure 3.4-7. Three aluminum buttons, three uranium buttons, and three stainless steel buttons were placed in the socket hole. The difference between the reactivity of the reference benchmark model and the perturbed benchmark models for each button type yields the worth of the buttons in the socket hole.

The mass of the 0.635-cm-thick × 1.10744-cm-OR × 0.22479-cm-IR uranium buttons was given as 43.9 g each. The 0.635-cm-thick uranium buttons have a density of 18.71428 g/cm^3 in the benchmark models.

The mass of three, 0.3175-cm-thick × 1.10744-cm-OR × 0.22479-cm-IR uranium buttons was given as 65.2 g for three buttons. The 0.3175-cm-thick uranium buttons have a density of 18.52956 g/cm^3 in the benchmark models.

The aluminum Type 6061buttons and stainless steel Type 304 holding screws and buttons are modeled at nominal compositions as given in Table 2.4-6 and Table 2.4-7.

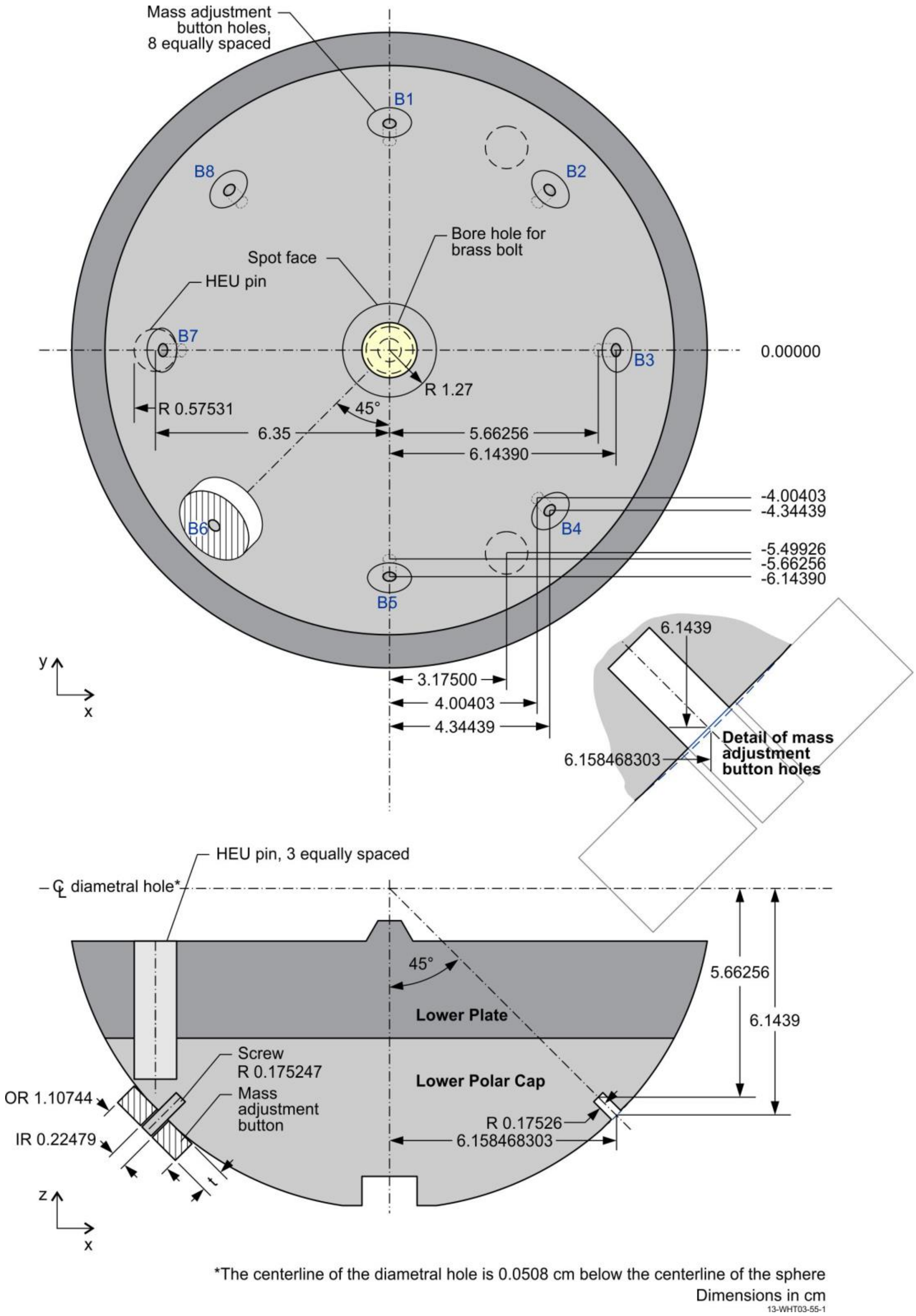

Figure 3.4-5. General Button Placement on Lower Polar Cap.

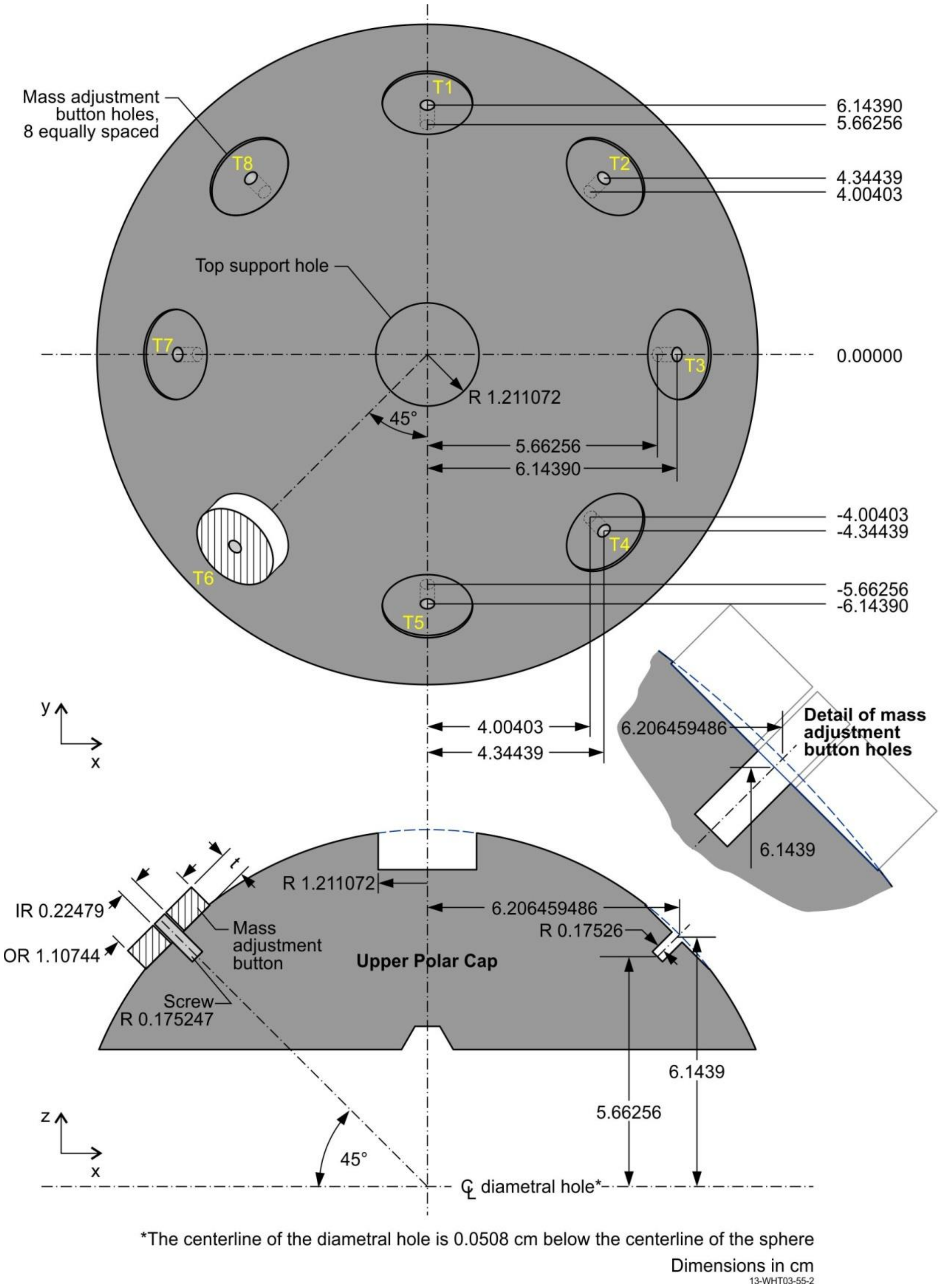

Figure 3.4-6. General Button Placement on Upper Polar Cap.

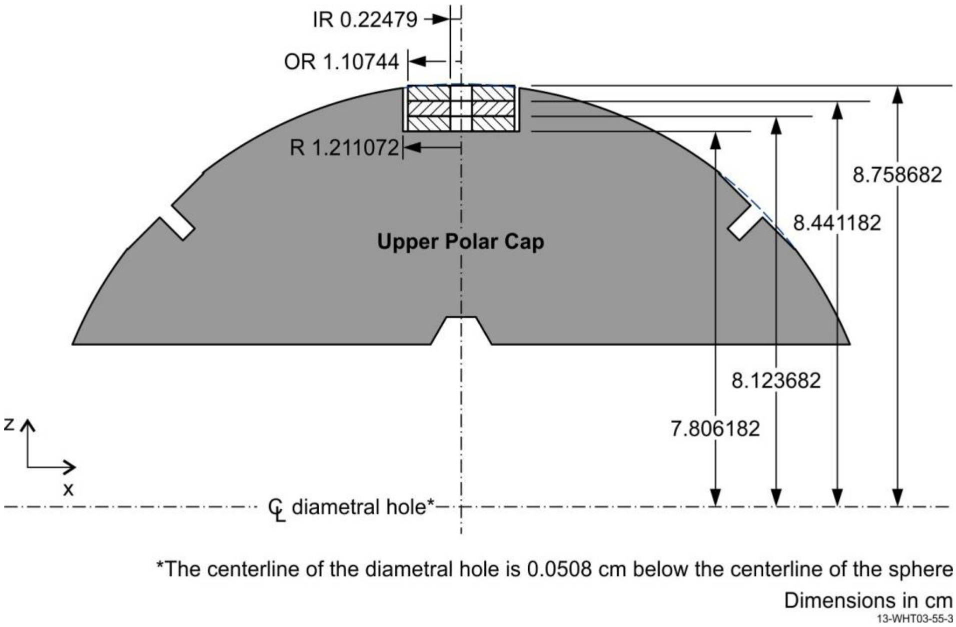

Figure 3.4-7. Button Placement in Empty Socket Hole of Upper Polar Cap.

3.4.2.3 Diametral Filler Rod Worth Measurements

The reference benchmark model was identical to the critical sphere shown in Figure 3.4-1, Figure 3.4-2, and Figure 3.4-3. For the perturbed benchmark model the diametral filler rod, whose dimensions are given in Figure 3.4-2, was removed. The difference between the base reference and perturbed benchmark models yields the worth of the diametral filler rod.

3.4.3 Material Data

The material data for the bottom, center, and upper section of the sphere of the Case 2 core are given in HEU-MET-FAST-100.

The material data for the central void reactivity measurement are given in Table 3.4-1.

The material data for the 0.635-cm-thick and 0.3175-cm-thick uranium buttons are given in Table 3.4-2.

The material data for the stainless steel holding screws and buttons are given in Table 3.4-3.

The material data for the aluminum buttons are given in Table 3.4-4.

The material data for the diametral filler rod is the same as for the 0.164211-cm-radius plug for the diametral hole section given in Table 3.4-1.

Table 3.4-1. Atom Densities for Plugs and Sphere for Central Void Reactivity Measurement.

Element/ Isotope	Atom Density (atom/b-cm)			
	0.63627-cm-Radius Plug for Diametral Hole Section and Small Sphere	0.164211-cm-Radius Plug for Diametral Hole Section	0.48641-cm-Radius Plug for Diametral Hole Section	0.63627-cm-Radius Plug for Surface Hole
U Total	4.7850E-02	4.7722E-02	4.7850E-02	4.7850E-02
^{234}U	*4.7509E-04*	*4.7738E-04*	*4.7509E-04*	*4.7509E-04*
^{235}U	*4.4608E-02*	*4.4485E-02*	*4.4608E-02*	*4.4608E-02*
^{236}U	*2.1264E-04*	*2.1446E-04*	*2.1264E-04*	*2.1264E-04*
^{238}U	*2.5539E-03*	*2.5450E-03*	*2.5539E-03*	*2.5539E-03*
Al	2.0866E-06	2.0810E-06	2.0866E-06	2.0866E-06
Si	4.8109E-05	4.7981E-05	4.8109E-05	4.8109E-05
Mn	3.7851E-06	3.7751E-06	3.7851E-06	3.7851E-06
Ni	6.3270E-06	6.3102E-06	6.3270E-06	6.3270E-06
Cr	4.9991E-07	4.9858E-07	4.9991E-07	4.9991E-07
Cu	1.4609E-06	1.4570E-06	1.4609E-06	1.4609E-06
B	3.1245E-07	3.1162E-07	3.1245E-07	3.1245E-07
C	1.5749E-04	1.5707E-04	1.5749E-04	1.5749E-04
O	1.4075E-05	1.4038E-05	1.4075E-05	1.4075E-05
N	2.4117E-05	2.4052E-05	2.4117E-05	2.4117E-05
Total	4.8108E-02	4.7980E-02	4.8108E-02	4.8108E-02

Table 3.4-2. Atom Densities for Uranium Buttons.

Element/ Isotope	Atom Density (atom/b-cm) 0.635-cm-Thick Uranium Buttons	Atom Density (atom/b-cm) 0.3175-cm-Thick Uranium Buttons
U Total	4.7885E-02	4.7412E-02
^{234}U	*4.7382E-04*	*4.6914E-04*
^{235}U	*4.4674E-02*	*4.4233E-02*
^{236}U	*1.7149E-05*	*1.6979E-05*
^{238}U	*2.7202E-03*	*2.6934E-03*
Be	6.2518E-09	6.1901E-09
Li	1.6235E-07	1.6074E-07
Al	8.3527E-07	8.2703E-07
Si	8.0244E-05	7.9452E-05
Mn	4.1546E-06	4.1136E-06
Ni	6.9447E-06	6.8761E-06
Cr	5.4871E-07	5.4329E-07
Cu	1.6035E-06	1.5877E-06
B	2.0846E-07	2.0640E-07
C	9.5604E-08	9.4660E-08
O	1.4058E-06	1.3919E-06
N	2.8708E-04	2.8425E-04
Total	1.4086E-05	1.3947E-05

Table 3.4-3. Atom Densities for Stainless Steel Screws and Buttons.

Element	Atom Density (atom/b-cm) Stainless Steel Type 304
Fe	6.0319E-02
C	1.6044E-04
Mn	8.7693E-04
Si	8.5768E-04
Cr	1.7604E-02
Ni	7.7983E-03
P	3.4997E-05
S	2.2534E-05
Total	8.7674E-02

Table 3.4-4. Atom Densities for Aluminum Buttons.

Element	Atom Density (atom/b-cm) Aluminum Type 6061
Al	5.8638E-02
Cr	6.0978E-05
Cu	7.0365E-05
Fe	1.0190E-04
Mg	6.6898E-04
Mn	2.2197E-05
Si	3.4736E-04
Ti	2.5469E-05
Zn	3.1082E-05
Total	5.9967E-02

3.4.4 Temperature Data

The benchmark models for the worth measurements are evaluated at room temperature (294 K).

3.4.5 Experimental and Benchmark-Model Reactivity Effect Parameters

The various worth measurements with uncertainties, as derived in Section 2.4, are summarized in Table 3.4-5.

Table 3.4-5. Benchmark Worth Values.

	Worth (¢)
Central Void	9.165 ± 0.123
16, 0.635-cm-thick Uranium Buttons on Sphere Surface	35.4 ± 2.868
4, 0.3175-cm-thick Uranium Buttons on Sphere Surface	6.1415 ± 0.117
1, 0.3175-cm-thick Aluminum Button on Sphere Surface	0.7058 ± 0.062
3, 0.3175-cm-thick Uranium Buttons in Socket Hole	7.86 ± 0.127
3, 0.3175-cm-thick Stainless Steel Buttons in Socket Hole	4.7228 ± 0.076
3, 0.3175-cm-thick Aluminum Buttons in Socket Hole	3.1259 ± 0.074
Diametral Filler Rod	11.2340 ± 0.168

3.5 Benchmark-Model Specifications for Reactivity Coefficient Measurements

3.5.1 Description of the Benchmark-Model Simplifications

There are two benchmark models for the worth per gram of uranium on the surface of the sphere. The first was based on the Case 1 detailed benchmark model in HEU-MET-FAST-100; the tilt between the lower and center plates was removed. This was done by moving the small volume of pin protruding above the upper surface of the lower plate into the remaining volume of the pin. This slightly increased the density of the pin. The tilt was then removed so the center plate sat flush on the lower plate. The second benchmark model was identical to the Case 2 detailed benchmark model in HEU-MET-FAST-100. Detailed models of the spheres were created with MCNP5 with ENDF/B-VII.0 neutron cross section libraries. Various simplifications were made to the two spheres to create detailed benchmark models from the as-built models. These simplifications are described in detail in HEU-MET-FAST-100. Because the two spheres are nearly identical, the benchmark-model simplifications are highly correlated and the effect of the system simplifications on the change in system reactivity is negligible.

3.5.2 Dimensions

The dimensions for the two critical spheres are given as Case 1 for the 8.80491-cm-average-radius sphere and as Case 2 for the 8. 74268-cm-average-radius sphere in HEU-MET-FAST-100. The 8.80491-cm-average-radius sphere is modified so the pin no longer protrudes above the upper surface of the lower plate but is flush with it and the tilt is removed. This is done by moving the 6.0746×10^{-3} cm^3 volume above the surface of the plate into the 3.89776 cm^3 below the surface of the sphere. This increases the density from 18.8013 g/cm^3 to 18.8306 g/cm^3. Only one pin is affected; all other pins and surrounding material do not change. No change is made to the 8. 74268-cm-average-radius sphere.

There is a change in mass of 1,125.04 grams between the two spheres.

3.5.3 Material Data

The materials for the two critical spheres, except for the pin in the lower section that is shaved to remove the tilt, are given as Case 1 for the 8.80491-cm-average-radius sphere and as Case 2 for the 8. 74268-cm-average-radius sphere in HEU-MET-FAST-100. The pin that protrudes above the surface of the lower plate has an increased density and the material data are given in Table 3.5-1.

Table 3.5-1. Material Data for Shaved Pin for 8.80491-cm-Average-Radius Sphere.

Element/ Isotope	Atom Density (atom/b-cm)
	Shaved Pin (x=-6.35, y=0)
U Total	4.8195E-02
^{234}U	*4.8211E-04*
^{235}U	*4.4926E-02*
^{236}U	*2.1658E-04*
^{238}U	*2.5702E-03*
Be	-
Li	-
Al	2.1016E-06
Si	4.8457E-05
Mn	3.8124E-06
Ni	6.3727E-06
Cr	5.0352E-07
Cu	1.4714E-06
B	3.1471E-07
Co	-
Ca	-
C	1.5863E-04
O	1.4177E-05
N	2.4291E-05
Total	4.8455E-02

3.5.4 Temperature Data

The benchmark models for the two spheres are evaluated at room temperature (294 K).

3.5.5 Experimental and Benchmark-Model Reactivity Coefficient Measurements

The benchmark worth per gram of uranium surface material is 0.086 ± 0.003 ¢.

3.6 Benchmark-Model Specifications for Kinetics Measurements

3.6.1 Description of the Benchmark Model Simplifications

3.6.1.1 Effective Delayed Neutron Fraction

The effective delayed neutron fraction, β_{eff}, was evaluated using the critical benchmark models for the two spheres described in HEU-MET-FAST-100. The effect on the β_{eff} value of the simplifications made to the as-built model to get the detailed benchmark models for the critical sphere was evaluated using MCNP5 and ENDF/B-VII.0 neutron cross section libraries and was found to be negligible.

3.6.1.2 Prompt Neutron Decay Constant

The prompt neutron decay constant, α, was measured using the smaller, Case 2, sphere from HEU-MET-FAST-100, but with a variable number of uranium buttons to bring the system to delayed critical. The system reactivity for the numerous measurements varied between ±0.5 ¢. The reactivity for the prompt neutron decay constant benchmark value must also be at exactly delayed critical. Because no single system configuration was given for exactly delayed critical the simple critical benchmark model for Case 2 of HEU-MET-FAST-100 was corrected to delayed critical. The model was corrected using the worth per gram of surface material worth coefficient, see Section 3.5.5.

The simple benchmark model of the Case 2 critical assembly of HEU-MET-FAST-100 had a radius of 8.72995881 cm and mass of 52,350.943 g which corresponds to a volume of 2,786.924436 cm^3 and density of 18.78448598 g/cm^3.[a] The worth per gram of surface material was 0.086 ± 0.003 ¢/g; which converts to $5.65 \pm 0.21 \times 10^{-6}$ $\Delta k_{eff}/g$. The benchmark k_{eff} of the simple benchmark model is 0.9966 ± 0.0007. Because the reactivity measurement uncertainty of 2.0 ¢ was included in the sphere and the worth per gram of surface material uncertainties, the uncertainty in the sphere was reduced from 0.0007 to 0.00069 so as to not double count the reactivity measurement uncertainty. This uncertainty includes all material, dimensional and bias uncertainty in the sphere model. In order to bring the system to exactly delayed critical 603.8015 ± 125.526 grams of material must be added to the sphere. This mass is added by increasing the sphere volume, i.e. radius, and maintaining constant density. The volume is increased by 32.1436 ± 6.7953 cm^3 and a final radius of 8.76339 ± 0.00692 cm. If α is calculated using the benchmark model with the sphere radius perturbed by ±0.00692 cm the change in α is ±0.1068 μsec^{-1}. This is taken to be the bias uncertainty. When added with the experimental uncertainty of ±0.0079 μsec^{-1} the benchmark uncertainty is ±0.1071 μsec^{-1}.

3.6.1.3 Mean Neutron Generation Time

The benchmark model for the mean neutron generation time or prompt neutron lifetime, since the system was at delayed critical, was identical to the benchmark model for the prompt neutron decay constant. When the bias uncertainty in the sphere radius discussed in Section 3.6.1.2 is taken into account the uncertainty in Λ is increased from ±0.15 nanosec for the experimental uncertainty to ±0.59 nanosec for the benchmark uncertainty.

3.6.2 Dimensions

3.6.2.1 Effective Delayed Neutron Fraction

The effective delayed neutron fraction, β_{eff}, was determined using the critical benchmark models for the two spheres. The dimensions are described in HEU-MET-FAST-100.

3.6.2.2 Prompt Neutron Decay Constant

The benchmark model for the prompt neutron decay constant was similar to the simple benchmark model of the 8.74268- cm-core but was corrected to delayed critical. The benchmark model was a solid, homogenous sphere of radius 8.76328034 cm.

3.6.2.3 Mean Neutron Generation Time

The benchmark model for the mean neutron generation time was identical to the prompt neutron decay constant benchmark model (Section 3.6.2.2).

3.6.3 Material Data

3.6.3.1 Effective Delayed Neutron Fraction

The effective delayed neutron fraction, β_{eff}, was determined using the critical benchmark models for the two spheres. The material data for the spheres are given in HEU-MET-FAST-100.

[a] It should be noted that a high number of decimals are reported here for the purpose of calculation reproducibility. For calculations no rounding was performed until the end of the calculation.

3.6.3.2 Prompt Neutron Decay Constant

The atom densities of the sphere were identical to those for the Case 2 simple benchmark model of HEU-MET-FAST-100. The atom densities are given in Table 3.6-1.

Table 3.6-1.Uranium Atom Densities.[(a)]

Element/ Isotope	Atom Density (atom/b-cm)
U Total	4.8075E-02
^{234}U	*4.7568E-04*
^{235}U	*4.4838E-02*
^{236}U	*2.1938E-05*
^{238}U	*2.7390E-03*
Si	4.9746E-05
B	3.4357E-07
C	1.5920E-04
Total	4.8284E-02

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

3.6.3.3 Mean Neutron Generation Time

The atom densities of the sphere were identical to those for the prompt neutron decay constant. The atom densities are given in Table 3.6-1.

3.6.4 Temperature Data

The benchmark models temperature for effective delayed neutron fraction, prompt neutron decay constant, and mean neutron generation time are all room temperature (294 K).

3.6.5 Experimental and Benchmark-Model Kinetics Measurements

3.6.5.1 Effective Delayed Neutron Fraction

The benchmark value for the effective delayed neutron fraction, β_{eff}, of the core with central void is 0.00657 ± 0.00009.

3.6.5.2 Prompt Neutron Decay Constant

The benchmark value for the prompt neutron decay constant, α, is 1.1061 ± 0.1071 μsec^{-1}.

3.6.5.3 Mean Neutron Generation Time

The benchmark value for the mean neutron generation time, Λ, is 5.94 ± 0.59 nanosec. Because the system is at delayed critical the prompt neutron lifetime, l, is equal to Λ.

3.7 Benchmark-Model Specifications for Reaction-Rate Distribution Measurements

3.7.1 Description of the Benchmark Model Simplifications

3.7.1.1 Relative Neutron Importance

Simplification biases were evaluated using the critical benchmark models for 8.74268-cm-average-radius sphere in HEU-MET-FAST-100 (Case 2). The source was a solid ^{252}Cf source, within a 0.315-cm-diameter × 0.961-cm-long welded stainless-steel cylinder, passed through the diametral hole of the sphere. The source material was not modeled explicitly but rather modeled as an isotropic point source. The counters were three BF_3 counters located at (0, -295, -249.5); (295, 0, -249.5); and (0, -295, -249.5). Results from the three detectors were averaged. There was not sufficient information to explicitly model the BF_3 counters; therefore the relative count rates were taken to be representative of the relative neutron importance for BF_3 detector response and a Cf source. The relative neutron importance for BF_3 response and a Cf source is the relative response of detectors to a change in neutron flux, normalized to the flux when the Cf source is at the center of the sphere, where the BF_3 detectors are using a (n,α) reaction. The simplification bias for the relative neutron importance was calculated for the identical simplifications as were done for the critical benchmark models (HEU-MET-FAST-100, Section 3.1.1 and 3.1.2). Additionally, the detailed benchmark model was modeled in MCNP6 with different spectra and it was found that the effect of changing the source was negligible. A bias in the relative neutron importance for BF_3 detector response and a Cf source is considered negligible if it is less than the statistical uncertainty of the Monte Carlo calculation. For biases that are negligible, the bias uncertainty is preserved; as can be seen in Table 3.7-1. The biases in the detailed and simple benchmark models for the relative neutron importance for BF_3 detector response and a Cf source are given in Table 3.7-1.

Table 3.7-1. Simplification Bias of the Relative Neutron Importance for BF_3 Detector Response and a Cf Source.

Radius	Detailed Benchmark Model Simplification Bias	Simple Benchmark Model Simplification Bias
-8.138	NEG ± 0.0027	NEG ± 0.0027
-8.105	NEG ± 0.0027	NEG ± 0.0028
-8.100	0.003 ± 0.0027	NEG ± 0.0027
-8.004	NEG ± 0.0027	NEG ± 0.0027
-7.480	0.008 ± 0.0032	0.0067 ± 0.0032
-6.833	NEG ± 0.0038	NEG ± 0.0038
-6.825	NEG ± 0.0040	NEG ± 0.0040
-6.759	NEG ± 0.0039	NEG ± 0.0039
-6.731	0.010 ± 0.0039	0.0086 ± 0.0039
-5.730	NEG ± 0.0047	NEG ± 0.0047
-5.583	0.013 ± 0.0047	0.0082 ± 0.0047
-5.484	0.012 ± 0.0049	NEG ± 0.0049
-5.428	NEG ± 0.0050	NEG ± 0.0050
-4.392	0.006 ± 0.0057	NEG ± 0.0057
-4.288	0.007 ± 0.0057	NEG ± 0.0057
-4.221	NEG ± 0.0059	NEG ± 0.0059
-4.166	NEG ± 0.0058	NEG ± 0.0058
-3.208	0.017 ± 0.0063	0.0118 ± 0.0063
-3.170	0.027 ± 0.0064	0.0147 ± 0.0063

Table 3.7-1 (cont'd). Simplification Bias of the Relative Neutron Importance for BF_3 Detector Response and a Cf Source.

Radius	Detailed Benchmark Model Simplification Bias	Simple Benchmark Model Simplification Bias
-3.012	0.016 ± 0.0063	0.0075 ± 0.0063
-2.891	0.016 ± 0.0065	0.0094 ± 0.0065
-1.900	NEG ± 0.0070	NEG ± 0.0070
-1.740	0.023 ± 0.0070	0.0117 ± 0.0069
-1.618	0.009 ± 0.0071	NEG ± 0.0071
-0.632	0.022 ± 0.0072	0.0123 ± 0.0072
-0.470	0.011 ± 0.0073	NEG ± 0.0073
0	NEG(a)	NEG(a)
0.660	0.018 ± 0.0073	0.0169 ± 0.0073
0.805	NEG ± 0.0074	NEG ± 0.0074
0.904	0.018 ± 0.0072	0.0117 ± 0.0072
1.905	0.023 ± 0.0071	0.0228 ± 0.0071
2.024	0.031 ± 0.0071	0.0193 ± 0.0071
2.078	0.012 ± 0.0072	NEG ± 0.0072
3.175	0.008 ± 0.0068	NEG ± 0.0068
3.449	0.017 ± 0.0066	0.0115 ± 0.0066
4.445	0.018 ± 0.0062	0.0149 ± 0.0061
4.646	0.018 ± 0.0061	NEG ± 0.0061
4.722	0.014 ± 0.0060	0.0125 ± 0.0060
5.712	0.016 ± 0.0054	0.0160 ± 0.0054
5.895	0.007 ± 0.0054	NEG ± 0.0053
5.994	0.011 ± 0.0052	NEG ± 0.0052
7.216	NEG ± 0.0043	NEG ± 0.0043
7.419	0.017 ± 0.0041	0.0084 ± 0.0041
7.650	0.007 ± 0.0040	NEG ± 0.0040
8.273	0.005 ± 0.0035	0.0065 ± 0.0035
8.400	0.012 ± 0.0033	0.0099 ± 0.0033
8.443	0.004 ± 0.0034	0.0059 ± 0.0034
8.590	NEG ± 0.0033	NEG ± 0.0033
8.618	0.015 ± 0.0031	0.0116 ± 0.0031
8.745	0.004 ± 0.0031	NEG ± 0.0031
9.091	0.005 ± 0.0026	NEG ± 0.0026

(a) There is no bias or uncertainty associated with the normalization point of the trend.

3.7.1.2 Relative Fission Density

Simplification biases for the relative fission density were evaluated using the critical benchmark models for 8.74268-cm-average-radius sphere in HEU-MET-FAST-100 (Case 2). The fission density was measured through the diametral hole of the sphere. The uranium activation cylinders were not modeled explicitly but rather the neutron flux through the center of the sphere was calculated. The simplification bias for the relative fission density was calculated for the identical simplifications as were done for the critical benchmark models (HEU-MET-FAST-100, Section 3.1.1 and 3.1.2). A bias in the relative fission density is considered negligible if it is less than the statistical uncertainty of the Monte Carlo calculation. For biases that are negligible, the bias uncertainty is preserved; as can be seen in Table 3.7-2. The biases in the detailed and simple benchmark models for the relative fission density are given in Table 3.7-2.

Table 3.7-2. Simplification Bias of the Relative Radial Fission Density Uncertainty.

Radius[a]	Detailed Benchmark Model Simplification Bias	Simple Benchmark Model Simplification Bias
-8.265	NEG ± 0.0000	-0.001 ± 0.0000
-7.633	NEG ± 0.0001	-0.001 ± 0.0001
-6.995	NEG ± 0.0001	-0.002 ± 0.0001
-6.355	NEG ± 0.0001	NEG ± 0.0001
-5.725	NEG ± 0.0001	NEG ± 0.0001
-5.088	NEG ± 0.0001	NEG ± 0.0001
-4.450	NEG ± 0.0001	NEG ± 0.0001
-3.815	NEG ± 0.0001	NEG ± 0.0001
-3.180	NEG ± 0.0001	NEG ± 0.0001
-2.54	NEG ± 0.0001	NEG ± 0.0001
-1.908	NEG ± 0.0001	NEG ± 0.0001
-1.272	NEG ± 0.0001	NEG ± 0.0001
-0.635	NEG ± 0.0001	NEG ± 0.0001
0	NEG[a]	NEG[a]
0.635	NEG ± 0.0001	NEG ± 0.0001
1.272	NEG ± 0.0001	NEG ± 0.0001
1.908	NEG ± 0.0001	NEG ± 0.0001
2.543	NEG ± 0.0001	NEG ± 0.0001
3.180	NEG ± 0.0001	NEG ± 0.0001
3.815	NEG ± 0.0001	NEG ± 0.0001
4.450	NEG ± 0.0001	NEG ± 0.0001
5.088	NEG ± 0.0001	NEG ± 0.0001
5.725	NEG ± 0.0001	-0.001 ± 0.0001
6.355	NEG ± 0.0001	-0.001 ± 0.0001
6.995	NEG ± 0.0001	-0.001 ± 0.0001
7.633	NEG ± 0.0001	-0.001 ± 0.0000
8.265	NEG ± 0.0000	-0.002 ± 0.0000

(a) There is no bias or uncertainty associated with the normalization point of the trend.

3.7.2 Dimensions

3.7.2.1 Relative Neutron Importance

The simple and detailed benchmark models are identical to the simple and detailed critical benchmark models for the 8.74268-cm-average-radius sphere in HEU-MET-FAST-100 (Case 2). The source was modeled as a 1.4 MeV isotropic point source with a Maxwellian distribution at the appropriate radius along the center line of the sphere; this was the diametral filler rod in the detailed benchmark model.

3.7.2.2 Relative Fission Density

The simple and detailed benchmark models are identical to the simple and detailed critical benchmark models for the 8.74268-cm-average-radius sphere in HEU-MET-FAST-100 (Case 2). The fission rate measurements are over a 0.330cm-diameter×0.318-cm-long volume at the appropriate radius along the center line of the sphere; this was the diametral filler rod in the detailed benchmark model.

3.7.3 Material Data

3.7.3.1 Relative Neutron Importance

The simple and detailed benchmark models are identical to the simple and detailed critical benchmark models for the 8.74268-cm-average-radius sphere in HEU-MET-FAST-100 (Case 2).

3.7.3.2 Relative Fission Density

The simple and detailed benchmark models are identical to the simple and detailed critical benchmark models for the 8.74268-cm-average-radius sphere in HEU-MET-FAST-100 (Case 2).

3.7.4 Temperature Data

The benchmark model temperature for the relative neutron importance for BF_3 detector response and a Cf source and relative fission density is room temperature (294 K) for both the simple and detailed models.

3.7.5 Experimental and Benchmark-Model Reaction Rate Measurements

3.7.5.1 Relative Neutron Importance

The benchmark values for the relative neutron importance for BF_3 detector response and a Cf source are found by applying the biases in Table 3.7-1 to the experimental results. The uncertainty in the benchmark model is found by adding, in quadrature, the uncertainty in the experimental results, discussed in Section 2.7, and the bias uncertainty given in Table 3.7-1. The benchmark results are given in Table 3.7-3 and plotted in Figure 3.7-1.

Table 3.7-3. Benchmark Relative Neutron Importance for BF_3 Detector Response and a Cf Source.

Radius	Detailed Benchmark Model Value	Simple Benchmark Model Value
-8.138	0.278 ± 0.004	0.278 ± 0.004
-8.105	0.267 ± 0.003	0.267 ± 0.003
-8.100	0.292 ± 0.003	0.289 ± 0.003
-8.004	0.299 ± 0.003	0.299 ± 0.003
-7.480	0.387 ± 0.004	0.386 ± 0.004
-6.833	0.464 ± 0.004	0.464 ± 0.004
-6.825	0.458 ± 0.005	0.458 ± 0.005
-6.759	0.425 ± 0.004	0.425 ± 0.004
-6.731	0.478 ± 0.005	0.477 ± 0.005
-5.730	0.578 ± 0.005	0.578 ± 0.005
-5.583	0.633 ± 0.005	0.628 ± 0.005
-5.484	0.636 ± 0.005	0.624 ± 0.005

Table 3.7-3 (cont'd). Benchmark Relative Neutron Importance for BF_3 Detector Response and a Cf Source.

Radius	Detailed Benchmark Model Value	Simple Benchmark Model Value
-5.428	0.633 ± 0.006	0.633 ± 0.006
-4.392	0.735 ± 0.006	0.729 ± 0.006
-4.288	0.766 ± 0.006	0.759 ± 0.006
-4.221	0.770 ± 0.006	0.770 ± 0.006
-4.166	0.761 ± 0.006	0.761 ± 0.006
-3.208	0.877 ± 0.006	0.872 ± 0.006
-3.170	0.876 ± 0.006	0.864 ± 0.006
-3.012	0.891 ± 0.006	0.883 ± 0.006
-2.891	0.902 ± 0.007	0.895 ± 0.007
-1.900	0.936 ± 0.007	0.936 ± 0.007
-1.740	0.979 ± 0.008	0.968 ± 0.008
-1.618	0.967 ± 0.007	0.958 ± 0.007
-0.632	1.009 ± 0.007	0.999 ± 0.007
-0.470	1.003 ± 0.007	0.992 ± 0.007
0	1.000[(a)]	1.000[(a)]
0.660	1.004 ± 0.007	1.003 ± 0.007
0.805	0.985 ± 0.008	0.985 ± 0.008
0.904	1.010 ± 0.007	1.004 ± 0.007
1.905	0.974 ± 0.007	0.974 ± 0.007
2.024	0.987 ± 0.007	0.975 ± 0.007
2.078	0.944 ± 0.007	0.932 ± 0.007
3.175	0.872 ± 0.007	0.864 ± 0.007
3.449	0.865 ± 0.090	0.859 ± 0.090
4.445	0.768 ± 0.006	0.765 ± 0.006
4.646	0.734 ± 0.006	0.716 ± 0.006
4.722	0.751 ± 0.006	0.750 ± 0.006
5.712	0.624 ± 0.005	0.624 ± 0.005
5.895	0.583 ± 0.005	0.576 ± 0.005
5.994	0.600 ± 0.005	0.589 ± 0.005
7.216	0.418 ± 0.004	0.418 ± 0.004
7.419	0.431 ± 0.005	0.422 ± 0.005
7.650	0.371 ± 0.004	0.364 ± 0.004
8.273	0.282 ± 0.004	0.284 ± 0.004
8.400	0.276 ± 0.003	0.274 ± 0.003
8.443	0.247 ± 0.004	0.249 ± 0.004
8.590	0.230 ± 0.003	0.230 ± 0.003
8.618	0.239 ± 0.003	0.236 ± 0.003
8.745	0.208 ± 0.004	0.204 ± 0.004
9.091	0.170 ± 0.003	0.165 ± 0.003

(a) There is no bias or uncertainty associated with the normalization point of the trend.

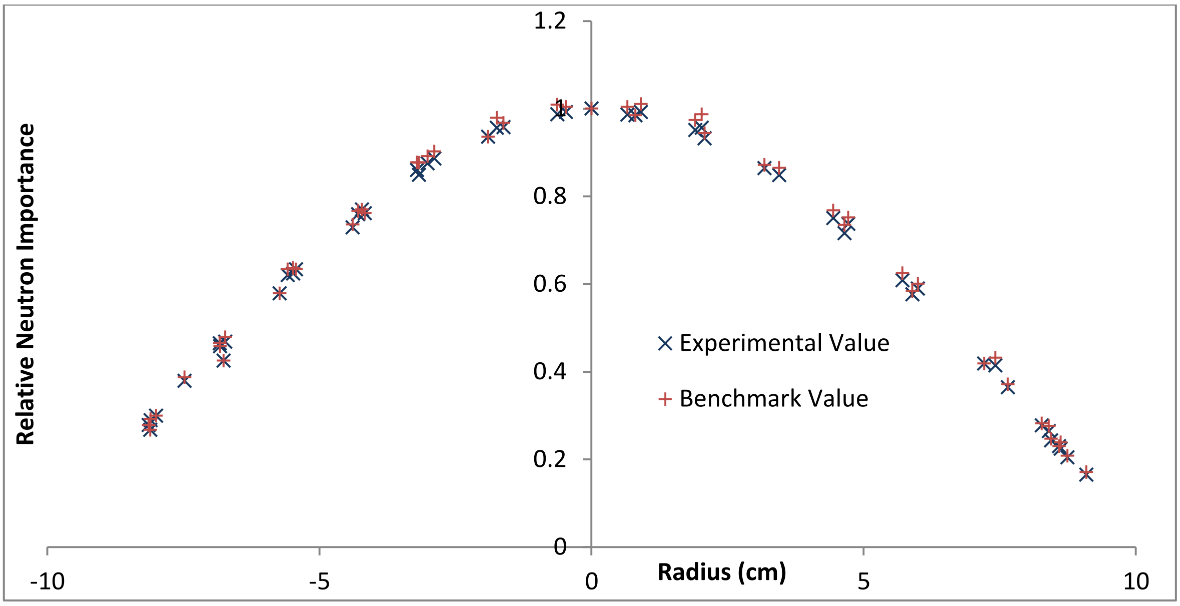

Figure 3.7-1. Experimental and Benchmark Relative Neutron Importance for BF_3 Detector Response and a Cf Source.

3.7.5.2 Relative Fission Density

The benchmark values for the relative fission density are found by applying the biases in Table 3.7-2 to the experimental results. The uncertainty in the benchmark model is found by adding, in quadrature, the uncertainty in the experimental results, discussed in Section 2.7, and the bias uncertainty given in Table 3.7-2. The benchmark results are given in Table 3.7-4 and plotted in Figure 3.7-2.

Table 3.7-4. Relative Radial Fission Density Uncertainty.

Radius[a]	Detailed Benchmark Model Value	Simple Benchmark Model Value
-8.265	0.261 ± 0.002	0.260 ± 0.002
-7.633	0.354 ± 0.002	0.353 ± 0.002
-6.995	0.440 ± 0.003	0.438 ± 0.003
-6.355	0.519 ± 0.003	0.519 ± 0.003
-5.725	0.603 ± 0.004	0.603 ± 0.004
-5.088	0.672 ± 0.005	0.672 ± 0.005
-4.450	0.746 ± 0.004	0.746 ± 0.004
-3.815	0.810 ± 0.006	0.810 ± 0.006
-3.180	0.871 ± 0.005	0.871 ± 0.005
-2.54	0.910 ± 0.006	0.910 ± 0.006
-1.908	0.951 ± 0.006	0.951 ± 0.006
-1.272	0.978 ± 0.006	0.978 ± 0.006
-0.635	1.001 ± 0.007	1.001 ± 0.007
0	1[a]	1[a]
0.635	0.996 ± 0.006	0.996 ± 0.006
1.272	0.978 ± 0.006	0.978 ± 0.006
1.908	0.956 ± 0.006	0.956 ± 0.006
2.543	0.910 ± 0.006	0.910 ± 0.006
3.180	0.872 ± 0.006	0.872 ± 0.006
3.815	0.810 ± 0.005	0.810 ± 0.005
4.450	0.742 ± 0.005	0.742 ± 0.005
5.088	0.675 ± 0.004	0.675 ± 0.004
5.725	0.600 ± 0.004	0.599 ± 0.004
6.355	0.518 ± 0.006	0.517 ± 0.006
6.995	0.438 ± 0.003	0.437 ± 0.003
7.633	0.351 ± 0.002	0.350 ± 0.002
8.265	0.257 ± 0.003	0.255 ± 0.003

(a) There is no bias or uncertainty associated with the normalization point of the trend.

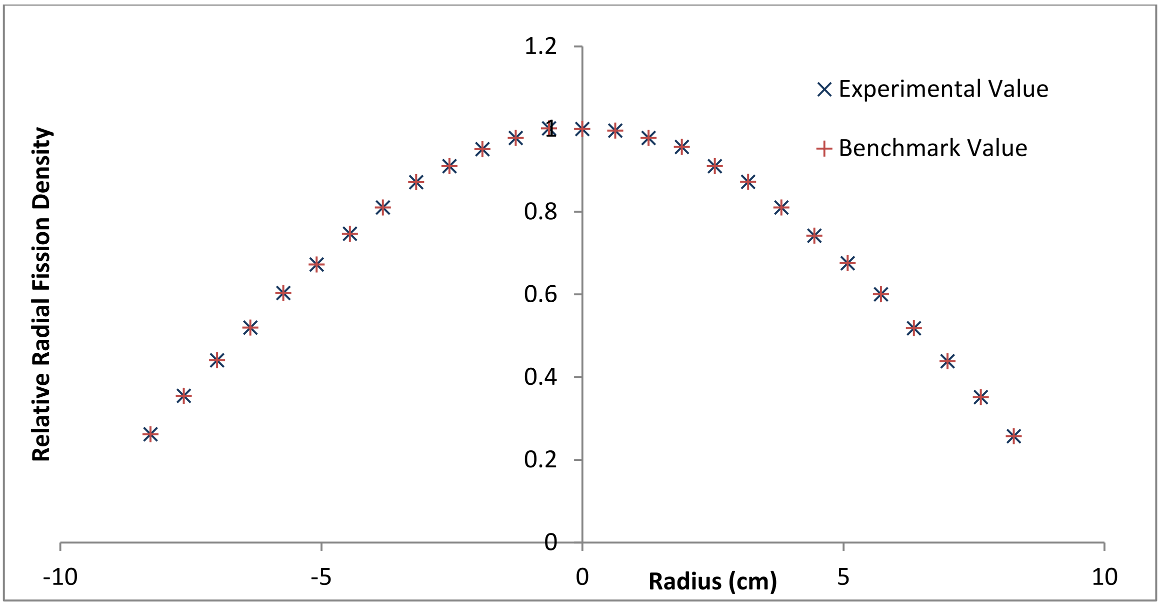

Figure 3.7-2. Experimental and Benchmark Relative Fission Density.

3.8 Benchmark-Model Specifications for Power Distribution Measurements

Power distribution measurements were not performed.

3.9 Benchmark-Model Specifications for Isotopic Measurements

Isotopic measurements were not performed.

3.10 Benchmark-Model Specifications for Other Miscellaneous Types of Measurements

Other miscellaneous types of measurements were not performed.

4.0 RESULTS OF SAMPLE CALCULATIONS

4.1 Results of Calculations of the Critical or Subcritical Configurations

The criticality portion of this evaluation has been reviewed and approved by the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and has been published under the following identifier: HEU-MET-FAST-100.[a]

4.2 Results of Buckling and Extrapolation Length Calculations

Buckling and extrapolation-length measurements were not performed.

4.3 Results of Spectral-Characteristics Calculations

Spectral-characteristic measurements were not performed.

4.4 Results of Reactivity-Effects Calculations

The worth measurements were evaluated using models as described in Section 3.4 with MCNP5-1.60 and ENDF/B-VII.0 neutron cross section libraries. Models were run using 500000 histories per cycle for 2650 cycles, skipping the first 150 cycles. The benchmark worths and sample calculation results are given in Table 4.4-1. It should be noted that calculated worths that deviate from the benchmark worths by more than three sigma of the benchmark uncertainty are still within three sigma for the uncertainty inherent to the Monte Carlo calculation.

[a] International Handbook of Evaluated Criticality Safety Benchmark Experiments, NEA/NSC/DOC(95)03, OECD-NEA, Paris (2013).

Table 4.4-1. Benchmark Worth Values.

	Benchmark Worth (¢)	MCNP5 ENDF/B-VII.0[(a)] (¢)	$\frac{C-E}{E}$[(b)]	C/E[(b)] Ratio	# of σ[(c)]	# of σ_{MC}[(d)]
Central Void	9.165 ± 0.123	9.4123 ± 0.1659[(e)]	2.70%	0.973	2.01	1.49
16, 0.635-cm-thick Uranium Buttons on Sphere Surface	35.4 ± 2.868	43.5627 ± 0.4508	23.06%	0.813	2.85	18.11
4, 0.3175-cm-thick Uranium Buttons on Sphere Surface	6.1415 ± 0.117	6.0050 ± 0.1638[(e)]	-2.22%	1.023	-1.17	-0.83
1, 0.3175-cm-thick Aluminum Button on Sphere Surface	0.7058 ± 0.062	0.7813 ± 0.0569[(f)]	10.70%	0.903	1.21	1.33
3, 0.3175-cm-thick Uranium Buttons in Socket Hole	7.86 ± 0.127	8.2442 ± 0.6114	4.89%	0.953	3.02	0.63
3, 0.3175-cm-thick Stainless Steel Buttons in Socket Hole	4.7228 ± 0.076	4.7339 ± 0.4322	0.23%	0.998	0.15	0.03
3, 0.3175-cm-thick Aluminum Buttons in Socket Hole	3.1259 ± 0.074	3.6652 ± 0.4321	17.25%	0.853	7.29	1.25
Diametral Filler Rod	11.234 ± 0.168	10.8532 ± 0.4336	-3.39%	1.035	-2.27	-0.88

(a) Because of the large statistical uncertainty in the sample calculation these results are truncated to fewer decimal points.
(b) "E" is the experimental benchmark value. "C" is the calculated value.
(c) This value shows how far the calculated worth deviates from the benchmark worth in terms of the benchmark worth uncertainty. (C-E)/σ
(d) This value shows how close the calculated worth are to the benchmark worth in terms of the statistical uncertainty of the Monte Carlo calculation. (C-E)/σ_{MC}
(e) For this calculated worth seven runs with different random numbers were performed and a variance weighted average of all results was taken.
(f) For this calculated worth seven runs with different random numbers were performed and a variance weighted average of all results was taken. The statistical uncertainty was also reduced because it was divided by the number of buttons, 3 or 4.

4.5 Results of Reactivity Coefficient Calculations

The worth per gram of uranium surface material benchmark models is described in Section 3.5. The models were created and run in MCNP5-1.60 and MCNP6-1.0 using ENDF/B-VII.0 neutron cross section libraries and MCNP6-1.0 using ENDF/B-VII.1 . For each model 500,000 histories per cycle were used for 2650 cycles, skipping the first 150 cycles. The benchmark and sample calculation worth per gram of uranium surface material are given in Table 4.5-1. The [(C-E)/E] for the sample calculation result is -7.2%, -7.8% and -8.1% below the benchmark value; this corresponds to 2.44 to 2.76σ below the benchmark value. The benchmark β_{eff} value of 0.00657 ± 0.00009 was used to convert reactivity from units of Δk to units of ¢.

Table 4.5-1. Sample Calculation of Worth per Gram of Surface Material using MCNP5-1.60 and ENDF/B-VII.0.

	MCNP5 ENDF/B-VII.0			Calculated System Reactivity (¢)			Mass		
8.80491-cm-Average-Radius Sphere	1.00411	±	0.00002	62.301	±	0.905	53,475.983	±	1.017 g
8.74268-cm-Average-Radius Sphere	0.99821	±	0.00002	-27.294	±	0.483	52,350.943	±	0.210 g
			Change	89.59	±	1.026	1,125.04	±	1.038 g
Benchmark Worth per Gram of Surface Material						0.086	±	0.003	¢ per gram
Sample Calculation of Worth per Gram of Surface Material						0.0796	±	0.0009	¢ per gram

Table 4.5-2. Sample Calculation of Worth per Gram of Surface Material using MCNP6-1.0 and ENDF/B-VII.0.

	MCNP6-1.0 ENDF/B-VII.0			Calculated System Reactivity			Mass		
8.80491-cm-Average-Radius Sphere	1.00407	±	0.00002	61.697	±	0.897	53,475.983	±	1.017 g
8.74268-cm-Average-Radius Sphere	0.99821	±	0.00002	-27.294	±	0.483	52,350.943	±	0.210 g
			Change	88.99	±	1.019	1,125.04	±	1.038 g
Benchmark Worth per Gram of Surface Material						0.086	±	0.003	¢ per gram
Sample Calculation of Worth per Gram of Surface Material						0.0791	±	0.0009	¢ per gram

Table 4.5-3. Sample Calculation of Worth per Gram of Surface Material using MCNP6-1.0 and ENDF/B-VII.1.

	MCNP6-1.0 ENDF/B-VII.1			Calculated System Reactivity			Mass		
8.80491-cm-Average-Radius Sphere	1.00402	±	0.00002	60.942	±	0.897	53,475.983	±	1.017 g
8.74268-cm-Average-Radius Sphere	0.99818	±	0.00002	-27.294	±	0.483	52,350.943	±	0.210 g
			Change	88.69	±	1.013	1,125.04	±	1.038 g
Benchmark Worth per Gram of Surface Material							0.086	± 0.003	¢ per gram
Sample Calculation of Worth per Gram of Surface Material							0.0788	± 0.0009	¢ per gram

4.6 Results of Kinetics Parameter Calculations

4.6.1 Delayed Neutron Fraction

The β_{eff} value was calculated for the benchmark models described in Section 3.6 using two methods. The first method used k_{prompt}, calculated by MCNP5, and compared it to k_{eff} to calculate β_{eff} ($\beta_{eff} = 1 - k_{prompt}/k_{eff}$). [a] The second method used MCNP5 to calculate β_{eff} directly using adjoint-weighted methods capabilities in MCNP5-1.60. [b] Both methods used ENDF/B-VII.0 neutron cross section libraries. The results of the two methods for the two critical benchmark models is given in Table 4.6-1.

Table 4.6-1. Sample Calculation Results for Delayed Neutron Fraction.

						β_{eff}			$(C-E)/E^{(a)}$
Method 1	Case 1	k_{prompt}	0.99721	±	0.00002	0.00650	±	0.00003	-0.46%
	Case 2	k_{eff}	1.00373	±	0.00002	0.00654	±	0.00003	-1.11%
Method 2	Case 1	k_{prompt}	0.99172	±	0.00002	0.00650	±	0.00003	-0.37%
	Case 2	k_{eff}	0.99821	±	0.00002	0.00654	±	0.00003	-1.02%

(a) "E" is the expected or benchmark value. "C" is the calculated value.

4.6.2 Prompt Neutron Decay Constant

The prompt neutron decay constant, α, was calculated for the prompt neutron decay constant benchmark model described in Section 3.6 using the adjoint-weighted methods capabilities in MCNP5-1.60. This yields the three variables in Equation 2.6.3, ρ (in the form of k_{eff}), β_{eff}, and Λ needed to calculate α. These values are given in Table 4.6.2.

[a] 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).
[b] B.C. Kiedrowski, et al., "MCNP5-1.60 Feature Enhancements and Manual Clarifications," LA-UR-10-06217, Los Alamos National Laboratory (2010).

Table 4.6-2. Sample Calculation Results for Prompt Neutron Decay Constant.

k_{eff}	1.00141	±	0.00002	Benchmark α (μs)	-1.1061	±	0.1071
β_{eff}	0.00647	±	0.00003	Calculated α (μs)	-0.8842	±	0.0902
Λ (ns)	5.72499	±	0.00297	$(C-E)/E$ [(a)]			-20%

(a) "E" is the expected or benchmark value. "C" is the calculated value.

The calculated α is approximately 20% below the benchmark value. This is very far outside the range of the benchmark uncertainty; however, it is within 3σ for the calculated value uncertainty.

The model used for these calculation results is the benchmark model, which has been adjusted to delayed critical. The expected k_{eff} is 1.0000, but, as can be seen in Table 4.6-2, the calculated k_{eff} is approximately 0.14% high due to calculational bias. The k_{eff} contributes a non-zero value for the reactivity in Equation 2.6.4. It is of interested to note that, if the calculational bias is ignored and the reactivity is set to zero the calculated α becomes -1.1301 μsec which is 2% above the benchmark value.

4.6.3 Mean Generation Time

The mean generation time, Λ, was calculated for the prompt neutron decay constant benchmark model described in Section 3.6 using the adjoint-weighted methods capabilities in MCNP5-1.60. The calculated value is 5.72499 ± 0.00297 nanosec, which is -3.6% below the benchmark value of 5.94 ± 0.14 nanosec.

4.7 Results of Reaction-Rate Distribution Calculations

4.7.1 Relative Neutron Importance

The relative neutron importance for BF_3 detector response and a Cf source was calculated using the models described in Section 3.7 with MCNP5-1.60 and ENDF/B-VII.0 neutron cross section libraries. The source was modeled as isotropic point sources distributed across the center line of the sphere. A Maxwellian source distribution with a temperature of 1.4 MeV was used. The flux at the detectors was modeled using a point detector tally (F5). The SCX tally treatment was used. An SCX tally treatment bins tally results based on the location of the original source neutron in the source distribution. The tally results for the three detectors were averaged. The model was run for 250,000,000 particle histories. The sample calculation results are given in Table 4.7-1 for the detailed benchmark model and Table 4.7-2 for the simple benchmark model. The deviation between the calculated values and benchmark model values is quite variable and rather large, especially at the edges of the sphere. The cause for this deviation is unknown.

Table 4.7-1. Sample Calculation Results for the Relative Neutron Importance for BF_3 Detector Response and a Cf Source, Detailed Model. MCNP5-1.60, ENDF/B-VII.0.

Radius	Detailed Benchmark Model Value			Sample Calculation Results[(a)]			(C-E)/E[(b)]	(C-E)/σ[(c)]
-8.138	0.278	±	0.004	0.223	±	0.001	-19.93%	-13.52
-8.105	0.267	±	0.003	0.224	±	0.001	-16.18%	-12.54
-8.100	0.292	±	0.003	0.227	±	0.001	-22.12%	-22.28
-8.004	0.299	±	0.003	0.236	±	0.001	-20.93%	-21.18
-7.480	0.387	±	0.004	0.314	±	0.001	-18.95%	-19.12
-6.833	0.464	±	0.004	0.396	±	0.001	-14.69%	-15.66
-6.825	0.458	±	0.005	0.403	±	0.001	-12.08%	-11.02
-6.759	0.425	±	0.004	0.407	±	0.001	-4.12%	-3.94
-6.731	0.478	±	0.005	0.414	±	0.001	-13.41%	-13.01
-5.730	0.578	±	0.005	0.539	±	0.002	-6.83%	-7.64
-5.583	0.633	±	0.005	0.561	±	0.002	-11.40%	-14.01
-5.484	0.636	±	0.005	0.576	±	0.002	-9.50%	-11.33
-5.428	0.633	±	0.006	0.577	±	0.002	-8.81%	-9.58
-4.392	0.735	±	0.006	0.705	±	0.002	-4.16%	-4.75
-4.288	0.766	±	0.006	0.714	±	0.002	-6.81%	-8.91
-4.221	0.770	±	0.006	0.722	±	0.002	-6.18%	-7.63
-4.166	0.761	±	0.006	0.725	±	0.002	-4.67%	-5.79
-3.208	0.877	±	0.006	0.828	±	0.002	-5.55%	-7.57
-3.170	0.876	±	0.006	0.835	±	0.002	-4.75%	-6.44
-3.012	0.891	±	0.006	0.840	±	0.002	-5.68%	-7.86
-2.891	0.902	±	0.007	0.854	±	0.002	-5.32%	-7.07
-1.900	0.936	±	0.007	0.930	±	0.003	-0.60%	-0.79
-1.740	0.979	±	0.008	0.943	±	0.003	-3.65%	-4.71
-1.618	0.967	±	0.007	0.946	±	0.003	-2.12%	-2.78
-0.632	1.009	±	0.007	0.989	±	0.003	-2.02%	-2.80
-0.470	1.003	±	0.007	0.990	±	0.003	-1.30%	-1.79
0	1.000			1			-	-
0.660	1.004	±	0.007	0.999	±	0.003	-0.50%	-0.68
0.805	0.985	±	0.008	1.001	±	0.003	1.61%	2.06
0.904	1.010	±	0.007	0.997	±	0.003	-1.27%	-1.76
1.905	0.974	±	0.007	0.978	±	0.003	0.41%	0.54
2.024	0.987	±	0.007	0.980	±	0.003	-0.70%	-0.96
2.078	0.944	±	0.007	0.973	±	0.003	3.06%	3.86
3.175	0.872	±	0.007	0.909	±	0.003	4.35%	5.47
3.449	0.865	±	0.090	0.886	±	0.002	2.46%	0.24
4.445	0.768	±	0.006	0.799	±	0.002	4.09%	5.01
4.646	0.734	±	0.006	0.791	±	0.002	7.75%	9.11
4.722	0.751	±	0.006	0.773	±	0.002	2.87%	3.55
5.712	0.624	±	0.005	0.669	±	0.002	7.27%	8.29

Table 4.7-1 (cont'd). Sample Calculation Results for the Relative Neutron Importance for BF_3 Detector Response and a Cf Source, Detailed Model. MCNP5-1.60, ENDF/B-VII.0.

Radius	Detailed Benchmark Model Value			Sample Calculation Results[(a)]			(C-E)/E[(b)]	(C-E)/σ[(c)]
5.895	0.583	±	0.005	0.650	±	0.002	11.34%	12.08
5.994	0.600	±	0.005	0.635	±	0.002	5.78%	6.50
7.216	0.418	±	0.004	0.485	±	0.002	15.94%	14.84
7.419	0.431	±	0.005	0.461	±	0.002	6.96%	6.49
7.650	0.371	±	0.004	0.427	±	0.001	15.27%	13.52
8.273	0.282	±	0.004	0.343	±	0.001	21.93%	16.81
8.400	0.276	±	0.003	0.327	±	0.001	18.72%	14.84
8.443	0.247	±	0.004	0.319	±	0.001	29.20%	20.22
8.590	0.230	±	0.003	0.298	±	0.001	29.42%	19.51
8.618	0.239	±	0.003	0.297	±	0.001	24.29%	17.38
8.745	0.208	±	0.004	0.277	±	0.001	33.40%	18.67
9.091	0.170	±	0.003	0.230	±	0.001	34.81%	20.53

(a) Sample calculation models were run in source mode with 250,000,000 neutron particle histories.
(b) 'E' is the expected or benchmark value. 'C' is the calculated value.
(c) 'E' is the expected or benchmark value. 'C' is the calculated value. σ is the benchmark model uncertainty.

Table 4.7-2. Sample Calculation Results for the Relative Neutron Importance for BF_3 Detector Response and a Cf Source, Simple Model. MCNP5-1.60, ENDF/B-VII.0

Radius	Simple Benchmark Model Value			Sample Calculation Results[(a)]			(C-E)/E[(b)]	(C-E)/σ[(c)]
-8.138	0.278	±	0.004	0.219	±	0.001	-21.12%	-14.34
-8.105	0.267	±	0.003	0.223	±	0.001	-16.57%	-12.82
-8.100	0.289	±	0.003	0.227	±	0.001	-21.51%	-21.44
-8.004	0.299	±	0.003	0.237	±	0.001	-20.86%	-21.05
-7.480	0.386	±	0.004	0.312	±	0.001	-19.01%	-19.11
-6.833	0.464	±	0.004	0.394	±	0.001	-15.02%	-16.03
-6.825	0.458	±	0.005	0.398	±	0.001	-13.18%	-12.04
-6.759	0.425	±	0.004	0.407	±	0.001	-4.13%	-3.94
-6.731	0.477	±	0.005	0.412	±	0.001	-13.46%	-13.01
-5.730	0.578	±	0.005	0.535	±	0.002	-7.41%	-8.30
-5.583	0.628	±	0.005	0.556	±	0.002	-11.49%	-14.02
-5.484	0.624	±	0.005	0.566	±	0.002	-9.23%	-10.82
-5.428	0.633	±	0.006	0.575	±	0.002	-9.19%	-9.99
-4.392	0.729	±	0.006	0.698	±	0.002	-4.22%	-4.77
-4.288	0.759	±	0.006	0.710	±	0.002	-6.51%	-8.45
-4.221	0.770	±	0.006	0.717	±	0.002	-6.93%	-8.56
-4.166	0.761	±	0.006	0.721	±	0.002	-5.28%	-6.55
-3.208	0.872	±	0.006	0.823	±	0.002	-5.58%	-7.56
-3.170	0.864	±	0.006	0.822	±	0.002	-4.82%	-6.47
-3.012	0.883	±	0.006	0.832	±	0.002	-5.73%	-7.87
-2.891	0.895	±	0.007	0.847	±	0.002	-5.36%	-7.08
-1.900	0.936	±	0.007	0.921	±	0.003	-1.58%	-2.08
-1.740	0.968	±	0.008	0.932	±	0.003	-3.70%	-4.72
-1.618	0.958	±	0.007	0.937	±	0.003	-2.20%	-2.85
-0.632	0.999	±	0.007	0.979	±	0.003	-2.04%	-2.80
-0.470	0.992	±	0.007	0.983	±	0.003	-0.87%	-1.18
0		1			1		-	-
0.660	1.003	±	0.007	0.998	±	0.003	-0.50%	-0.68
0.805	0.985	±	0.008	1.003	±	0.003	1.84%	2.36
0.904	1.004	±	0.007	0.991	±	0.003	-1.28%	-1.76
1.905	0.974	±	0.007	0.978	±	0.003	0.41%	0.54
2.024	0.975	±	0.007	0.968	±	0.003	-0.71%	-0.96
2.078	0.932	±	0.007	0.963	±	0.003	3.38%	4.21
3.175	0.864	±	0.007	0.906	±	0.003	4.88%	6.09
3.449	0.859	±	0.090	0.881	±	0.002	2.48%	0.24
4.445	0.765	±	0.006	0.796	±	0.002	4.10%	5.02
4.646	0.716	±	0.006	0.779	±	0.002	8.75%	10.05
4.722	0.750	±	0.006	0.771	±	0.002	2.88%	3.55
5.712	0.624	±	0.005	0.669	±	0.002	7.27%	8.28
5.895	0.576	±	0.005	0.642	±	0.002	11.54%	12.15

Table 4.7-2 (cont'd). Sample Calculation Results for the Relative Neutron Importance for BF_3 Detector Response and a Cf Source, Simple Model. MCNP5-1.60, ENDF/B-VII.0

Radius	Simple Benchmark Model Value			Sample Calculation Results(a)			(C-E)/E(b)	(C-E)/σ(c)
5.994	0.589	±	0.005	0.629	±	0.002	6.75%	7.47
7.216	0.418	±	0.004	0.478	±	0.002	14.26%	13.29
7.419	0.422	±	0.005	0.452	±	0.002	7.10%	6.50
7.650	0.364	±	0.004	0.421	±	0.001	15.69%	13.67
8.273	0.284	±	0.004	0.345	±	0.001	21.77%	16.77
8.400	0.274	±	0.003	0.325	±	0.001	18.85%	14.85
8.443	0.249	±	0.004	0.321	±	0.001	28.92%	20.17
8.590	0.230	±	0.003	0.299	±	0.001	30.03%	19.87
8.618	0.236	±	0.003	0.294	±	0.001	24.61%	17.40
8.745	0.204	±	0.004	0.276	±	0.001	35.51%	19.50
9.091	0.165	±	0.003	0.223	±	0.001	35.34%	20.25

(a) Sample calculation models were run in source mode with 250,000,000 neutron particle histories.
(b) 'E' is the expected or benchmark value. 'C' is the calculated value.
(c) 'E' is the expected or benchmark value. 'C' is the calculated value. σ is the benchmark model uncertainty.

4.7.2 Relative Fission Density

The relative fission density was calculated using the models described in Section 3.7 with MCNP5-1.60 and ENDF/B-VII.0 neutron cross section libraries. The flux was calculated using a superimposed mesh tally over the center line of the sphere. The sample calculation results are given in Table 4.7-3 for the detailed benchmark model and Table 4.7-4 for the simple benchmark model. The deviation between the calculated values and benchmark model values is quite variable although all but one point is within 3σ.

Table 4.7-3. Sample Calculation Results for the Relative Fission Density, Detailed Model. MCNP5-1.60, ENDF/B-VII.0

Radius[(a)]	Detailed Benchmark Model Value	Sample Calculation Results[(a)]	(C-E)/E[(b)]	(C-E)/σ[(c)]
-8.265	0.261 ± 0.002	0.2579 ± 0.00003	-1.17%	-1.6
-7.633	0.354 ± 0.002	0.3461 ± 0.00004	-2.23%	-3.4
-6.995	0.440 ± 0.003	0.4319 ± 0.00004	-1.83%	-2.9
-6.355	0.519 ± 0.003	0.5154 ± 0.00005	-0.70%	-1.2
-5.725	0.603 ± 0.004	0.5946 ± 0.00006	-1.39%	-2.1
-5.088	0.672 ± 0.005	0.6710 ± 0.00006	-0.15%	-0.2
-4.450	0.746 ± 0.004	0.7424 ± 0.00007	-0.49%	-0.8
-3.815	0.810 ± 0.006	0.8063 ± 0.00007	-0.46%	-0.7
-3.180	0.871 ± 0.005	0.8627 ± 0.00008	-0.95%	-1.5
-2.54	0.910 ± 0.006	0.9110 ± 0.00008	0.11%	0.2
-1.908	0.951 ± 0.006	0.9490 ± 0.00008	-0.21%	-0.3
-1.272	0.978 ± 0.006	0.9775 ± 0.00009	-0.05%	-0.1
-0.635	1.001 ± 0.007	0.9942 ± 0.00009	-0.68%	-1.0
0	1	1	-	-
0.635	0.996 ± 0.006	0.9945 ± 0.00009	-0.15%	-0.3
1.272	0.978 ± 0.006	0.9778 ± 0.00009	-0.02%	0.0
1.908	0.956 ± 0.006	0.9497 ± 0.00008	-0.66%	-1.0
2.543	0.910 ± 0.006	0.9115 ± 0.00008	0.17%	0.3
3.180	0.872 ± 0.006	0.8632 ± 0.00008	-1.01%	-1.5
3.815	0.810 ± 0.005	0.8061 ± 0.00007	-0.48%	-0.8
4.450	0.742 ± 0.005	0.7418 ± 0.00007	-0.02%	0.0
5.088	0.675 ± 0.004	0.6707 ± 0.00006	-0.63%	-1.0
5.725	0.600 ± 0.004	0.5944 ± 0.00006	-0.93%	-1.6
6.355	0.518 ± 0.006	0.5154 ± 0.00005	-0.51%	-0.4
6.995	0.438 ± 0.003	0.4316 ± 0.00004	-1.46%	-2.0
7.633	0.351 ± 0.002	0.3463 ± 0.00004	-1.33%	-2.0
8.265	0.257 ± 0.003	0.2579 ± 0.00003	0.34%	0.3

(a) Sample calculation models were run in kcode mode with 500,000 histories for 2650 cycles, skipping the first 150 cycles.
(b) 'E' is the expected or benchmark value. 'C' is the calculated value.
(c) 'E' is the expected or benchmark value. 'C' is the calculated value. σ is the benchmark model uncertainty.

Table 4.7-4. Sample Calculation Results for the Relative Fission Density, Simple Model. MCNP5-1.60, ENDF/B-VII.0

Radius[(a)]	Simple Benchmark Model Value			Sample Calculation Results[(a)]			(C-E)/E[(b)]	(C-E)/σ[(c)]
-8.265	0.260	±	0.002	0.2565	±	0.00003	-1.27%	-1.8
-7.633	0.353	±	0.002	0.3453	±	0.00004	-2.11%	-3.2
-6.995	0.438	±	0.003	0.4305	±	0.00004	-1.74%	-2.8
-6.355	0.519	±	0.003	0.5144	±	0.00005	-0.89%	-1.5
-5.725	0.603	±	0.004	0.5941	±	0.00006	-1.47%	-2.2
-5.088	0.672	±	0.005	0.6700	±	0.00006	-0.30%	-0.4
-4.450	0.746	±	0.004	0.7417	±	0.00007	-0.57%	-1.0
-3.815	0.810	±	0.006	0.8058	±	0.00007	-0.52%	-0.8
-3.180	0.871	±	0.005	0.8629	±	0.00008	-0.92%	-1.5
-2.54	0.910	±	0.006	0.9110	±	0.00008	0.11%	0.2
-1.908	0.951	±	0.006	0.9496	±	0.00008	-0.15%	-0.2
-1.272	0.978	±	0.006	0.9774	±	0.00009	-0.06%	-0.1
-0.635	1.001	±	0.007	0.9936	±	0.00009	-0.74%	-1.1
0		1			1		-	-
0.635	0.996	±	0.006	0.9941	±	0.00009	-0.19%	-0.3
1.272	0.978	±	0.006	0.9764	±	0.00009	-0.16%	-0.3
1.908	0.956	±	0.006	0.9490	±	0.00008	-0.73%	-1.1
2.543	0.910	±	0.006	0.9107	±	0.00008	0.08%	0.1
3.180	0.872	±	0.006	0.8627	±	0.00008	-1.07%	-1.6
3.815	0.810	±	0.005	0.8064	±	0.00007	-0.45%	-0.8
4.450	0.742	±	0.005	0.7413	±	0.00007	-0.09%	-0.1
5.088	0.675	±	0.004	0.6704	±	0.00006	-0.68%	-1.1
5.725	0.599	±	0.004	0.5934	±	0.00006	-0.93%	-1.5
6.355	0.517	±	0.006	0.5144	±	0.00005	-0.46%	-0.4
6.995	0.437	±	0.003	0.4309	±	0.00004	-1.35%	-1.8
7.633	0.350	±	0.002	0.3452	±	0.00004	-1.31%	-2.0
8.265	0.255	±	0.003	0.2566	±	0.00003	0.45%	0.4

(a) Sample calculation models were run in kcode mode with 500,000 histories for 2650 cycles, skipping the first 150 cycles.
(b) 'E' is the expected or benchmark value. 'C' is the calculated value.
(c) 'E' is the expected or benchmark value. 'C' is the calculated value. σ is the benchmark model uncertainty.

4.8 Results of Power Distribution Calculations

Power distribution measurements were not performed.

4.9 Results of Isotopic Calculations

Isotopic measurements were not performed.

4.10 Results of Calculations for Other Miscellaneous Types of Measurements

Other miscellaneous types of measurements were not performed.

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).

3. 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," *Nuc. Sci. and Eng.*, **130**, 153-163 (1998).

4. 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).

5. 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).

6. 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).

7. J.T. Mihalczo, "Propmt Neutron Decay for an unreflected and Unmoderated Uranium (HEU) Metal Sphere," *PHYSOR 1996*, Mito, Japan, September 16-20, (1996).

8. J. T. Mihalczo, "Neutron Importance and Fission Density in Uranium-235-Enriched Uranium and Plutonium Metal Spheres," *Nucl. Sci. Eng.*, **56**, 271-290 (1975).

APPENDIX A: COMPUTER CODES, CROSS SECTIONS, AND TYPICAL INPUT LISTINGS

Models were created using Monte Carlo n-Particle (MCNP), Version 5-1.60, and ENDF/B-VII.0 neutron cross section libraries. Models were run using 500000 histories per cycle for 2650 cycles, skipping the first 150 cycles. Isotopic abundances for all elements except uranium were taken from "Nuclides and Isotopes: Chart of the Nuclides," Sixteenth Edition, KAPL, 2002. The uranium is highly enriched in ^{235}U and the isotopic abundances are given for the benchmark models in Section 3.

A.1 Critical/Subcritical Configurations

The criticality portion of this evaluation has been reviewed and approved by the International Criticality Safety Benchmark Evaluation Project (ICSBEP) and has been published under the following identifier: HEU-MET-FAST-100[a].

A.2 Buckling and Extrapolation Length Configurations

Buckling and extrapolation-length measurements were not performed.

A.3 Spectral-Characteristics Configurations

Spectral Characteristic measurements were not performed.

A.4 Reactivity-Effects Configurations

A.4.1 Name(s) of Code System(s) Used

1. Monte Carlo n-Particle, Version 5.1.60 (MCNP5).

A.4.2 Bibliographic References for the Codes Used

1. 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).

A.4.3 Origin of Cross-section Data

The evaluated neutron data file library ENDF/B-VII.0[b] was utilized in the benchmark-model analysis.

A.4.4 Spectral Calculations and Data Reduction Methods Used

Not applicable.

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[a] International Handbook of Evaluated Criticality Safety Benchmark Experiments, NEA/NSC/DOC(95)03, OECD-NEA, Paris (2013).

[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).

A.4.5 Number of Energy Groups or If Continuous-energy Cross Sections are Used in the Different Phases of Calculation

1. Continuous-energy cross sections.

A.4.6 Component Calculations

Not applicable

A.4.7 Other Assumptions and Characteristics

Not applicable.

A.4.8 Typical Input Listings for Each Code System Type

The following sample input decks are provided:

MCNP5 Input Deck for Central Void Reactivity Benchmark Models
MCNP5 Input Deck for Surface Button Worth Benchmark Models
Benchmark Model 16, 0.635-cm-thick Uranium Buttons
Perturbed Benchmark Model for Worth of 4, 0.3175-cm-thick Buttons
MCNP5 Input Deck for Button Worth in Empty Socket Hole Benchmark Models
MCNP5 Input Deck for Diametral Filler Rod Worth Benchmark Models

MCNP5 Input Deck for Central Void Reactivity Benchmark Models:
Reference Benchmark Model
For the perturbed benchmark model the small 0.5842-cm-radius sphere (cell number 354) is removed.

```
HMF100-Case 2-Detailed Model--> ORSphere-Central Void
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 Holes
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
          330 331 332 333 307 308 309 310 311 410 411 412  u=1 imp:n=1
302   0 -307  u=1 imp:n=1
C  303   0 (-301  -308:-309:-310 -301)  u=1 imp:n=1
304   17 4.84213E-02 -323 -301 310  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   0 -301 -311 352 u=1 imp:n=1 $SH
315   0 -301 -308 350 u=1 imp:n=1 $.386" section of DH
316   0  -309 351 u=1 imp:n=1 $.136" section of DH
317   0 -301 -310  353 u=1 imp:n=1 $.504" section of DH
C   Support Screw Holes
310   0  -330   u=1 imp:n=1
311   0  -331   u=1 imp:n=1
312   0  -332   u=1 imp:n=1
313   0  -333   u=1 imp:n=1
C  Pins
320   15 4.84213E-02 -410 308 309 -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 -306 309 350 353 352 330 331 332 333) u=1 imp:n=1
C
350   18 4.79799E-02 -350 u=1 imp:n=1 $.386" section of DH
351   18 4.79799E-02 -351 u=1 imp:n=1 $.136" section of DH
352   18 4.79799E-02 -352 u=1 imp:n=1 $.504" SH
353   18 4.79799E-02 -353 354 u=1 imp:n=1 $.504" Section of plug
354   18 4.79799E-02 -355 u=1 imp:n=1 $.460" Sphere
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 holes
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 Holes
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 rcc -8.735918143 0 0  2.54 0 0  0.49022
309 rcc -6.195918143 0 0  5.527898143 0 0  0.17272
310 rcc -0.66802 0 0  9.403938143 0 0  0.64008
311 rcc -8.43824895 -2.261021992 0  2.453451599 0.657400375 0  0.64008
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
330 rcc 5.74467 5.74467 0 0.43734 0.43734 0 0.351028
331 rcc 5.74467 -5.74467 0 0.43734 -0.43734 0 0.351028
332 rcc -5.74467 -5.74467 0 -0.43734 -0.43734 0 0.351028
333 rcc -5.74467 5.74467 0 -0.43734 0.43734 0 0.351028
C
350 rcc -8.735918143 0 0  2.54 0 0  0.48641
351 rcc -6.195918143 0 0  5.527898143 0 0  0.164211
352 rcc -8.43824895 -2.261021992 0  2.453451599 0.657400375 0  0.63627
353 rcc -0.66802 0 0  9.4107 0 0  0.63627
```

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354 so 0.5842
355 so 0.5842
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 Holes
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
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      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
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      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
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      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
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      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
print
```

MCNP5 Input Deck for Surface Button Worth Benchmark Models:
Benchmark Model 16, 0.635-cm-thick Uranium Buttons

The reference benchmark model for this measurement had zero mass adjustment buttons and holding screws present. The buttons are modeled as cells 800-807 and 850-857. The holding screws are modeled as cells 110-117, 560-567, 820-827, and 870-877.

```
HMF100-Case 2-Detailed Model-->ORSphere 16, 0.635-cm-thick U Buttons
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 Holes
110   20 8.76744E-02 -150 160 -101 820  imp:n=1
111   20 8.76744E-02 -151 161 -101 821  imp:n=1
112   20 8.76744E-02 -152 162 -101 822  imp:n=1
113   20 8.76744E-02 -153 163 -101 823  imp:n=1
114   20 8.76744E-02 -154 164 -101 824  imp:n=1
115   20 8.76744E-02 -155 165 -101 825  imp:n=1
116   20 8.76744E-02 -156 166 -101 826  imp:n=1
117   20 8.76744E-02 -157 167 -101 827  imp:n=1
120   0 -160 -101 800   imp:n=1
121   0 -161 -101 801  imp:n=1
122   0 -162 -101 802  imp:n=1
123   0 -163 -101  803 imp:n=1
124   0 -164 -101  804 imp:n=1
125   0 -165 -101  805 imp:n=1
126   0 -166 -101  806 imp:n=1
127   0 -167 -101  807 imp:n=1
C
130   0 101 -104 -900 103 800 801 802 803 804 805 806 807 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 holes
560   20 8.76744E-02 -750 760 -500 870 u=1  imp:n=1
561   20 8.76744E-02 -751 761 -500 871 u=1  imp:n=1
562   20 8.76744E-02 -752 762 -500 872 u=1  imp:n=1
563   20 8.76744E-02 -753 763 -500 873 u=1  imp:n=1
564   20 8.76744E-02 -754 764 -500 874 u=1  imp:n=1
565   20 8.76744E-02 -755 765 -500 875 u=1  imp:n=1
566   20 8.76744E-02 -756 766 -500 876 u=1  imp:n=1
567   20 8.76744E-02 -757 767 -500 877 u=1  imp:n=1
570   0 -760 -500 850 u=1  imp:n=1
571   0 -761 -500 851 u=1  imp:n=1
572   0 -762 -500 852 u=1  imp:n=1
573   0 -763 -500 853 u=1  imp:n=1
574   0 -764 -500 854 u=1  imp:n=1
575   0 -765 -500 855 u=1  imp:n=1
576   0 -766 -500 856 u=1  imp:n=1
577   0 -767 -500 857 u=1  imp:n=1
590   0 500 501 508 850 851 852 853 854 855 856 857 u=1  imp:n=1
591   0 -508  u=1 imp:n=1
C   ************************************************************************
C   ************************************************************************
C   ************************************************************************
C   ****Bottom Buttons******************************************************
C   ************************************************************************
800  50 4.83066E-02 -800 810 imp:n=1
801  50 4.83066E-02 -801 811 #100 imp:n=1
802  50 4.83066E-02 -802 812 imp:n=1
803  50 4.83066E-02 -803 813 #100 imp:n=1
804  50 4.83066E-02 -804 814 imp:n=1
805  50 4.83066E-02 -805 815 #100 imp:n=1
806  50 4.83066E-02 -806 816 imp:n=1
807  50 4.83066E-02 -807 817 #100 imp:n=1
C
810  0 -810 820 imp:n=1
811  0 -811 821 #100 imp:n=1
812  0 -812 822 imp:n=1
813  0 -813 823 #100 imp:n=1
814  0 -814 824 imp:n=1
815  0 -815 825 #100 imp:n=1
816  0 -816 826 imp:n=1
817  0 -817 827 #100 imp:n=1
C
820  20 8.76744E-02 -820 imp:n=1
```

```
821  20 8.76744E-02 -821 #100 imp:n=1
822  20 8.76744E-02 -822 imp:n=1
823  20 8.76744E-02 -823 #100 imp:n=1
824  20 8.76744E-02 -824 imp:n=1
825  20 8.76744E-02 -825 #100 imp:n=1
826  20 8.76744E-02 -826 imp:n=1
827  20 8.76744E-02 -827 #100 imp:n=1
C    ****************************************************************************
C   ****Upper Buttons***********************************************************
C    ****************************************************************************
850  50 4.83066E-02 -850 860 u=1 imp:n=1
851  50 4.83066E-02 -851 861 #500 u=1  imp:n=1
852  50 4.83066E-02 -852 862 u=1  imp:n=1
853  50 4.83066E-02 -853 863 #500 u=1  imp:n=1
854  50 4.83066E-02 -854 864 u=1  imp:n=1
855  50 4.83066E-02 -855 865 #500 u=1  imp:n=1
856  50 4.83066E-02 -856 866 u=1  imp:n=1
857  50 4.83066E-02 -857 867 #500 u=1  imp:n=1
C
860  0 -860 870 u=1  imp:n=1
861  0 -861 871 #500 u=1  imp:n=1
862  0 -862 872 u=1  imp:n=1
863  0 -863 873 #500 u=1  imp:n=1
864  0 -864 874 u=1  imp:n=1
865  0 -865 875 #500 u=1  imp:n=1
866  0 -866 876 u=1  imp:n=1
867  0 -867 877 #500 u=1  imp:n=1
C
870  20 8.76744E-02 -870  u=1  imp:n=1
871  20 8.76744E-02 -871  u=1  imp:n=1
872  20 8.76744E-02 -872  u=1  imp:n=1
873  20 8.76744E-02 -873  #500 u=1  imp:n=1
874  20 8.76744E-02 -874  u=1  imp:n=1
875  20 8.76744E-02 -875  #500 u=1  imp:n=1
876  20 8.76744E-02 -876  u=1  imp:n=1
877  20 8.76744E-02 -877  #500 u=1  imp:n=1
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 Holes
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 Holes
750 rcc 0.0000 5.6626 5.6626 0.0000000 0.5634551 0.5634551 0.17526
751 rcc 4.0040 4.0040 5.6626 0.3984229 0.3984229 0.5634551 0.17526
752 rcc 5.6626 0.0000 5.6626 0.5634551 0.0000000 0.5634551 0.17526
753 rcc 4.0040 -4.0040 5.6626 0.3984229 -0.3984229 0.5634551 0.17526
754 rcc 0.0000 -5.6626 5.6626 0.0000000 -0.5634551 0.5634551 0.17526
755 rcc -4.0040 -4.0040 5.6626 -0.3984229 -0.3984229 0.5634551 0.17526
756 rcc -5.6626 0.0000 5.6626 -0.5634551 0.0000000 0.5634551 0.17526
757 rcc -4.0040 4.0040 5.6626 -0.3984229 0.3984229 0.5634551 0.17526
C
760 rcc 0.0000 6.1439 6.1439 0.0000000 0.0821133 0.0821133 1.11125
761 rcc 4.3444 4.3444 6.1439 0.0580629 0.0580629 0.0821133 1.11125
762 rcc 6.1439 0.0000 6.1439 0.0821133 0.0000000 0.0821133 1.11125
763 rcc 4.3444 -4.3444 6.1439 0.0580629 -0.0580629 0.0821133 1.11125
764 rcc 0.0000 -6.1439 6.1439 0.0000000 -0.0821133 0.0821133 1.11125
765 rcc -4.3444 -4.3444 6.1439 -0.0580629 -0.0580629 0.0821133 1.11125
766 rcc -6.1439 0.0000 6.1439 -0.0821133 0.0000000 0.0821133 1.11125
767 rcc -4.3444 4.3444 6.1439 -0.0580629 0.0580629 0.0821133 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   ***********************************************************************
C   ****Bottom Buttons 1/4-inch thick**************************************
C   ***********************************************************************
```

```
C    Button OD
800 rcc 0.00000 6.1439 -6.1439 0.00000 0.44901 -0.44901 1.10744
801 rcc 4.34439 4.34439 -6.1439 0.31750 0.3175 -0.44901 1.10744
802 rcc 6.14390 0 -6.1439 0.44901 0 -0.44901 1.10744
803 rcc 4.34439 -4.34439 -6.1439 0.31750 -0.3175 -0.44901 1.10744
804 rcc 0.00000 -6.1439 -6.1439 0.00000 -0.44901 -0.44901 1.10744
805 rcc -4.34439 -4.34439 -6.1439 -0.31750 -0.3175 -0.44901 1.10744
806 rcc -6.14390 0 -6.1439 -0.44901 0 -0.44901 1.10744
807 rcc -4.34439 4.34439 -6.1439 -0.31750 0.3175 -0.44901 1.10744
C   Button ID
810 rcc 0.00000 6.1439 -6.1439 0.00000 0.44901 -0.44901 0.22479
811 rcc 4.34439 4.34439 -6.1439 0.31750 0.3175 -0.44901 0.22479
812 rcc 6.14390 0 -6.1439 0.44901 0 -0.44901 0.22479
813 rcc 4.34439 -4.34439 -6.1439 0.31750 -0.3175 -0.44901 0.22479
814 rcc 0.00000 -6.1439 -6.1439 0.00000 -0.44901 -0.44901 0.22479
815 rcc -4.34439 -4.34439 -6.1439 -0.31750 -0.3175 -0.44901 0.22479
816 rcc -6.14390 0 -6.1439 -0.44901 0 -0.44901 0.22479
817 rcc -4.34439 4.34439 -6.1439 -0.31750 0.3175 -0.44901 0.22479
C     Screws
820 rcc 0.00000 6.1439 -6.1439 0.00000 0.44901 -0.44901 0.1752473
821 rcc 4.34439 4.34439 -6.1439 0.31750 0.31750 -0.44901 0.1752473
822 rcc 6.14390 0 -6.1439 0.44901 0.00000 -0.44901 0.1752473
823 rcc 4.34439 -4.34439 -6.1439 0.31750 -0.31750 -0.44901 0.1752473
824 rcc 0.00000 -6.1439 -6.1439 0.00000 -0.44901 -0.44901 0.1752473
825 rcc -4.34439 -4.34439 -6.1439 -0.31750 -0.31750 -0.44901 0.1752473
826 rcc -6.14390 0 -6.1439 -0.44901 0.00000 -0.44901 0.1752473
827 rcc -4.34439 4.34439 -6.1439 -0.31750 0.31750 -0.44901 0.1752473
C   ***********************************************************************
C   ****Upper Buttons 1/4-inch thick**********************************************
C   ***********************************************************************
C    Button OD
850 rcc 0.0000 6.1439 6.1439 0.0000000 0.4490128 0.4490128 1.10744
851 rcc 4.3444 4.3444 6.1439 0.3175000 0.3175000 0.4490128 1.10744
852 rcc 6.1439 0.0000 6.1439 0.4490128 0.0000000 0.4490128 1.10744
853 rcc 4.3444 -4.3444 6.1439 0.3175000 -0.3175000 0.4490128 1.10744
854 rcc 0.0000 -6.1439 6.1439 0.0000000 -0.4490128 0.4490128 1.10744
855 rcc -4.3444 -4.3444 6.1439 -0.3175000 -0.3175000 0.4490128 1.10744
856 rcc -6.1439 0.0000 6.1439 -0.4490128 0.0000000 0.4490128 1.10744
857 rcc -4.3444 4.3444 6.1439 -0.3175000 0.3175000 0.4490128 1.10744
C   Button ID
860 rcc 0.0000 6.1439 6.1439 0.0000000 0.4490128 0.4490128 0.22479
861 rcc 4.3444 4.3444 6.1439 0.3175000 0.3175000 0.4490128 0.22479
862 rcc 6.1439 0.0000 6.1439 0.4490128 0.0000000 0.4490128 0.22479
863 rcc 4.3444 -4.3444 6.1439 0.3175000 -0.3175000 0.4490128 0.22479
864 rcc 0.0000 -6.1439 6.1439 0.0000000 -0.4490128 0.4490128 0.22479
865 rcc -4.3444 -4.3444 6.1439 -0.3175000 -0.3175000 0.4490128 0.22479
866 rcc -6.1439 0.0000 6.1439 -0.4490128 0.0000000 0.4490128 0.22479
867 rcc -4.3444 4.3444 6.1439 -0.3175000 0.3175000 0.4490128 0.22479
C   Screws
870 rcc 0.0000 6.1439 6.1439 0.0000000 0.4489421 0.4489421 0.17526
871 rcc 4.3444 4.3444 6.1439 0.3174500 0.3174500 0.4489421 0.17526
872 rcc 6.1439 0.0000 6.1439 0.4489421 0.0000000 0.4489421 0.17526
873 rcc 4.3444 -4.3444 6.1439 0.3174500 -0.3174500 0.4489421 0.17526
874 rcc 0.0000 -6.1439 6.1439 0.0000000 -0.4489421 0.4489421 0.17526
875 rcc -4.3444 -4.3444 6.1439 -0.3174500 -0.3174500 0.4489421 0.17526
876 rcc -6.1439 0.0000 6.1439 -0.4489421 0.0000000 0.4489421 0.17526
877 rcc -4.3444 4.3444 6.1439 -0.3174500 0.3174500 0.4489421 0.17526
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    0.25 inch thick uranium button
m50   92234.70c   4.73822E-04
      92235.70c   4.46739E-02
      92236.70c   1.71486E-05
      92238.70c   2.72022E-03
      4009.70c   6.25177E-09
      3006.70c   1.23221E-08
      3007.70c   1.50024E-07
      13027.70c   8.35272E-07
      14028.70c   7.40087E-05
      14029.70c   3.75798E-06
      14030.70c   2.47729E-06
      25055.70c   4.15461E-06
      28058.70c   4.72771E-06
      28060.70c   1.82110E-06
      28061.70c   7.91622E-08
      28062.70c   2.52404E-07
      28064.70c   6.42798E-08
      24050.70c   2.38415E-08
      24052.70c   4.59759E-07
      24053.70c   5.21330E-08
```

```
      24054.70c   1.29770E-08
      29063.70c   1.10914E-06
      29065.70c   4.94357E-07
      5010.70c   4.14840E-08
      5011.70c   1.66979E-07
      27059.70c   9.56035E-08
      20040.70c   1.36281E-06
      20042.70c   9.09562E-09
      20043.70c   1.89785E-09
      20044.70c   2.93253E-08
      20046.70c   5.62326E-11
      20048.70c   2.62887E-09
      6000.70c   2.87082E-04
      8016.70c   1.40519E-05
      8017.70c   3.42292E-08
      7014.70c   2.40463E-05
      7015.70c   8.88172E-08   $ Total   4.83066E-02
C   SS304 at Typical Density
m20   26054.70c   3.52565E-03
      26056.70c   5.53452E-02
      26057.70c   1.27816E-03
      26058.70c   1.70100E-04
      6000.70c   1.60442E-04
      25055.70c   8.76930E-04
      14028.70c   7.91037E-04
      14029.70c   4.01669E-05
      14030.70c   2.64783E-05
      24050.70c   7.64912E-04
      24052.70c   1.47506E-02
      24053.70c   1.67260E-03
      24054.70c   4.16344E-04
      28058.70c   5.30881E-03
      28060.70c   2.04494E-03
      28061.70c   8.88923E-05
      28062.70c   2.83428E-04
      28064.70c   7.21807E-05
      15031.70c   3.49966E-05
      16032.70c   2.13911E-05
      16033.70c   1.71255E-07
      16034.70c   9.66691E-07
      16034.70c   4.50672E-09   $ tot   8.76744E-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 Deck for Surface Button Worth Benchmark Models:
<u>Perturbed Benchmark Model for Worth of 4, 0.3175-cm-thick Buttons</u>

4, 0.3175-cm-thick uranium buttons:

The perturbed benchmark model for this measurement is given below. The reference benchmark model had buttons B1 and B5 in Figure 3.4-5 and T3 and T7 in Figure 3.4-6 removed (cells 800, 804, 852, and 856) but the holding screws were not removed.

Worth per 0.3175-cm-thick aluminum button:

The worth per aluminum button was measured with the worth of three or four aluminum buttons. For the reference benchmark models 12 or 13, 0.3175-cm-thick uranium buttons with holding screws were present; locations B1, T3, and T7 (cells 800, 850, and 856) for the three buttons and B1, B5, T3, and T7 (cells 800, 804, 850, and 856) for the four buttons, see Figure 3.4-5 and Figure 3.4-6. For the perturbed model three or four aluminum buttons (material m50) and holding screws were added to the empty locations. The dimensions of the 0.3175-cm-thick aluminum buttons and holding screws were equal to the dimensions of the 0.3175-cm-thick uranium buttons and holding screws. The cell cards in the below model can be easily modified to obtain the reference and perturbed benchmark models for this measurement.

```
HEU-COMP-FAST-100-Case 2-Detailed Model-->ORSphere 4, 0.3175-cm-thick U Button Worth
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 Holes
110   20 8.69072E-02 -150 160 -101 820  imp:n=1
111   20 8.69072E-02 -151 161 -101 821  imp:n=1
112   20 8.69072E-02 -152 162 -101 822  imp:n=1
113   20 8.69072E-02 -153 163 -101 823  imp:n=1
114   20 8.69072E-02 -154 164 -101 824  imp:n=1
115   20 8.69072E-02 -155 165 -101 825  imp:n=1
116   20 8.69072E-02 -156 166 -101 826  imp:n=1
117   20 8.69072E-02 -157 167 -101 827  imp:n=1
120   0 -160 -101 820   imp:n=1
121   0 -161 -101 801  imp:n=1
122   0 -162 -101 802  imp:n=1
123   0 -163 -101  803 imp:n=1
124   0 -164 -101  824 imp:n=1
125   0 -165 -101  805 imp:n=1
126   0 -166 -101  806 imp:n=1
127   0 -167 -101  807 imp:n=1
C
130   0 101 -104 -900 103 820 801 802 803 824 805 806 807 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 holes
560   20 8.69072E-02 -750 760 -500 870 u=1  imp:n=1
561   20 8.69072E-02 -751 761 -500 871 u=1  imp:n=1
562   20 8.69072E-02 -752 762 -500 872 u=1  imp:n=1
563   20 8.69072E-02 -753 763 -500 873 u=1  imp:n=1
564   20 8.69072E-02 -754 764 -500 874 u=1  imp:n=1
565   20 8.69072E-02 -755 765 -500 875 u=1  imp:n=1
566   20 8.69072E-02 -756 766 -500 876 u=1  imp:n=1
567   20 8.69072E-02 -757 767 -500 877 u=1  imp:n=1
570   0 -760 -500 850 u=1  imp:n=1
571   0 -761 -500 851 u=1  imp:n=1
572   0 -762 -500 872 u=1  imp:n=1
573   0 -763 -500 853 u=1  imp:n=1
574   0 -764 -500 854 u=1  imp:n=1
575   0 -765 -500 855 u=1  imp:n=1
576   0 -766 -500 876 u=1  imp:n=1
577   0 -767 -500 857 u=1  imp:n=1
590   0 500 501 508 850 851 872 853 854 855 876 857 u=1  imp:n=1
591   0 -508  u=1 imp:n=1
C   ***********************************************************************
C   ***********************************************************************
C   ***********************************************************************
C   ****Bottom Buttons*****************************************************
C   ***********************************************************************
C  800  50 4.77065E-02 -800 810 imp:n=1
801  50 4.77065E-02 -801 811 #100 imp:n=1
802  50 4.77065E-02 -802 812 imp:n=1
803  50 4.77065E-02 -803 813 #100 imp:n=1
C  804  50 4.77065E-02 -804 814 imp:n=1
805  50 4.77065E-02 -805 815 #100 imp:n=1
806  50 4.77065E-02 -806 816 imp:n=1
807  50 4.77065E-02 -807 817 #100 imp:n=1
C
C  810  0 -810 820 imp:n=1
811  0 -811 821 #100 imp:n=1
812  0 -812 822 imp:n=1
813  0 -813 823 #100 imp:n=1
C  814  0 -814 824 imp:n=1
815  0 -815 825 #100 imp:n=1
816  0 -816 826 imp:n=1
817  0 -817 827 #100 imp:n=1
C
820  20 8.69072E-02 -820 imp:n=1
821  20 8.69072E-02 -821 #100 imp:n=1
822  20 8.69072E-02 -822 imp:n=1
823  20 8.69072E-02 -823 #100 imp:n=1
824  20 8.69072E-02 -824 imp:n=1
825  20 8.69072E-02 -825 #100 imp:n=1
826  20 8.69072E-02 -826 imp:n=1
827  20 8.69072E-02 -827 #100 imp:n=1
C   ***********************************************************************
C   ****Upper Buttons*****************************************************
C   ***********************************************************************
850  50 4.77065E-02 -850 860 u=1 imp:n=1
851  50 4.77065E-02 -851 861 #500 u=1  imp:n=1
C 852  50 4.77065E-02 -852 862 u=1  imp:n=1
853  50 4.77065E-02 -853 863 #500 u=1  imp:n=1
854  50 4.77065E-02 -854 864 u=1  imp:n=1
```

```
855  50 4.77065E-02 -855 865 #500 u=1  imp:n=1
C 856  50 4.77065E-02 -856 866 u=1  imp:n=1
857  50 4.77065E-02 -857 867 #500 u=1  imp:n=1
C
860  0 -860 870 u=1  imp:n=1
861  0 -861 871 #500 u=1  imp:n=1
C 862  0 -862 872 u=1  imp:n=1
863  0 -863 873 #500 u=1  imp:n=1
864  0 -864 874 u=1  imp:n=1
865  0 -865 875 #500 u=1  imp:n=1
C  866  0 -866 876 u=1  imp:n=1
867  0 -867 877 #500 u=1  imp:n=1
C
870  20 8.69072E-02 -870  u=1  imp:n=1
871  20 8.69072E-02 -871  u=1  imp:n=1
872  20 8.69072E-02 -872  u=1  imp:n=1
873  20 8.69072E-02 -873  #500 u=1  imp:n=1
874  20 8.69072E-02 -874  u=1  imp:n=1
875  20 8.69072E-02 -875  #500 u=1  imp:n=1
876  20 8.69072E-02 -876  u=1  imp:n=1
877  20 8.69072E-02 -877  #500 u=1  imp:n=1
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 Holes
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 Holes
750 rcc 0.0000 5.6626 5.6626 0.0000000 0.5634551 0.5634551 0.17526
751 rcc 4.0040 4.0040 5.6626 0.3984229 0.3984229 0.5634551 0.17526
752 rcc 5.6626 0.0000 5.6626 0.5634551 0.0000000 0.5634551 0.17526
753 rcc 4.0040 -4.0040 5.6626 0.3984229 -0.3984229 0.5634551 0.17526
754 rcc 0.0000 -5.6626 5.6626 0.0000000 -0.5634551 0.5634551 0.17526
755 rcc -4.0040 -4.0040 5.6626 -0.3984229 -0.3984229 0.5634551 0.17526
756 rcc -5.6626 0.0000 5.6626 -0.5634551 0.0000000 0.5634551 0.17526
757 rcc -4.0040 4.0040 5.6626 -0.3984229 0.3984229 0.5634551 0.17526
C
760 rcc 0.0000 6.1439 6.1439 0.0000000 0.0821133 0.0821133 1.11125
761 rcc 4.3444 4.3444 6.1439 0.0580629 0.0580629 0.0821133 1.11125
762 rcc 6.1439 0.0000 6.1439 0.0821133 0.0000000 0.0821133 1.11125
763 rcc 4.3444 -4.3444 6.1439 0.0580629 -0.0580629 0.0821133 1.11125
764 rcc 0.0000 -6.1439 6.1439 0.0000000 -0.0821133 0.0821133 1.11125
765 rcc -4.3444 -4.3444 6.1439 -0.0580629 -0.0580629 0.0821133 1.11125
766 rcc -6.1439 0.0000 6.1439 -0.0821133 0.0000000 0.0821133 1.11125
767 rcc -4.3444 4.3444 6.1439 -0.0580629 0.0580629 0.0821133 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   *********************************************************************
C   ****Bottom Buttons  1/8-inch thick***********************************
C   *********************************************************************
C    Button OD
800 rcc 0.00000 6.1439 -6.1439 0.00000 0.22451 -0.22451 1.10744
801 rcc 4.34439 4.34439 -6.1439 0.15875 0.15875 -0.22451 1.10744
802 rcc 6.14390 0 -6.1439 0.22451 0 -0.22451 1.10744
803 rcc 4.34439 -4.34439 -6.1439 0.15875 -0.15875 -0.22451 1.10744
804 rcc 0.00000 -6.1439 -6.1439 0.00000 -0.22451 -0.22451 1.10744
805 rcc -4.34439 -4.34439 -6.1439 -0.15875 -0.15875 -0.22451 1.10744
806 rcc -6.14390 0 -6.1439 -0.22451 0 -0.22451 1.10744
807 rcc -4.34439 4.34439 -6.1439 -0.15875 0.15875 -0.22451 1.10744
C   Button ID
810 rcc 0.00000 6.1439 -6.1439 0.00000 0.22451 -0.22451 0.22479
811 rcc 4.34439 4.34439 -6.1439 0.15875 0.15875 -0.22451 0.22479
812 rcc 6.14390 0 -6.1439 0.22451 0 -0.22451 0.22479
813 rcc 4.34439 -4.34439 -6.1439 0.15875 -0.15875 -0.22451 0.22479
814 rcc 0.00000 -6.1439 -6.1439 0.00000 -0.22451 -0.22451 0.22479
```

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815 rcc -4.34439 -4.34439 -6.1439 -0.15875 -0.15875 -0.22451 0.22479
816 rcc -6.14390 0 -6.1439 -0.22451 0 -0.22451 0.22479
817 rcc -4.34439 4.34439 -6.1439 -0.15875 0.15875 -0.22451 0.22479
C     Screws
820 rcc 0.00000 6.1439 -6.1439 0.00000 0.22451 -0.22451 0.1752473
821 rcc 4.34439 4.34439 -6.1439 0.15875 0.15875 -0.22451 0.1752473
822 rcc 6.14390 0 -6.1439 0.22451 0.00000 -0.22451 0.1752473
823 rcc 4.34439 -4.34439 -6.1439 0.15875 -0.15875 -0.22451 0.1752473
824 rcc 0.00000 -6.1439 -6.1439 0.00000 -0.22451 -0.22451 0.1752473
825 rcc -4.34439 -4.34439 -6.1439 -0.15875 -0.15875 -0.22451 0.1752473
826 rcc -6.14390 0 -6.1439 -0.22451 0.00000 -0.22451 0.1752473
827 rcc -4.34439 4.34439 -6.1439 -0.15875 0.15875 -0.22451 0.1752473
C    ***********************************************************************
C    ****Upper Buttons 1/8-inch thick******************************************
C    ***********************************************************************
C    Button OD
850 rcc 0.0000 6.1439 6.1439 0.0000000 0.2245064 0.2245064 1.10744
851 rcc 4.3444 4.3444 6.1439 0.1587500 0.1587500 0.2245064 1.10744
852 rcc 6.1439 0.0000 6.1439 0.2245064 0.0000000 0.2245064 1.10744
853 rcc 4.3444 -4.3444 6.1439 0.1587500 -0.1587500 0.2245064 1.10744
854 rcc 0.0000 -6.1439 6.1439 0.0000000 -0.2245064 0.2245064 1.10744
855 rcc -4.3444 -4.3444 6.1439 -0.1587500 -0.1587500 0.2245064 1.10744
856 rcc -6.1439 0.0000 6.1439 -0.2245064 0.0000000 0.2245064 1.10744
857 rcc -4.3444 4.3444 6.1439 -0.1587500 0.1587500 0.2245064 1.10744
C   Button ID
860 rcc 0.0000 6.1439 6.1439 0.0000000 0.2245064 0.2245064 0.22479
861 rcc 4.3444 4.3444 6.1439 0.1587500 0.1587500 0.2245064 0.22479
862 rcc 6.1439 0.0000 6.1439 0.2245064 0.0000000 0.2245064 0.22479
863 rcc 4.3444 -4.3444 6.1439 0.1587500 -0.1587500 0.2245064 0.22479
864 rcc 0.0000 -6.1439 6.1439 0.0000000 -0.2245064 0.2245064 0.22479
865 rcc -4.3444 -4.3444 6.1439 -0.1587500 -0.1587500 0.2245064 0.22479
866 rcc -6.1439 0.0000 6.1439 -0.2245064 0.0000000 0.2245064 0.22479
867 rcc -4.3444 4.3444 6.1439 -0.1587500 0.1587500 0.2245064 0.22479
C   Screws
870 rcc 0.0000 6.1439 6.1439 0.0000000 0.2244357 0.2244357 0.1752600
871 rcc 4.3444 4.3444 6.1439 0.1587000 0.1587000 0.2244357 0.1752600
872 rcc 6.1439 0.0000 6.1439 0.2244357 0.0000000 0.2244357 0.1752600
873 rcc 4.3444 -4.3444 6.1439 0.1587000 -0.1587000 0.2244357 0.1752600
874 rcc 0.0000 -6.1439 6.1439 0.0000000 -0.2244357 0.2244357 0.1752600
875 rcc -4.3444 -4.3444 6.1439 -0.1587000 -0.1587000 0.2244357 0.1752600
876 rcc -6.1439 0.0000 6.1439 -0.2244357 0.0000000 0.2244357 0.1752600
877 rcc -4.3444 4.3444 6.1439 -0.1587000 0.1587000 0.2244357 0.1752600
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
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      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
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      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    0.125 inch thick uranium button
m50   92234.70c   4.69209E-04
      92235.70c   4.42390E-02
      92236.70c   1.69817E-05
      92238.70c   2.69374E-03
      13027.70c   8.27141E-07
      14028.70c   7.32882E-05
      14029.70c   3.72140E-06
      14030.70c   2.45317E-06
      25055.70c   4.11417E-06
      28058.70c   4.68169E-06
      28060.70c   1.80338E-06
      28061.70c   7.83916E-08
      28062.70c   2.49947E-07
      28064.70c   6.36540E-08
      24050.70c   2.36094E-08
      24052.70c   4.55283E-07
      24053.70c   5.16255E-08
      24054.70c   1.28507E-08
      29063.70c   1.09834E-06
      29065.70c   4.89544E-07
      5010.70c   4.10802E-08
      5011.70c   1.65353E-07
      6000.70c   1.56079E-04
      8016.70c   1.39151E-05
      8017.70c   3.38960E-08
      7014.70c   2.38122E-05
      7015.70c   8.79526E-08   $ Total   4.77065E-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 Deck for Button Worth in Empty Socket Hole Benchmark Models:
<u>Perturbed Benchmark Model for Worth of 3, 0.3175-cm-thick Buttons in Socket Hole</u>

3, 0.3175-cm-thick uranium buttons in empty socket hole:

The perturbed benchmark model for this measurement is given below. The reference benchmark model had the three buttons in the socket hole removed (cell 580-582).

3, 0.3175-cm-thick aluminum buttons in empty socket hole:

The perturbed benchmark model for this measurement is the same as the model given below but the three buttons in the socket hole were aluminum (material m30, cell 580-582). The reference benchmark model was the same and had the three buttons in the socket hole removed (cell 580-582).

3, 0.3175-cm-thick stainless steel buttons in empty socket hole:

The perturbed benchmark model for this measurement is the same as the model given below but the three buttons in the socket hole were stainless steel (material m20, cell 580-582). The reference benchmark model was the same and had the three buttons in the socket hole removed (cell 580-582).

```
HMF100-Case 2-Detailed Model-->ORSphere 3, 0.375-cm-thick U Buttons in Socket
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 Holes
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 holes
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 -508 890 891 892 u=1 imp:n=1
580   18 4.78297E-02 -890 893 u=1 imp:n=1
581   18 4.78297E-02 -891 894 u=1 imp:n=1
582   18 4.78297E-02 -892 895 u=1 imp:n=1
583   0 -893 u=1 imp:n=1
584   0 -894 u=1 imp:n=1
585   0 -895 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 Holes
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 Holes
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   ****Socket Hole Buttons, 3       ******************************************
C   ***********************************************************************
890 rcc 0 0 7.806182 0 0 0.3175 1.10744
891 rcc 0 0 8.123682 0 0 0.3175 1.10744
892 rcc 0 0 8.441182 0 0 0.3175 1.10744
893 rcc 0 0 7.806182 0 0 0.3175 0.22479
894 rcc 0 0 8.123682 0 0 0.3175 0.22479
895 rcc 0 0 8.441182 0 0 0.3175 0.22479
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
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      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
```

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      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
```

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      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
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      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
m18   92234.70c   4.69144E-04
      92235.70c   4.42329E-02
      92236.70c   1.69793E-05
      92238.70c   2.69337E-03
      4009.70c   6.19006E-09
      3006.70c   1.22004E-08
      3007.70c   1.48543E-07
      13027.70c   8.27027E-07
      14028.70c   7.32781E-05
      14029.70c   3.72089E-06
      14030.70c   2.45283E-06
      25055.70c   4.11360E-06
      28058.70c   4.68104E-06
      28060.70c   1.80313E-06
      28061.70c   7.83808E-08
      28062.70c   2.49912E-07
      28064.70c   6.36453E-08
      24050.70c   2.36061E-08
      24052.70c   4.55221E-07
      24053.70c   5.16184E-08
      24054.70c   1.28489E-08
      29063.70c   1.09819E-06
      29065.70c   4.89477E-07
      5010.70c   4.10746E-08
      5011.70c   1.65330E-07
      27059.70c   9.46598E-08
      20040.70c   1.34936E-06
      20042.70c   9.00583E-09
      20043.70c   1.87912E-09
      20044.70c   2.90358E-08
      20046.70c   5.56775E-11
      20048.70c   2.60292E-09
      6000.70c   2.84248E-04
      8016.70c   1.39131E-05
      8017.70c   3.38913E-08
      7014.70c   2.38089E-05
      7015.70c   8.79405E-08   $ Total   4.78297E-02
C   SS304 at Typical Density
m20   26054.70c   3.52565E-03
      26056.70c   5.53452E-02
      26057.70c   1.27816E-03
      26058.70c   1.70100E-04
      6000.70c   1.60442E-04
      25055.70c   8.76930E-04
      14028.70c   7.91037E-04
      14029.70c   4.01669E-05
      14030.70c   2.64783E-05
      24050.70c   7.64912E-04
      24052.70c   1.47506E-02
      24053.70c   1.67260E-03
      24054.70c   4.16344E-04
      28058.70c   5.30881E-03
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      28060.70c   2.04494E-03
      28061.70c   8.88923E-05
      28062.70c   2.83428E-04
      28064.70c   7.21807E-05
      15031.70c   3.49966E-05
      16032.70c   2.13911E-05
      16033.70c   1.71255E-07
      16034.70c   9.66691E-07
      16034.70c   4.50672E-09   $ tot   8.76744E-02
C   Al 6061 at Typical Density
m30   13027.70c   5.86382E-02
      24050.70c   2.64951E-06
      24052.70c   5.10932E-05
      24053.70c   5.79356E-06
      24054.70c   1.44214E-06
      29063.70c   4.86714E-05
      29065.70c   2.16935E-05
      26054.70c   5.95613E-06
      26056.70c   9.34986E-05
      26057.70c   2.15929E-06
      26058.70c   2.87362E-07
      12024.70c   5.28431E-04
      12025.70c   6.68985E-05
      12026.70c   7.36552E-05
      25055.66c   2.21973E-05
      14028.70c   3.20370E-04
      14029.70c   1.62676E-05
      14030.70c   1.07237E-05
      22046.70c   2.10123E-06
      22047.70c   1.89492E-06
      22048.70c   1.87760E-05
      22049.70c   1.37789E-06
      22050.70c   1.31932E-06
      30000.70c   3.10821E-05   $ tot   5.99666E-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 Deck for Diametral Filler Rod Worth Benchmark Models:

Reference Benchmark Model Diametral Filler Rod Worth

The reference benchmark model for the diametral filler rod worth was identical to the Case 2 detailed benchmark model of HEU-MET-FAST-100, given below. For the perturbed benchmark model the diametral filler rod was removed (cell 308).

```
HMF100-Case 2-Detailed Model-->ORSphere 3, 0.375-cm-thick U Buttons in Socket
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 Holes
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 holes
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
```

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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 -508 890 891 892 u=1 imp:n=1
580   18 4.78297E-02 -890 893 u=1 imp:n=1
581   18 4.78297E-02 -891 894 u=1 imp:n=1
582   18 4.78297E-02 -892 895 u=1 imp:n=1
583   0 -893 u=1 imp:n=1
584   0 -894 u=1 imp:n=1
585   0 -895 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 Holes
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 Holes
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   ****Socket Hole Buttons, 3       *****************************************
C   ***********************************************************************
890 rcc 0 0 7.806182 0 0 0.3175 1.10744
891 rcc 0 0 8.123682 0 0 0.3175 1.10744
892 rcc 0 0 8.441182 0 0 0.3175 1.10744
893 rcc 0 0 7.806182 0 0 0.3175 0.22479
894 rcc 0 0 8.123682 0 0 0.3175 0.22479
895 rcc 0 0 8.441182 0 0 0.3175 0.22479
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
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      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
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      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
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      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
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      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
m18   92234.70c   4.69144E-04
      92235.70c   4.42329E-02
      92236.70c   1.69793E-05
      92238.70c   2.69337E-03
      4009.70c   6.19006E-09
      3006.70c   1.22004E-08
      3007.70c   1.48543E-07
      13027.70c   8.27027E-07
      14028.70c   7.32781E-05
      14029.70c   3.72089E-06
      14030.70c   2.45283E-06
      25055.70c   4.11360E-06
      28058.70c   4.68104E-06
      28060.70c   1.80313E-06
      28061.70c   7.83808E-08
      28062.70c   2.49912E-07
      28064.70c   6.36453E-08
      24050.70c   2.36061E-08
      24052.70c   4.55221E-07
      24053.70c   5.16184E-08
      24054.70c   1.28489E-08
      29063.70c   1.09819E-06
      29065.70c   4.89477E-07
      5010.70c   4.10746E-08
      5011.70c   1.65330E-07
      27059.70c   9.46598E-08
      20040.70c   1.34936E-06
      20042.70c   9.00583E-09
      20043.70c   1.87912E-09
      20044.70c   2.90358E-08
      20046.70c   5.56775E-11
      20048.70c   2.60292E-09
      6000.70c   2.84248E-04
      8016.70c   1.39131E-05
      8017.70c   3.38913E-08
      7014.70c   2.38089E-05
      7015.70c   8.79405E-08   $ Total   4.78297E-02
C   SS304 at Typical Density
m20   26054.70c   3.52565E-03
      26056.70c   5.53452E-02
      26057.70c   1.27816E-03
      26058.70c   1.70100E-04
      6000.70c   1.60442E-04
      25055.70c   8.76930E-04
      14028.70c   7.91037E-04
      14029.70c   4.01669E-05
```

```
      14030.70c   2.64783E-05
      24050.70c   7.64912E-04
      24052.70c   1.47506E-02
      24053.70c   1.67260E-03
      24054.70c   4.16344E-04
      28058.70c   5.30881E-03
      28060.70c   2.04494E-03
      28061.70c   8.88923E-05
      28062.70c   2.83428E-04
      28064.70c   7.21807E-05
      15031.70c   3.49966E-05
      16032.70c   2.13911E-05
      16033.70c   1.71255E-07
      16034.70c   9.66691E-07
      16034.70c   4.50672E-09   $ tot   8.76744E-02
C   Al 6061 at Typical Density
m30   13027.70c   5.86382E-02
      24050.70c   2.64951E-06
      24052.70c   5.10932E-05
      24053.70c   5.79356E-06
      24054.70c   1.44214E-06
      29063.70c   4.86714E-05
      29065.70c   2.16935E-05
      26054.70c   5.95613E-06
      26056.70c   9.34986E-05
      26057.70c   2.15929E-06
      26058.70c   2.87362E-07
      12024.70c   5.28431E-04
      12025.70c   6.68985E-05
      12026.70c   7.36552E-05
      25055.66c   2.21973E-05
      14028.70c   3.20370E-04
      14029.70c   1.62676E-05
      14030.70c   1.07237E-05
      22046.70c   2.10123E-06
      22047.70c   1.89492E-06
      22048.70c   1.87760E-05
      22049.70c   1.37789E-06
      22050.70c   1.31932E-06
      30000.70c   3.10821E-05   $ tot   5.99666E-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
```

A.5 Reactivity Coefficient Configurations

A.5.1 Name(s) of Code System(s) Used

1. Monte Carlo n-Particle, Version 5.1.60 (MCNP5).

A.5.2 Bibliographic References for the Codes Used

1. 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).

A.5.3 Origin of Cross-section Data

The evaluated neutron data file library ENDF/B-VII.0[a] was utilized in the benchmark-model analysis.

A.5.4 Spectral Calculations and Data Reduction Methods Used

Not applicable.

A.5.5 Number of Energy Groups or If Continuous-energy Cross Sections are Used in the Different Phases of Calculation

1. Continuous-energy cross sections.

A.5.6 Component Calculations

Not applicable

A.5.7 Other Assumptions and Characteristics

Not applicable.

A.5.8 Typical Input Listings for Each Code System Type

The benchmark models for the worth per gram of uranium surface material are given below.

Benchmark Model for the Larger Sphere

```
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    120 4.84551E-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 Holes
110   0 -150 160 -101   imp:n=1
111   0 -151 161 -101   imp:n=1
```

[a] 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).

```
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    120 4.84551E-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     $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     $Lower Half
302   0 -307  u=1 imp:n=1
303   0 (-301 303 -308 309):(-302 -303 -308 309)  u=1 imp:n=1
304   17 4.83091E-02 -323 -301 303 308  u=1 imp:n=1     $Target Hole Plug
305   17 4.83091E-02 -323 -302 -303 308  u=1 imp:n=1     $Target Hole Plug
306   17 4.83091E-02 -324 -301  u=1 imp:n=1     $Thermocouple
307   17 4.83091E-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 4.83090E-02 -410 308 -306  u=1 imp:n=1
321   15 4.83090E-02 -411 308 -306  u=1 imp:n=1
322   15 4.83090E-02 -412 308 -306  u=1 imp:n=1
330   0 (302 -303 305 309 310 311 312 313) u=1 imp:n=1
331   0 -305 u=1 imp:n=1
332   0 (301 303 -306 309 310 311 312 313) u=1 imp:n=1
C              imp:n=1
C
C   ************************************************************************
C   Upper Plate
C   ************************************************************************
406   14 4.82894E-02 -401 406 -407 410 411 412 u=1  imp:n=1
407   14 4.82894E-02 -408 u=1  imp:n=1
408   0  401 406 -407  u=1  imp:n=1
430   15 4.83090E-02 -410 308 406 -407 u=1  imp:n=1
431   15 4.83090E-02 -411 308 406 -407 u=1  imp:n=1
432   15 4.83090E-02 -412 308 406 -407 u=1  imp:n=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
501   0   -503 408 u=1  imp:n=1
C 502   0  -500 -508 u=1  imp:n=1     $ Socket
C  Mass Adjustment Button holes
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
905   0  205 206  -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 Holes
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 2.637282 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 Holes
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    Shaved pin
m120   92234.70c   4.82106E-04
      92235.70c   4.49261E-02
      92236.70c   2.16579E-04
      92238.70c   2.57020E-03
      13027.70c   2.10164E-06
      14028.70c   4.46914E-05
      14029.70c   2.26932E-06
      14030.70c   1.49595E-06
      25055.70c   3.81244E-06
      28058.70c   4.33834E-06
      28060.70c   1.67112E-06
      28061.70c   7.26424E-08
      28062.70c   2.31616E-07
      28064.70c   5.89857E-08
      24050.70c   2.18779E-08
      24052.70c   4.21893E-07
      24053.70c   4.78393E-08
      24054.70c   1.19082E-08
      29063.70c   1.01779E-06
      29065.70c   4.53642E-07
      5010.70c   6.26271E-08
      5011.70c   2.52082E-07
      6000.70c   1.58629E-04
      8016.70c   1.41424E-05
      8017.70c   3.44498E-08
      7014.70c   2.42013E-05
      7015.70c   8.93896E-08   $ Total   4.84551E-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
```

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      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
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      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
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
```

Benchmark Model for the Smaller Sphere

```
HEU-COMP-FAST-100-Case 2-Detailed Model/ ORSphere
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 Holes
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 holes
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 Holes
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 Holes
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
```

A.6 Kinetics Parameter Configurations

A.6.1 Name(s) of Code System(s) Used

1. Monte Carlo n-Particle, Version 5.1.60 (MCNP5).

A.6.2 Bibliographic References for the Codes Used

1. 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).

A.6.3 Origin of Cross-section Data

The evaluated neutron data file library ENDF/B-VII.0[a] was utilized in the benchmark-model analysis.

A.6.4 Spectral Calculations and Data Reduction Methods Used

Not applicable.

A.6.5 Number of Energy Groups or If Continuous-energy Cross Sections are Used in the Different Phases of Calculation

1. Continuous-energy cross sections.

A.6.6 Component Calculations

Not applicable

A.6.7 Other Assumptions and Characteristics

Not applicable.

A.6.8 Typical Input Listings for Each Code System Type

The benchmark model for the effective delayed neutron fraction, β_{eff}, was identical to the detailed Case 1 and Case 2 benchmark model in HEU-MET-FAST-100. To calculate the β_{eff} the following data cards were added to the input decks given in HEU-MET-FAST-100.

Calculation using k_{prompt}	*Calculation using adjoint-weighted method*
`totnu no`	`kopts blocksize=10 kinetics=yes precursor=yes`

A sample input deck for the benchmark model for the prompt neutron decay constant and the mean neutron generation time is provided.

MCNP5 Input Deck for Prompt Neutron Decay Constant and Mean Neutron Generation Time Benchmark Models:

```
HEU-COMP-FAST-100
C
C
C   Cell Cards
C
1     1 4.82842E-02 -1  imp:n=1
2     0          1  -900 imp:n=1
```

[a] 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).

```
910   0            900 imp:n=0

C   Surface Cards
C
1   so 8.763393588
900  rpp -100 100 -100 100 -100 100

C   Data Cards
m1   92234.70c   4.75683E-04
      92235.70c   4.48383E-02
      92236.70c   2.19377E-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
kopts  blocksize=10 kinetics=yes precursor=yes
print
```

A.7 Reaction-Rate Configurations

A.7.1 Name(s) of Code System(s) Used

1. Monte Carlo n-Particle, Version 5.1.60 (MCNP5).

A.7.2 Bibliographic References for the Codes Used

1. 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).

A.7.3 Origin of Cross-section Data

The evaluated neutron data file library ENDF/B-VII.0[a] was utilized in the benchmark-model analysis.

A.7.4 Spectral Calculations and Data Reduction Methods Used

Not applicable.

A.7.5 Number of Energy Groups or If Continuous-energy Cross Sections are Used in the Different Phases of Calculation

1. Continuous-energy cross sections.

A.7.6 Component Calculations

Not applicable

A.7.7 Other Assumptions and Characteristics

Not applicable.

[a] 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).

A.7.8 Typical Input Listings for Each Code System Type

The simple benchmark models for the relative neutron importance for BF_3 detector response and a Cf source sample calculation is given:

MCNP5 Input Deck for Relative Neutron Importance for BF3 Detector Response and a Cf Source Models:

```
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 8.72992816
900  rpp -1000 1000 -1000 1000 -1000 1000

C   Data Cards
m1   92234.70c   4.75683E-04
      92235.70c   4.48383E-02
      92236.70c   2.19377E-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
C
C kcode  500000 1 150 2650
C sdef    pos 0 0 0 rad=d1 erg=d3
C si1       0 3.4665
C sp1      -21 2
C sp3     -3 0.988 2.249.
C
C
sdef    pos = d4  rad = d1  ext = d2  axs=1 0 0  erg=d3
SI1     0 0.1575
SP1     -21 1
SI2     -0.4805 0.4805
SP2     -21 0
SP3     -2  1.4
SI4 L   -8.6185 0 0    -8.5855 0 0    -8.5805 0 0    -8.4845 0 0
        -7.9605 0 0    -7.3135 0 0    -7.3055 0 0    -7.2395 0 0
        -7.2115 0 0    -6.2105 0 0    -6.0635 0 0    -5.9645 0 0
        -5.9085 0 0    -4.8725 0 0    -4.7685 0 0    -4.7015 0 0
        -4.6465 0 0    -3.6885 0 0    -3.6505 0 0    -3.4925 0 0
        -3.3715 0 0    -2.3805 0 0    -2.2205 0 0    -2.0985 0 0
        -1.1125 0 0    -0.9505 0 0    -0.4805 0 0     0.1795 0 0
         0.3245 0 0     0.4235 0 0     1.4245 0 0     1.5435 0 0
         1.5975 0 0     2.6945 0 0     2.9685 0 0     3.9645 0 0
         4.1655 0 0     4.2415 0 0     5.2315 0 0     5.4145 0 0
         5.5135 0 0     6.7355 0 0     6.9385 0 0     7.1695 0 0
         7.7925 0 0     7.9195 0 0     7.9625 0 0     8.1095 0 0
         8.1375 0 0     8.2645 0 0     8.6105 0 0
SP4 D   1 50r
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
f15:n  0 295 -249.5  3
ft15   scx 4
C
f25:n  295 0 -249.5  3
ft25   scx 4
C
f35:n  0 -295 -249.5  3
ft35   scx 4
C
```

```
nps  250000000
```

A sample input deck for the relative fission density is provided.

MCNP5 Input Deck for Relative Fission Density Models:

```
HEU-COMP-FAST-100 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 8.72992816
900  rpp -100 100 -100 100 -100 100

C   Data Cards
m1   92234.70c   4.75683E-04
      92235.70c   4.48383E-02
      92236.70c   2.19377E-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
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
fmesh4:n  geom cyl    origin -8.9 0 0
       axs 1 0 0   vec 0 1 1
       imesh 0.165
       jmesh 18 jints 18000
       kmesh 1
```

A.8 Power Distribution Configurations

Power distribution measurements were not performed.

A.9 Isotopic Configurations

Isotopic measurements were not performed.

A.10 Configurations of Other Miscellaneous Types of Measurements

Other miscellaneous types of measurements were not performed.

APPENDIX B: SAMPLE CALCULATION USING INHOUR EQUATION TO CONVERT STABLE REACTOR PERIOD TO REACTIVITY IN CENTS

The stable reactor period was measured to determine system reactivity. The change in system reactivity corresponding to changes in the system yields the worth of those changes. To convert the stable reactor period to reactivity in dollars or cents the Inhour Equation is used, Equation B.1. It should be noted that this is the equation the experimenter refers to as "the Inhour Equation" and will be referred to as such in this evaluation. In "Nuclear Reactor Engineering" by Glasstone and Sesonske this equation is simply referred to as the relationship between stable reactor period and reactivity. The actual Inhour equation yields reactivity in units of Inhours but is not used in this evaluation because the desired reactivity is in units of dollars.[a]

Equation B.1

$$\rho^k = \frac{l}{T_p} + \sum_{i=1}^{6} \frac{\beta_i}{1 + \lambda_i T_p}$$

Equation B.2

$$Ih = \frac{\frac{l}{T_p} + \sum_{i=1}^{6} \frac{\beta_i}{1 + \lambda_i T_p}}{\frac{l}{3600} + \sum_{i=1}^{6} \frac{\beta_i}{1 + 3600\lambda_i}}$$

where:

	ρ^k	System Reactivity, Δk_{eff}
	Ih	System Reactivity, Inhours
	T_p	Stable Reactor Period, s
	l	Prompt neutron lifetime, s
	β_i	Delayed neutron fraction of i^{th} group
	λ_i	Decay constant for i^{th} group

The first simplification to Equation B.1 employs the very small prompt neutron lifetime, $l \cong 6 \times 10^{-9}$s, for HEU systems, as measured with GODIVA.[b] When divided by the stable reactor period, which for the ORSphere measurements were typically on the order of 100-200 s, the first term in Equation B.1 become negligible. Next, the remaining two terms are divided by the delayed neutron fraction, β. For these calculations "it was assumed that the effectiveness of the delayed neutrons relative to prompt neutrons was the same for all six delayed neutron groups" (Reference 3). By this assumption $\beta^i_{eff}/\beta_{eff}$ equals β^i/β. With these two simplifications and (1) the fact that β^i/β equals the relative yield, α_i, and (2) the fact that the system reactivity in units of Δk_{eff} over the effective delayed neutron fraction equals the system reactivity in units of dollars, $\rho^{\$}$, Equation B.1 becomes Equation B.3

Equation B.3

$$\rho^{\$} = \sum_{i=1}^{6} \frac{\alpha_i}{1 + \lambda_i T_p}$$

The six-group delayed neutron parameters and the measured stable reactor period are used in this equation. In order to combine the ^{235}U and ^{238}U groups the fission fractions are used. Since Keepin data for the delayed neutron parameters is only given for ^{235}U and ^{238}U, 50% of the ^{234}U fission fraction and 50% of the ^{236}U fission fraction were added to the ^{235}U and the other half to ^{238}U for the Inhour calculations. Equation B.4 shows the reactivity calculation using the fission fractions, ff^k.

[a] S. Glassstone and A. Sesonske, "Nuclear Reactor Engineering," Van Nostrand Reinhold Company, New York, 1967. Equations 5.37 and 5.39.

[b] Personal email communication with J.T. Mihalczo, July 17. 2013.

Equation B.4
$$\rho^{\$} = ff^{235}\sum_{i=1}^{6}\frac{\alpha_i^{235}}{1+\lambda_i^{235}T_p} + ff^{238}\sum_{i=1}^{6}\frac{\alpha_i^{238}}{1+\lambda_i^{238}T_p}$$

The delayed neutron parameters for uranium isotopes 235 and 238 and the fission fractions are given in Table 1.4-1. When the fission fractions from ^{234}U and ^{236}U are split 50/50 between ^{235}U and ^{238}U the resulting fission fractions are 98.6104% and 1.3896% for ^{235}U and ^{238}U, respectively. The following is a sample calculation for the stable reactor period 94.9 s, measured for the central void reactivity (run 528A Ion Chamber A).

$$\begin{aligned}
\rho^{\$} = \quad ff^{235} * &\left[\frac{0.038}{1+0.0127\cdot 94.9}\right. & +ff^{238} * &\left[\frac{0.013}{1+0.0132\cdot 94.9}\right. & &\text{(Group 1)}\\
&+\frac{0.213}{1+0.0317\cdot 94.9} & &+\frac{0.137}{1+0.0321\cdot 94.9} & &\text{(Group 2)}\\
&+\frac{0.188}{1+0.115\cdot 94.9} & &+\frac{0.162}{1+0.139\cdot 94.9} & &\text{(Group 3)}\\
&+\frac{0.407}{1+0.311\cdot 94.9} & &+\frac{0.388}{1+0.358\cdot 94.9} & &\text{(Group 4)}\\
&+\frac{0.128}{1+1.40\cdot 94.9} & &+\frac{0.225}{1+1.41\cdot 94.9} & &\text{(Group 5)}\\
&\left.+\frac{0.026}{1+3.87\cdot 94.9}\right] & &\left.+\frac{0.075}{1+4.02\cdot 94.9}\right] & &\text{(Group 6)}
\end{aligned}$$

$$\begin{aligned}
\rho^{\$} = \quad &98.6104\%[1.7232+5.3139+1.578+1.3338+.09562+.007060]\times 10^{-2}\\
&+1.3896\%[0.5771+3.3858+1.1416+1.1094+0.1669+0.0196079]\times 10^{-2}
\end{aligned}$$

This calculation yields a system reactivity of 0.1000091 \$ or 10.00091 ¢. This calculation can be repeated for stable reactor period for run 528B from the same ion chamber, 1750 s.

$$\begin{aligned}
\rho^{\$} = \quad ff^{235} * &\left[\frac{0.038}{1+0.0127\cdot 1750}\right. & +ff^{238} * &\left[\frac{0.013}{1+0.0132\cdot 1750}\right. & &\text{(Group 1)}\\
&+\frac{0.213}{1+0.0317\cdot 1750} & &+\frac{0.137}{1+0.0321\cdot 1750} & &\text{(Group 2)}\\
&+\frac{0.188}{1+0.115\cdot 1750} & &+\frac{0.162}{1+0.139\cdot 1750} & &\text{(Group 3)}\\
&+\frac{0.407}{1+0.311\cdot 1750} & &+\frac{0.388}{1+0.358\cdot 1750} & &\text{(Group 4)}\\
&+\frac{0.128}{1+1.40\cdot 1750} & &+\frac{0.225}{1+1.41\cdot 1750} & &\text{(Group 5)}\\
&\left.+\frac{0.026}{1+3.87\cdot 1750}\right] & &\left.+\frac{0.075}{1+4.02\cdot 1750}\right] & &\text{(Group 6)}
\end{aligned}$$

$$\begin{aligned}
\rho^{\$} = \quad &98.6104\%[0.1636+0.3772+0.093+0.0746+0.00522+0.0003838]\times 10^{-2}\\
&+1.3896\%[0.0539+0.2396+0.0663+0.0618+0.0091148+0.00106]\times 10^{-2}
\end{aligned}$$

This calculation yields a system reactivity of 0.0071006 \$ or 0.71006 ¢.

The resulting worth for the central void for run 528, measured with ion chamber A, is 9.29 ¢ (10.00091 ¢ - 0.71006 ¢). This agrees well with the worth given by the experimenter in Table 1.4-3 (9.28 ¢).

If the delayed neutron parameters are given with a consistent set of half-lives, rather than a half life for each group, this calculation must be modified slightly. To do this a yield for all isotopes for each group is found. This is done by multiplying the yield for each isotope by its respective fission fraction and then summing the four results together. This value is then used in Equation B.3. Since the values in Table 2.4-2 have eight groups rather than six, Equation B.5 is updated accordingly.

Equation B.5

$$\rho^{\$} = \sum_{i=1}^{8} \frac{\sum_{k=1}^{4} ff^k \cdot \alpha^k}{1 + \lambda_i T_p}$$