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The Central Void Reactivity in the Oak Ridge Enriched Uranium (93.2) Metal Sphere

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Instrumentation and Controls Division

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ABSTRACT

The central reactivity void worth was measured in the Oak Ridge unmoderated and unreflected uranium (93.20 wt % ^{235}U) metal sphere by replacement measurements in a small (0.460-cm-diam) central spherical region in an 8.7427-cm-radius sphere. The central void worth was 9.165 ± 0.023 cents using the delayed neutron relative abundances and decay constants of Keepin, Wimett, and Zeigler to obtain the reactivity in cents from the stable reactor period measurements using the Inhour equation. This value is slightly larger than measurements with GODIVA I with larger cylindrical samples of uranium (93.70 wt % ^{235}U) in the center: 135.50 ± 0.12 cents/mole for GODIVA I and 138.05 ± 0.34 cents/mole for the Oak Ridge sphere measurements, and the difference could be due to sample size effect. The central worth in Δk units was calculated by neutron transport theory methods to be 6.02 ± 0.01 × 10^{-4} Δk. The measured and calculated values are related by the effective delayed neutron fraction. The value of the effective delayed neutron fraction obtained in this way from the Oak Ridge sphere is 0.00657 ± 0.00002, which is in excellent agreement with that obtained from GOVIDA I measurements, where the effective delayed neutron fraction was determined as the increment between delayed and prompt criticality and was 0.0066. From these Oak Ridge measurements, using the delayed neutron parameters of ENDF-B/VI to obtain the reactivity from the stable reactor period measurements, the central void worth is 7.984 ± 0.021 cents, and the inferred effective delayed neutron fraction is 0.00754. This central void worth and effective delayed neutron fractions are 14.2% higher than those obtained from use of the Keepin et al. delayed neutron data and produce a value of delayed neutron fraction in disagreement with GODIVA I measurements, thus questioning the usefulness of the relative abundances and decay constants of the six-group delayed neutron parameters of ENDF-B/VI for uranium for obtaining the reactivity from the measured reactor period using the Inhour equation.

ACKNOWLEDGMENT

The work of M. S. Wyatt of the Nuclear Engineering Department at The University of Tennessee in Knoxville in recalculation of the central worth from the measured reactor periods is acknowledged.

1. INTRODUCTION

A nearly spherical uranium (93.70 wt % ^{235}U) metal assembly (GODIVA I) has been previously reported.[1] An exactly spherical (i.e., all major parts machined to the same radius with the same center) enriched uranium (93.20 wt % ^{235}U) metal system was assembled to delayed criticality in 1971 at the Oak Ridge Critical Experiments Facility at the Y-12 Plant for a variety of reactor physics measurements.[2] This paper describes the measurement of the stable reactor period with and without a central spherical void region filled with uranium. These stable reactor period measurements are used to obtain the reactivity worth of a small spherical void at the center of the sphere. These central void worths are compared with previous measurements of the worth of a central cylindrical region at the center of GODIVA I.[3] These measurements and neutron transport theory calculations of the central worth are then used to obtain the effective delayed neutron fraction, which can be used to evaluate the six-group delayed neutron parameters (relative abundances and decay constants) of ENDF/B-VI data[4] as compared to those of Keepin, Wimett, and Zeigler.[5]

2. DESCRIPTION OF THE URANIUM SPHERE

This uranium metal sphere with an average radius of 3.4420 in. consisted of five major parts: upper polar cap, upper plate, central plate, lower plate, and lower polar cap. The upper and central plate were pinned together with uranium metal pins, as were the lower plate and lower polar cap. Pins were inserted by a shrink-fit process into the parts pressed together. The measured dimensions and masses of the three major sections are given in Table 1. Table 1 gives the mass for the central section with only a 0.360-cm-diam diametral hole. A photograph of the major sections disassembled is given in Fig. 1, and, when assembled, in Fig. 2. The average isotopic enrichments of the uranium in weight percent were: $^{235}U = 93.20$, $^{234}U = 0.9843$, $^{236}U = 0.03593$, and, by difference, $^{238}U = 5.77977$. For these and other measurements the central plate was modified as shown in Fig. 3. Both the 0.070-cm. wide, 0.116-cm. deep thermocouple groove and the 2.54 in. diam. radial hole were filled with enriched uranium. The central section plate had a 0.5010-in.-diam hole slightly past the center. A 0.5010-in.-diam insert for the hole was fabricated in three pieces, as shown in Fig. 4, so that a 15.614-g, 0.4600-in.-diam uranium metal sphere could be inserted and removed from the 0.4600-in.-diam central cavity in the sphere.* All other holes shown in Fig. 3 were filled with plugs for the measurements. The dimensions given in Fig. 4 are specifications, and those from production are usually within 0.0001 to 0.0005 in. above or below that specified. Those underlined are measured values. The center of the Oak Ridge sphere was 0.020 in. above the center of the small spherical cavity, so the reactivity worth is that for a spherical near central void displaced 0.020 in. off center.

* Dimensions given in inches and masses in grams because that was the way they were measured.

Table 1. Measured Radial Dimensions at 70°F and Masses of the 3.4420-in.-Radius Uranium Metal Sphere Parts[a]

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

[a]Dimensions are given in inches and masses in grams because these are the units of measurement.
[b]The central section now consists of the central and upper plates pinned together, and the bottom section consists of the lower polar cap and lower plate pinned together.
[c]Measured with a sweep gage at 70°F at the Oak Ridge Y-12 Plant. There is near-continuous variation between end points. Average radius is 3.4420 in., or 8.7427 cm.
[d]The radius obtained from the sum of vertical heights divided by 2 is 3.4427 in., or 8.7445 cm.
[e]The masses of the sphere sections with all penetration holes empty. The sum of these certified masses is 52,322.78 g.
[f]Polar height.

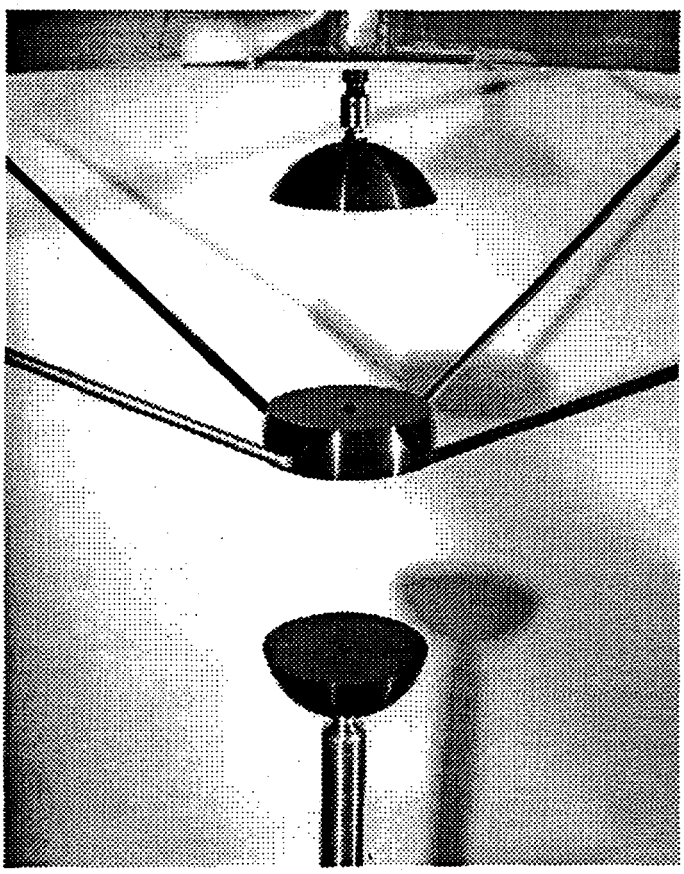

Figure 1. Photograph of Three Major Sphere Sections Disassembled

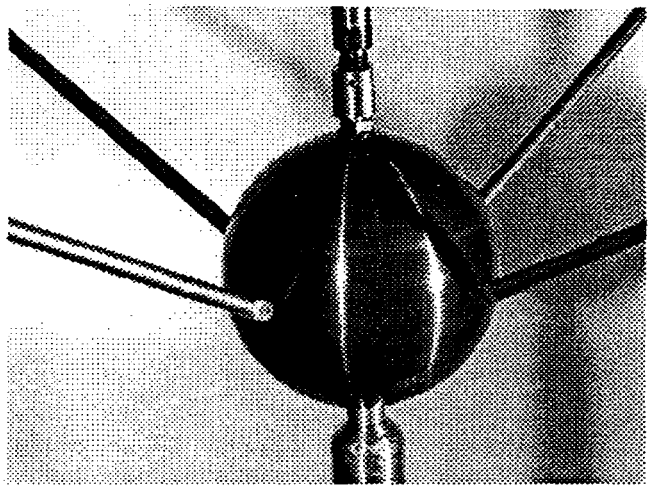

Figure 2. Photograph of the Assembled Sphere

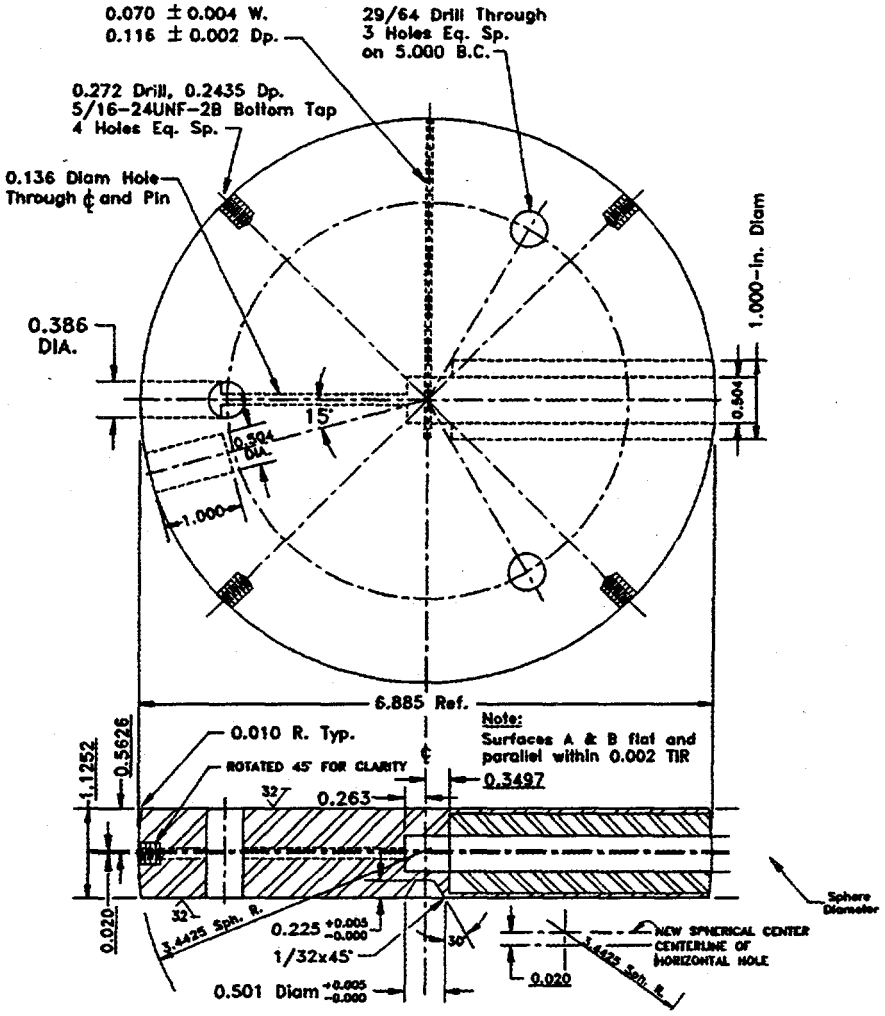

Figure 3. Sketch of the Modified Central Plate of the Central Section (all dimensions in inches, dimensions underlined are measured)

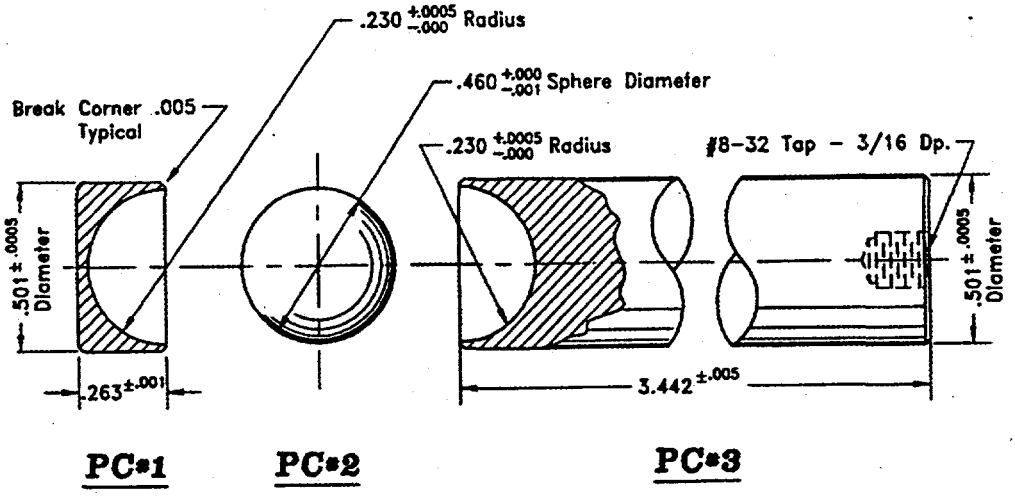

Figure 4. Enriched Uranium Metal Parts for the Central Worth Measurement (all dimensions in inches)

3. MEASUREMENT OF THE STABLE REACTOR PERIOD

The central reactivity worth (in cents) was obtained from stable reactor period (T) measurements with and without the small sphere present in a nearly delayed critical configuration of the sphere. The sphere configuration of Table 1 (~30 cents subcritical) was made critical by the addition of 0.2500-in.-thick 0.8750-in.-diam uranium mass adjustment buttons to the surface, usually five on the upper polar cap and five on the lower polar cap for most of the measurements. The measurements were performed as follows. The system was assembled with the small central uranium metal sphere in place to above delayed criticality by use of a small removable reflector. When the power reached the appropriate level, the small reflector was quickly removed. The positive stable reactor period was obtained from the reaction rate as a function of time in seven external detectors 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; and 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 ft and were surrounded by at least 2 in. of paraffin moderator. 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 min of purely exponential change. The sphere was then disassembled by either raising the upper polar cap or by lowering the lower section. The small, central uranium sphere was removed, and the system was reassembled with the small reflector in place to a flux level from which the reactor period could be measured after the small reflector was removed. This process was repeated 43 times to reduce the experimental uncertainty. The configuration of the sphere was with all other holes filled and varying numbers of surface mass adjustment buttons.

The stable reactor periods obtained in the measurement are given in Table 2, where the results are given in pairs (sample in, sample out). Whether the upper polar cap or the lower section was removed to shut down the assembly is indicated in the second column of Table 2. The number of uranium mass adjustment buttons on the sphere surface is also indicated in Table 2. For most of the measurements the sequence of measurements was not alternating but as follows: assemble the sphere, for example, with void in the center and the stable reactor period T_1 measured; disassemble and insert sample, reassemble, and measure T_2; disassemble, reassemble, and measure T_3; disassemble and remove sample, reassemble, and measure T_4; etc. In this way, T_1 and T_2 give one reactivity worth, and T_3 and T_4 give another. The reactor periods vary because of the statistics of the measurement process, small temperature changes in the assembly over the day or from day to day, and variation in the reassembly of the sphere. These 43 comparisons with seven instruments for most of the measurements yielded 296 measurements of the reactivity change or worth of a central void. The average reproducibility of absolute value of the reactivity of the assembly upon disassembly and reassembly on the same day was 0.18 ± 0.18 cent and that from day to day was 0.27 ± 0.22 cent.

4. CENTRAL VOID REACTIVITY WORTH

The stable reactor periods can be converted to reactivity using the Inhour equation and the differences in reactivity for each pair of measurements used to obtain the central void worth. The sample in-sample out measurements give the central reactivity worth in cents. To use the Inhour equation to obtain reactivity, the delayed neutron relative abundances and decay constants have to be known for the uranium isotopes that produce fission in the sphere. The six-group delayed neutron parameters were measured by Keepin, Wimmett, and Zeigler in 1957 and are given in Table 3 for fast fission in ^{235}U and ^{238}U. The Keepin et al. data are not in ENDF/B-VI, but a revised set of six-group parameters for the relative abundances and decay constants of Brady and England are the ENDF/B-VI values. These ENDF/B-VI values for ^{234}U, ^{235}U, ^{236}U, and ^{238}U are also given in Table 3. To use these delayed neutron parameters, the fraction of fissions in each uranium isotope has to be known. These have not been measured for the Oak Ridge sphere. The ratios of total sphere and central sphere fission ratios for each uranium isotope relative to ^{235}U were obtained from one-dimensional S_n neutron transport calculation with ENDF/B-VI cross section for a delayed critical sphere and are given in Table 4. These calculations show that there is less fission in the isotopes other than ^{235}U at the center than averaged over the sphere. For this sphere at delayed criticality, 98.19% of the fissions are in ^{235}U, so how the other isotopes are treated can only introduce small error. ENDF/B-VI data have six-group parameters for all isotopes, whereas the Keepin, Wimett, and Zeigler data have parameters for only ^{235}U and ^{238}U. In using the Keepin et al. data, it was assumed that half the ^{234}U fissions (0.41205%) and half the ^{236}U fissions (0.00615%) were in ^{235}U and the other half were in ^{238}U. Using these assumptions, the stable reactor periods were converted to reactivity in cents using the Inhour equation and the central void worth obtained. These values are given in Table 5 along with those from the Keepin et al. data, assuming all fission is in ^{235}U. The effect of using all ^{235}U delayed

Table 2. Stable Reactor Period Measurements for Central Void Reactivity Coefficient Measurements

Run Number	Shutdown Method[a]	Number of Mass Adjustment Buttons	Reactor Period (s) from						
			Ion Chambers			Neutron Counters			
			A	D	Ln	1	2	3	4
528 A	UPC	12[b]	94.9	103.3	99.3	97.7	—	97.7	99.3
B			1750	2081	2314	2149	—	2149	2070
529 A	UPC	12[b]	86.7	99.1	97.7	96.4	—	91.9	98.5
B			1002	1110	964	1244	—	1231	1164
530 A	UPC	12[b]	249	250	239	286	—	278	244
B			60.4	63.1	61.4	61.9	—	63.2	62.7
531 A	UPC	9[b]	216	196	186	180	—	179	169
B			-415	-456	-429	-438	—	-427	-416
532 A	UPC	9[b]	172	167	193	184	—	181	184
B			-507	-555	-523	-518	—	-533	-560
533 A	UPC	9[b]	-282	-278	-258	-261	-261	-261	-260
B			250	261	266	245	242	245	262
534 A	UPC	9[b]	-320	-305	-312	-305	-305	-298	-292
B			231	243	253	255	256	254	247
535 A	UPC	9[b]	241	248	246	240	254	245	249
B			-277	-297	-302	-292	-287	-289	-289
536 A	UPC	9[b]	281	307	287	261	261	267	281
B			-234	-319	-289	-302	-293	-297	-317
537 A	UPC	9[b]	-305	-300	-290	-289	-289	-287	-287
B			320	350	332	322	317	324	331
538 A	LS	9[b]	293	294	295	304	300	298	311
B			-327	-288	-302	-305	-313	-308	-326
539 A	LS	9[b]	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	-284
B			242	255	251	248	246	250	-227
541 A	LS	10	-299	-314	-304	-302	-316	-304	-301
B			278	233	237	240	234	238	240

Table 2 (continued)

Run Number	Shutdown Method[a]	Number of Mass Adjustment Buttons	Reactor Period (s) from Ion Chambers			Reactor Period (s) from Neutron Counters			
			A	D	Ln	1	2	3	4
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	-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

Table 2 (continued)

Run Number	Shutdown Method[a]	Number of Mass Adjustment Buttons	Reactor Period (s) from						
			Ion Chambers			Neutron Counters			
			A	D	Ln	1	2	3	4
B			273	310	294	300	296	301	276
557 A	LS	10	268	276	278	266	266	294	270
B			-297	-299	-281	-294	-291	-291	-287
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	270	263	262	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	282	-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	-311
572 A	UPC	10	-263	-271	-265	-280	-277	-274	-276
B			286	298	302	292	291	293	289

Table 2 (continued)

[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]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 lower.

Table 3. Six-Group Delayed Neutron Parameters of Uranium Isotopes

Group	^{235}U–Keepin et al.		^{238}U–Keepin et al.	
	Relative Yield, a_i	Decay Constant, λ_i	Relative Yield, a_i	Decay Constant, λ_i
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

Group	^{234}U–ENDF/B-VI		^{235}U–ENDF/B-VI	
	Relative Yield, a_i	Decay Constant, λ_i	Relative Yield, a_i	Decay Constant, λ_i
1	0.055	0.0131	0.035	0.0133
2	0.1964	0.0337	0.1807	0.0327
3	0.1803	0.121	0.1725	0.1208
4	0.3877	0.2952	0.3868	0.3028
5	0.1324	0.8136	0.1586	0.8495
6	0.0482	2.5721	0.0664	2.853

Group	^{236}U–ENDF/B-VI		^{238}U–ENDF/B-VI	
	Relative Yield, a_i	Decay Constant, λ_i	Relative Yield, a_i	Decay Constant, λ_i
1	0.0302	0.0134	0.0139	0.0136
2	0.1722	0.0322	0.1128	0.0313
3	0.1619	0.1202	0.131	0.1233
4	0.3841	0.3113	0.3851	0.3237
5	0.1775	0.8794	0.254	0.906
6	0.0741	2.8405	0.1031	3.0487

Table 4. Calculated Fission Ratios in Uranium (93.20) Metal Sphere

U	Fission Rates per Atom		Percent of Fissions in Each Isotope
	Center	Total	
234	0.780	0.792	0.8241
235	1.000	1.000	98.1922
236	0.322	0.328	0.0123
238	0.1588	0.1618	0.9714

Table 5. Central Void Reactivity Worth in a Uranium (93.20) Metal Sphere

Source of Worth	Central Void Worth	
	Cents	Cents/Mole
Oak Ridge Measurements[a]		
Keepin et al. Data[b]	9.165 ± 0.023	138.05 ± 0.34
Keepin et al. Data (^{235}U only)	9.216 ± 0.006	
ENDF/B-VI	7.984 ± 0.021	120.26 ± 0.31
GODIVA I Measurement[c]		
Keepin Data	Not Available	135.5 ± 0.12

[a]Void diameter, 0.460 in.; density of sample, 18.750 g/cm^3; 93.20 wt % ^{235}U.
[b]The uncertainty introduced as a result of the treatment of fission in ^{234}U and ^{236}U is not significant. This was evaluated by assuming all fission occurred in ^{235}U and resulted in a change in the central worth of only 0.038.
[c]Void 0.500-in.-OD, 0.500-in.-high cylinder; density of sample, 18.70 g/cm^3; 93.80 wt % ^{235}U.

neutron parameters is only 0.5% in the central worth, so uncertainties in the number of fissions in the minor isotopes will not introduce significant error. This uncertainty introduced was also evaluated by using the delayed neutron data of ENDF/B-VI to obtain the central worth assuming half ^{234}U and ^{236}U fissions occurred in the ^{235}U and ^{238}U isotopes. The effect of this approximation was only 0.3%. The average central void worth from the measurements for a central spherical region is 9.165 ± 0.023 cents using the delayed neutron parameters of Keepin et al. or 138.05 ± 0.34 cents/mole, which is slightly larger than that from the GODIVA I measurements, 135.5 ± 0.12 cents/mole also using the Keepin data. The error given on the central worth is the standard deviation of the mean of all measurements with all detectors, and the distribution of measured central worth values obtained from the Keepin, et. al. delayed neutron data is given in Fig. 5. In the GODIVA I measurements, the center of the sample region was also slightly off center at a radius of 0.030 in. The sample was a right circular cylinder with a height and diameter of 0.500 in. The differences in the void worth could be due to sample size effects, the GODIVA I central void worth being slightly smaller than the Oak Ridge central void worth.

The value obtained for the central void worth using the six-group delayed neutron parameters of ENDF/B-VI is 7.984 ± 0.021 cents or 120.26 ± 0.31 cents/mole. The difference between the central void worth for the two sets of delayed neutron parameters is considerable (14%). If the ENDF/B-VI data for uranium are used to obtain reactivity from stable reactor period measurements, previous calculations for reactivity coefficient

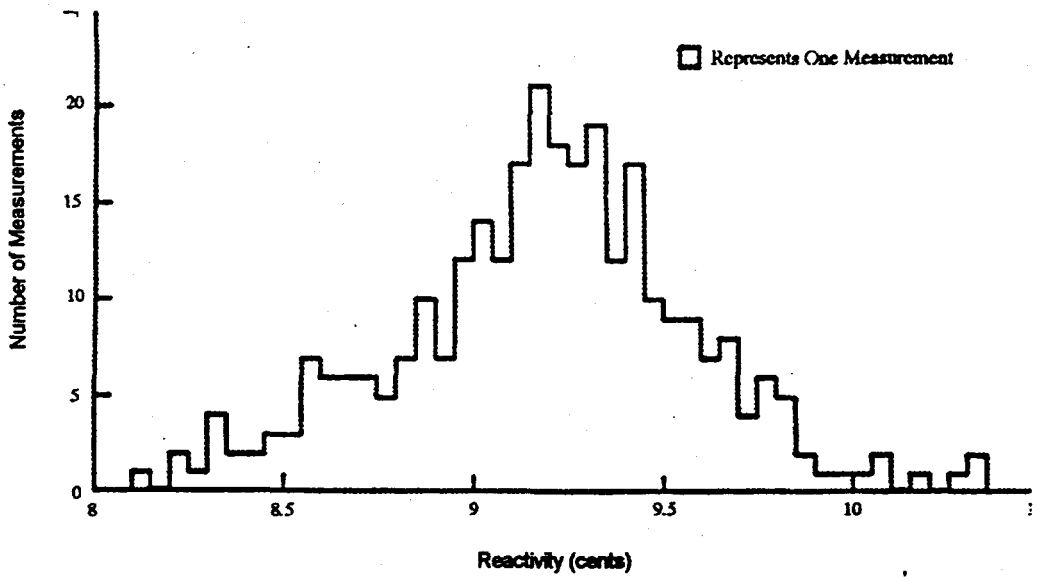

Figure 5. Distribution of Measured Central Worth Values

measured near delayed criticality that used the Keepin data (which are conventional) that agreed with measurements will now disagree and some calculations that disagreed may now agree.

5. CALCULATED CENTRAL VOID WORTH

The central void worth of this sphere was calculated in Δk units using S_n transport theory methods with Hansen-Roach[6] and ENDF/B-VI cross sections. Since the measured reactivity is known within ±0.023 cent (1.5×10^{-6} Δk), the precision of the calculation should be better than 10^{-7} Δk to make a precise comparison between measurement and calculation. For these calculations, both ONEDANT[7] and XSDRNPM[8] S_n transport theory were used to obtain the estimate of mathematical precision of the two codes. To obtain the Δk value for infinite S_n, the calculations were performed as a function of n (the order of S_n) with the restriction that the number of radial intervals used (n for the sample region and the total sphere) increase proportionally with n. Only in this way does a plot of Δk vs 1/n yield the desired value of Δk at 1/n = 0 (i.e., infinite order S_n). The ONEDANT calculations were performed by O'Dell[9] with Hansen-Roach cross sections and with Gaussian and DP quadrature and are given in Table 6. Since the Hansen-Roach cross section set contains only ^{235}U and ^{238}U, ^{236}U and ^{234}U were treated as ^{238}U for these calculations. The mathematical precision of the ONEDANT calculations was verified by performing a Δk calculation with the adjoint, and the difference between the adjoint and the forward calculation was 10^{-8} in Δk. The extrapolated value of the central worth of the 0.460-in.-diam region for ∞ order of S_n is $6.021 \pm 0.001 \times 10^{-4}$ Δk.

Table 6. ONEDANT Calculated Central Void Reactivity Worths

Quadrature and Radial Intervals	Δk (10^{-4})
S8[a]-2[b]-20[c]	6.3048
S16-4-40	6.0934
S32-8-80	6.0429
S48-12-120	6.0336
S- - -	6.020[d]
DP16-2-20	6.2279
DP24-3-30	6.1148
DP48-6-60	6.0482
DP96-12-120	6.0316
DP- - -	6.021[d]

[a]Order of S_n.
[b]Number of radial intervals in the sample region.
[c]Number of radial intervals in the sphere, not including the sample region.
[d]Extrapolated values.

The XSDRNPM calculations by Wright[10] were performed with both Hansen-Roach and ENDF/B-VI cross section data to obtain the effect of different cross-section data. Comparison of the XSDRNPM calculations using the Hansen-Roach cross sections with ONEDANT gives another estimate of the mathematical precision of the calculated Δk, and comparison of XSDRNPM calculations with two cross section sets gives an estimate of the uncertainty due to cross sections. A summary of the XSDRNPM calculations is given in Table 7. The extrapolated Δk value with Hansen-Roach cross sections is 6.030×10^{-4} Δk and that for the ENDF/B-VI cross section is $6.005 \times 10^{-4} \Delta k$.

The difference in the calculation as a result of the codes used is $0.01 \times 10^{-4} \Delta k$ or 0.15% in Δk and that due to the cross sections is 0.025×10^{-4} or ~0.4% in Δk. The calculated value was taken as the average of all three extrapolations and is $6.02 \pm 0.01 \times 10^{-4}$. The uncertainty was taken as $\pm$ 0.01×10^{-4} Δk and essentially includes all the variation in these calculated values, and this choice is somewhat arbitrary.

Table 7. XSDRNPM Calculated Central Void Reactivity Worths

Description of Calculation	Δk
Hansen-Roach Cross Sections	
S16[a]-4[b]-40[c]	6.10-4
S32-8-80	6.05-4
S48-12-120	6.04-4
S --	6.03-4[d]
ENDF/B-VI Cross Sections	
S16-4-40	6.08-4
S32-8-80	6.06-4
S48-12-120	6.02-4
S --	6.005-4[d]

[a]Order of S_n.
[b]Number of radial intervals in the central void region of the sphere.
[c]Number of radial intervals in the uranium of the sphere.
[d]Extrapolated values.

6. EFFECTIVE DELAYED NEUTRON FRACTION FROM CENTRAL WORTH

The measurement yields the central void worth in cents where 1 cent is 0.01 dollar and 1 dollar is the reactivity equal to the effective delayed neutron fraction, which in k units is the increment between delayed and prompt criticality. The calculation yields the central worth in Δk units. The proportionality constant between the worth in dollars and the worth in Δk units is the effective delayed neutron fraction [i.e., $\beta eff = \rho(\Delta k)/\rho(\$)$]. The Keepin et al. delayed neutron data, the measured central void worth (9.165 ± 0.023 cents), and the calculated central void worth (6.02 ± 01 × 10^{-4} Δk) for the Oak Ridge sphere give an effective delayed neutron fraction of 0.00657 ± 0.00002, which agrees well with the measured increment between delayed and prompt criticality for GODIVA I (0.0066). The delayed neutron fraction obtained in this way using the ENDF/B-VI data is 0.00754, which is 14.2% higher than that measured for GODIVA I. The six-group delayed neutron relative abundances and decay constants for uranium in ENDF/B-VI yield central worth values from the measurements that are not consistent with the measured delayed neutron fraction for GODIVA I, if the transport theory calculations of the reactivity worths are correct.

7. CONCLUSIONS

The central reactivity void worth was measured in the Oak Ridge unmoderated and unreflected uranium (93.20 wt % ^{235}U) metal sphere by replacement measurements in a small, central spherical region 0.4600 cm in diameter in a 3.4420-cm-radius sphere. The central void worth was 9.165 ± 0.023 cents or 138.05 ± 0.34 cents/mole, and this was

obtained from the stable reactor period measurements using the delayed neutron parameters of Keepin et al. This value is ~1.9% higher than that from measurements with GODIVA I with cylindrical samples of uranium (93.70 wt % ^{235}U) in the center: 135.5 ± 0.12 cents/mole, and this difference could be due to sample size effects since the GODIVA sample (0.500-in.-high, 0.500-in.-diam. cylinder) was larger than the Oak Ridge sample (0.4600-in.-diam. sphere). The central worth was also calculated by neutron transport theory methods to be $6.02 \pm 0.01 \times 10^{-4}\ \Delta k$. The measured and calculated values are related by the effective delayed neutron fraction. The value of the effective delayed neutron fraction obtained in this way from the Oak Ridge central worth is 0.00657 ± 0.00002, which is in excellent agreement with that obtained from GODIVA I measurements, where the effective delayed neutron fraction was determined as the increment between delayed and prompt criticality and was 0.0066. From these Oak Ridge measurements, using the six-group delayed neutron relative abundances and decay constants of ENDF/B-VI data to obtain the reactivity in cents from the stable reactor period measurements using the Inhour equation, the central void worth is 7.984 ± 0.0021. These values are 14.2% higher than those obtained from use of the Keepin delayed neutron data and produce a value of delayed neutron fraction in disagreement with GODIVA I measurements, thus questioning the usefulness of the six-group delayed neutron relative abundances and decay constants of ENDF/B-VI for uranium fission.

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