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PROMPT NEUTRON DECAY FOR AN UNREFLECTED AND UNMODERATED URANIUM (HEU) METAL SPHERE

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ABSTRACT

Prompt neutron decay constants have been measured for a delayed critical, unmoderated and unreflected uranium metal sphere[1] at the Oak Ridge Critical Experiments Facility. The prompt neutron decay constant for this delayed critical configuration of the sphere is 1.1095 ± 0.0013 μs^{-1}. Together with the accurate description of this sphere, this result can be used to verify calculational methods, both deterministic and Monte Carlo neutron transport methods. This value is in agreement with the value from the GODIVA I measurements corrected for the effects of support structure (i.e., 1.10 ± 0.01 μs^{-1}) but has a much smaller error as a result of the large number (167) of measurements described here and the high degree of sphericity of the sphere.

INTRODUCTION

Prompt neutron decay constants have been measured for a delayed critical, unmoderated and unreflected uranium metal sphere.[1] In this system the prompt neutron decay for the sphere at delayed criticality can be represented by a single exponential decay and can be used to verify reactor physics calculations of the prompt neutron decay constant. In the past, these calculations have been higher than the experimental values by 10%.[2] This paper briefly describes this sphere and presents the results of the prompt neutron decay constant measurements both by the Rossi-α technique[3] and by the randomly pulsed neutron method[4] with ^{252}Cf. These measurements are the most extensive measurements of the prompt neutron decay for a uranium metal sphere that was more spherical than GODIVA I[5] with much less structural material supporting it. Previous Rossi-α measurements with GODIVA I at delayed criticality have not always been consistent, but the recommended value[6] of the prompt neutron decay constant is $1.10 \pm 0.01 \times 10^6\ s^{-1}$ and has been corrected (+0.01) for the structural material in and near the assembly.

URANIUM METAL SPHERE

The delayed critical configuration of the 93.20 wt % ^{235}U enriched, unreflected and unmoderated uranium metal sphere (density, 18.754 g U/cm^3) was assembled for

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special reactor physics experiments in 1971 at the Oak Ridge Critical Experiments Facility. The sphere was composed of three major sections (upper, central, and lower). The central section was composed of an upper plate and central plate held together by pins, and the lower section was composed of the lower plate and lower polar cap, also pinned together. Sketches of these plates are given in Figs. 1—5. Some characteristics of the uranium sphere are given in Tables I—III. The central plate of the sphere was modified to accommodate the source ionization chambers and detectors for the prompt neutron decay measurements, as shown in Fig. 6. Delayed criticality of this sphere was achieved by the addition of surface mass adjustment buttons (up to 16) depending on the locations of the sources and counters internal to the sphere. A 70–g aluminum reflector with ~2 cents in reactivity was used for fine reactivity adjustment by positioning it various distances from the surface.

PROMPT NEUTRON DECAY MEASUREMENTS

A wide variety of Rossi-α measurements and randomly pulsed neutron experiments was performed at exactly delayed criticality with a ^{252}Cf source and a spiral ^{235}U fission chamber inserted into various positions in the sphere. The sphere had a diametral hole and various radial holes near the surface for location of the source and detectors. Various plugs were available to fill the holes with special split plugs which were located around the shafts of the source ionization chamber and the spiral fission counter when they were interior to the sphere surface. The configurations of source and detectors in the measurements reported here are summarized in Table IV. The sources (three) were located at the surface of the sphere and at various radial locations in the sphere, including the center. The spiral fission chamber detector was located also at different radii, including the center. Usually the detector and source were on opposite sides of the sphere center with as much uranium metal between them as possible. The data were accumulated in a Type I time analyzer,[7] which was a two–channel shift register that measured the time distribution of counts in the detector after a previous count in the same detector (Rossi-α). The analyzer also had another mode of operation in which the time distribution of counts in the detector after a count from spontaneous fission in the ^{252}Cf ionization chamber was measured.

DISCUSSION OF RESULTS

In a typical Rossi-α measurement, the sphere was assembled continuously. For the randomly pulsed neutron measurement with ^{252}Cf, it was assembled and disassembled 25 times to reduce the background from fission chains initiated by delayed neutrons from previous fission that produced counts not correlated with the californium source fission. Usually every other measurement on a given day was of the same type. For a given measurement time, the Rossi-α data accumulated more correlated counts. The measurements were performed on 14 different working days with several of each type of measurement each day, with at least two (usually more) verifications of delayed criticality each day. For this verification the power level was raised sufficiently high that the contributions of the californium sources neutrons were insignificant. The reproducibility of the sphere reactivity on reassembly was usually much less than 0.5 cents and was adjusted each time the delayed critical condition was verified. In all, 167 measurements were performed. The data from both types of measurements were fitted by a nonlinear least-squares method to the function $D + E\ \exp(-\alpha t)$ to determine the prompt neutron decay constant with the value of D fixed. In calculations of the background (D) for the Rossi-α measurement, the nonconstant power was accounted for by multiplying the background determined in the usual ways (i.e., the time a channel was open multiplied by the average counting rate) by the ratio of the average square of the count rate to the square of the average count rate. The count rate as a function of time in this measurement was monitored using a time analyzer with a sampling time sufficiently large (≥ 5 s) that the reactor fluctuations did not affect the value of $(\overline{C})^2 / \overline{C^2}$ determined. In the randomly pulsed neutron measurement, the value of the background, D, was obtained from the number of californium fissions that triggered the analyzer, the channel width, and the average counting rate. Typical results of both types of measurements are given in Fig. 7. The measurements were numbered sequentially (1→167), and the prompt neutron decay constants (ordinate) were displayed as a function of sequence number (abscissa) in Fig. 8. The divisions shown on the abscissa are divisions of the 167 measurements by days. These data (Fig. 8) have no noticeable trends during the 14 days of measurements in which the source size and location and detector locations were changed. The prompt neutron decay constants were not as accurately measured in any one measurement as desirable because the main purpose of these measurements was to measure the total correlated counts in the measurements accurately. Because of the large number of measurements, the prompt neutron decay was accurately measured. The 167 values were averaged, and the standard deviations of an individual value were obtained. With this estimate of the standard deviation, all values (four) beyond three standard deviations were discarded, and a new average and value of the standard deviation of the mean were obtained. This averaging was also done by weighting the values with the inverse of the uncertainty (σ) in α obtained from the least–squares analysis and the inverse of the uncertainty squared. These average values are summarized in Table V. The total spread in the average values as a result of the different weights is only ~0.2%. The prompt neutron decay constant is chosen as that for $1/\sigma^2$ weighting and discarding the four values above 3σ from the average of the unweighted data with all values. Its value is 1.1095 ± 0.0013 μs^{-1}, where the uncertainty is the standard deviation of the mean.

CONCLUSIONS

The prompt neutron decay constant for this delayed critical configuration of the sphere is 1.1095 ± 0.0013 μs^{-1}. Together with the accurate description of this sphere, this result can be used to verify the calculational method, both deterministic and Monte Carlo neutron transport methods. This value is in agreement with the value from the GODIVA I measurements corrected for the effects of support structure (i.e., 1.10 ± 0.01 μs^{-1}) but has a much smaller error as a result of the large number (167) of measurements performed and described here.

REFERENCE

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Table I. Isotopic enrichments of oralloy for major sphere parts, plugs, pins and other small uranium metal parts

Description	Isotopic enrichment (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 (0.125 and 0.250 in. thick) and upper socket	0.9846	93.23[b]	0.03594	5.74946
Plug for target hole[b]	0.9954	93.156	0.451	5.3976
Pins for central part[b]	0.9860	93.171	0.424	5.4190
Pins for lower part[b]	0.9954	93.156	0.451	5.3976
Filler rods for 0.136-in.-diam diametral hole[b]	0.9954	93.156	0.451	5.3976
Mass adjustment buttons (0.063 in. thick)[b]	0.9954	93.156	0.451	5.3976

[a]These enrichments were from the average monthly enrichments of ~93.2 wt % ^{235}U oralloy parts made at the Y-12 Plant 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. The ^{238}U percentage is by difference and is not accurate beyond the third digit. The weighted average enrichments for these parts comprising the major parts, target hole filler, and pins are 0.9844 wt % ^{234}U, 93.20 wt % ^{235}U, 0.04626 wt % ^{236}U, and 5.7693 wt % ^{238}U.

[b]Measured values.

Table II. Impurity content of enriched uranium sphere parts

ORNL Part No.	Part description	Grams[a] U per gram x100	Impurity content (ppm)[c] Boron[b] equivalent	Be	Li	Al	Si	Total Fe, Mn, Ni, Cr, V, Cu	B	Co	Ca	C
1-6	Upper polar cap	99.961	0.647	<0.01	<0.2	6	80	85	0.5	<1	<10	202
1-8	Upper plate	99.966	0.408	<0.01	<0.2	4	100	34	0.3	<1	<10	159
1-10	Central plate	99.966	0.328	<0.01	<0.2	4	200	50	0.2	<1	<10	159
1-11	Lower plate	99.949	0.629	<0.01	<0.2	8	125	57	0.5	<1	<10	142
1-12	Lower polar cap	99.912	0.242	<0.01	<0.2	5	100	83	0.1	<1	<10	179
1-4	16 mass adjustment buttons, 0.025 in. thick	99.955	0.348	<0.01	<0.2	2	200	68	0.2	<1	<10	306[d]
1-5	16 mass adjustment buttons, 0.125 in. thick											
1-1	Socket for upper polar cap											

[a]Reported to 5 digits; accurate to 4 digits.
[b]Boron equivalent is the parts per million boron that has the same thermal neutron absorption cross section as all impurities. Boron equivalent is only for elements in the table excluding oxygen and nitrogen. Boron equivalent is an approximation for the effect of impurities for assemblies with thermal neutron spectra where the predominant effect is neutron absorption and is irrelevant for these critical assemblies where there are no thermal neutrons.
[c]In addition to these impurities, there were 20 ppm oxygen and 30 ppm nitrogen.
[d]Values on this line are for part numbers 1-4, 1-5 and 1-1.

TABLE III. Measured radial dimensions at 70 F and certified masses of the 3.4420-in.-radius uranium metal sphere parts

Section[a]	Variation from 3.4425-in. radius[b] (10^{-3})	Vertical height[c] (in.)	Certified mass[d] (g)
Top	+1.2 at pole to -0.5 at bottom	2.1332[e]	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[e]	19,624.59

[a]The central section now consists of the central and upper plate pinned together, and the bottom section consists of the lower polar cap and lower plate pinned together.
[b]Measured with a sweep gage at 70 F at the Y-12 Plant. There is near-continuous variation between end points. Average radius is 3.4420 in., or 8.7427 cm.
[c]The radius obtained from the sum of vertical heights divided by 2 is 3.4427 in., or 8.7445 cm.
[d]The masses of the sphere sections with all penetration holes empty. The sum of these certified masses is 52,322.78 g and represents the parts as shown in Fig. 1–5.
[e]Polar height.

Table IV. Californium chamber and spiral fission counter locations for prompt neutron decay constant measurements

Californium chamber[a]			Spiral fission counter[b]	
Number	Location	Radius (cm)	Location	Radius (cm)
59	Diametral hole	6.90	Diametral hole	4.27
59	Diametral hole	6.90	Diametral hole	0
59	Diametral hole	6.90	Diametral hole	3.81
2	Surface	8.92	Diametral hole	0
61	Diametral hole	0.26	Surface hole	6.84
61	Diametral hole	0.26	Surface hole	6.84
61	Surface hole	4.27	Diametral hole	6.84
61	Surface hole	6.28	Diametral hole	0

[a]Chamber 61 (1.27 cm diam; 9×10^4 fissions/s) could be at any radius. Chamber 59 (0.95 cm diam; 2.6×10^4 fissions/s) could only be located at one end of the diametral hole, and chamber 2 (2.54 cm diam; 5.6×10^4 fissions/s), only adjacent to the surface.

[b]The 1.27-cm-diam spiral fission counter could be placed at any radius in the diametral hole or surface hole.

Table V. Average prompt neutron decay constant and uncertainties

	Prompt neutron decay (μs^{-1}) and standard deviation of the mean	
Weighting	All values	Within 3 sigma[a]
Unweighting	1.1097 ± 0.0030	1.1116 ± 0.0026
$1/\sigma$ Weighted	1.1089 ± 0.0014	1.1099 ± 0.0014
$1/\sigma^2$	1.1089 ± 0.0013	1.1095 ± 0.0013

[a]The four values beyond three standard deviations obtained from the unweighted average of all values were discarded in the average values.

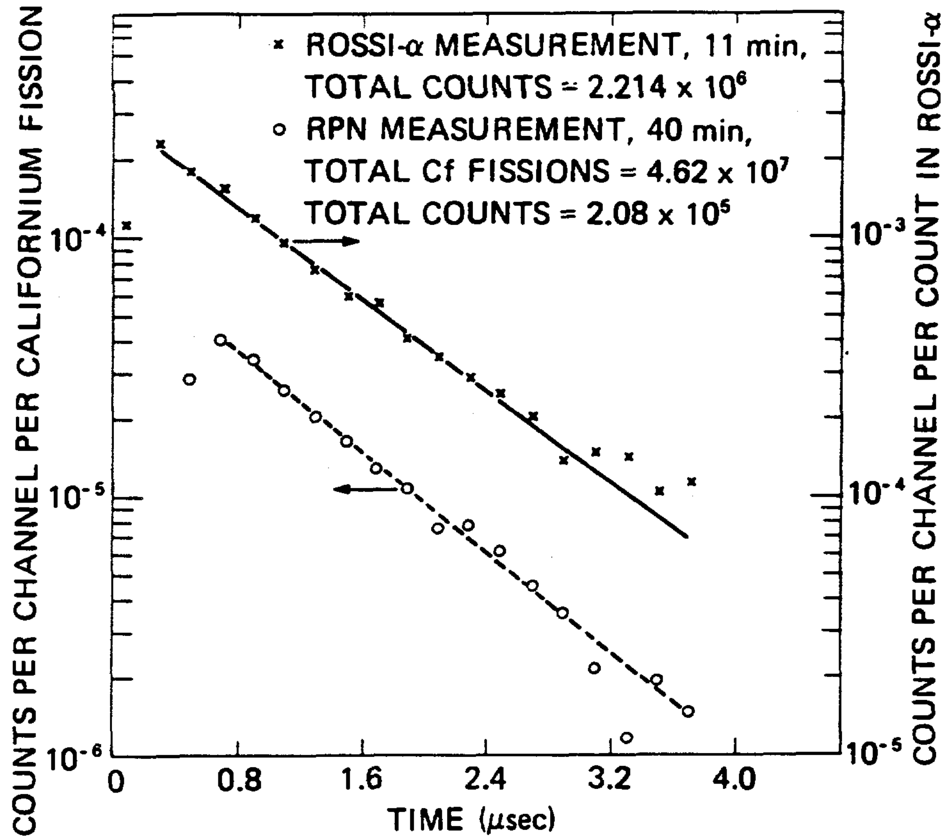

Fig. 7. Typical results of a Rossi-α and a randomly pulsed neutron measurement after subtraction of background.

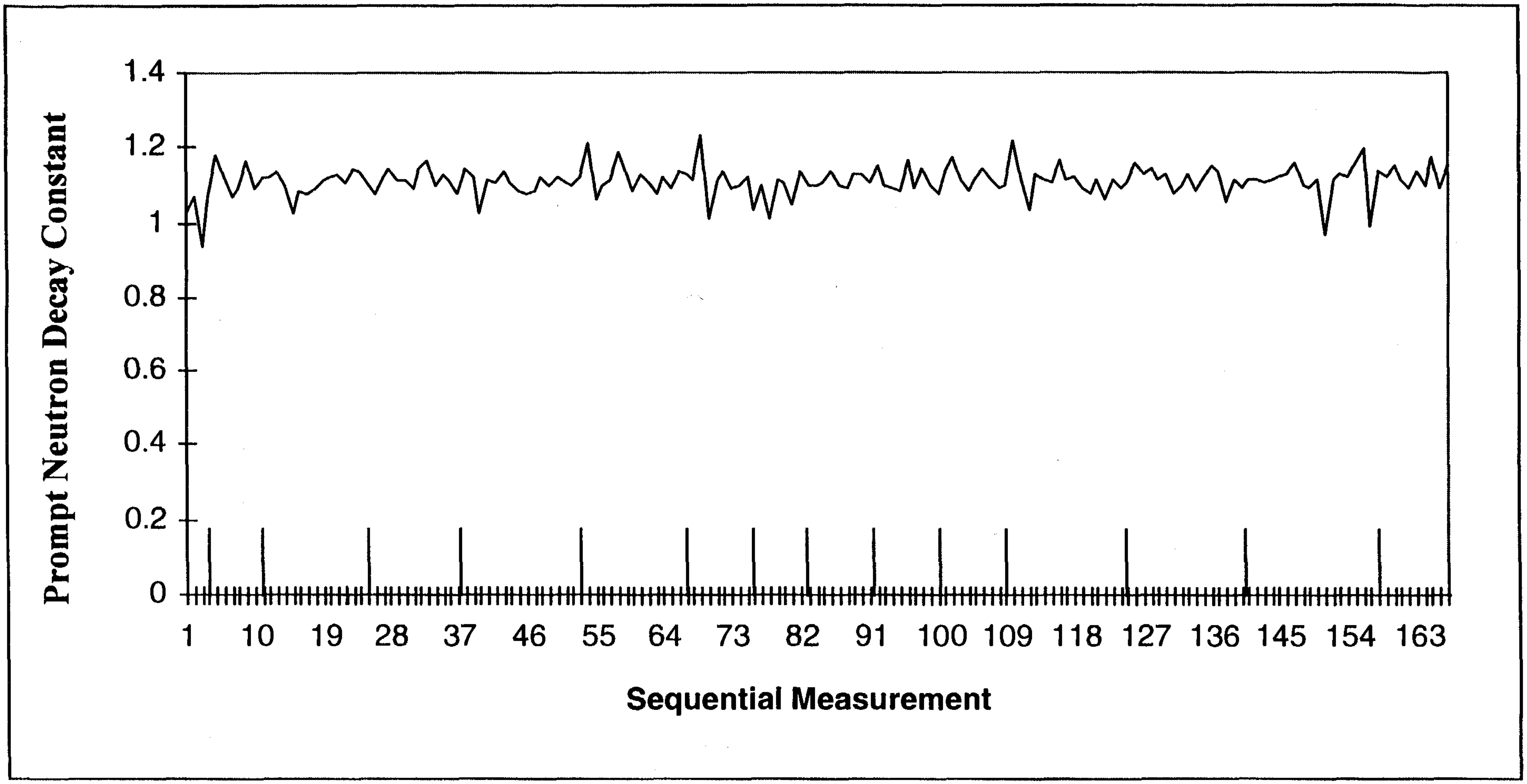

Fig. 8. Prompt neutron decay constant as a function of time during the 14 days of the measurements.

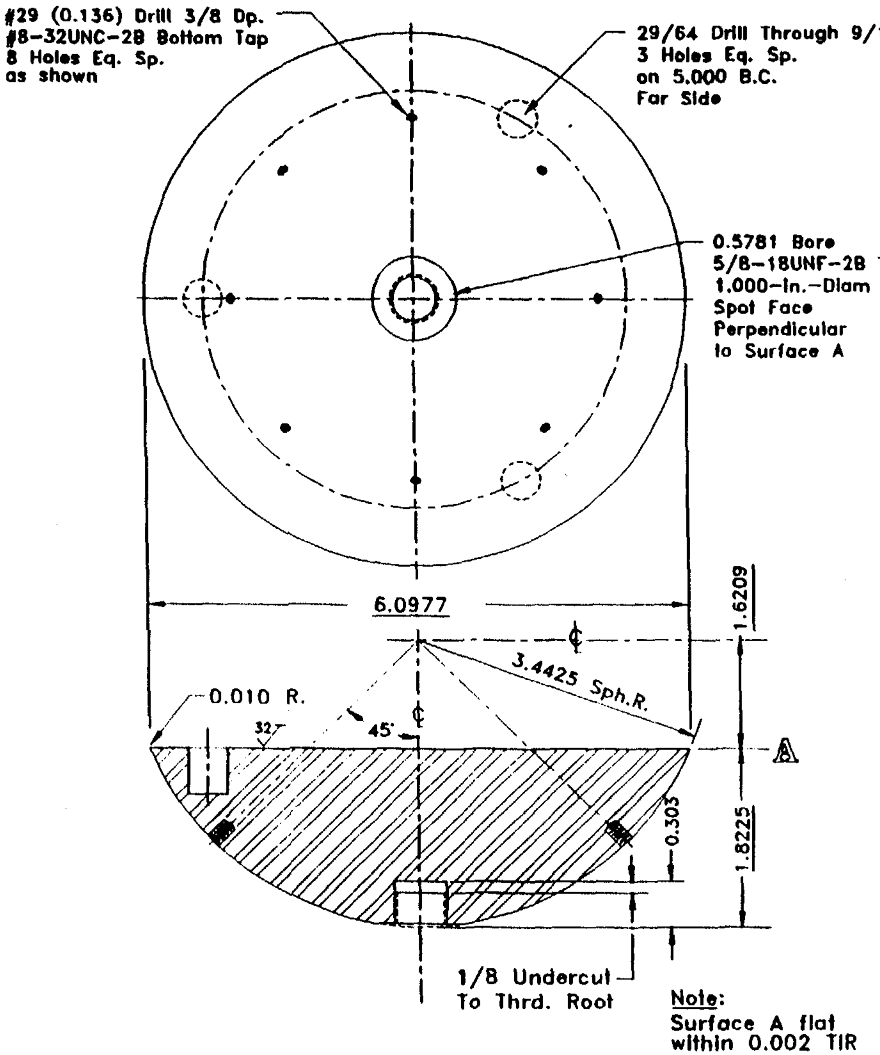

Fig. 1. Lower polar cap—nominal radius, 3.4425 in.; material, oralloy.

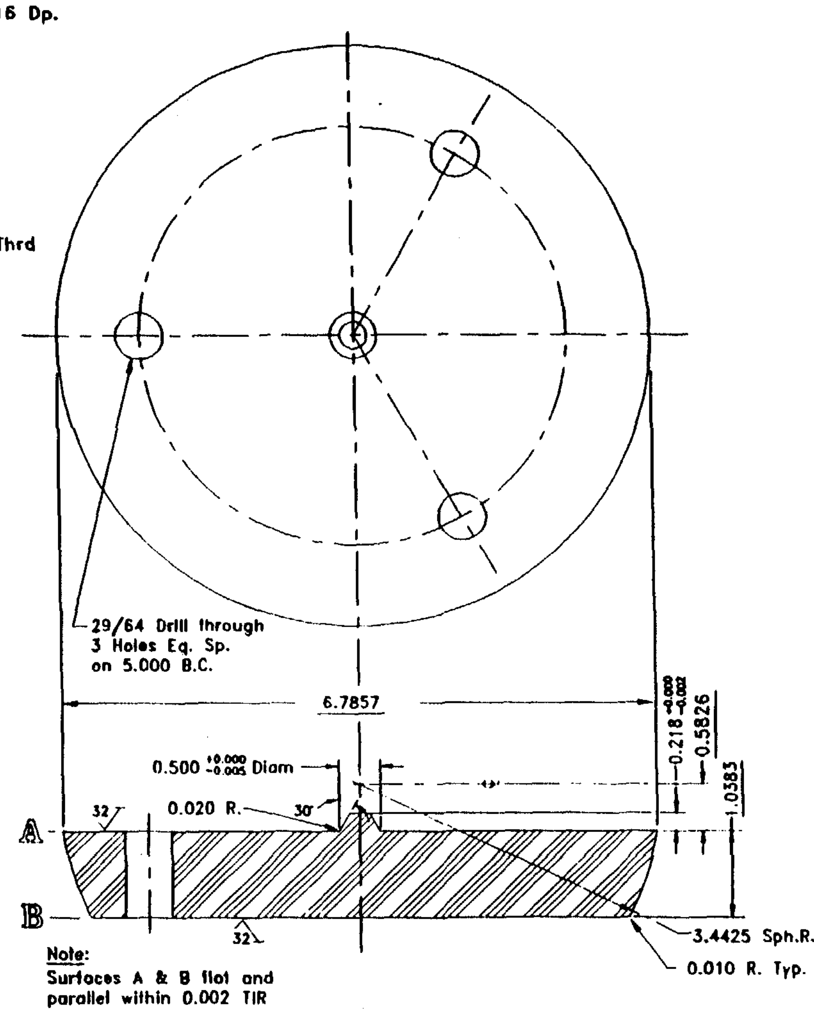

Fig. 2. Lower plate—nominal radius, 3.4425 in.; material, oralloy.

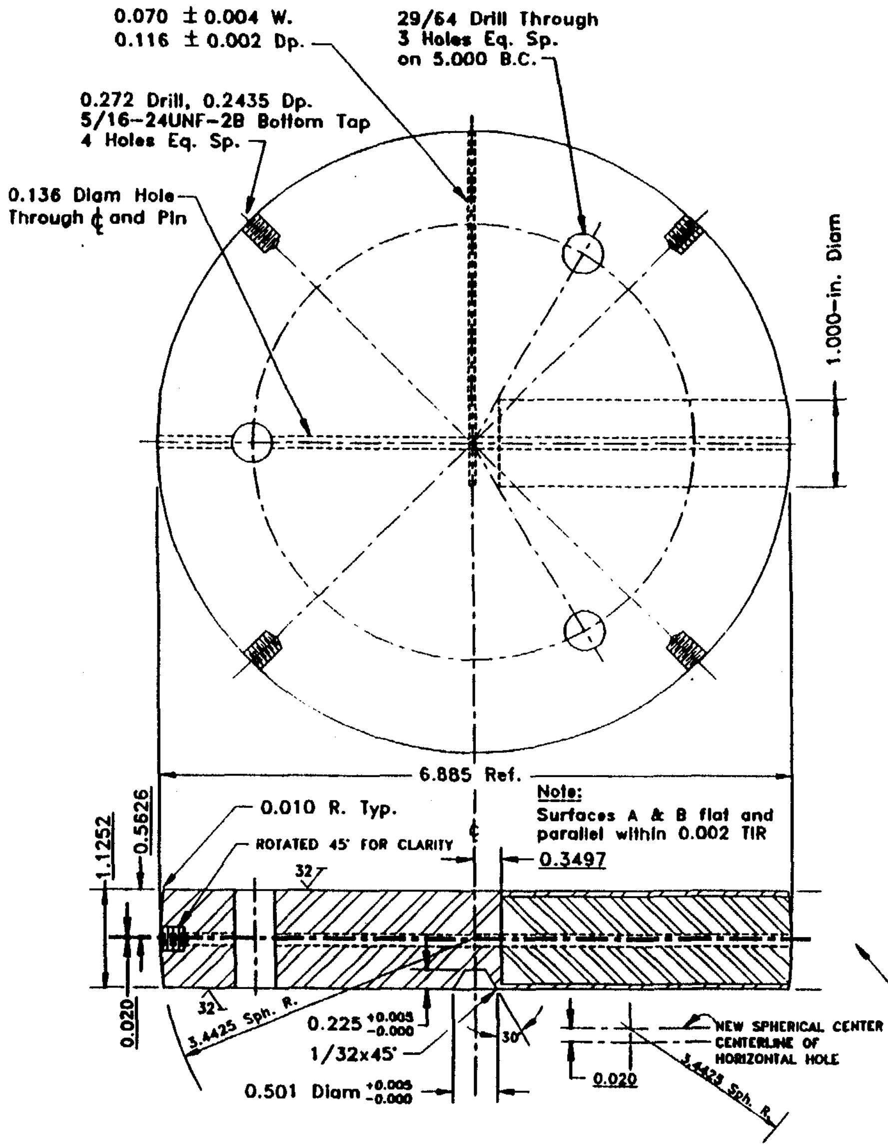

Fig. 3. Center plate—nominal radius, 3.4425 in.; material, oralloy.

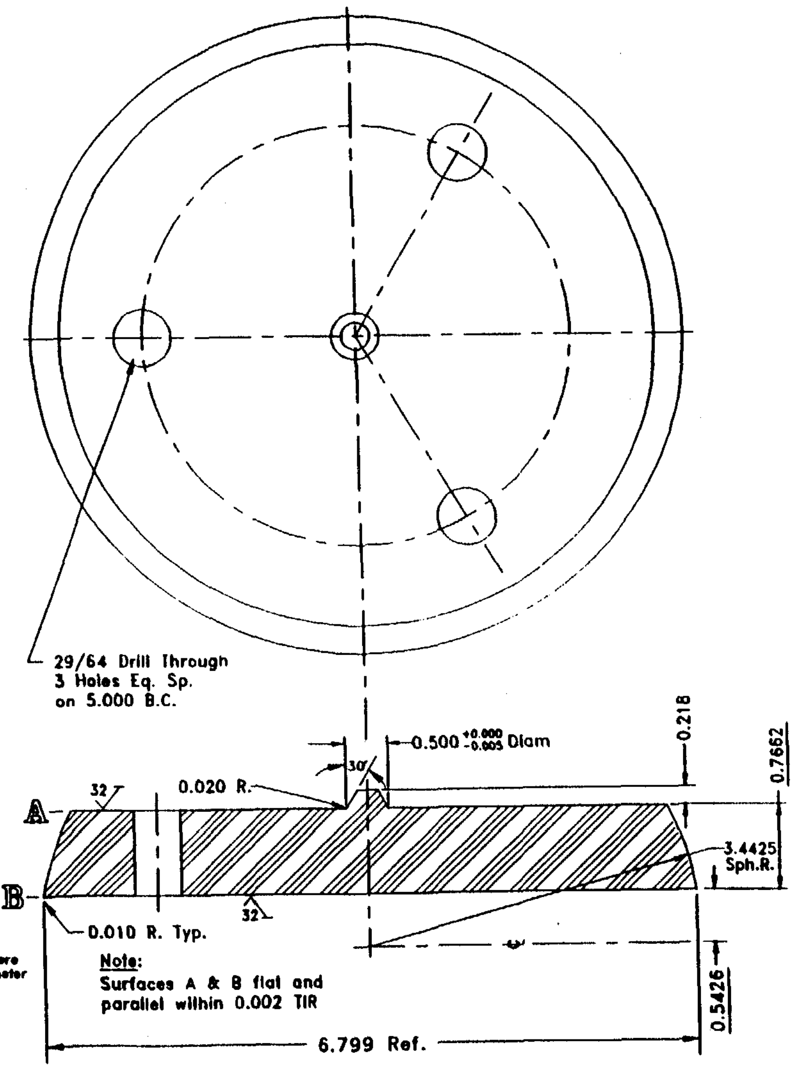

Fig. 4. Upper plate—nominal radius, 3.4425 in.; material, oralloy.

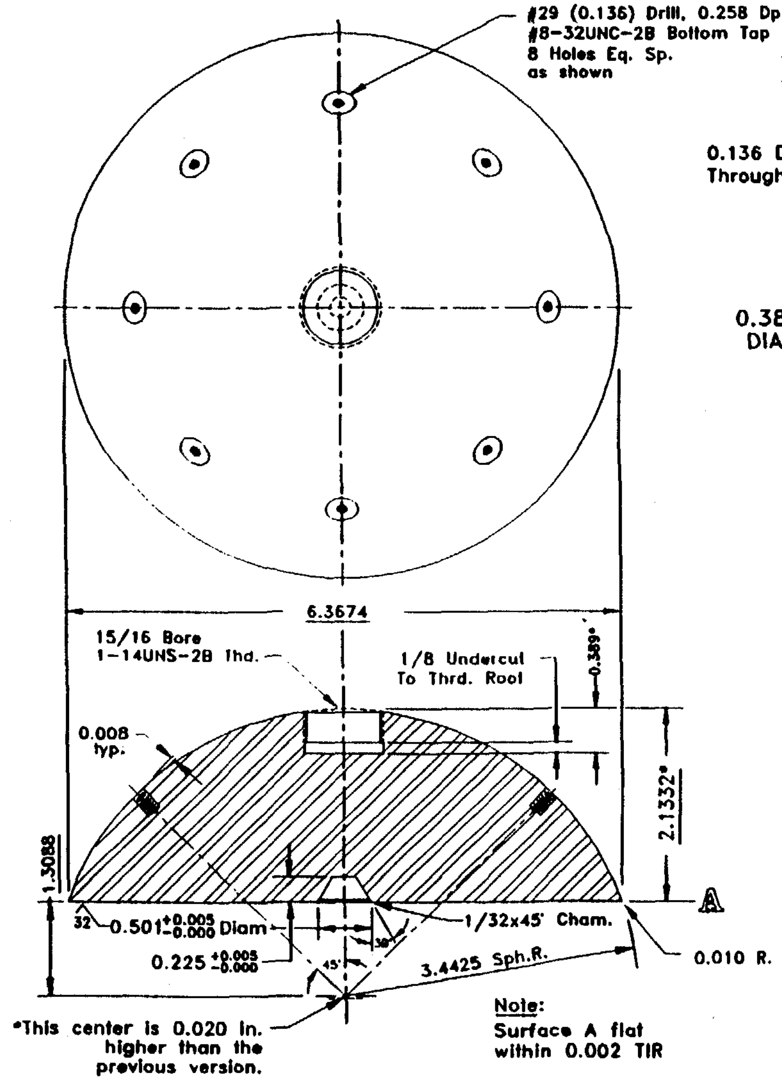

Fig. 5. Upper polar cap—nominal radius, 3.4425 in.; material, oralloy.

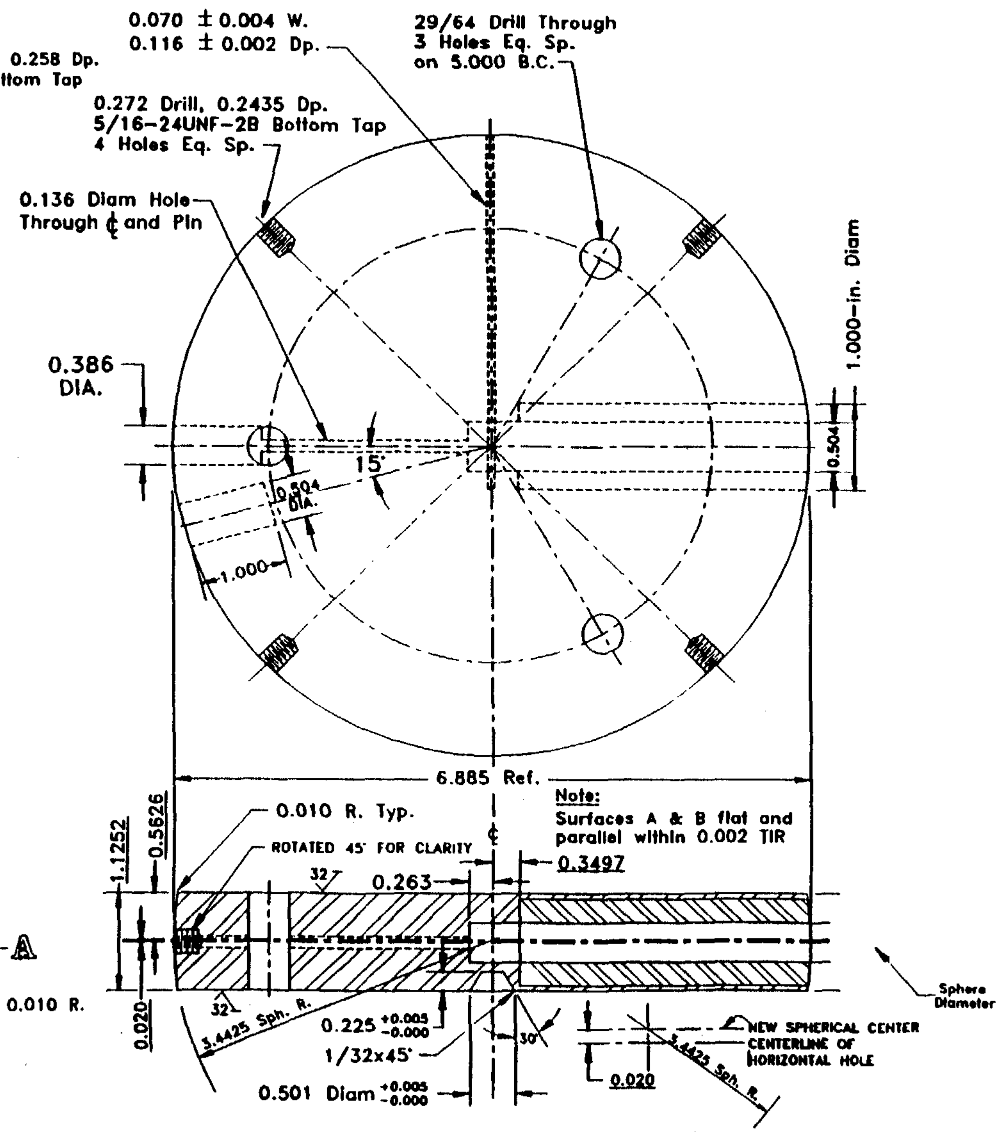

Fig. 6. Modified central plate to accommodate sources and detectors.