INL/CON-12-26763
PREPRINT

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International Conference on Nuclear Data for Science and Technology

M. A. Marshall
J. D. Bess
T. M. Murray

March 2013

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M. A. Marshall,[1,2] J. D. Bess,[1] and T. M. Murray
[1] *Idaho National Laboratory, 2525 North Fremont, Idaho Falls, Idaho 83415-3860, U.S.A.*
[2] *Center for Space Nuclear Research, Idaho Falls, Idaho 83415, U.S.A*

In 1971 and 1972 experimenters at the Oak Ridge Critical Experiment Facility performed critical experiments using an unreflected metal sphere of highly enriched uranium (HEU). The sphere used for the criticality experiments, originally used for neutron leakage spectrum measurements by General Atomic Company, consisted of three main parts and were assembled with a vertical assembly machine. Two configurations were tested. The first was nearly spherical with a nominal radius of 3.467 inches and had a reactivity of 68.1 ± 2.0 cents. The sphere parts were then re-machined as a sphere with a nominal radius of 3.4425 inches. This assembly had a reactivity of -23 cents. The method, dimensions, and uncertainty of the critical experiment were extensively recorded and documented. The original purpose of the experiments was for comparison to GODIVA I experiments. The ORNL unreflected HEU Metal Spheres have been evaluated for inclusion in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (scheduled for inclusion in the September 2013 edition).

I. INTRODUCTION

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. The purpose of the Oak Ridge ORALLOY Sphere (ORSphere) experiments was to estimate the unreflected and unmoderated critical mass of an idealized sphere of uranium metal corrected to a density, purity, and enrichment such that it could be compared with the GODIVA I experiments. "The very accurate description of this sphere, as assembled, establishes it as an ideal benchmark for calculational methods and cross-section data files." [1] While performing the ORSphere experiments care was taken to accurately document component dimensions (±0. 0001 in. for non-spherical parts), masses (±0.01 g), and material data The experiment was also set up to minimize the amount of structural material in the sphere proximity. A three part sphere was initially assembled with an average radius of 3.4665 in. and was then machined down to an average radius of 3.4420 in. (3.4425 in. nominal). These two spherical configurations were evaluated and judged to be acceptable benchmark experiments; however, the two experiments are highly correlated. The evaluation of the ORSphere experiments will be included in the September 2013 edition of the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* [2].

Information for the evaluation was compiled from the published results [1],[3] the experimental logbook [4], additional experimental drawings and notes, and communication with the experimenter, John T. Mihaclzo.

II. EVALUATION OF BENCHMARK

The process of evaluating the 3.4465-in.-average-radius sphere (Case 1) and the 3.4420-in.-average-radius sphere (Case 2) included the compilation of all available experiment information, the evaluation of the experimental uncertainty, and the development of a detailed and simple benchmark model. Sample calculation results for the benchmark models were also compiled using various codes and neutron cross section libraries.

A. Experimental Setup

The ORSphere was a five part sphere with two pairs of plates pinned together with HEU pins to create three sections (Fig. 1). The three sections were assembled on the vertical assembly machine.

Lateral alignment of the assembled sphere sections was achieved using cutoff cones and corresponding holes in between sections of sphere. The target hole and thermocouple groove were filled with HEU during the critical assembly of the sphere. A 0.136-in.-diameter diametral hole ran the radial length of the center of the sphere for Case 1 and was 0.02 in. below the center of the sphere for Case 2.

FIG. 1. Disassembled ORSphere.

B. Experimental Uncertainty

The experimental uncertainty was evaluated for the uncertainty in the reactivity measurement, dimensions, mass, and material data. A summary of the uncertainty effects is given in Table I. A full description of the evaluation of the experimental uncertainty is given in the benchmark evaluation [2]. The small, total uncertainty of 60 and 86 pcm is typical of HEU Oak Ridge experiments performed by Dr. Mihalczo.

TABLE I. Experimental Uncertainty

	Case 1	Case 2
Reactivity Measurement	0.00026	0.00015
Radius	0.00052	0.00083
Sphere Component Dimensions	NEG	NEG
Gap Between Plates	0.00003	0.00003
Diametral Hole/Rod Dimensions	0.00006	0.00006
Brass Bolt Dimensions and Material	0.00006	0.00006
Mass	0.00006	NEG
Uranium Fraction and Impurities	0.00006	0.00006
Isotopics	0.00011	0.00010
Temperature	0.00002	0.00002
Total	**0.00060**	**0.00086**

C. Benchmark Models

The detailed benchmark model included all details of the sphere as well as the brass bolt that held the bottom section of sphere to the lower support structure. Experimentally measured corrections were used to account for the surrounding support structure and a bias was calculated to account for the atmosphere and room return as well as the steel table of the vertical assembly machine.

The simple benchmark model was a simple, solid sphere of homogenized HEU with only Si, B, and C impurities. The enrichment and material density were averaged to maintain total mass and HEU metal volume. The bias of the simple model simplifications was calculated. A summary of the benchmark model corrections and biases is given in Table II.

TABLE II. Model Corrections and Biases

	Case 1	Case 2
Measured Corrections		
Support Structure	-0.001663	-0.001663
Temperature	-0.0000770	-0.0000770
Calculated Biases		
Detailed Model	-0.00038	-0.00033
Simple Model	0.00032	-0.00030
Bias Uncertainty	±0.00007	±0.00007

The two spheres had a measured reactivity of +0.00449 and -0.00152 Δk_{eff} for Case 1 and 2, respectively. Using the system reactivity, the corrections and biases benchmark k_{eff}s for the detailed and benchmark model were 1.0024 ± 0.0006 and 1.0031 ± 0.0006 for Case 1 and 0.9964 ± 0.0009 for both models for Case 2. The benchmark k_{eff} for Case 2 was the same for the detailed and simple benchmark models due to competing effects of model simplifications not because the changes were negligible. The benchmark report gives further details of this analysis [2].

D. Sample Calculations

Results from MCNP, KENO, and MONK were compiled for the detailed and simple benchmark models using various neutron cross section libraries in the benchmark evaluation [2]. MCNP results using ENDF/B-VII.0 for the detailed and simple benchmark models are provided in Table III.

III. CONCLUSION

The two spherical configurations were evaluated and judged to be acceptable and benchmark experiments; however, the two spheres are highly correlated. The benchmark k_{eff} for the detailed model is 1.0024 $\pm$ 0.0006 and 0.9964 $\pm$ 0.0009 for the 3.4665-in. and the 3.4420-in.-radius sphere, respectively. The simple benchmark model k_{eff} is 1.0031 $\pm$ 0.0006 for the 3.4665-in sphere and 0.9964 $\pm$ 0.0009 for the 3.4420-in. sphere. Sample calculation results all calculate lower than the expected benchmark values.

These results are still undergoing the International Criticality Safety Benchmark Evaluation Project review process. Final results will be published in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* [2] as well as a comprehensive description of the experiment, the experimental uncertainty analysis, the development of the benchmark models, and sample input decks.

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

[3] 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).

[4] Radiation Safety Information Computation Center (RSICC), The ORNL Critical Experiments Logbooks, Book 108r, http://rsicc.ornl.gov/RelatedLinks.aspx?t=criticallist.

TABLE III. Sample Results for the Models, MCNP5 with ENDF/B-VII.0.[a]

		Benchmark Model k_{eff}			Sample Calculation Results			$\frac{C-E}{E}$ [b]
		k_{eff}	±	σ	k_{eff}	±	σ	
Detailed Model	Case 1	1.0024	±	0.0006	0.99350	±	0.00002	-0.89%
	Case 2	0.9964	±	0.0009	0.98804	±	0.00002	-0.85%
Simple Model	Case 1	1.0031	±	0.0006	0.99420	±	0.00002	-0.89%
	Case 2	0.9964	±	0.0009	0.98800	±	0.00002	-0.85%

(a) Results obtained using 500,000 histories for 2650 cycles, skipping the first 150 cycles.
(b) ‘E’ is the expected or benchmark value. ‘C’ is the calculated value.