INL/CON-12-26706
PREPRINT

What if Lady Godiva Was Wrong?

International Conference on Nuclear Data for Science and Technology (ND 2013)

J. D. Bess
J. B. Briggs
M. A. Marshall

March 2013

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J. D. Bess,[1,*] J. B. Briggs,[1] and M. A. Marshall[1]

[1] *Idaho National Laboratory, 2525 North Fremont, Idaho Falls, Idaho 83415-3860, U.S.A.*

The experiment from which benchmark specifications of "Lady Godiva" were derived consisted of nested hemispheres forming a bare sphere of highly enriched uranium (HEU). That experiment was performed in the early 1950s and the critical configuration was later (1995) evaluated and published in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments*. The benchmark eigenvalue is reported as 1.000 ± 0.001, which is representative of a high-quality benchmark experiment. Our current neutronic codes and cross section data are tailored to provide qualitative results that concur with the GODIVA I benchmark. Since 1995, additional high-fidelity HEU metal benchmark data have been evaluated and published. Calculated results from those benchmarks are consistently low. Those findings are investigated further in this paper.

I. INTRODUCTION

The experiment from which benchmark specifications of "Lady Godiva" [1] were derived consisted of nested hemispheres forming a bare sphere of highly enriched uranium (HEU) enriched to ∼94 wt.% ^{235}U. That experiment was performed in the early 1950s, and the critical configuration was later evaluated and published in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (ICSBEP Handbook) in 1995 with the identifier HEU-MET-FAST-001 [2]. The benchmark eigenvalue is reported as 1.000 ± 0.001, which is representative of a very high-quality benchmark experiment. Our current neutronic codes and cross section data are tailored to provide qualitative results that concur with the GODIVA I benchmark [3] [4]. But what if our understanding of the experiment wasn't perfect? Since 1995, a multitude of HEU metal benchmark data have been evaluated and published; furthermore, the rigor through which benchmark experiments are examined has increased over the past two decades.

II. BENCHMARK COMPARISON

Forty-one additional, bare-HEU (enriched between 90 and 96 wt.% ^{235}U), experiments were compared with the original GODIVA I evaluation. Those experiments include COMET and GODIVA IV (5 configurations) from Los Alamos National Laboratory (LANL); a sphere and two cylinders from the Russian Federal Nuclear Center - Institute of Technical Physics (RFNC – VNIITF); a sphere from the Russian Federal Nuclear Center – Institute of Experimental Physics (RFNC - VNIIEF); as well as TINKERTOY (12 configurations), cylinders (18 configurations), and GROTESQUE from the Oak Ridge Critical Experiments Facility (ORCEF).

Eigenvalues were calculated with MCNP5-1.60 [5] and the ENDF/B-VII.0 neutron cross section library [6]. There is no notable difference when using the ENDF/B-VII.1 neutron cross section library [7] in this evaluation, because the delayed neutron contribution to fission is negligible. The differences between the calculated and benchmark experiment eigenvalues, (C-E)/E %, are shown in Fig. 1. Shaded error bars represent 1σ and 3σ uncertainties; the single additional error bar for the "Lady Godiva" experiment represents the originally evaluated 1σ uncertainty of 0.1 k (100 pcm). Calculations for all but one of the HEU experiments fall below the benchmark eigenvalue. The results fall between -1.18 and +0.14% , with the average value approximately -0.35% ; the variance weighted mean is -0.21%.

The GODIVA IV results differ the most compared to the original GODIVA I benchmark. It should be noted that the HEU utilized for all these US experiments, except "Lady Godiva", was ∼93% enriched and sometimes designated as Oralloy (Oak Ridge Alloy). The dominant sources of uncertainty in the experiments with larger benchmark uncertainties are generally from uncertainties in the fuel mass, fuel dimensions, or measured distances between assembly components. The uncertainties in the VNIIEF sphere benchmark and many of the ORCEF benchmark experiments appear abnormally low. The ORCEF cylinder experiments were reported to have a high degree of precision in their measured masses, dimensions, impurity content, and isotopics [8]. When those sources of uncertainty are significantly reduced, the re-

* Corresponding author, electronic address: john.bess@inl.gov

maining uncertainty in the benchmark experiment is due to uncertainties in the experimental method or measurement and the placement of experiment components that was not as precisely measured as the properties of the components themselves.

III. REEVALUATION OF GODIVA I

It is recommended that, if possible, the uncertainty in the original GODIVA I benchmark be reevaluated. A preliminary investigation was performed to reassess what is currently provided in the benchmark report. The uncertainty analysis for GODIVA I pivots on a mass uncertainty of 0.3 %, obtained from independent analyses of the extrapolation to critical mass, correction for the diaphragm, correction for room return reflection, model defects, filling of voids in the shell experiment (including dimensional uncertainties), and removal of impurities, which were summarized in a separate report[9]. Details regarding the initial uncertainty calculations are not recorded in either the reference or benchmark reports. The impact of the mass uncertainty was evaluated using the customary method of maintaining the benchmark model mass density constant and adjusting the radius of the sphere such that the total HEU mass was adjusted by $\pm$0.3 %. Repetition of this analysis using MCNP5 and ENDF/B-VII.0 produces a 1σ uncertainty of $\pm$0.089 %k (89 pcm), which is close to the originally calculated value.

If the uncertainty in the mass is evaluated by maintaining the sphere radius constant and perturbing the mass density, the resultant 1σ uncertainty is $\pm$0.265 %Δk (265 pcm), nearly triple the value calculated when varying the radius. Measurements with the GODIVA I sphere demonstrated that the reactivity contribution of additional HEU material was proportional to its radial position within the sphere [1]. Evaluation of the mass uncertainty perturbed across the entire sphere volume would have a greater worth than adding a thin shell of HEU onto the spheres surface. The initially reported mass uncertainties were divided into components roughly relating to the mass or dimensions of GODIVA I; the combination of extrapolation, room return, and impurity uncertainties resulted in a mass uncertainty of 0.25 % with the remaining uncertainties combined to form a radius uncertainty of 0.19 %, for a total uncertainty of 0.32 %, which more closely matches the combination of the original reported values [9]. The revised GODIVA I uncertainty is now 0.213 %Δk (213 pcm), which is comparable to the uncertainties reported for the other bare HEU experiments performed at LANL (see Fig. 1).

IV. ORCEF SPHERE EXPERIMENTS

In 1971, a bare HEU sphere was assembled and brought slightly above delayed criticality at ORCEF [10]. The spherical parts were then machined to reduce the radius, and the assembly was then slightly below delayed criticality. Various reactivity effects and imperfections were experimentally evaluated and a variety of reactor physics measurements were performed with the sphere until 1975. The purpose of those two critical configurations was to provide quality experimental data to validate one-dimensional transport theory methods as well as verification of Monte Carlo methods using the as-assembled descriptions. Those assemblies provide better estimates of the unreflected and unmoderated pure HEU spherical critical mass because they were more nearly spherical than GODIVA I. Furthermore, high precision was used to characterize the components of those experiments [8]; this information was documented in detail with the express intent to support the smaller critical mass uncertainty, which is ∼60 % lower than the mass uncertainty reported for GODIVA I [10]. Benchmark evaluation of the ORCEF sphere critical configurations would be imperative in the verification of the GODIVA I critical configuration and validation of current, and future, neutronics codes and cross section data.

V. CONCLUSIONS

The “Lady Godiva” experiment, the cornerstone HEU benchmark for validation of our current methods and cross section data, appears anomalous when compared with eigenvalue calculations using modern Monte Carlo codes and neutron cross section data for other bare HEU benchmark experiments, which are, on average, low by ∼0.21 %. Inclusion of other, more precisely measured bare HEU metal benchmark assemblies for nuclear data testing is recommended, as well as a more rigorous evaluation of the GODIVA I uncertainties. Preliminary investigations indicate that a revised uncertainty of ∼0.2 %Δk may be more appropriate than what was originally reported. Benchmark evaluation of the very precisely measured ORCEF sphere experiments would serve to verify the GODIVA I critical configuration with respective uncertainties, and further serve to validate cross section data and neutronics codes. Evaluation of the ORCEF sphere reactor physics measurements for inclusion in the *International Handbook of Evaluated Reactor Physics Benchmark Experiments* (IRPhEP Handbook) [11] will also provide additional means of validation.

The authors would like to acknowledge the time and effort of the many individuals, companies, and countries that have supported the experiments and subsequent benchmark evaluation for the ICSBEP and IRPhEP Handbooks; those benchmark experiments provide the backbone for our neutronic methods, codes, and data. This paper was prepared at the Idaho National Laboratory for the U.S. Department of Energy under Contract Number (DE-AC07-05ID14517).

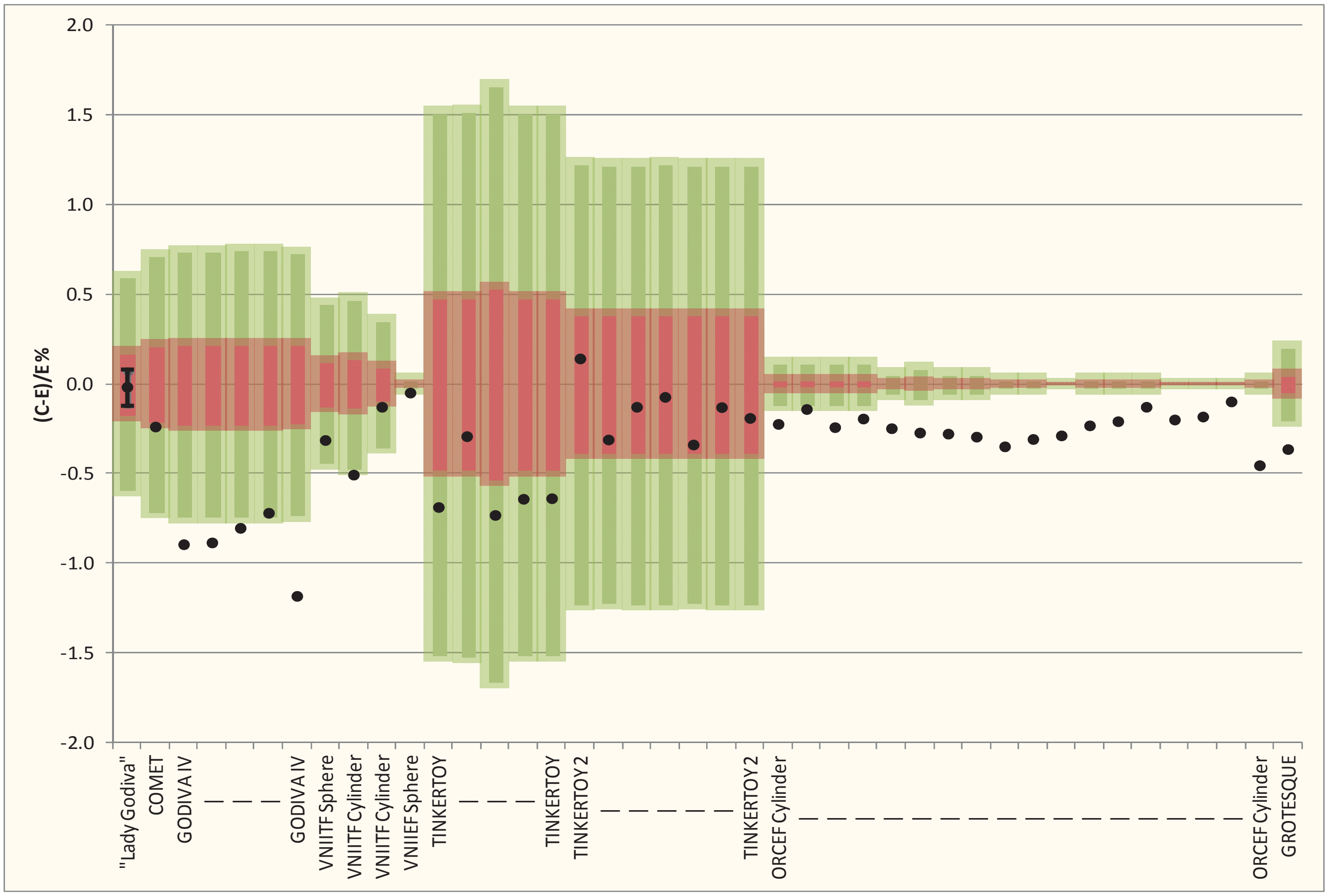

FIG. 1. Comparison of Difference between Calculated and Benchmark Experiment Eigenvalues for Bare HEU Configurations [2]. Calculations were performed using MCNP5 [5] with ENDF/B-VII.0 [6]. Shaded error bars represent 1σ and 3σ uncertainties; the single additional error bar for the "Lady Godiva" experiment [1] represents its originally evaluated 1σ uncertainty.

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