Why Lady Godiva Should be Replaced as the Default Validation Experiment for U-235 Nuclear Data

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INTRODUCTION

For the past seven decades the Lady Godiva benchmark (HEU-MET-FAST-001) has been the primary experiment used for ^{235}U nuclear data validation. The papers associated with large nuclear data library releases such as ENDF/B-VII.1 [1] and ENDF/B-VIII.0 [2] refer to it frequently. The reasons why HEU-MET-FAST-001 has been used as the primary validation experiment for ^{235}U nuclear data validation will be discussed in the following section. However, as discussed among the benchmark community, the standards associated with International Criticality Safety Benchmark Evaluation Project (ICSBEP) evaluations have changed throughout time; this is subject of the OECD/NEA WPEC (Working Party on Nuclear Criticality Safety) Subgroup 8. HEU-MET-FAST-001 is an older benchmark (issued during the inaugural year of ICSBEP in 1996 with only minor revisions occurring since then) and (along with many of the other benchmarks from this era) does not meet the standards for a modern benchmark. This work explores why HEU-MET-FAST-001 is useful for ^{235}U nuclear data validation and discusses other alternative validation experiments.

BACKGROUND

Los Alamos was very interested in understanding critical masses of fissile material during the Manhattan Project [3]. Bare assemblies were not constructed during the Manhattan Project, however, because enough nuclear material was not available. The first bare Highly Enriched Uranium (HEU) system was built in 1951 at Pajarito Site in Los Alamos [4, 5].

It should be noted that there is some confusion associated with experiments with the name "Lady Godiva" (or just "Godiva"). Most often, the term Lady Godiva is given to the assembly that later became the first Fast Burst Reactor (FBR), sometimes also referred to as Godiva-I [5]. Note that while the Dragon experiment predated Lady Godiva, it is not classified as a FBR due to the neutron spectra and mechanism via which pulses were terminated [6]. The term Lady Godiva, however, was used for many other experiments during that era. The experiment in HEU-MET-FAST-001 is not the same as the Lady Godiva FBR. The experiment in HEU-MET-FAST-001 (sometimes referred to as the "split-hemisphere assembly," was an experiment performed before the Lady Godiva FBR was constructed, and was used to determine the required dimensions for the FBR [7, 8]. As seen in Figure 1, this experiment consisted of nesting hemishells, quite different than the Lady Godiva FBR which primarily contained three large masses of HEU. The term Lady Godiva actually predates these experiments; Otto Frisch uses the term to describe experiments he was performing, and he left Los Alamos in 1946 (well before the split-hemisphere assembly experiments) [9].

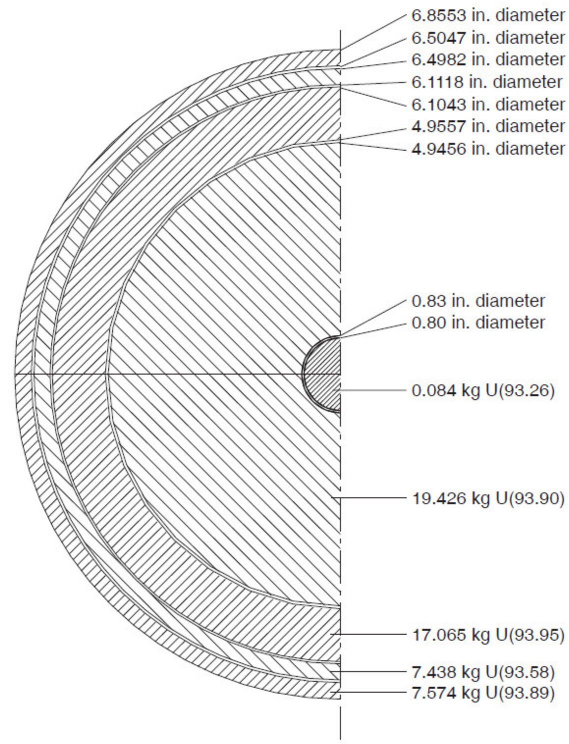

Fig. 1. Figure of the experiments in HEU-MET-FAST-001.

Data from the split-hemisphere assembly and the Lady Godiva FBR have both been used for nuclear data validation since their inception. The reason for the reevaluation of the split-hemisphere experiment in the late 1960s was to better document details to be used for analytical methods and nuclear data validation [7]. Since that time, the experiment was often used for validation of nuclear data and methods [10]. It has often been noted that nuclear data libraries are "tuned" to ensure that models of HEU-MET-FAST-001 result in $k_{\rm eff}$ of exactly 1.

One reason why HEU-MET-FAST-001 has been so useful for ^{235}U nuclear data validation is that it is a very simple experiment, that is therefore easy to model in one dimensional (1D) codes. In addition, because it is a sphere of HEU (93.71 wt.% ^{235}U), it has very high $k_{\rm eff}$ sensitivities to ^{235}U nuclear data. Here sensitivity is defined as

$$S_{k,x} = \frac{\partial k}{k}\frac{x}{\partial x}, \quad (1)$$

where $S_{k,x}$ is the sensitivity coefficient of $k_{\rm eff}$ with respect to some nuclear data x. Figure 2 compares HEU-MET-FAST-001 to 1101 other benchmarks in the Whisper [11] library, all with ENDF/B-VII.1 nuclear data. The sensitivities for HEU-MET-FAST-001 are among the highest sensitivities for these reactions of all benchmarks.

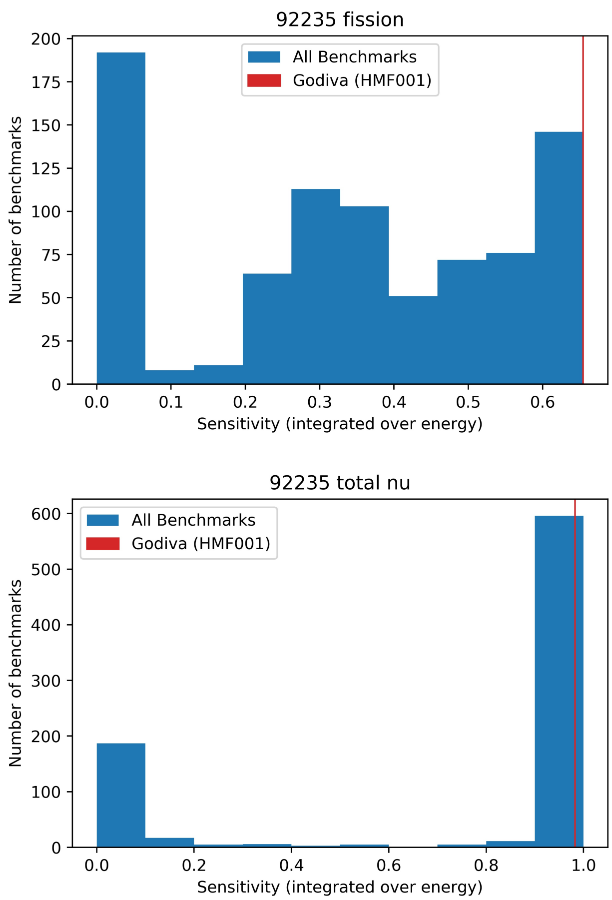

Fig. 2. Comparison of energy-integrated sensitivities between HEU-MET-FAST-001 and 1101 benchmarks in the Whisper library: ^{235}U fission at top and ^{235}U total ν at bottom.

Previous work has asked the question "what if Lady Godiva was wrong" [12]? This work showed that while HEU-MET-FAST-001 was yielding k_{eff} near 1 using MCNP® Code Version 5[1] [13] using ENDF/B-VII.0 [14] nuclear data, other HEU fast benchmarks largely calculated with lower k_{eff} values using the same code and nuclear data library. This work also looked into a comparison of C/E for HEU fast metal benchmarks, but with ENDF/B-VIII.0 nuclear data [15] using MCNP6.2 [16], compiled with the FAUST tool. As shown in Figure 3, there is no clear trend of other HEU fast metal benchmarks under-predicting k_{eff} . Perhaps this is due to changes in ^{235}U nuclear data between ENDF/B-VII.0 and ENDF/B-VIII.0.

As previously mentioned, the standards associated with

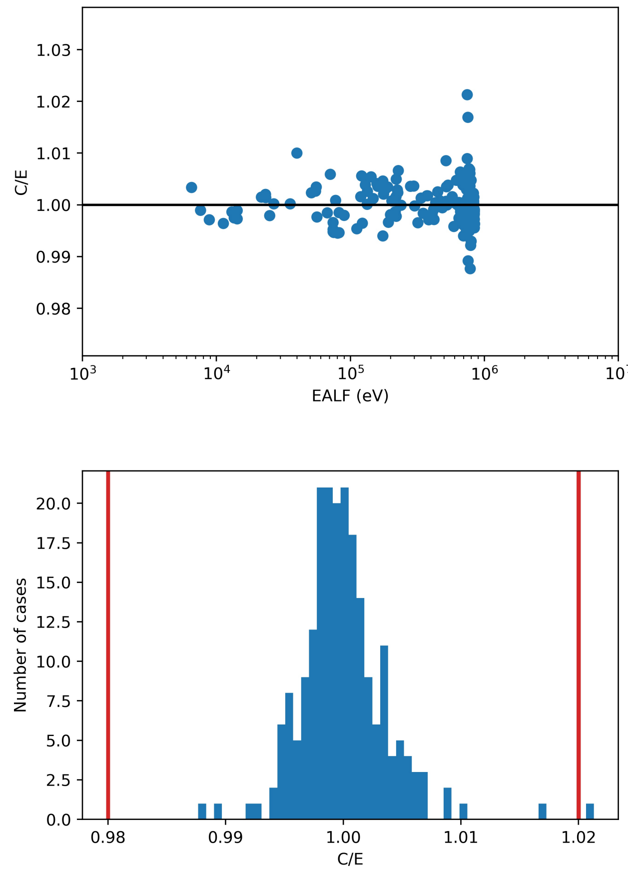

Fig. 3. Comparison of Computed (C) and Experimental (E) k_{eff} results for HEU fast metal benchmarks. C/E versus energy of average lethargy causing fission (EALF) at top and a histogram of the number of benchmark cases for various C/E bins shown at bottom.

ICSBEP evaluations has changed over time. Many of the early benchmarks either have experiment uncertainties that were not evaluated (resulting in underestimating the actual uncertainty), contain a bias that was not captured, or have other issues. The report mentioned previously concluded that the uncertainties in HEU-MET-FAST-001 were perhaps too low [12]. Regardless, like many other early benchmarks, the documentation of HEU-MET-FAST-001 does not meet current standards. One example of this is that the entirety of the sensitivity/uncertainty analysis (Section 2 of an ICSBEP evaluation) is only 3 pages long. While page length does not guarantee that a benchmark is adequate, a lack of pages is often a clear sign that many details are missing. In recent years, a major effort was put forward to perform a modern update to the Jezebel benchmark (PU-MET-FAST-001, essentially the Pu equivalent of the HEU-MET-FAST-001 benchmark) [17]. No such revision has been performed for HEU-MET-FAST-001 to date. And it would likely be even harder to do, given the confusion of the Godiva name as described above. This work proposes alternate benchmarks to use for ^{235}U nuclear data validation instead of HEU-MET-FAST-001.

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TABLE I. Experiment and simulated k_{eff}. MUSiC results [19] are preliminary and the uncertainty is still being evaluated.

Benchmark	Experiment k_{eff}	Simulated k_{eff}
HMF001-001	1.00000 ± 0.00100	1.00000 ± 0.00004
HMF100-001	1.00310 ± 0.00070	1.00504 ± 0.00004
HMF100-002	0.99660 ± 0.00070	0.99888 ± 0.00004
MUSiC: C8	1.00068	0.99996
MUSiC: C9	1.00080	0.99967

RESULTS

This work will compare two other experiments to HEU-MET-FAST-001. One is the ORSphere, an ORNL experiment from the 1970s that utilized spherical HEU [18]. This experiment was very similar to HEU-MET-FAST-001 in that it was bare HEU and was intended to be a very simple critical assembly. While the experiment was performed many decades ago, the benchmark evaluation was performed in 2014 and does meet current benchmark standards.

The second experiment that will be compared in this work is the MUSiC (Measurement of Uranium Subcritical and Critical) experiment [19, 20, 21]. This experiment was performed in 2021 at the National Criticality Experiments Research Center (NCERC) on the Planet critical assembly machine [22]. The MUSiC experiment is also a spherical HEU system, constructed using the Rocky Flats HEU hemishells [23]. Two critical configurations, designated C8 and C9 were constructed.

Experiment and simulated k_{eff} values are shown in Table I. Here simulated data uses MCNP6.2 with ENDF/B-VIII.0 nuclear data. The simulated average neutron energy causing fission (ANECF) and average neutron lethargy causing fission (ANLCF) are within 20 keV for all five of the experiments. Similarly, the simulated β_{eff} results are all within 10 pcm.

k_{eff}sensitivities for three ^{235}U reactions are shown in Figure 4 for each of the experiments. It can be seen that the shapes are very similar for all reactions for all of the experiments. For fission (and also total ν, not shown), the sensitivities are all essentially identical. For (n,γ), a slight difference can be seen, which is larger for the scattering sensitivities (only elastic is shown). The presentation will include plots of all reactions and values of these sensitivities integrated over energy.

CONCLUSIONS

HEU-MET-FAST-001(known as the "split-hemisphere assembly", Godiva, and/or Lady Godiva) has been the primary validation experiment for ^{235}U nuclear data for 7 decades. This benchmark, however, does not meet current standards for benchmark evaluations. This work compares HEU-MET-FAST-001 to HEU-MET-FAST-100 (performed at ORNL in the 1970s) and the MUSiC experiment (performed at NCERC in 2021). Both HEU-MET-FAST-100 and MUSiC have very similar spectral and reactor kinetics values compared to HEU-MET-FAST-001. Given this, combined with the fact that they are recent benchmark evaluations conforming to current ICSBEP standards (MUSiC to be submitted to ICSBEP in the near future), mean that HEU-MET-FAST-001should be replaced as the default experiment for ^{235}U nuclear data validation and MUSiC and HEU-MET-FAST-100 should be relied upon more.

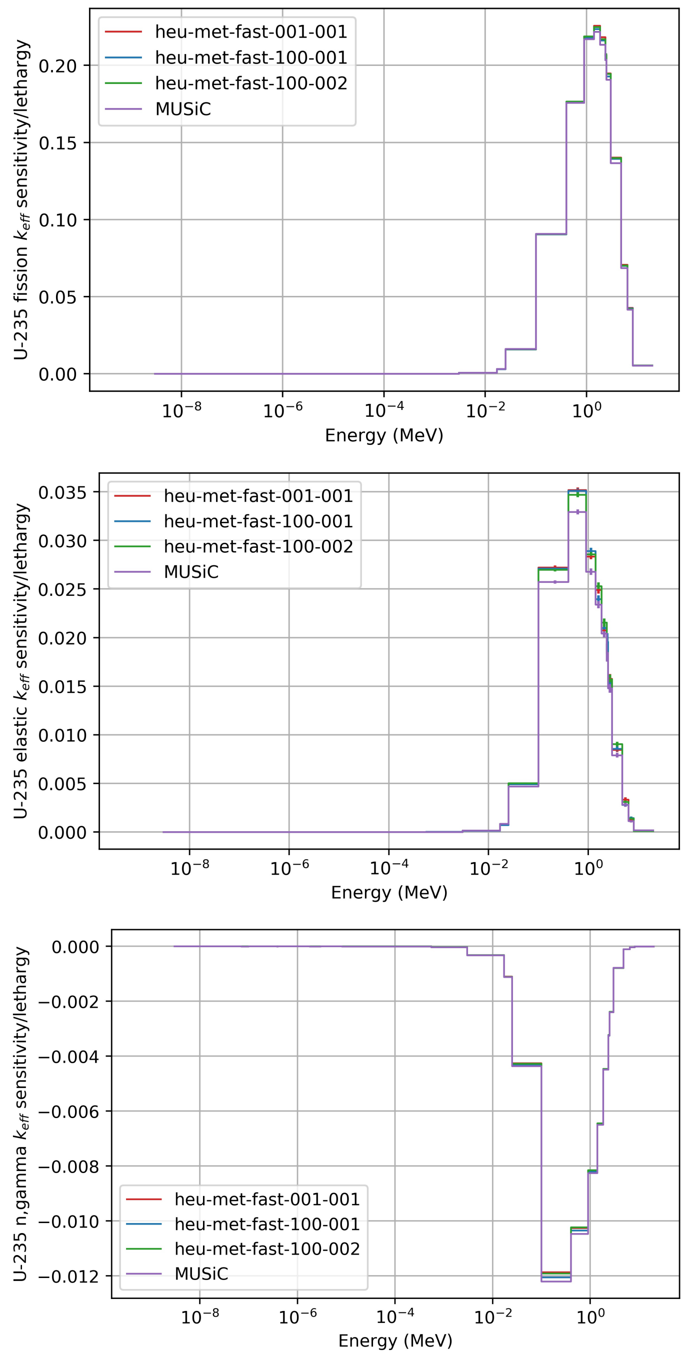

Fig. 4. k_{eff} sensitivities for HEU-MET-FAST-001, HEU-MET-FAST-100, and MUSiC. Only one of the MUSiC configurations are shown (but both have very similar sensitivities).

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