Jupiter: A Proposed Benchmark for Lead Void Worth with Plutonium

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INTRODUCTION

In the summer of 2017, a series of measurements were performed at the National Criticality Experiments Research Center (NCERC) in collaboration with the Japanese Atomic Energy Agency (JAEA) to measure the reactivity worth of voids in an array of lead and plutonium [1]. This experiment, called Jupiter, measured multiple configurations of an array of aluminum boxes containing plutonium, aluminum, and lead plates. For some configurations, a selection of the lead interstitial plates were swapped with aluminum spacer frames to create “voids” in the lead interstitial material. Comparing the excess reactivity of the systems provides an empirical value of the lead void reactivity worth. These measurements were part of a larger collaboration to measure lead void reactivity worth with multiple nuclear material types and enrichments. This included other measurement series with both highly-enriched uranium (HEU), and a mixture of HEU and natural uranium to simulate low-enriched uranium (LEU) [2]. These data sets will be useful to the JAEA for a potential lead-bismuth cooled accelerator driven system [3]. Additionally, there are not very many benchmarks in the International Criticality Safety Benchmark Evaluation Project (ICSBEP) handbook sensitive to lead cross sections. Figure 1 shows a heat map of benchmarks sensitive to various materials, including lead [4], and shows that less than a couple dozen benchmarks have significant sensitivities to any isotope of this element. Given that lead is widely used as a radiation shield and is part of new reactor designs, having more benchmarks in the ICSBEP handbook to better support cross section validation is important. Additional integral experiments could also aid in determining whether improvements have been made in new lead cross section evaluations [5].

A benchmark evaluation for this experiment is being proposed in order to help fulfill these needs. Such evaluations contain both measured data, results from detailed transport code models, and analyses of the uncertainties associated with each. Examples of these uncertainties include the uncertainty in the measured excess reactivity, the composition of components, or their positioning within the model. This means it is easier to make comparisons between the measured and simulated data and better understand where improvements can be made to nuclear data.

MEASUREMENTS

The basic element of the core array is a 5.715 cm by 5.715 cm by 8.31 cm aluminum container filled with 6 stainless steel clad plates of plutonium, each with about 105.4 grams of nuclear material. These plates were historically used in Idaho National Laboratory’s Zero Power Physics Reactor (ZPPR) experiments [6]. The as-built average composition of the plate core is shown in Table I. These values are based on a database of composition measurements for over 1,200 plates.

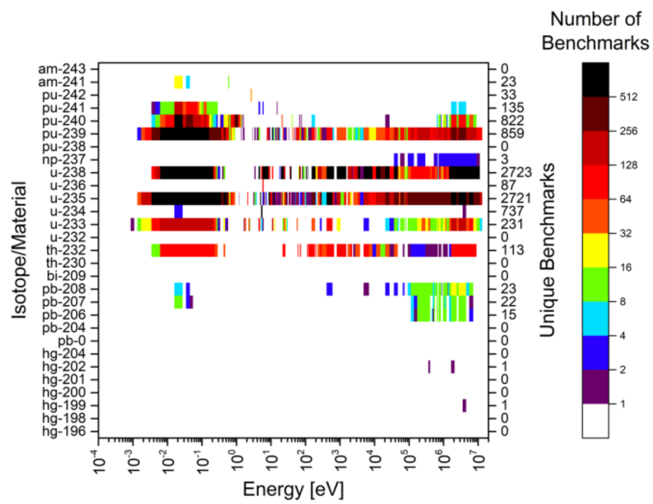

Figure 1. A heat map showing the number of ICSBEP benchmarks sensitive to various materials including lead.

TABLE I. The Average As-Built Composition of the ZPPR Plate Cores.

Nuclide	Average Wt. %
^{239}Pu	93.971
^{240}Pu	4.483
^{241}Pu	0.437
^{242}Pu	0.005
^{241}Am	0
Al	1.099

Interspersed between these plutonium plates are those of lead and aluminum. A depiction of these boxes is shown Figure 2. The purpose of the aluminum plates here is to minimize contact between the lead and the plutonium plates.

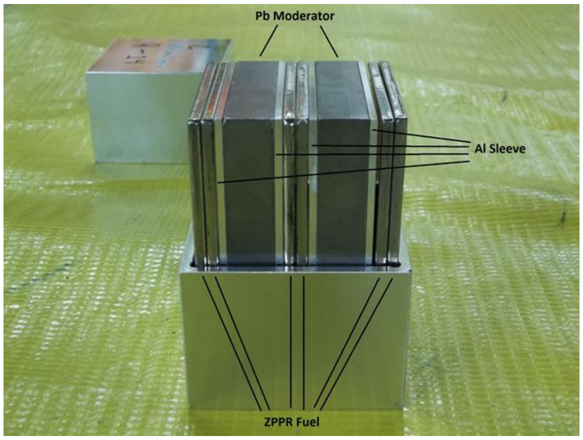

Figure 2. A unit of the core, consisting of clad plutonium plates, aluminum spacers, and lead interstitial plates.

These fuel containers were arranged in a three-layer array inside of large copper reflectors, which were used for the Zeus experiments [7-9]. Some copper filler blocks were also placed inside the array to provide more reflection. Figure 3 shows the entire assembly, including these reflectors. Also shown is that the core was split into an upper stack and a lower stack for remote closure on Comet, a heavy duty vertical lift machine at NCERC. All configurations for this benchmark included 80 fuel containers, with seven plates removed from the outermost containers on the bottom layer. This loading for the reference configuration is detailed in Figure 4. Shims were added to the bottom two layers to reduce uncertainties in the positioning of the fuel containers in the lower stack, and the aforementioned figure depicts this as well.

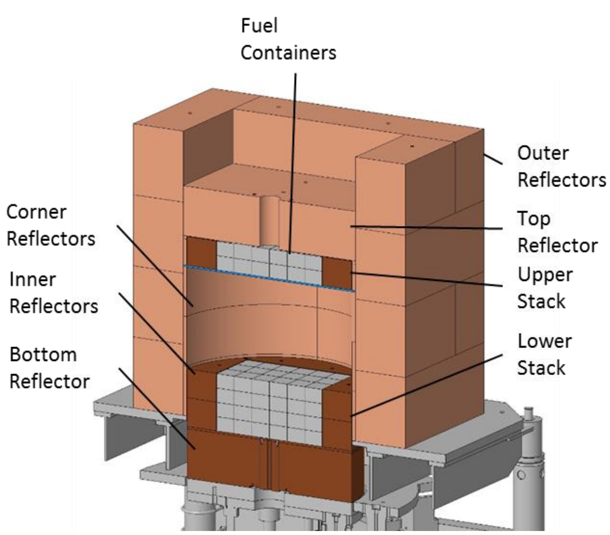

Figure 3. The full Jupiter Assembly, complete with all the copper reflectors.

Cu	Cu	6 Pu 2 Pb	6 Pu 2 Pb	Cu	Cu
Cu	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	Cu
6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb
6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb
Cu	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	Cu
Cu	Cu	6 Pu 2 Pb	6 Pu 2 Pb	Cu	Cu

Top Layer

Cu	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	Cu	.032" Al springs
6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	
6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	
6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	
6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	
Cu	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	Cu	
.032" Al springs						

Middle Layer

Cu	Cu	6 Pu 2 Pb	6 Pu 2 Pb	Cu	Cu	.032" Al shim
Cu	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	Cu	
5 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	4 Pu 2 Pb	.040" Al shim
4 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	4 Pu 2 Pb	
Cu	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	6 Pu 2 Pb	Cu	.032" Al shim
Cu	Cu	6 Pu 2 Pb	6 Pu 2 Pb	Cu	Cu	
.032" Al shim		.040" Al shim		.040" Al shim		

Bottom Layer

Figure 4. The loading of the core for the reference configuration.

The other configurations assembled introduced voids into the center of the core by swapping out the lead interstitial plates for aluminum spacer frames. The drawing for these frames is detailed in Figure 5, which also shows the loading changes between configurations. The changes depicted are the only difference between them. The change in excess reactivity between the configurations was the measured void worth of the experiment. Table II shows the measured excess reactivity of each configuration, along with an inferred effective multiplication factor k_{eff}.

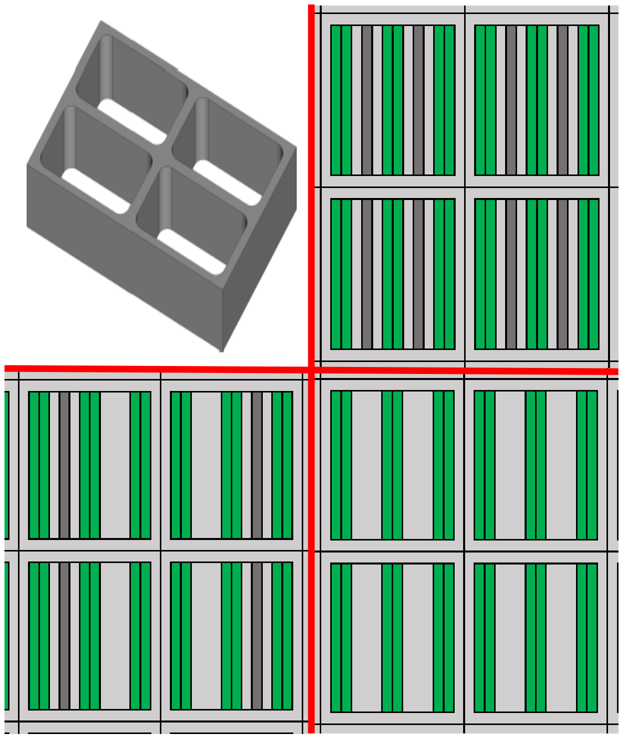

Figure 5. The change in the central boxes of the middle layer between configurations. Shown are the spacer frames (upper left), and the Reference (upper right), A1 (lower left), and A12 (lower right) configurations. Green represents the ZPPR plates, dark gray represents lead, and light gray is aluminum.

TABLE II. The Average Measured Excess Reactivity of the Critical Configurations

Configuration	Average Excess Reactivity (cents)	Inferred k_{eff}
Reference	34.5	1.00072
A12	11.2	1.00024
A1	23.7	1.00050

SIMULATION MODEL

Detailed models were created in MCNP®[1] 6.2 [10]. These models depict almost all of the features of the assemblies, including the rounded corners of the plutonium plate cores, the shims and springs included in the array, and an approximation of the facility. The only simplification is in the exclusion of the pins and screws. Each calculation used 2,250 cycles of one million particles each.

The three configurations have been simulated with both ENDF/B-VII.1 [11] and ENDF/B-VIII.0 [12] nuclear data libraries. The results of these calculations are shown in Table III. All statistical uncertainties are 1 pcm. A full analysis of systematic uncertainties in these models is ongoing. The ICSBEP benchmark will include calculations with JENDL-4.0 [13].

TABLE III. The Simulated Effective Multiplication Factor of the Configurations

Configuration	ENDF/VII.1	ENDF/B-VIII.0
Reference	1.00333	0.99746
A12	1.00162	0.99565
A1	1.00307	0.99719

CONCLUSIONS

While the uncertainty analysis is ongoing, current progress shows that these results will be a strong candidate for inclusion in future versions of the ICSBEP handbook. This experiment, along with others in the collaboration, has already provided useful data on lead void reactivity worth for use in new reactor designs, but a benchmark made from these measurements will also help support the validation of cross section data, including that of lead. Better cross sections for lead, a material in use across the world, would make it overall a more predictable material in nuclear applications, potentially increasing the efficiency of operations involving this material. It is expected that the evaluation will be ready for submission before the 2020 ICSBEP meeting. The JAEA and Los Alamos National Laboratory are also working on ICSBEP benchmarks for the HEU and LEU experiments.

ACKNOWLEDGEMENTS

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