A New Benchmark Evaluation of Historical Experiments with HEU Cylinders and Annuli with 10-Inch Graphite Reflectors

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INTRODUCTION

Throughout the 1950s and 1960s, many criticality experiments were conducted at the Oak Ridge Critical Experiments Facility (ORCEF), which was located at what is now Y-12 National Security Complex. These experiments served to form criticality safety bases for operations at Y-12, and as such, they frequently incorporated highly-enriched uranium (HEU). Many of these experiments have already been benchmarked for inclusion in the International Criticality Safety Benchmark Experiments Project (ICSBEP) Handbook, such as in HEU-MET-FAST-051, which featured bare HEU metal parts, and HEU-MET-FAST-071, which featured HEU metal annuli with thin graphite reflectors [1]. Experiments with varying dimensions of HEU metal annuli and cylinders, as well as increasing graphite reflector thickness of 3 inches and greater, were also performed, but have not yet been benchmarked [2].

A new benchmark covering a selection of nine of these historical experiments, which include HEU metal cylinders and annuli with 10-inch-thick graphite reflectors, is currently under development. This benchmark will be presented to the ICSBEP Technical Review Group (TRG) in April of 2025. Preliminary uncertainty analysis suggests that all nine configurations will be judged to be acceptable as benchmark experiments.

THE EXPERIMENTS

Table 1 gives an overview of the nine configurations which have been evaluated. Figures 1 and 2 show schematics representative of the first and last configurations' benchmark models, respectively, in the SCALE [3] KENO3D visualization program. One-quarter of the model has been cut away such that the core of the assembly is visible. The composition definitions have been simplified in these models in order to more easily distinguish between HEU, graphite, and support materials.

Table 1. Overview of the nine configurations included in the benchmark

Case No.	Config. Identifier	HEU OD (in.)	HEU ID (in.)	Reflector Thickness (in.)	Annulus Material
1	15-13-10V	15	13	10	Air
2	15-13-10C	15	13	10	Graphite
3	15-11-10V	15	11	10	Air
4	15-11-10C	15	11	10	Graphite
5	15-9-10V	15	9	10	Air
6	15-9-10C	15	9	10	Graphite
7	15-7-10V	15	7	10	Air
8	15-7-10C	15	7	10	Graphite
9	15-0-10	15	N/A	10	N/A

The values in Table 1 correspond to the identifying dimensions of each configuration. As displayed in the two figures, there is a central HEU region which is either annular (Figure 1) or solid (Figure 2). The inner diameter of the annular HEU regions varies. The material in the center of the annulus, when applicable, also varies, between air (Figure 1) and graphite (not shown).

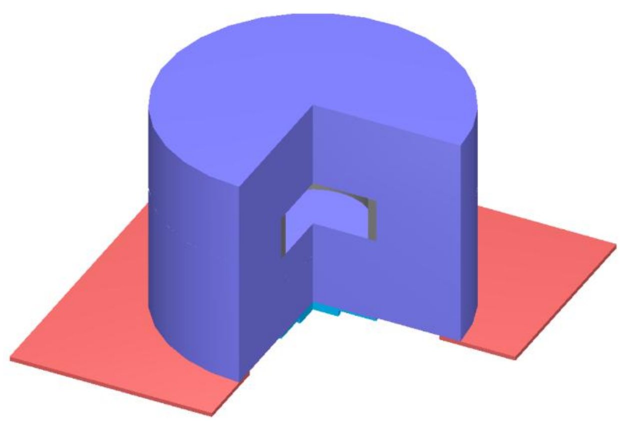

Figure 1. Schematic of the configuration 15-13-10V benchmark model. Graphite is shown in purple, and HEU in gray, with stainless steel and aluminum support structures below the assembly in red and blue, respectively.

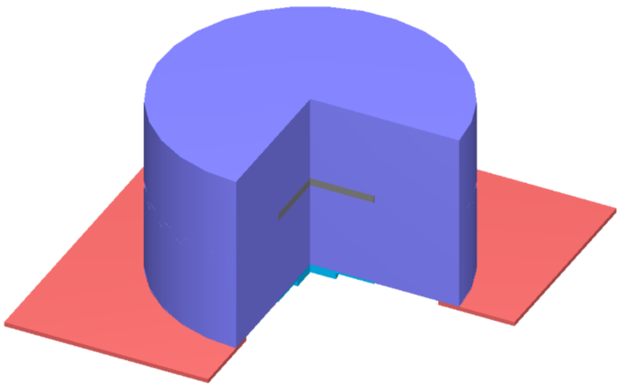

Figure 2. Schematic of the configuration 15-0-10 benchmark model. Graphite is shown in purple, and HEU in gray, with stainless steel and aluminum support structures below the assembly in red and blue, respectively.

UNCERTAINTY QUANTIFICATION

Both manual perturbations and sensitivity-based uncertainty quantification methods were employed to analyze the uncertainty on experimental k_{eff} values due to various dimension and composition uncertainties on the as-assembled configurations. All cases were simulated to an uncertainty of 10pcm. Some significant sources of uncertainty in the experiments were found to be associated with the uranium enrichment and isotopic content, the measured stack heights of graphite parts, the worth of the aluminum support stand, and the heights and diameters of the parts. Uncertainties on k due to the presence of impurities, the mass density of the parts, the fuel stack heights, and the experimental measurement uncertainty were much lower in comparison.

In all of the HEU fuel parts present in these experiments, the ^{234}U, ^{235}U, and ^{236}U weight percents were measured upon receipt at ORCEF when the parts were first delivered. The measurements were taken to two decimal places, and the uncertainty assigned to each of these three isotopes' content is ±0.005%. Manual perturbations were performed on the weight percents of each of these isotopes in each HEU part of a configuration, varying them between their respective uncertainty boundaries. The resulting Δk values for each fuel part were added in quadrature to get a single Δk for each uranium isotope for one configuration; these values for Case 1 are presented in Table 2.

Table 2. Uncertainty due to Uranium Isotope Weight Percent

Uranium Isotope	Standard Uncertainty in k (pcm)
^{234}U	24
^{235}U	29
^{236}U	22
Total	44

At the time of the experiments, stack height measurements were taken on the stacks of fuel parts, top and side reflectors, lower reflectors, and graphite cores, by re-assembling the parts on a marble table in the same order they were stacked on the lift machine. These stack height measurements frequently vary from the sum of the individually measured part heights; the impacts of these discrepancies were previously investigated in Ref. 3. The standard uncertainty in k_{eff} due to the combined uncertainty in measured and calculated stack height was calculated by calculating an uncertainty in the approximated gap thickness between parts in each region; the gap width was then manually perturbed between its bounds. For Case 1, gaps were modeled between fuel parts, between the parts of the lower reflector, and between the parts of the top and side reflectors. Table 3 lists the calculated gap thicknesses for the experiment based on the available data, and the uncertainty on each of those gaps.

Table 3. Gap Thickness Uncertainty for Case 1

Region	Gap Thickness (cm)	Uncertainty (cm)
Top and Side Reflector	0.04445	0.00148
Lower Reflector	0.006604	0.00258

The resulting uncertainty on k_{eff} due to uncertainty in the gap between the top and side reflector and the lower reflector were 32 pcm and 22 pcm, respectively. The standard uncertainty on k_{eff} due to graphite stack height uncertainty was then generalized by combining the values from both reflector regions; this yielded a value of approximately 39 pcm.

A low-mass aluminum support stand was present on the lift machine for the experiments; it held the lower reflector and fuel parts above the stainless steel lift table. A schematic of this stand is shown in Figure 3.

During the performance of the experiments, additional runs were performed to approximate the worth of the support stand. Data on the mass of this structure is not available, and due to geometric limitations of SCALE CSAS5, some simplifications were made in the modeling of the structure. However, as the dimensions and aluminum type were specified, much is still known about the support structures, and therefore a 50% uncertainty on its mass was imposed. One perturbed case was run for each configuration which removed this aluminum stand entirely, as well as aluminum cylinders and a large stainless steel plate which supported the assemblies, and 50% of the resulting Δk of this change was then assigned as the standard uncertainty in k_{eff} due to the presence of the support stand. For Case 1, this standard uncertainty was approximately 29 pcm.

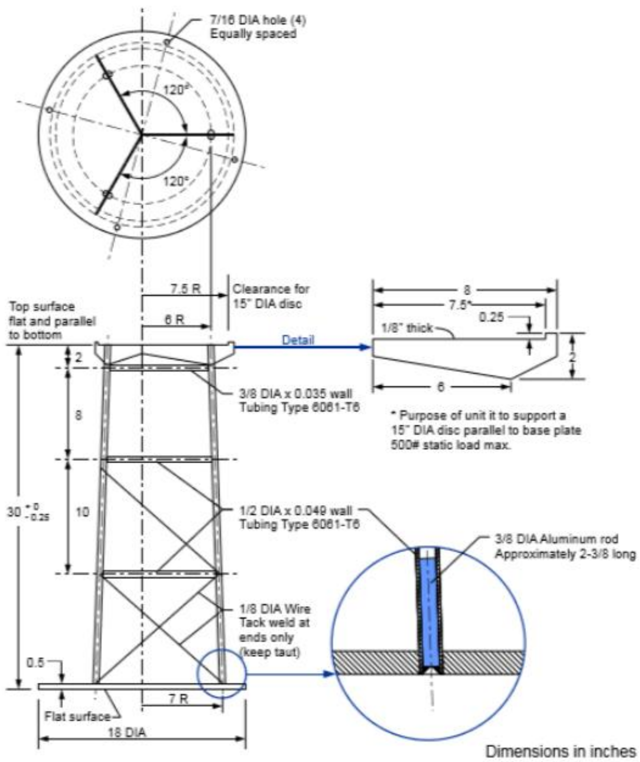

Figure 3. Schematic of the aluminum support stand used in the experiments.

Every fuel part has associated measured values for outer and (if applicable) inner diameter, as well as height. For the reflector parts, many of these dimensions were instead assigned nominal values. Manual perturbations were performed on every part of every configuration in order to determine the standard uncertainty on k_{eff} due to part diameter and height; the Δk values were summed in quadrature to yield two final uncertainty values. For Case 1, the resulting uncertainty on k due to part diameter was approximately 40 pcm, whereas the uncertainty due to part height was approximately 62 pcm.

For Case 1, after all of the standard uncertainties on k_{eff} from each individual parameter were added in quadrature, the total uncertainty on the experimental configuration was determined to be approximately 92 pcm. Preliminary calculations for the remaining cases suggest that the total uncertainty on any case will fall between about 100 and 200 pcm.

BENCHMARK MODELS

A number of simplifications were made to each configuration in order to define the benchmark models. These simplifications included removal of the air and concrete walls and floor of the experiment cell, removal of impurities from graphite (except for boron and cadmium) and from uranium, averaging the density of graphite and the density and enrichment of uranium, removing the source hole from the thick top reflector, removing axial gaps between parts, and finally, removing the majority of the support structures.

Each of these simplifications were made individually and their SCALE-calculated k_{eff} compared to an initial unbiased model to determine the bias imposed by making each change. Table 4 lists each simplification along with its associated bias, in Δk:

Table 4. Calculated biases associated with the Case 1 Benchmark Model

Bias Component	**Configuration 15-13-10V**
Room Return	0.00015 ± 0.00016
Graphite Impurity Removal	-0.00161 ± 0.00016
Graphite Density Standardization	-0.00072 ± 0.00015
Uranium Impurity Removal	-0.00024 ± 0.00016
Uranium Enrichment Standardization	0.00003 ± 0.00016
Uranium Density Standardization	-0.00002 ± 0.00016
Partial Support Stand Removal	-0.00008 ± 0.00016
Source Hole Removal	0.00009 ± 0.00016
Gap Removal	-0.00180 ± 0.00016
Total Bias	**-0.00420 ± 0.00044**

The SCALE-calculated k_{eff} of the Case 1 benchmark model using continuous-energy nuclear data based on ENDF/B-VII.1 is 0.996354 ± 0.00010.

CONCLUSION

Nine experimental configurations will be included in this newly-evaluated benchmark of historical experiments performed at ORCEF, and they will build upon the wealth of existing benchmarks covering experiments at this facility. The evaluation will be presented at the 2025 meeting of the ICSBEP TRG in April. Internal and independent review is currently underway on the benchmark. The largest sources of uncertainty in the experiments include both HEU and graphite dimensions and compositions, specifically the uranium enrichment and isotopic content, the measured stack heights of graphite parts, the worth of the aluminum support stand, and the heights and diameters of all fuel and reflector parts. The first configuration has an uncertainty of about 92 pcm, and all nine configurations are expected to be judged as acceptable benchmarks, with remaining uncertainties most likely ranging between approximately 100 and 200 pcm.

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REFERENCES

1. *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA/NSC/DOC(95)03, Nuclear Energy Agency/Organisation for Economic Co-operation and Development, Paris, France. (2024).
2. J. T. MIHALCZO, "Criticality of Graphite- and Polyethylene-Reflected Uranium (93.2%)-Metal Cylinders and Annuli," *Nuclear Science and Engineering*, **49**, 4, p. 489-504 (1972).
3. W. WIESELQUIST, R. LEFEBVRE, M. JESSEE, D. WIARDA, M. DUNN, N. GREENE, M. WILLIAMS, C. CELIK, and L. PETRIE, "SCALE Code System, Version 6.2.4," ORNL/TM-2005/39, Oak Ridge National Laboratory (2020).
4. K. WORRELL, V. SOBES, and W. J. MARSHALL, "On Estimating Uncertainty in Integral Benchmarks due to Inconsistencies in Geometrical Measurements," *Transactions of the American Nuclear Society*, **130**, p. 742-744 (2024).