INL/CON-15-34039
PREPRINT

Bare, Complex, and Potassium-filled HEU Oralloy Annuli Benchmark Experiments

International Conference on Nuclear Criticality Safety (ICNC 2015)

John D. Bess, Quinton S. Beaulieu,
Andrew J. Hummel

September 2015

BARE, COMPLEX, AND POTASSIUM-FILLED HEU ORALLOY ANNULI BENCHMARK EXPERIMENTS

John D. Bess, Quinton S. Beaulieu, and Andrew J. Hummel
Idaho National Laboratory
2525 North Fremont Avenue
Idaho Falls, ID 83415-3855
United States of America
John.Bess@inl.gov

ABSTRACT

Hundreds of critical experiments were constructed from Oak Ridge Alloy (oralloy) during the 1960s and 1970s at the Oak Ridge Critical Experiments Facility (ORCEF) in support of criticality safety operations at the Y-12 Plant. The purpose of these experiments included the evaluation of storage, casting, and handling limits and providing data for verification of calculation methods and cross sections for nuclear criticality safety applications. Recent contributions to the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (ICSBEP Handbook) include bare, complex, and potassium-filled annuli comprising multiple stacked units of highly enriched uranium (HEU), ~93.2 wt.% ^{235}U, annuli, discs, and parallelepipeds. Prior contributions to the ICSBEP Handbook include bare (unreflected and unmoderated) cylinders; configurations of cylinders and annuli reflected with polyethylene, beryllium, or thin-graphite reflectors; GROTESQUE; and ORSphere. The newest contributions include a bare HEU 11-7 (11 inch outer diameter and 7 inch inner diameter) annulus oralloy-capped at the top and bottom; bare HEU 13-7, 15-7, and 15-9 annuli; bare HEU complex annuli consisting of a 15-9 annulus containing either an off-center 7-inch-diameter cylinder, 5 × 5 inch parallelepiped, or split parallelepiped; and an HEU 13-7 annulus containing either empty stainless steel cans or potassium-metal-filled cans. The purpose of this latter pair of annulus configurations was to test the fast neutron cross sections of potassium as it was a candidate for coolant in some early space power reactor designs. A total of nine new configurations were evaluated as acceptable benchmark experiment measurements. Additional ORCEF oralloy experiments have also been identified for future benchmark evaluation.

KEYWORDS
Annuli, Benchmark, Highly Enriched Uranium, ICSBEP, Oralloy

1. INTRODUCTION

Hundreds of delayed critical experiments were constructed of highly enriched uranium (~93.2 wt.% ^{235}U) Oak Ridge Alloy (oralloy) during the 1960s and 1970s at the Oak Ridge Critical Experiments Facility (ORCEF) in support of criticality safety operations at the Y-12 Plant. The purpose of these experiments included evaluation of storage, casting, and handling limits and providing data for verification of calculation methods and cross-sections for nuclear criticality safety applications. Most of these experiments included solid cylinders of various diameters, annuli of various inner and outer diameters, two and three interacting cylinders of various diameters, and graphite- or polyethylene-reflected cylinders and annuli. Many of these experiments have been evaluated as benchmarks and contributed to the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (ICSBEP Handbook) [1]. A summary of the oralloy experimental series using discs, annuli, or spherical components, and their respective benchmark progress is provided in Table I.

Table I. Summary of Current Oralloy Cylinder, Annulus, and Sphere Benchmark Experiments.

ICSBEP Identifier	Basic Description	Status
HEU-MET-FAST-051	Bare and Two-Interacting Cylinders	Previously Completed
HEU-MET-FAST-059	Bare Annulus with Beryllium Core	Previously Completed
HEU-MET-FAST-069	Beryllium-Top-Reflected Cylinder	Previously Completed
HEU-MET-FAST-071	Thin-Graphite-Reflected Annuli	Previously Completed
HEU-MET-FAST-074	Bare Annuli	Subject of this Paper
HEU-MET-FAST-076	Polyethylene-Reflected Annuli and Cylinders	Previously Completed
HEU-MET-FAST-077	Bare Annuli with Graphite Core	In Progress
HEU-MET-FAST-081	GROTESQUE	Previously Completed
HEU-MET-FAST-083	Complex Annuli Configurations	Subject of this Paper
HEU-MET-FAST-099	Potassium Measurement with Bare Annuli	Subject of this Paper
HEU-MET-FAST-100	ORSphere	Previously Completed
HEU-MET-FAST-###	Two- and Three-Interacting Cylinders	Future Evaluation
HEU-MET-FAST-###	Thick-Graphite-Reflected Annuli	Future Evaluation
HEU-MET-FAST-###	Bare Annuli with Plexiglas Cores	Future Evaluation
HEU-MET-FAST-###	USS Sandwich	Future Evaluation
HEU-MET-FAST-###	Uranium-Graphite Sandwiches	Future Evaluation
TBD	Prompt Neutron Lifetime Measurements	Future Evaluation

The newest three contributions to the ICSBEP Handbook include the following:

1. Potassium Worth Measurement with Bare Annuli [2]
    - 1.1. Annulus with 13 in. (33.02 cm) outer diameter and 7 in. (17.78 cm) inner diameter with empty stainless steel cans placed in the core.
    - 1.2. Same annulus with potassium-metal-filled stainless steel cans placed in the core.
2. Bare Annuli [3]
    - 2.1. Annulus with 13 in. (33.02 cm) outer diameter and 7 in. (17.78 cm) inner diameter.
    - 2.2. Annulus with 15 in. (38.1 cm) outer diameter and 7 in. (17.78 cm) inner diameter.
    - 2.3. Annulus with 15 in. (38.1 cm) outer diameter and 9 in. (22.86 cm) inner diameter.
    - 2.4. Annulus with 11 in. (27.94 cm) outer diameter and 7 in. (17.78 cm) inner diameter capped at the top and bottom with oralloy discs.
3. Complex Annuli [3]
    - 3.1. Annulus with 15 in. (38.1 cm) outer diameter and 11 in. (27.94 cm) inner diameter containing an off-center 7-in.-(17.78-cm)-diameter cylinder.
    - 3.2. Annulus with 15 in. (38.1 cm) outer diameter and 11 in. (27.94 cm) inner diameter containing an off-center parallelepiped stack of 5 in. (12.7 cm) × 5 in. (12.7 cm) plates.
    - 3.3. Annulus with 15 in. (38.1 cm) outer diameter and 11 in. (27.94 cm) inner diameter containing two off-center parallelepiped stacks of 5 in. (12.7 cm) × 5 in. (12.7 cm) plates split along the assembly midplane.

These benchmark evaluations were prepared as part of ongoing efforts to train next generation nuclear engineers in the processes of benchmark analysis and development, including comprehensive assessment of biases and uncertainties. The oralloy experiments have the advantage of not only simplicity in design, but the materials utilized were well-characterized in regards to dimensions, mass, and composition. Additionally, high precision and accuracy were implemented in manufacturing the oralloy parts used at ORCEF [4]. All nine configurations have been evaluated as acceptable benchmark experiments for inclusion in the ICSBEP Handbook. Brief descriptions of the individual benchmark efforts will be provided in this paper.

2. POTASSIUM MEASUREMENT WITH BARE ANNULI

The primary purpose of the potassium measurement experiment was to test the fast neutron cross sections of potassium as it was a candidate for coolant in some early space power reactor designs, such as the Medium-Power Reactor Experiments (MPRE) program [5]. Additional experiments at ORCEF were performed to support a UO_2 variant of the Systems Auxiliary Nuclear Power Program (SNAP) reactor, which also included measurement of the potassium worth [6]. Oralloy annuli of varying heights and diameters were stacked to form the overall annulus with approximately half of the experiment supported by a thin stainless steel diaphragm and the remaining portion lifted from underneath to contact the underside of the diaphragm and form the near-critical configuration. As shown in Figure 1, two stainless steel cans were placed in the core of the annulus. Comparison of the system reactivity for an experimental loading with empty cans against a loading using cans filled with potassium metal provided the measured worth of the potassium.

Both detailed and simple benchmark models were prepared with biases assessed to account for room return, geometry simplification, homogenization of oralloy annuli into a single annulus, removal of impurities, and removal of experimental support structures. To visualize the level of detail between simple and detailed benchmark models, respectively, please compare Figures 2 and 3. Due to the quality of the experimental components [4], many of the evaluated uncertainties were determined to be negligible. The primary constituents of the benchmark uncertainty include reproducibility of the experiment and the uncertainty in the measured reactivity worth, including measurements to account for support structure removal; there is an additional bias uncertainty because the properties of the concrete room are not entirely well known. The total benchmark uncertainty in both configurations of the potassium measurement experiment is 50 pcm. There was no calculable uncertainty associated with the potassium properties. Calculated results using MCNP6.1 are provided in Table II for the detailed benchmark configuration. Simple benchmark calculation results were comparable.

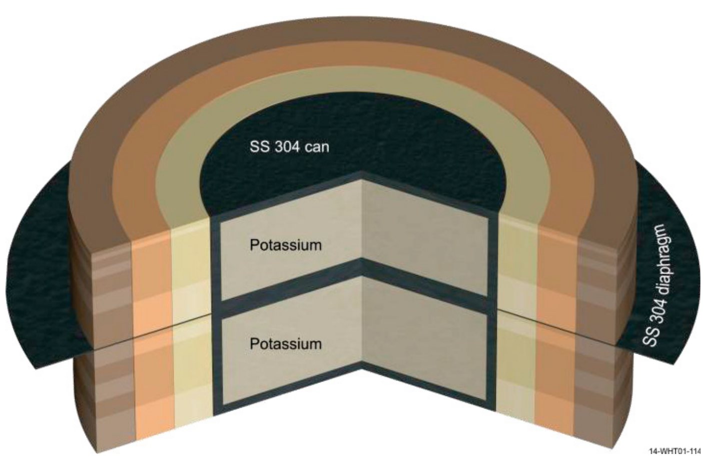


Figure 1. Oralloy Metal Annuli with Potassium-Filled Stainless Steel Cans.

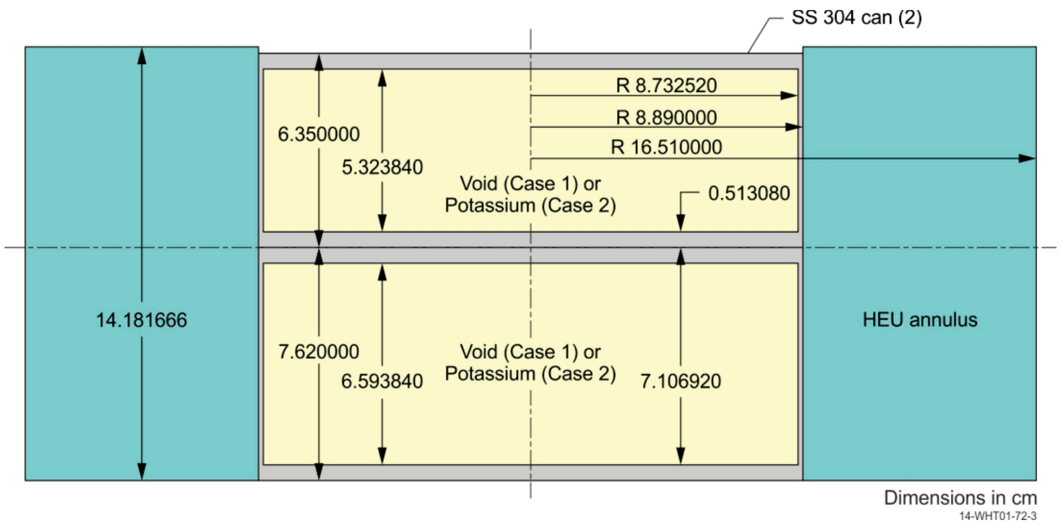


Figure 2. Simple Benchmark Model Dimensions for Potassium Measurement Experiments.

Table II. MCNP6.1 Calculations of Potassium Measurement Detailed Configurations.

Core Content	Neutron Cross Section Library	Calculated k_{eff}	$\pm$	σ	Benchmark Experiment k_{eff}	$\pm$	σ	$\frac{C-E}{E}$%	$\pm$	
Empty	ENDF/B-VII.1	0.99554	±	0.00002	0.9981	±	0.0005	-0.26	±	0.05
	ENDF/B-VII.0	0.99572	±	0.00002				-0.24	±	0.05
	JEFF-3.1	0.99243	±	0.00002				-0.57	±	0.05
	JENDL-3.3	0.99999	±	0.00002				0.19	±	0.05
K-Filled	ENDF/B-VII.1	0.99579	±	0.00002	0.9989	±	0.0005	-0.31	±	0.05
	ENDF/B-VII.0	0.99592	±	0.00002				-0.30	±	0.05
	JEFF-3.1	0.99258	±	0.00002				-0.63	±	0.05
	JENDL-3.3	1.00015	±	0.00002				0.13	±	0.05

Results for the empty configuration are typical for calculations of ORCEF bare cylinder configurations [8]. However, calculations for the potassium-filled configuration fail to introduce the additional bias expected for inclusion of potassium. The measured worth for the addition of potassium was +10.32 ¢. Calculated potassium worth is between 2 to 4 ¢, which is significantly lower. Deficiencies in the cross sections of potassium may exist and further benchmark evaluation of experiments containing potassium is recommended. One possible experiment is the aforementioned potassium worth measurement discussed briefly above for a beryllium-reflected space reactor mockup with simulated potassium coolant [6]; however, additional benchmark data for experiments containing potassium and possibly sodium-potassium (NaK) eutectic alloy coolant might be beneficial for more comprehensive nuclear data adjustment.

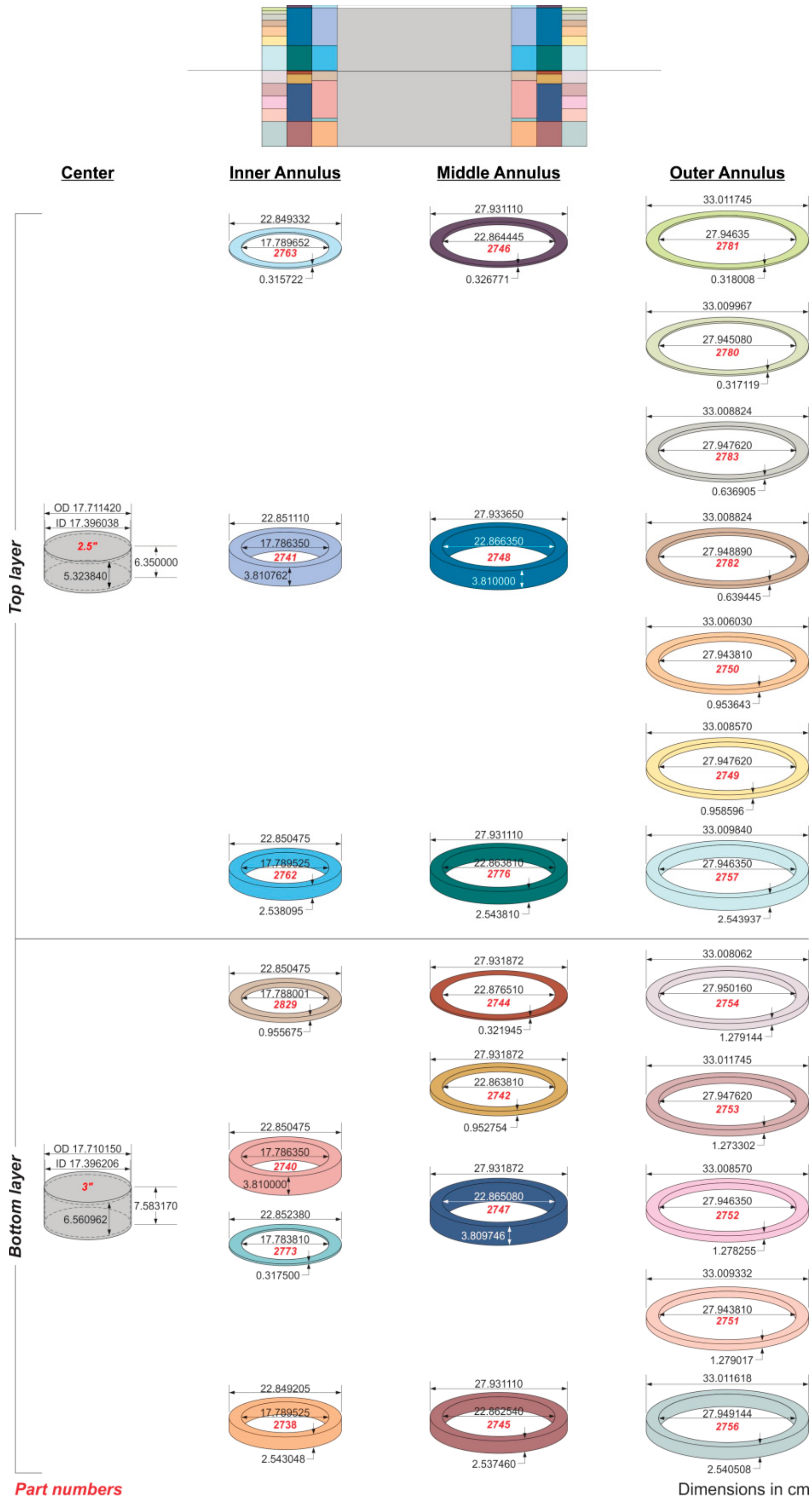


Figure 3. Detailed Benchmark Model Dimensions for Potassium Measurement Experiments.

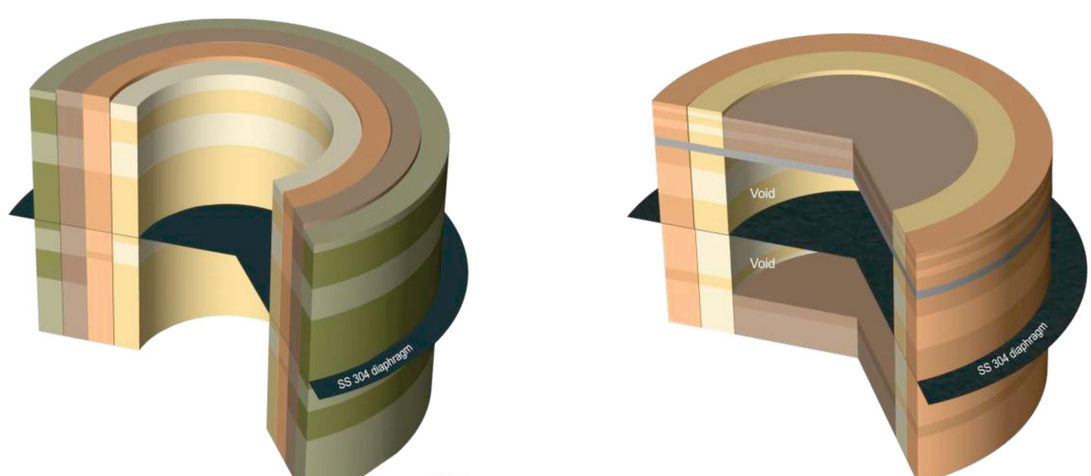
3. BARE ANNULI

The bare annuli experiments (see Figure 4) provide basic reference configurations against which other ORCEF experiments with material placed as external or in-core reflectors can be compared. These annuli configurations, excepting the 11”-7”” annulus, and five bare-cylinder configurations (HEU-MET-FAST-051) were also used in additional measurements to characterize their prompt-neutron lifetime, α, as a function of configuration of height and diameter [9].

Detailed and simple benchmark models were similarly prepared. The total benchmark uncertainty in all four cases is approximately 50 pcm with the dominant contributors from experiment reproducibility, measured reactivity worth, and ^{235}U content. Calculated results using MCNP6.1 are provided in Table III and are also comparable to results typical of bare oralloy calculations [8]. Future benchmark efforts are to include evaluation of the prompt-neutron lifetime measurements, similar to what has been previously evaluated for the ORSphere [10].

Table III. MCNP6.1 Calculations of Bare Annuli Detailed Configurations.

Annulus	Neutron Cross Section Library	Calculated			Benchmark Experiment			$\frac{C-E}{E}\%$		
		k_{eff}	±	σ	k_{eff}	±	σ			
13”-7”	ENDF/B-VII.1	0.99640	±	0.00002	0.9988	±	0.0005	-0.24	±	0.05
15”-7”	ENDF/B-VII.1	0.99629	±	0.00002	0.9979	±	0.0005	-0.16	±	0.05
15”-9”	ENDF/B-VII.1	0.99471	±	0.00002	0.9970	±	0.0005	-0.23	±	0.05
11”-7”	ENDF/B-VII.1	0.99593	±	0.00002	0.9975	±	0.0005	-0.17	±	0.05

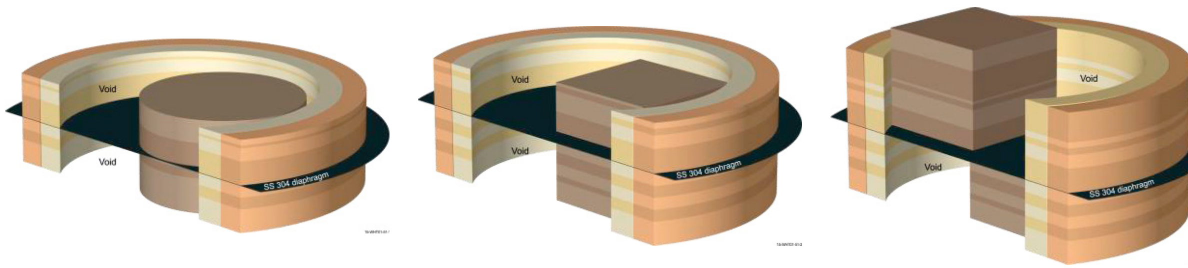


Cases 1-3: Annulus (15”-7” Shown) Case 4: Capped 11”-7” Annulus

Figure 4. Bare Annuli Configurations.

4. COMPLEX BARE ANNULI

The primary purpose of the complex annuli experiments was to validate criticality safety activities at the Y-12 Plant for non-standard geometries [3], and was performed as a predecessor to the more complex GROTESQUE experiment [11]. Basic depictions of the three complex annuli configurations (without steel diaphragm) are shown in Figure 5. In all three configurations, the steel diaphragm was roughly located midplane of each experiment (see Figure 6); for example, the split in the parallelepiped in Case 3 occurs at the location of the diaphragm.



Case 1: Cylinder Case 2: Parallelepiped Case 3: Split Parallelepiped

Figure 5. Three Complex Annuli Configurations.

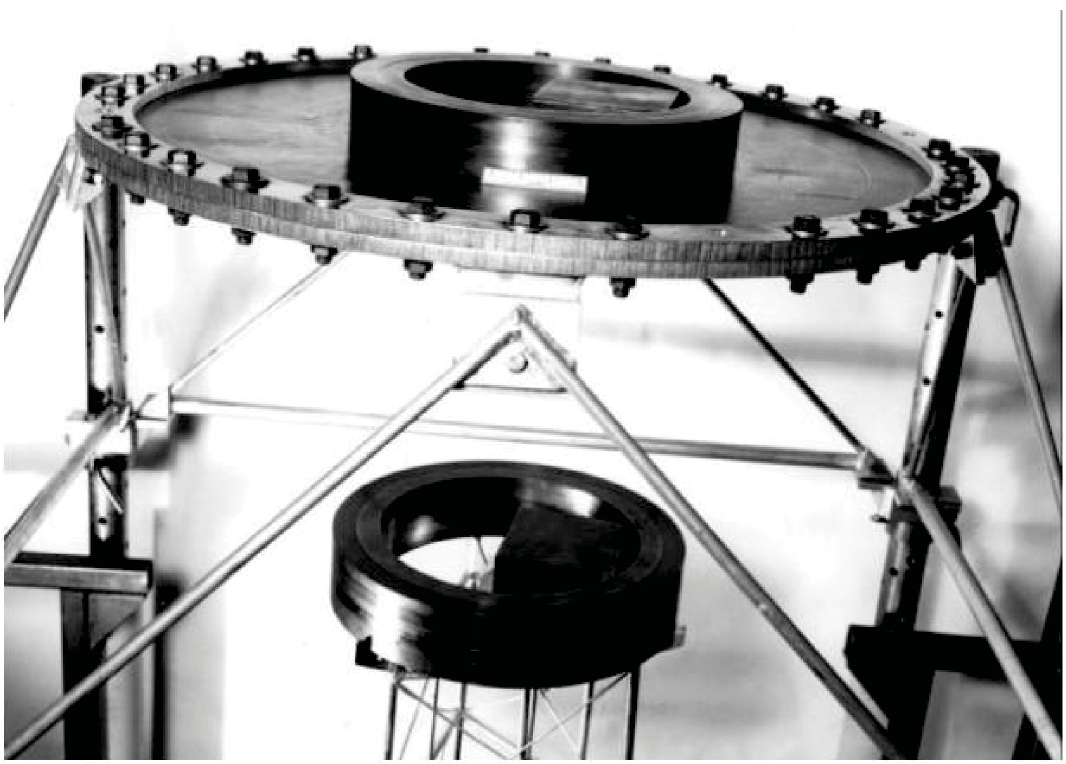


Figure 6. Photograph of Parallelepiped in Annulus Loading.

The total benchmark uncertainty in the complex annuli configurations is approximately 60 pcm for the annulus containing a cylinder. Additional uncertainty was introduced because a few parts in the configurations were unknown; however, the total uncertainty is still primarily due to uncertainties deriving from experiment reproducibility, measured reactivity worth, and ^{235}U content. Calculated results using MCNP6.1 are provided in Table IV. Results for the first configuration are comparable to results typical of bare oralloy calculations [8]. Recently additional information was gathered to support a more comprehensive analysis of the complex annuli configurations containing parallelepipeds. Calculations are in progress and will be reported at the conference. The completed benchmark evaluation, HEU-MET-FAST-083, will contain the final results for comparison against other oralloy benchmark calculations.

Table IV. MCNP6.1 Calculations of Complex Annuli Detailed Configurations.

Annulus Content	Neutron Cross Section Library	Calculated			Benchmark Experiment			$\frac{C-E}{E}\%$		
		k_{eff}	±	σ	k_{eff}	±	σ			
Cylinder	ENDF/B-VII.1	0.99693	±	0.00002	0.9996	±	0.0006	-0.27	±	0.06
Box	ENDF/B-VII.1		(a)			(a)			(a)	
Split-Box	ENDF/B-VII.1		(a)			(a)			(a)	

(a) Final values will be available in HEU-MET-FAST-083.

5. REMAINING ORCEF EXPERIMENTAL DATA

Numerous configurations of graphite-reflected annuli and cylinders yet remain to be evaluated. Various thick (> 15 in., 38.1 cm) graphite reflector configurations have been reported [12] and many additional configurations with graphite reflectors between 3 and 15 in. (7.62 and 38.1 cm) are also unevaluated [13]. Additional interacting cylinder configurations are found in the logbook records kept during the ORCEF experiments. Prompt neutron decay measurements for these coupled-core systems have also been reported [14]. Other logbook experiments include bare annuli with methacrylate plastic (Plexiglas) cores, the USS Sandwich (oralloy cylinder reflected by stainless steel discs along the axis), and graphite-uranium sandwich configurations (oralloy cylinder reflected by graphite discs along the axis). Additional data stored in archived records will be needed to complete evaluations of these latter configurations as the logbooks contain insufficient data for a formal benchmark analysis.

6. CONCLUSIONS

Three new benchmark evaluations have been prepared for inclusion in the ICSBEP Handbook. As the benchmark evaluations are currently undergoing final technical review, final results may slightly vary from those reported herein. Final, peer-reviewed results will be reported in three benchmark evaluations included in the September 2015 edition of the ICSBEP Handbook. These evaluations include a total of nine acceptable configurations: two configurations used to measure the fast-neutron integral worth of potassium, four bare annuli configurations, and three complex annuli configurations. These evaluations contribute to an already comprehensive set of benchmark evaluations of ORCEF experimental data. Numerous experiments still remain that can be evaluated.

ACKNOWLEDGMENTS

The ICSBEP is a collaborative effort that involves numerous scientists, engineers, and administrative support personnel from over 20 different countries. The author would like to acknowledge the efforts of all of these dedicated individuals without whom these projects would not be possible. This paper was prepared at the Idaho National Laboratory for the U.S. Department of Energy under Contract Number (DE-AC07-05ID14517).

REFERENCES

1. *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA/NSC/DOC(95)03, OECD-NEA, Paris, France (2014).
2. J. T. Mihalczo, M. S. Wyatt, "Potassium Reactivity Worth in a ^{235}U Fission Spectrum Critical Assembly," *Trans. Am. Nucl. Soc.*, **76**, pp. 359-360 (1997).
3. J. T. Mihalczo, "Brief Summary of Unreflected and Unmoderated Cylindrical Critical Experiments with Oralloy at Oak Ridge," ORNL/TM-1999/302, Oak Ridge National Laboratory (1999).
4. J. T. Mihalczo, G. Schaaff, "Uncertainties in Masses, Dimensions, Impurities, and Isotopics of HEU Metal Used in Critical Experiments at ORCEF," ORNL/TM-2012/32, Oak Ridge National Laboratory (2012).
5. A. P. Fraas, "Summary of the MPRE Design and Development Program," ORNL-4048, Oak Ridge National Laboratory (1967).
6. J. T. Mihalczo, "A Small Beryllium-Reflected UO_2 Assembly," ORNL-TM-655, Oak Ridge National Laboratory (1964).
7. J. T. Goorley, et al., "Initial MCNP6 Release Overview – MCNP6 version 1.0," LA-UR-13-22934, Loa Alamos National Laboratory (2013).
8. J. D. Bess, M. A. Marshall, J. B. Briggs, "The ORSphere Benchmarak Evaluation and Its Potential Impact on Nuclear Criticality Safety," *Proceedings of NCSD 2013*, Wilmington, NC, September 29 – October 3 (2013).
9. J. T. Mihalczo, "Prompt-Neutron Lifetime in Critical Enriched-Uranium Metal Cylinders and Annuli," *Nucl. Sci. Eng.*, **20**, pp. 60-65 (1964).
10. M. A. Marshall, J. D. Bess, "Benchmark Specifications and Results for α and Λ in HEU Metal System Using ORSphere," *Trans. Am. Nucl. Soc.*, **111**, pp. 830-833 (2014).
11. J. R. Knight, "GROTESQUE Without Tears," ORNL/CSD/TM-220, Oak Ridge National Laboratory (1984).
12. J. T. Mihalczo, "Monte Carlo Calculations of Thick-Graphite-Reflected Uranium-Metal Critical Assemblies," *Trans. Am. Nucl. Soc.*, **11**, pp. 385-386 (1968).
13. J. T. Mihalczo, "Graphite and Polyethylene Reflected Uranium Metal Cylinders and Annuli," Y-DR-81, Union Carbide Corporation, Oak Ridge, TN (1972).
14. J. T. Mihalczo, "Prompt-Neutron Time Behavior in Delayed-Critical Coupled Uranium-Metal Cylinders," *Proc. of the International Conference on Fast Critical Experiments and Their Analysis*, Argonne, IL, October 10-13, pp. 237-241, ANL-7320, Argonne National Laboratory (1966).