INL/CON-06-11658
PREPRINT

Highly Enriched Uranium Metal Annuli and Cylinders With Polyethylene Reflectors and/or Internal Polyethylene Moderator

Conference on Nuclear Criticality Safety

Tyler Sumner
J. Blair Briggs
Leland M. Montierth

May 2007

Idaho National Laboratory

HIGHLY ENRICHED URANIUM METAL ANNULI AND CYLINDERS WITH POLYETHYLENE REFLECTORS AND/OR INTERNAL POLYETHYLENE MODERATOR

Tyler Sumner, Georgia Institute of Technology, United States of America
J Blair Briggs and Leland M. Montierth, Idaho National Laboratory, United States of America

1. Introduction

During the 1960s and 1970s, a variety of critical experiments were constructed of enriched uranium metal at the Oak Ridge Critical Experiments Facility in support of criticality safety operations at the Y-12 Plant (References 1–3). The purposes of these experiments included evaluating the storage, casting, and handling limits for the Y-12 Plant and providing data for verification of calculation methods and cross-sections for nuclear criticality safety applications. Of the many delayed critical experiments, experiments of uranium metal annuli with and without polyethylene reflectors and with the central void region either empty or filled with polyethylene are described in this article.

The outer diameter of the uranium annuli varied from 9–15 inches in 2-inch increments. In addition, there were uranium metal cylinders with diameters varying from 7–15 inches with complete reflection and reflection on one flat surface to simulate floor reflection. Most of the experiments were performed between February 1964 and April 1964. Five partially-reflected (reflected on one side) experiments were assembled in November 1967, but are judged not to be of benchmark quality (See Section 5.0). Twenty-five experiments are described and evaluated in this report of which 20 are considered acceptable for use as criticality safety benchmarks. Twenty-four of the 25 experiments have been determined to have fast spectra. Experiment 4 is an exception and has mixed spectra.

Unreflected and unmoderated experiments with the same high-enriched uranium metal parts were performed at the Oak Ridge Critical Experiments Facility in the 1960s and are evaluated in the *International Handbook of Evaluated Criticality Safety Benchmark Experiments (ICSBEP Handbook*) [4] as HEU-MET-FAST-051. Thin graphite reflected (2 inches or less) experiments also using the same highly enriched uranium metal parts are evaluated in HEU-MET-FAST-071 [4].

2. Experiment Methodology

Uranium cylinders with nominal outside diameters of 7 inches, 9 inches, 11 inches, 13 inches, and 15 inches fully reflected and one-side reflected with polyethylene were assembled until delayed criticality was achieved. Delayed critical assemblies of annuli with nominal outside diameters of 9 inches, 11 inches, 13 inches, and 15 inches and thick polyethylene reflectors and/or moderators (centers of annuli either void or containing polyethylene) were also constructed. All but the one-side-reflected experiments were performed at the Oak Ridge Critical Experiments Facility between February and April of 1964 in a controlled environment at room temperature. The one-side-reflected experiments were performed in November 1967 at the same location under the same conditions.

2.1 Experiment Types

The five types of experiments performed were:

- Unreflected, internally moderated uranium metal annuli (Experiments 1–3);

- Fully reflected uranium metal cylinders (Experiments 4–8);
- Uranium metal cylinders reflected on one flat surface (Experiments 9–13);
- Fully reflected uranium metal annuli with the central void region empty (Experiments 14, 16, 18, 20, 22, and 24);
- Fully reflected, internally moderated uranium metal annuli (Experiments 15, 17, 19, 21, 23, and 25).

Sketches of the five types of experiments are illustrated in Figures 1–5.

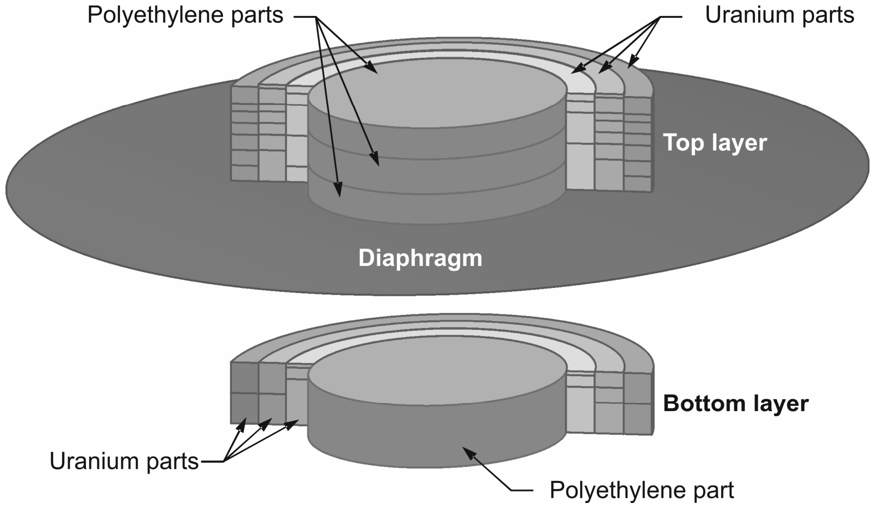

Figure 1. Geometry of uranium metal annulus with internal polyethylene moderator for Experiments 1–3.

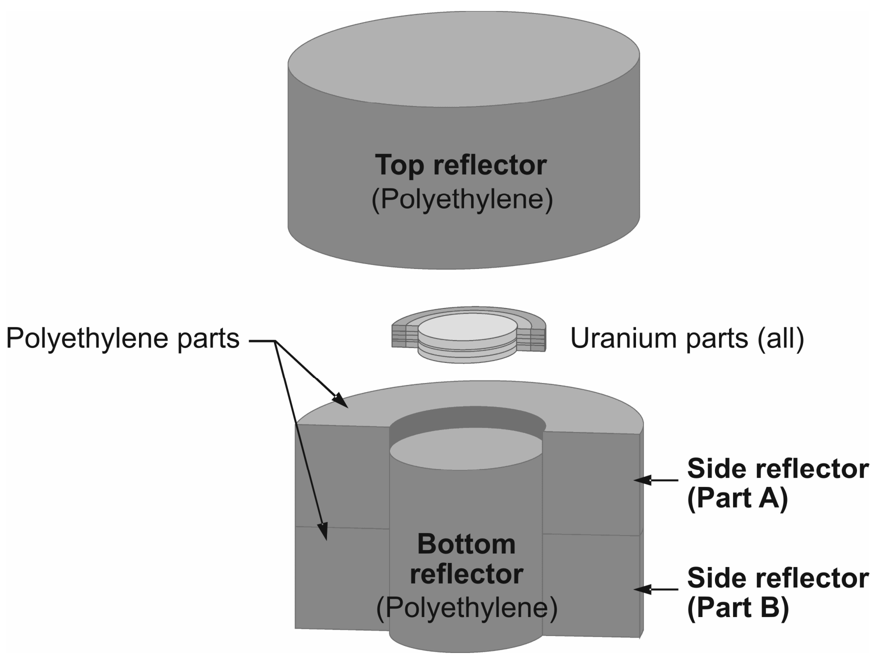

Figure 2. Geometry of uranium metal cylinder with thick polyethylene reflector for Experiments 4–8.

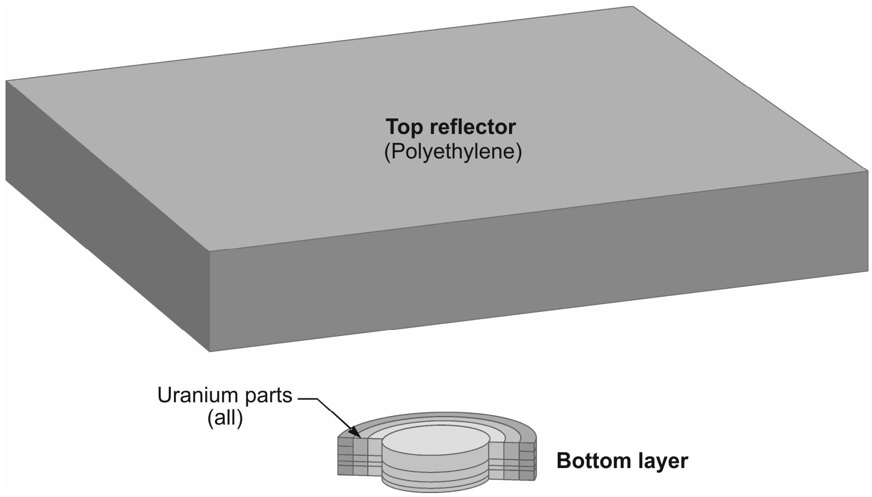

Figure 3. Geometry of uranium metal cylinder with thick polyethylene reflector on one flat surface for Experiments 9–13.

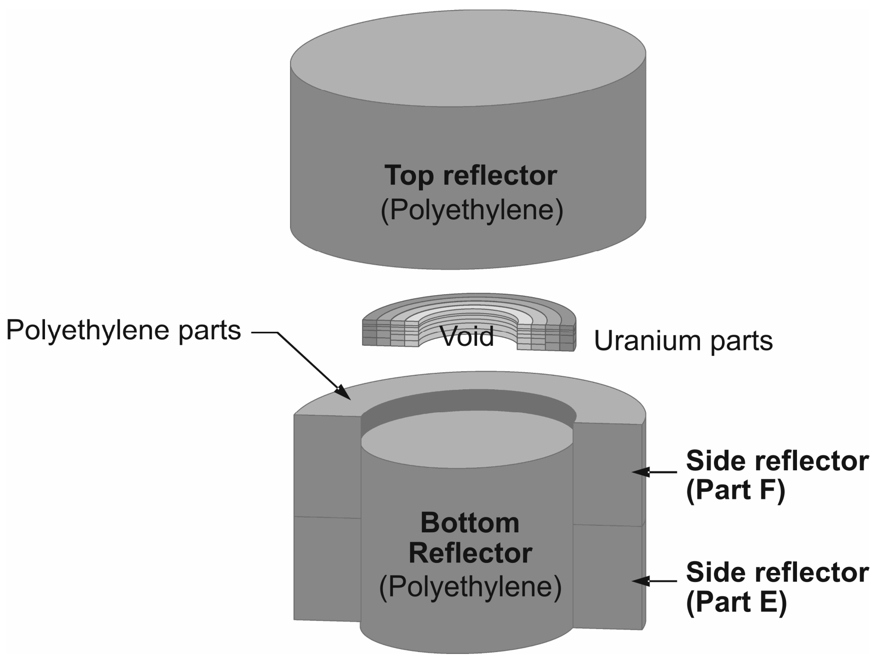

Figure 4. Geometry of uranium metal annulus with thick polyethylene reflector and void in the center of the annulus for Experiments 14, 16, 18, 20, 22, 24.

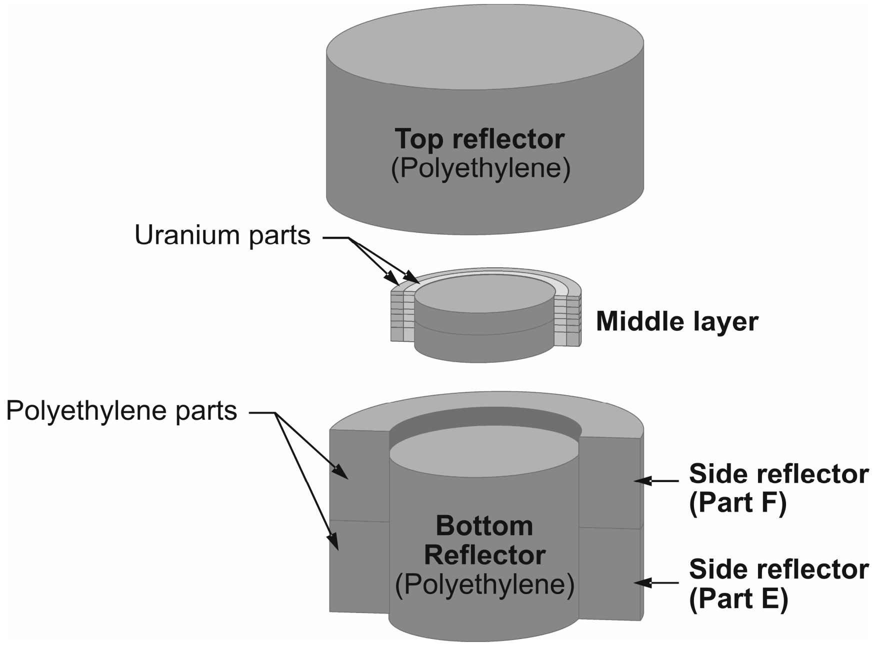

Figure 5. Geometry of uranium metal annulus with thick polyethylene reflector and with polyethylene in the center of the annulus for Experiments 15, 17, 19, 21, 23, 25.

2.2 Description of Material Data

The uranium metal parts for these critical experiments were carefully fabricated at the Oak Ridge Y-12 Plant in the early 1960s. Each uranium metal part was a separate casting, which was then machined. The average isotopic contents of the uranium are 0.97 wt% ^{234}U, 93.14 wt% ^{235}U and 0.25 wt% ^{236}U with an average impurity content of 500 ppm. For the parts not measured, a weighted average of other isotopic measurements was used. The uncertainty in the measured values for ^{234}U, ^{235}U, and ^{236}U are 5x10^{-3} wt%. The ^{238}U values were obtained by subtracting the sum of the other three from unity.

3. Experimental Uncertainty

This section describes how experimental uncertainties are converted to uncertainties in calculated k_{eff} values. Uncertainties are evaluated using two approaches: measured data and Monte Carlo calculations. Measured data were used where sufficient experimental information is available to analyze the uncertainties. Where experimental data were not available, Monte Carlo calculations were performed using the MCNP4C code with an ENDF/B-VI cross-section library. Models used to calculate uncertainties included 2500 neutrons per generation with 5000 generations and 50 skipped generations. Standard deviations in k_{eff} ranged from 0.00018–0.00023. The basis for all uncertainties was provided by the principal experimentalist.

Where possible, the effects of uncertainties on calculated k_{eff} values were evaluated using simplified models in which uranium and polyethylene impurities and the support structure were excluded. Evaluations of uncertainties for all critical experiments were performed for the uranium impurities, polyethylene impurities, uranium isotopics, mass of uranium parts, mass of polyethylene parts, dimensional uncertainty associated with the radius of uranium parts, height perturbation uncertainties for the uranium parts, dimensional uncertainty associated with radius of polyethylene parts, height perturbation uncertainties for the polyethylene reflector parts, and lateral alignment uncertainty. The principal experimentalist indicated that systematic uncertainties are small in all cases.

Uncertainty calculations for uranium isotopics, mass of uranium parts, mass of polyethylene parts, radius of uranium parts, radius of polyethylene parts, and height of the polyethylene reflector parts were performed by simultaneously increasing and then decreasing the parameter of interest. Δk_{eff} values were determined by comparing both results with the reference value, the larger of these two values was then used to calculate the final uncertainty for each experiment.

When the changes in k_{eff} between the base case and the uncertainty model were within the statistical uncertainty of the Monte Carlo results, the changes in the variable are amplified and the calculations repeated. The resulting calculated change is then normalized back to the actual uncertainty. This assumes linearity, but should be adequate for small k_{eff} changes. All parameters were assumed to be uniformly distributed about the nominal value over the uncertainty range.

The total uncertainty for each experiment was calculated by taking the square root of the sum of the squares of the individual uncertainties discussed in this section. The average uncertainty for the 25 experiments is 0.00052 with Experiment 10 having the largest uncertainty of 0.0011. The total uncertainty for each experiment is small and is attributed to the accuracy of the experimental information. However, only 20 of the 25 experiments are judged to be acceptable for use as criticality safety benchmark experiments. The five partially-reflected experiments were judged not to be of benchmark quality. These five experiments are discussed in more detail in Section 5.0.

4. Benchmark Specifications

All benchmark models consisted of cylinders, annuli, and plates of uranium metal reflected and/or internally moderated by polyethylene that had the same dimensions and alignments as the original experiments. The outer diameter of the uranium annuli and cylinders varied from 7–15 inches in 2-inch increments. To create external reflection around the uranium annuli and cylinders, polyethylene parts were used to surround the uranium on all sides. Internal moderation of the uranium was accomplished by placing cylinders of polyethylene inside the uranium annuli.

If the height of an annular or cylindrical region is larger than the sum of the heights of the individual parts, interstitial gaps are included in the models. Gaps were assumed to be radially symmetric, and gaps within each annular and cylindrical region were assumed to be equal. When the heights of annular and cylindrical regions were less than the sum of the heights of the individual annuli and cylinders, interstitial gaps were not included in the model and the height of the region equals the sum of the heights of the individual parts. Polyethylene gaps were included in two places: between the internal moderators and between the side and top polyethylene reflectors.

Polyethylene reflectors resting on top of the uranium annuli and cylinders were modeled without gaps between the uranium and the polyethylene reflector. Side reflectors for reflected assemblies were modeled 0.00508 cm lower than the top reflectors to account for the rise in uranium during the assembly process.

Irregularities in the height of the uranium regions were represented in the models at the top surface of the uranium, adjacent to the top reflector, for configurations with thick reflectors on all sides. Irregularities in the height of the uranium regions were also represented at the top for moderated, but unreflected configurations. However, irregularities in the height of the uranium regions were positioned at the bottom of the uranium cylinders for configurations with polyethylene reflection on one flat surface.

The following simplifications were made to the model:

The support structure was not included in the model. The reactivity effect of the support structure was determined experimentally to be very small and is included as a bias. The diaphragm for Experiments 1–3 was also excluded and the upper and lower sections were represented as being in contact.

The cell walls, floor, and ceiling were also excluded from the model. The effects of room-return were considered negligible for all fully reflected experiments. For the fully reflected experiments, Experiments 4–8 and 14–25, room return effects were zero because of the presence of the thick reflector. For Experiments 1–3 and 9–13 (not considered to be of benchmark quality) the reactivity effects of neutrons reflected from the experimental cell walls, floor, and ceiling were obtained from Monte Carlo calculations where the calculations were performed with and without the surrounding concrete. Models were created using both Oak Ridge and Magnuson Concrete for the walls, floor, and ceiling. The difference in the room return reactivity correction for the two types of concrete was insignificant. For the partially reflected experiments, the values varied from 2.9 cents for Experiment 13 to 7.4 cents for Experiment 9. The larger diameter assemblies have a larger room return effect since neutrons reflecting off the surrounding concrete see a larger target because of the larger size of the assembly. The calculated value for the 7-inch-diameter cylinder is close to the 3 cents obtained from the indoor/outdoor measurements for GODIVA at Los Alamos National Laboratory (LANL), which is also approximately 7 inches. The larger calculated values for the three unreflected experiments are also because of their larger size.

Reactivity effects of the support structure and room return were between -9 to +25 cents for Experiments 1–3. Experiments 9-13 had larger reactivity magnitude changes for the removal of support structure and room return up to -103 cents for Experiment 10.

5. Partially Reflected (Reflected on Top Only) Uranium Cylinders

A comparison of experimental, benchmark-model, and MCNP-model k_{eff} values is shown in Figure 6. The experimental k_{eff} values are derived from the original reactivities reported by the principal experimentalist. The benchmark-model k_{eff} values are the experimental k_{eff} values adjusted to account for biases that were introduced by removing the support structure and surroundings. The MCNP-model k_{eff} values are the calculated values found from MCNP4C using ENDF/B-VI cross-section data.

Calculated results for most of the experiments are between 0.3–0.6% lower than the experimental values, which is consistent with past evaluations (HEU-MET-FAST-051 and HEU-MET-FAST-071). Results for Experiments 9–13, uranium-metal cylinders reflected only on the top flat surface, range from 0.8–3.0 % low. There is an almost linear improvement in agreement with experimental values with decreasing cylindrical diameter (decreased importance of axial leakage and increased importance on radial leakage).

No explanation has been found as to why Experiments 9–13 calculate differently than the other experiments in this series. All twenty-five cases have been modeled using ENDF/B-V, ENDF/B-VI, and JEF 3.0/3.1 cross-section libraries with similar results. Case 9 was independently modeled using MCNP and KENO. Experiments 9–13 were modeled with a higher density (0.96 g/cm^3) polyethylene reflector with negligible differences in results. Material compositions of the uranium metal parts have been extensively verified, and the same parts have been used in previously evaluated experiments (HEU-MET-FAST-051 and HEU-MET-FAST-071). To eliminate the possibility of input error, Case 9 has been independently modeled with varying degrees of detail by four individuals, all with similar results.

It was also determined that room return, which affects only the unreflected and partially reflected experiments, does not have a large enough effect on k_{eff} to account for the unexpectedly large deviation from the benchmark values. Likewise, the support structure, as described, does not have a significant effect on calculated k_{eff} values. Measured values for the worth of the support structure are significantly higher than calculated values and appear to be inconsistent with the measured values reported in HEU-MET-FAST-051. For example, the measured reactivity worth of the support stand for Case 9, a 15-inch-diameter, 2-inch-height metal cylinder with polyethylene reflection on one side is reported to be 129 cents (or 0.88% in k_{eff}). The measured reactivity worth of the support stand for Case 18 of HEU-MET-FAST-051, a 15-inch-diameter, 3-inch-height unreflected metal cylinder is only 23.6 cents. The neutron spectra in Case 9 of HEU-MET-FAST-076 is slightly softer than the spectrum for Case 18 of HEU-MET-FAST-051 and the critical mass is 1.5 time less, but these differences do not seem sufficient to increase the reactivity worth of the lower support structure by a factor of 5.5.

The observed inconsistency, especially for Experiment 9, can only be attributed to an inaccurately reported height of the uranium stack, unaccounted for reflection near the unreflected surface of the metal cylinder, or a major deficiency in analytical methods. Careful review of the different uranium parts given in this series of experiments indicates that there is no combination of parts with the same outer diameters that would bring k_{eff} for the partially-reflected experiments into agreement with the other experiments. Results for Experiments 9–13 are clearly inconsistent with results from other, widely accepted experiments, as well as similar experiments using the same uranium parts. HEU-MET-FAST-078 includes data for similar, partially-reflected highly-enriched uranium metal assemblies with various reflector materials that were performed at LANL. Included in HEU-MET-FAST-078 are 15-inch-diameter, highly-enriched uranium-metal cylinders with thick polyethylene reflection on the top surface of the assembly, essentially the same as Experiment 9. Excellent agreement exits between experimental results and calculations for the LANL experiments. The unique nature of these experiments (fission density strongly skewed toward the polyethylene reflector), and the lack of any clear explanation as to why the results are inconsistent, make it difficult to totally discard the data. However, based on the observed inconsistency with similar, but independent experiments, Experiments 9–13 are not considered to be of benchmark quality.

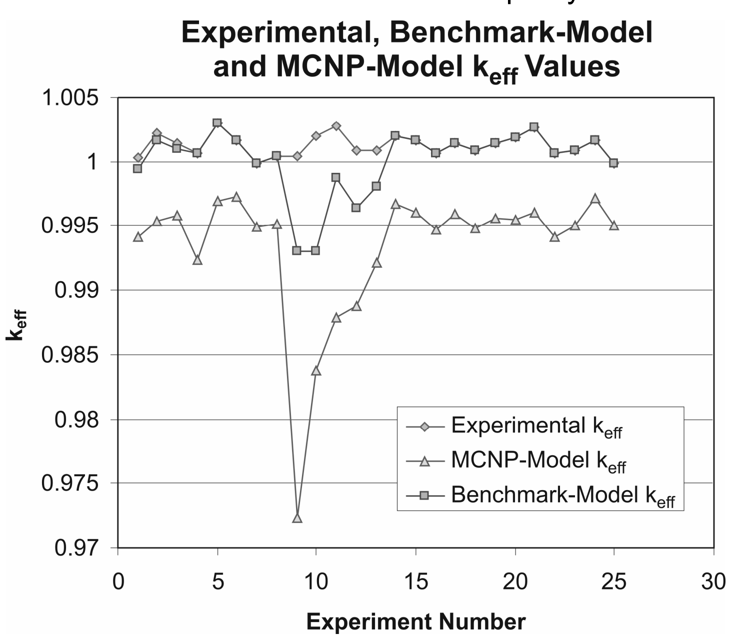

Figure 6. Comparison of experimental, benchmark-model and MCNP-Model k_{eff} value.

6. Experimental and Benchmark-Model k_{eff}

Table 23 gives both the Experimental k_{eff} and Benchmark-Model k_{eff} values with uncertainties. The Benchmark-Model k_{eff} for Experiments 1–3 includes the bias for support structure and room return. There is no bias for the other experiments since they are surrounded on all sides by thick polyethylene reflectors. Since they are not considered to be of benchmark quality, Experiments 9–13 are not included in Table 1.

Table 1. Summary of Experimental k_{eff}, MCNP-Model k_{eff} Benchmark-Model k_{eff} values and uncertainties for delayed-critical uranium (93.14 wt.% ^{235}U) metal cylinders and annuli with polyethylene thick reflector and/or moderator.

Case Number	Experiment Number	Experimental k_{eff}	MCNP (Continuous Energy ENDF/B-VI)	Benchmark-Model k_{eff} (a)
1	1	1.0003	0.9945 ± 0.0001	0.9994 ± 0.0006
2	2	1.0023	0.9952 ± 0.0001	1.0016 ± 0.0006
3	3	1.0014	0.9959 ± 0.0001	1.0010 ± 0.0005
4	4	1.0006	0.9924 ± 0.0001	1.0006 ± 0.0004
5	5	1.0030	0.9970 ± 0.0001	1.0030 ± 0.0006
6	6	1.0017	0.9973 ± 0.0001	1.0017 ± 0.0003
7	7	0.9999	0.9949 ± 0.0001	0.9999 ± 0.0004
8	8	1.0004	0.9952 ± 0.0001	1.0004 ± 0.0004
9	14	1.0020	0.9967 ± 0.0001	1.0020 ± 0.0004
10	15	1.0017	0.9962 ± 0.0001	1.0017 ± 0.0003
11	16	1.0006	0.9947 ± 0.0001	1.0006 ± 0.0006
12	17	1.0014	0.9959 ± 0.0001	1.0014 ± 0.0002
13	18	1.0009	0.9948 ± 0.0001	1.0009 ± 0.0006
14	19	1.0014	0.9956 ± 0.0001	1.0014 ± 0.0004
15	20	1.0019	0.9955 ± 0.0001	1.0019 ± 0.0005
16	21	1.0027	0.9960 ± 0.0001	1.0027 ± 0.0005
17	22	1.0006	0.9942 ± 0.0001	1.0006 ± 0.0008
18	23	1.0009	0.9950 ± 0.0001	1.0009 ± 0.0004
19	24	1.0016	0.9972 ± 0.0001	1.0016 ± 0.0003
20	25	0.9999	0.9950 ± 0.0001	0.9999 ± 0.0005

(a) The benchmark-model k_{eff} values are corrected for the effects of removing support structure and room return with uncertainties from the uncertainty analyses.

7. Acknowledgements

The authors would like to acknowledge the primary experimentalist, John T. Mihalczo of Oak Ridge National Laboratory, who provided the description of these experiments and responded to numerous questions.

This paper was prepared at Idaho National Laboratory (INL) for the United States Department of Energy under Contract Number (DE-AC07-05ID14517). Accordingly, the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for U.S. Government purposes.

8. References

1. 1.J. T. Mihalczo, “Monte Carlo Calculations of Two Core Delayed Critical Assemblies,” Trans. *Am. Nucl. Soc*. 11, 603 (1968).

2. J. T. Mihalczo, “Graphite and Polyethylene Reflected Uranium-Metal Cylinders and Annuli,” Union Carbide Corporation Nuclear Division, Oak Ridge Y-12 Plant, Y-DR-81 (1972).

3. John T. Mihalczo, “Critical Experiments with Uranium (93.14) Metal Annuli and Cylinders with Thick Polyethylene Reflectors and/or Internal Polyethylene Moderator,” ORNL/TM-2005/173 (2006).

4. *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA/NSC/DOC(95)03/I-IX, Organization for Economic Co-operation and Development–-Nuclear Energy Agency (OECD-NEA), September 2006 Edition.