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Benchmarking of HEU Mental Annuli Critical Assemblies with Internally Reflected Graphite Cylinder

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Three experimental configurations of critical assemblies, performed in 1963 at the Oak Ridge Critical Experiment Facility, which are assembled using three different diameter HEU annuli (15-9 inches, 15-7 inches and 13-7 inches) metal annuli with internally reflected graphite cylinder are evaluated and benchmarked. The experimental uncertainties which are 0.00057, 0.00058 and 0.00057 respectively, and biases to the benchmark models which are -0.00286, -0.00242 and -0.00168 respectively, were determined, and the experimental benchmark k_{eff} results were obtained for both detailed and simplified model. The calculation results for both detailed and simplified models using MCNP6-1.0 and ENDF VII.1 agree well to the benchmark experimental results within difference less than 0.2% and accepted for inclusion of ICSBEP Handbook.

I. INTRODUCTION

¹An extensive series of delayed critical experiments were performed at the Oak Ridge Critical Experiments Facility (ORCEF), using high enriched uranium (HEU) metal during the 1960s and 1970s in support of criticality safety operations at the Y-12 Plant. These experiments were designed to evaluate the storage, casting, and handling limits of the Y-12 Plant and to provide data for the verification of cross sections and calculation methods utilized in nuclear criticality safety applications.

Many of these experiments have already been evaluated and included in the International Handbook of Evaluated Criticality Safety Benchmark Experiments (ICSBEP Handbook ¹): unreflected cylinder (HEUMET-FAST-051), 1 and 2 inch-thick graphite-reflected (HEU-MET-FAST-071), polyethylene-reflected (HEU-MET-FAST-076), and beryllium-reflected ² (HEU-MET-FAST-059 and HEU-MET-FAST-069), and one case of HEU metal annuli surrounding potassium-filled, stainless steel cans was included in IRPhEP Handbook ³ (ORCEF-SPACE-EXP-001).

In this paper another three experimental configurations of critical assemblies, which are internal graphite reflected metal uranium assemblies with three different diameter HEU annuli (15-9 inches, 15-7 inches and 13-7 inches) are taken to evaluate the experimental uncertainty and bias, and to benchmark the detailed and simple model for further inclusion of ICSBEP Handbook¹. These experiments can be found in Reference 4 and in their associated logbook⁵.

Firstly, the experimental uncertainties were analyzed, then the experimental biases were determined, at last the

benchmark models were developed for both detailed and simple configurations. The calculation results agree to the benchmark experimental results within difference less than 0.2% (equivalently less than 3 times of experimental 1σ uncertainty). These three critical configurations were accepted for inclusion of ICSBEP Handbook.

II. EVALUATION OF UNCERTAINTIES AND BIASES

A. Descriptions of Assemblies

These experiments were performed on a vertical assembly machine previously described by Rohrer et al⁶. The assemblies were coaxial high enriched uranium metal (HEU) annuli with outside diameters varying in two-inch steps from 11 to 15 inches and the inside diameters varying in two-inches steps from 7 to 9 inches, and had only internal graphite cylinder without reflector.

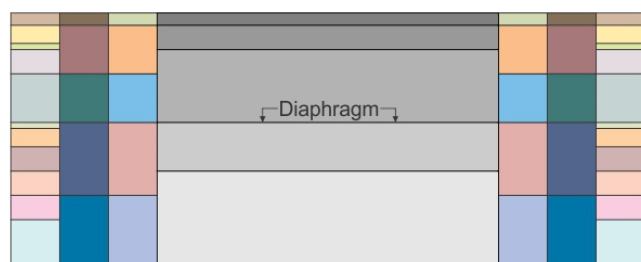


Figure 1 Sketch map for case 1
(Grey color refers to graphite cylinder)

Each assembly comprised of two sections: lower and upper section, of which the lower one was supported on a

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low-mass support stand and the upper section was mounted on a 0.010-inch-thick stainless steel diaphragm. The lower section was raised until it made contact with the diaphragm and actually slightly lifted the upper section of material mounted on the diaphragm and then the reactivity was measured. The sketch map of vertical cross-section view for case 1 is shown in Figure 1.

The basic information and measured reactivity for the three cases was summarized in Table 1.

Table 1 Basic information of Assemblies

Case	Nominal Dimensions (in.)			Internal Material	Reactivity (cents) ^a
	OD	ID	Height		
1	15	9	5 5/16	graphite	-11.5
2	15	7	4 1/16	graphite	-24.7
3	13	7	5 1/4	graphite	+15.6

(a) Measured reactivity values are for the assembled experiment corrected for support structure. These values can be converted to k_{eff} by using an effective delayed-neutron fraction of 0.0066.

B. Experimental Uncertainty Analysis

Uncertainties are evaluated using two approaches. Measured data are used where sufficient experimental information is available to analyze the uncertainties. Where experimental data are not available, Monte Carlo calculations were performed using the Monte Carlo N-Particle (MCNP) versions 6.1.0⁷ and ENDF/B-VII.1⁸ neutron cross section libraries.

For the last approach the bounding uncertainties and 1σ uncertainties for each of parameter were determined, and then the perturbations were introduced into MCNP model to calculate the uncertainties respectively. When the change in k_{eff} between the base case and the perturbed model (single-sided perturbation), or two perturbed models (double-sided perturbation directly comparing an upper and a lower perturbation from the base case), is less than the statistical uncertainty of the Monte Carlo results, the changes in the variable are amplified by scaling factor (SF), if possible. The resulting calculated change is then scaled to a value corresponding to the given uncertainty divided by SF, assuming linearity, which should be adequate for these small changes in k_{eff} . For double-sided perturbation with scaling factor, this method is equated as following:

$$\Delta k_{\text{eff}}(1\sigma) = \frac{|\Delta k_{\text{upper}} - \Delta k_{\text{lower}}|}{2 \times SF} \quad (1)$$

Sometimes, to find the effect of one kind of parameter on the k_{eff} value (which is assumed to be negligible based on evaluator experience), this parameter from several similar parts was perturbed simultaneously and the combination of the uncertainty should be decoded for accounting for this

circumstance. This is the case such as diameter, mass of HEU annuli parts for the all three configurations.

The uncertainty from experiment, dimensions and displacement, mass, isotopic content and impurities are evaluated respectively and all the uncertainties for the three cases are summarized in Table 2.

Table 2 Experimental Uncertainty

Perturbed Parameter	Δk_{eff}		
	Case 1	Case 2	Case 3
Temperature (K)	0.00004	0.00004	0.00004
Reproducibility (φ)	0.00013	0.00013	0.00013
Measured reactivity (φ)	0.00046	0.00046	0.00046
β_{eff}	0.00005	0.00005	0.00005
HEU stack height (cm) ^a	0.00003	0.00003	0.00003
²³⁴ U content (wt.%)	0.00003	0.00004	0.00003
²³⁵ U content (wt.%)	0.00019	0.00019	0.00019
²³⁶ U content (wt.%)	NEG ^b	0.00003	NEG
Uranium impurities (ppm)	0.00025	0.00025	0.00022
Graphite impurities (ppm)	NEG	0.00004	NEG
Graphite arrangement	N/A	N/A	0.00006
Total			
Experimental Uncertainty	0.00057	0.00058	0.00057

(a) The uncertainty contribution from any other factors in dimensions, mass, alignment and gaps are negligible.
(b) $\Delta k_{\text{eff}} < 0.00003$ are reported as negligible (neg).

The total experimental uncertainties for the three configurations are 0.00057, 0.00058 and 0.00057 respectively, in which the uncertainty from experiment itself accounts for most (more than 70%) contributions, otherwise the uncertainty from dimensions and mass accounts for almost negligible contribution due to high accurate manufacturing process and measuring.

C. Experimental Bias Analysis

Bias analysis included the effect of room return and air, temperature, the bias of removing the support structures, homogenization of the HEU annuli and graphite cylinder, and the removal of material impurities.

The same to uncertainty analysis, biases are also evaluated using two approaches. Measured data are used where sufficient experimental information is available to determine the correction. Where experimental data are not available, Monte Carlo calculations were performed using MCNP6.1.0 and ENDF/B-VII.1 neutron cross section libraries by comparing the benchmark models to a model with no simplifications.

Results of all the biases for both the detailed and simplified benchmark model are summarized in Table 3.

Table 3 Experimental Bias

Bias/Correction	Δk_{eff}		
	Case 1	Case 2	Case 3
1. Room Return and Air	-0.00117	-0.00125	-0.00094
2. Removal of Stainless Steel Diaphragm	0.00068	0.00108	0.00077
3. Removal of Diaphragm Support Ring	-0.00042	-0.00038	-0.00032
4. Removal of Support Structure	-0.00088	-0.00133	-0.00065
5. Temperature	NEG	NEG	NEG
6. Homogenization of Graphite Cylinder	-0.00035	-0.00003	-0.00015
7. Removal of Graphite Impurities	-0.00002	-0.00007	0.00000
8. Homogenization of HEU Annuli	-0.00070	-0.00043	-0.00039
9. Removal of HEU Impurities	0.00000	0.00000	0.00000
Total Bias			
for Detailed Model ^a	-0.00179	-0.00189	-0.00114
for Simplified Model ^b	-0.00286	-0.00286	-0.00286

(a) Bias is the arithmetic sum of Items 1 through 5; bias uncertainty is 0.00006 for all the three cases.
 (b) Bias is the arithmetic sum of Items 1 through 9; bias uncertainty is 0.00013 for all the three cases.

III. BENCHMARK RESULTS

The experiment benchmark k_{eff} for both detailed and simplified model can be obtained through the above uncertainty and bias analysis and the results are provided in Table 4.

Table 4 Experiment Benchmark Results

Case	Detailed Model			Simplified Model		
	k_{eff}	\pm	σ	k_{eff}	\pm	σ
1	0.9981	\pm	0.0006	0.9970	\pm	0.0006
2	0.9971	\pm	0.0006	0.9966	\pm	0.0006
3	1.0001	\pm	0.0006	0.9995	\pm	0.0006

Table 5 Calculation Results

Case	Calculation of Model		(C-E)/E %	
	Detailed	Simplified	Detailed	Simplified
1	0.9970 \pm 0.0006	0.99784 \pm 0.00004	-0.08	0.08
2	0.9966 \pm 0.0006	0.99619 \pm 0.00004	-0.08	-0.04
3	0.9995 \pm 0.0006	0.99911 \pm 0.00004	-0.12	-0.04

The calculated results for both detailed and simplified benchmark models, using MCNP6-1.0 and ENDF/B-VII.1 neutron cross section libraries, are summarized in Table 5, which agree well to the benchmark experimental results within difference less than 0.2% (equivalently less than 3

times of experimental 1σ uncertainty) and accepted for inclusion of ICSBEP Handbook.

IV. CONCLUSIONS

Three experimental configurations of critical assemblies, HEU annuli (15-9 inches, 15-7 inches and 13-7 inches) metal annuli with internally reflected graphite cylinder, are evaluated and benchmarked. The experimental uncertainties and biases were determined, and the experimental benchmark k_{eff} results were obtained for both detailed and simplified model.

The calculation results for both detailed and simplified models using MCNP6-1.0 and ENDF VII.1 agree well to the benchmark experimental results within difference less than 0.2%. The three configurations are accepted for inclusion of ICSBEP Handbook.

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