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AN IMPROVED BENCHMARK MODEL FOR THE BIG TEN CRITICAL ASSEMBLY

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ABSTRACT

A new benchmark specification is developed for the BIG TEN uranium critical assembly. The assembly has a fast spectrum, and its core contains approximately 10 wt.% enriched uranium. Detailed specifications for the benchmark are provided, and results from the MCNP5 Monte Carlo code using a variety of nuclear-data libraries are given for this benchmark and two others.

Key Words: BIG TEN, benchmark, MCNP, nuclear data

1. INTRODUCTION

The BIG TEN critical assembly [1] was constructed and operated at the Los Alamos Critical Experiments Facility at Los Alamos National Laboratory in the 1970s. It was designed to allow measurements of nuclear data in a spectrum reasonably representative of a liquid-metal fast breeder reactor. Its name reflects the fact that it was both massive (10 metric tons) and had a core with an average enrichment of approximately 10 wt.%.

A picture taken during the construction of the BIG TEN assembly is shown in Fig. 1. As the picture indicates, the assembly was divided into two subassemblies, each in its own steel cradle, on a split-table machine. One of the cradles was stationary, and the other was movable. Criticality was obtained by bringing the two subassemblies into contact.

The BIG TEN assembly is significant both for the spectrum it produced and the fact that its core contained intermediate enriched uranium. The assembly was formed by a stack of concentric uranium metal plates arranged in the form of a cylinder. The individual plates were made from highly enriched uranium (HEU), 10 wt.% (nominal) enriched uranium, natural uranium, or depleted uranium. The experiment was conducted at ambient temperatures.

Both the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* and the *Cross Section Evaluation Working Group Benchmark Specifications* contain multiple benchmark specifications for BIG TEN [2,3]. However, none of those benchmarks is entirely satisfactory. The two CSEWG benchmarks are nearly 40 years old and contain substantial unquantified simplifications: a sphere of 10 wt.% enriched uranium inside a spherical depleted

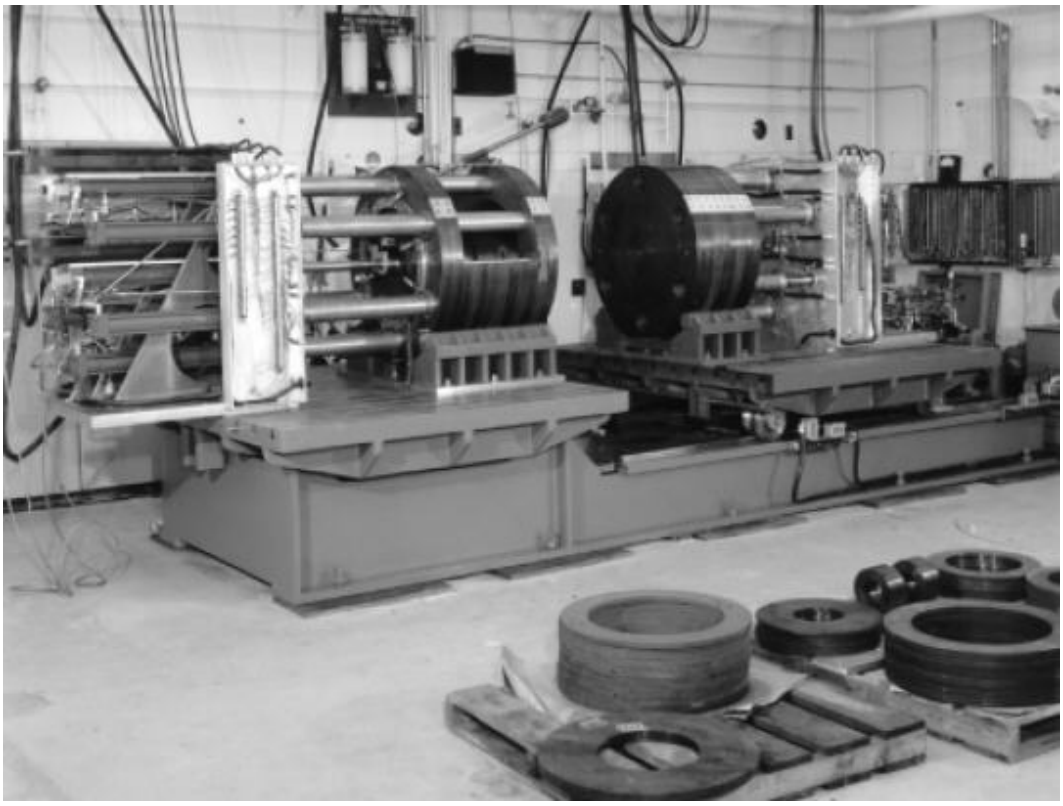

Figure 1. BIG TEN during Its Construction

U reflector, and a cylinder of 10 wt.% enriched uranium inside a cylindrical depleted U reflector. Two of the *Handbook* benchmarks, labeled "detailed" and "simplified," are fairly complicated and very similar (the only difference is that the "detailed" model explicitly retains six control rods in the depleted U reflector, while the "simplified" model homogenizes them within a ring in the reflector). The third benchmark in the *Handbook*, the "two-zone" model,[a] is very similar to the cylindrical CSEWG benchmark. However, its benchmark value for k_{eff} differs from the reference value for the experiment by more than 1% Δk. Biases of this magnitude are quite unusual for benchmark models of critical assemblies.

2. DEVELOPMENT OF THE BENCHMARK

The objective of the research described herein was to create a new benchmark specification for BIG TEN that is reasonably simple and also has a relatively small bias in its benchmark value

[a] The "two-zone" model was created by A. Tsiboulia, M. Nikolaev, and Y. Rozhikhin of the Institute of Physics and Power Engineering, Obninsk, Russia, in response to a specific request from the International Criticality Safety Evaluation Project Working Group.

for k_{eff}. The starting point for that development was the "simplified" benchmark model in the *Handbook*.

The "simplified" model is a cylinder made from concentric plates of different radii and compositions. Solid plates of approximately 10 wt.% enriched uranium but with several different outer radii form the central region of of the cylinder. Those radii range from 1.905 cm (0.75 inch) to 12.7 cm (5 inches). The middle annulus surrounds most of the central region and contains alternating plates of HEU and natural U as well as one plate of depleted U. The inner radii of these plates are the same as the outer radii of the specific 10 wt.% plates they enclose, and all of them have an outer radius of 26.67 cm (10.5 inches). The outer annulus is the depleted U reflector. It contains multiple rings of depleted U, including one into which the control rods have been homogenized. Rings of depleted U also form the top and bottom reflector regions. The outer radius of the depleted U annulus is 41.91 cm (16.5 inches), and the total length of the assembly is 96.52 cm (38 inches). The top and bottom reflectors are both 15.24 cm (6 inches) thick.

According to the *Handbook*, the reference value for k_{eff} for BIG TEN is 1.0062 ± 0.0005. The "simplified" benchmark model contains three simplifications: the transfer bar for inserting samples into the assembly is truncated (-0.0011 ± 0.0003 Δk), room return is ignored (-.0006 ± 0.0003 Δk), and the control rods are homogenized into the reflector (negligible). The benchmark value of k_{eff} for the "simplified" model therefore is 1.0045 ± 0.0007.

A representation for the "simplified" model of BIG TEN first was constructed using the MCNP5 Monte Carlo code [4] and its associated ENDF70 nuclear-data library that is derived from ENDF/B-VII.0 [5]. A calculation with this representation produces a value of 1.0044 ± 0.0002 for k_{eff}, which is in excellent agreement with the benchmark value.

A series of modifications then was made to simplify that representation. Many of the modifications produce only negligible changes in k_{eff}. The modifications that produce changes whose magnitudes are 0.0003 Δk or larger are summarized in Table I, along with the modifications already embodied in the "simplified" model. The calculations were performed in sequential order, with each step retaining all the previous modifications. This approach permits the reactivity impact of each modification to be determined, and it also allows the cumulative reactivity effect of all of them to be ascertained by direct comparison to the "simplified" benchmark model. This approach has the added advantages that it requires no assumptions about the mutual independence of individual modifications and that the standard deviations for each modification do not need to be compounded to produce the final standard deviation. Instead, the net reactivity change due to all of the modeling simplifications that have been introduced can be computed directly from the results for just the "simplified" and improved benchmark models.

The first significant modification is the conversion of the annular ring in the reflector to the same composition as the rest of the reflector. That ring resulted from the homogenization of the

Table I. Reactivity Impact of Simplifications for the Improved Benchmark Model

Simplification	Change in k_{eff}	
	Incremental	Cumulative
Omission of Room Return	-0.0006 ± 0.0003	-0.0006 ± 0.0003
Truncation of Transfer Bar	-0.0011 ± 0.0003	-0.0017 ± 0.0003
Conversion of DU Annulus with Homogenized Control Rods to DU	0.0005 ± 0.0003	-0.0012 ± 0.0003
Replacement of Inner DU Plate by Natural U Plate	0.0009 ± 0.0003	-0.0003 ± 0.0003
Conversion of 10 wt.% U Plates to 4 Stacked Cylinders	0.0010 ± 0.0004	0.0007 ± 0.0003
Homogenization of HEU Plates, NU Plates, and Voids	-0.0020 ± 0.0003	-0.0013 ± 0.0003

control rods in the "simplified" model. This change produces a uniform outer reflector annulus of depleted U. As Table I indicates, that conversion produces only a minor change in k_{eff}.

The second significant modification replaces the single depleted U plate in the middle annulus with an natural U plate with the same dimensions. This change produces a middle annulus comprised entirely of alternating plates of HEU and natural U, with very small gaps between some of them. This modification increases k_{eff} slightly.

The third significant modification combines adjacent 10 wt.% uranium plates with the same outer radius into solid cylinders. In addition, some cylinders are combined so that, in the end, only four cylinders remain. The total mass of the plates was conserved during this process, and it produces only a small increase in k_{eff}.

The last modification homogenizes most of the HEU and natural U plates in the middle annulus, along with any gaps between them, into a single region. The intent of the designers of BIG TEN was that the combination of HEU and natural U plates should simulate a region with an enrichment of approximately10 wt.%. Initially, all of the HEU plates were included in that homogenization, as well as the natural U plates between them. To obtain the desired enrichment of approximately 10 wt.%, however, it was necessary to include portions of the large natural U plates at the ends of the middle annulus in the homogenized region. Consequently, the outer portions of those two natural U plates remain as separate regions in the improved benchmark

model. This modification produces a negative change in k_{eff} that is still small but does have a magnitude larger than any of the other changes.

The final geometry of the improved benchmark model is compared with those of the "simplified" and "two-zone" models in Fig. 2, and the characteristics of the three models are compared in Table II. The calculated results in Table II were obtained with MCNP5 and its associated ENDF70 nuclear-data library. As an indication of the level of simplification achieved, the MCNP representation for the improved model uses 11 cells, 14 surfaces, and 4 compositions, while the "simplified" model uses 85 cells, 84 surfaces, and 7 compositions.

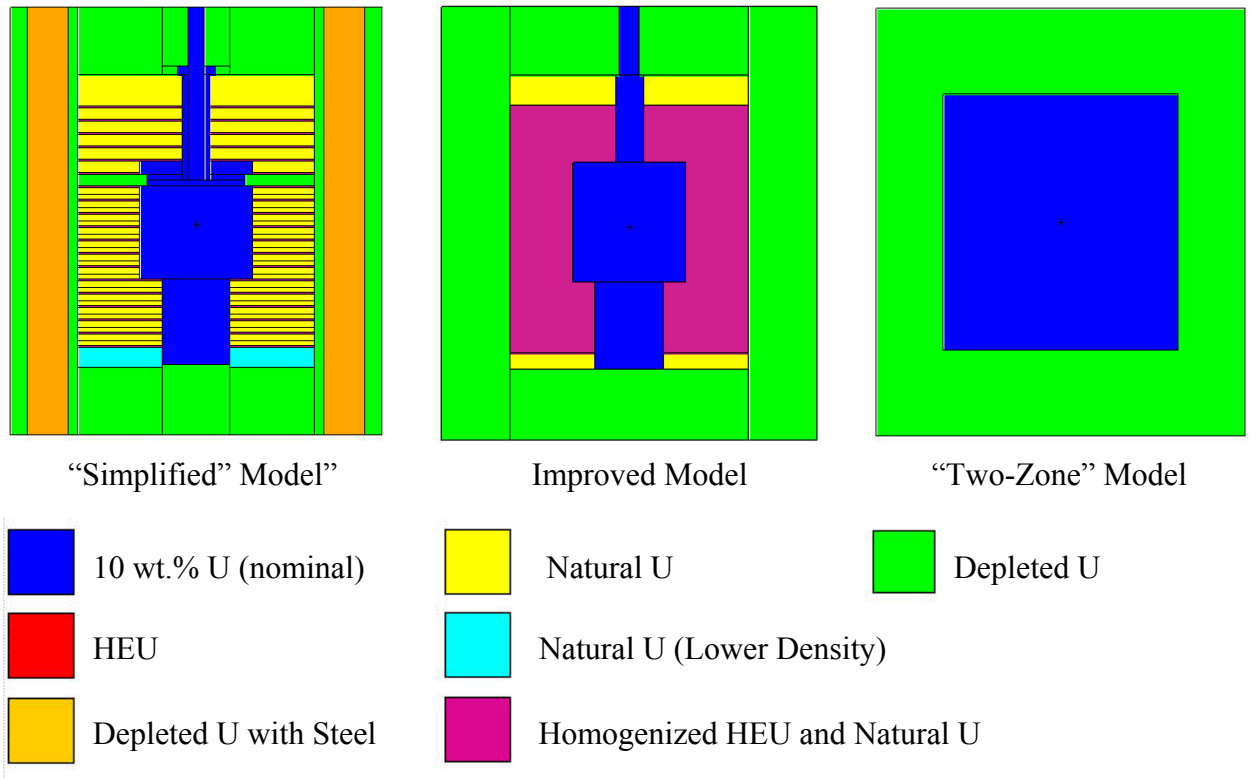

Figure 2. Vertical Slices through the Centers of Benchmark Models for BIG TEN

3. BENCHMARK SPECIFICATIONS

The dimensions of the nominally 10 wt.% central cylinders, the homogenized HEU and natural U cylinders, the two natural U cylinders, and the depleted U reflector are given in Tables III through VI, respectively. The origin of the coordinate system is at the center of the face where

the two physical subassemblies come into contact, which is the same as for the "simplified" benchmark .

Table II. Comparison of Benchmark Models for BIG TEN

Parameter		Benchmark Model		
		"Simplified"	Improved	"Two-Zone"
Benchmark k_{eff}		1.0045 ± 0.0007	1.0049 ± 0.0008	0.9948 ± 0.0013
Bias in Benchmark k_{eff}		-0.0017 ± 0.0005	-0.0013 ± 0.0006	-0.0114 ± 0.0012
External Neutron Leakage (%)		10.82	10.75	10.84
Fission Fraction, by Energy Range	Fast	0.8018	0.7988	0.7981
	Intermediate	0.1982	0.2012	0.2019
	Thermal	0.0	0.0	0.0
Fission Fraction, by Isotope	^{234}U	0.0022	0.0020	0.0021
	^{235}U	0.7439	0.7390	0.7360
	^{236}U	0.0003	0.0002	0.0002
	^{238}U	0.2536	0.2588	0.2617
Average Number of Neutrons Produced per Fission		2.567	2.565	2.566

Table III. Dimensions for the Central Cylinders

Region	Bottom (cm)	Top (cm)	Outer Radius (cm)
Top Cylinder	23.81250	39.05250	2.25014
Upper Middle Cylinder	4.35102	23.81250	3.10996
Lower Middle Cylinder	-22.39010	4.35102	12.54604
Bottom Cylinder	-41.73361	-22.39010	7.62000

Table IV. Dimensions for the Homogenized HEU and Natural U Cylinders

Region	Bottom (cm)	Top(cm)	Inner Radius (cm)	Outer Radius (cm)
Top Cylinder	4.35102	17.16665	3.10996	26.67000
Middle Cylinder	-22.39010	4.35102	12.54604	26.67000
Bottom Cylinder	-38.24644	-22.39010	7.62000	26.67000

Table V. Dimensions for the Natural U Cylinders

Region	Bottom (cm)	Top(cm)	Inner Radius (cm)	Outer Radius (cm)
Top Cylinder	17.16665	23.81250	3.10996	26.67000
Bottom Cylinder	-41.73361	-38.24644	7.62000	26.67000

Table VI. Dimensions for the Depleted U Reflector

Region	Bottom (cm)	Top(cm)	Inner Radius (cm)	Outer Radius (cm)
Top Cylinder	23.81250	39.05250	2.25014	41.91000
Middle Cylinder	-41.73361	23.81250	26.67000	41.91000
Bottom Cylinder	-57.46750	-41.73361	—	41.91000

The characteristics of the four materials are given in Table VII, and their isotopic compositions are given in Table VIII. It should perhaps be noted that both the nominally 10 wt.% enriched U and the homogenized HEU and natural U have enrichments that are slightly higher than 10 wt.%.

4. CALCULATED RESULTS FOR THE BENCHMARK MODELS

MCNP5 calculations were performed for the "simplified," "two-zone," and improved benchmark models using nuclear data derived from the ENDF/B-VII.0, ENDF/B-VI, JEFF-3.1 [6], and JENDL-3.3 [7] nuclear data libraries. As previously noted, the ENDF70 library that is part of the MCNP5 distribution was used for the ENDF/B-VII.0 data. Similarly, the ENDF66 [8] library that also is part of the MCNP5 distribution was used for the ENDF/B-VI data. Although

Table VII. Characteristics of the Materials

Material	Density (g/cm^3)	Enrichment (wt.%)
Nominal 10 wt.% Enriched U	18.795	10.063
Homogenized HEU and Natural U	19.012	10.230
Natural U	19.050	0.711
Depleted U	18.886	0.208

Table VIII. Isotopic Compositions of the Materials

Material	Isotope	Number Density (atoms/b-cm)
Nominal 10 wt.% Enriched U	^{234}U	2.4761×10^{-5}
	^{235}U	4.8461×10^{-3}
	^{236}U	4.3348×10^{-5}
	^{238}U	4.2695×10^{-2}
Homogenized HEU and Natural U	^{234}U	5.4058×10^{-5}
	^{235}U	4.9831×10^{-3}
	^{236}U	1.3733×10^{-5}
	^{238}U	4.3108×10^{-2}
Natural U	^{234}U	2.6518×10^{-6}
	^{235}U	3.4701×10^{-4}
	^{238}U	4.7846×10^{-2}
Depleted U	^{234}U	2.8672×10^{-7}
	^{235}U	1.0058×10^{-4}
	^{236}U	1.1468×10^{-6}
	^{238}U	4.7677×10^{-2}

ENDF66 is derived from the interim ENDF/B-VI.6 release of ENDF/B-VI, the ENDF/B-VI data for the uranium isotopes remained unchanged beyond that release.

The results obtained are presented in Table IX. Data at room temperature (293 to 300 K, depending on the library) were used for the calculations. The results from a given nuclear- data library depart from the benchmark value for k_{eff} by about the same amount, irrespective of the benchmark model. ENDF/B-VII.0 produces very close agreement with the benchmark values for k_{eff}, while ENDF/B-VI overestimates k_{eff} by more than 0.010 relative to the corresponding benchmark values. The JEFF-3.1 results are approximately 0.007 lower than the corresponding benchmark values, while the JENDL-3.3 results are about 0.010 lower than the corresponding benchmark values.

Table IX. MCNP5 Results for the BIG TEN Benchmark Models

Model		"Simplified"	Improved	"Two-Zone"
Benchmark k_{eff}		1.0045 ± 0.0007	1.0049 ± 0.0008	0.9948 ± 0.0013
Calculated k_{eff}	ENDF/B-VII.0	1.0044 ± 0.0002	1.0048 ± 0.0002	0.9948 ± 0.0002
	ENDF/B-VI	1.0165 ± 0.0002	1.0166 ± 0.0002	1.0071 ± 0.0003
	JEFF-3.1	0.9980 ± 0.0002	0.9979 ± 0.0002	0.9876 ± 0.0002
	JENDL-3.3	0.9952 ± 0.0002	0.9949 ± 0.0003	0.9851 ± 0.0002

$0.005 < |\Delta k| \leq 0.010$ $|\Delta k| > 0.010$

5. SUMMARY

An improved benchmark model for the BIG TEN critical assembly has been created. As Fig. 2 indicates, its geometry is much simpler than that of the "simplified" benchmark model and it has far fewer distinct regions and surfaces. Furthermore, as shown in Table II, it produces a benchmark value for k_{eff} that has only a small bias. Detailed specifications for the improved benchmark model are provided in Tables III through VIII.

MCNP5 calculations for the "simplified," improved, and "two-zone" benchmark models for BIG TEN were performed using data derived from the ENDF/B-VII.0, ENDF/B-VI, JEFF-3.1, and JENDL-3.3 nuclear-data libraries. The results are consistent across the three benchmark models. ENDF/B-VII.0 produces very close agreement with the benchmark values for k_{eff}, while ENDF/B-VI consistently overestimates k_{eff} by more than 0.010 relative to the corresponding

benchmark values. The JEFF-3.1 results are approximately 0.007 lower than the corresponding benchmark values, while the JENDL-3.3 results are about 0.010 lower than the corresponding benchmark values.

REFERENCES

1. J. L. Sapir, H. H. Helmick, J. D. Orndoff, "BIG TEN, A 10% Enriched Uranium Critical Assembly: Kinetics Studies," *Trans. Am. Nucl. Soc.*, **15**, p. 312 (June 1972).
2. J. L. Sapir, B. J. Krohn, "BIG TEN: A Large Mixed-Uranium-Metal Cylindrical Core with 10% Average ^{235}U Enrichment Surrounded by a Thick ^{238}U Reflector," IEU-MET-FAST-007, *International Handbook of Evaluated Criticality Safety Benchmark Experiments*, NEA/NSC/DOC(95)03 (September 2008 Edition).
3. CROSS SECTION EVALUATION WORKING GROUP, "Fast Reactor Benchmark No. 20: BIG TEN, A Reflected Cylinder of Uranium Containing10% ^{235}U," *Cross Section Evaluation Working Group Benchmark Specifications*, BNL-19302 (ENDF-202), Brookhaven National Laboratory (November 1974).
4. X-5 MONTE CARLO TEAM, "MCNP — A General Monte Carlo Particle Transport Code, Version 5," LA-UR-03-1987, Los Alamos National Laboratory (April 2003).
5. M. B. Chadwick, *et al.*, "ENDF/B-VII.0: Next Generation Evaluated Nuclear Data Library for Nuclear Science and Technology," *Nuclear Data Sheets*, **107**, pp. 2931-3059 (December 2006).
6. O. Cabellos, "Processing of the JEFF-3.1 Cross Section Library into a Continuous Energy Monte Carlo Radiation Transport and Criticality Data Library," OECD NEA Data Bank report NEA/NSC/DOC(2006)18 (May 2006).
7. K. Kosako, *et al.*, "The Libraries FSXLIB and MATXSLIB Based on JENDL-3.3," Japan Atomic Energy Research Institute report JAERI-Data/Code 2003-011 (2003).
8. J. M. Campbell, S. C. Frankle, R .C. Little, "ENDF66: A Continuous-Energy Neutron Data Library for MCNP4C,"*Proc. 12th Biennial Topl. Mtg. Radiation Protection and Shielding Div.*, Santa Fe, New Mexico, USA (April 2002).