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Title: An Expanded Criticality Validation Suite for MCNP and an Improved Benchmark Model for BIG TEN

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An Expanded Criticality Validation Suite for MCNP

and

An Improved Benchmark Model for BIG TEN

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To Be Presented at the 2010 CSEWG Meeting
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An expanded criticality validation suite has been created for the MCNP Monte Carlo code. The suite includes 119 benchmarks taken from the *International Handbook of Evaluated Criticality Safety Benchmark Experiments*. There are 119 benchmarks, which are divided into five categories of fuel – ^{233}U, highly enriched uranium (HEU), intermediate enriched uranium (IEU), low enriched uranium (LEU), and plutonium. The ^{233}U, HEU, IEU, and plutonium benchmarks are subdivided farther according to spectrum – fast, intermediate, or thermal. Each fast subcategory contains at least one unreflected metal case, one metal case reflected by uranium, one metal case reflected by a heavy reflector, and one metal case reflected by a light reflector. Each thermal subcategory contains at least one solution case and one lattice case. The LEU category contains only thermal cases, since LEU can reach criticality only with a thermal spectrum.

An improved benchmark for the BIG TEN experiment also will be described briefly. BIG TEN contains a cylindrical core enriched to ~ 10 wt.%, surrounded by an annulus of depleted uranium.

An Expanded Criticality Validation Suite for MCNP and an Improved Benchmark for BIG TEN

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Overview of Presentation

Description of the enhanced criticality validation suite for MCNP

Selected results from the expanded suite

Succinct description of an improved benchmark for BIG TEN

Background

For the past several years, the data team and the MCNP team at LANL have had separate criticality validation suites

The data team's suite includes only fast metal benchmarks and thermal solution benchmarks, most of them taken from CSWEG specifications or the *International Handbook of Evaluated Criticality Safety Benchmark Experiments*. It includes related benchmarks so that parameter studies (enrichment, reflector thickness, solution content, etc.) can be performed

The MCNP team's suite includes a wider variety of benchmarks, all taken from the *Handbook*, but it does not permit parameter studies

The objective for the expanded criticality benchmark suite is to consolidate the two suites, eliminate repitition and inconsistencies, and to add benchmarks that fill in gaps in nuclear data that neither suite addresses

Expanded Criticality Validation Suite for MCNP

Principal Fuel	Number of Benchmarks by Spectrum			
	Fast	Intermediate	Thermal	Total
^{233}U	10	1	7	18
HEU	29	5	6	40
IEU	10	1	6	17
LEU			8	8
Plutonium	21	1	14	36
Total	70	8	41	119

All benchmark specifications are taken from the *International Handbook of Evaluated Criticality Safety Benchmark Experiments*

Categorizations

Uranium

HEU: Enrichment $\geq$ 60 wt.%
IEU: Enrichment between 5 wt.% and 60 wt.%
LEU: Enrichment $\leq$ 5 wt.%

Spectrum

Fast: Majority of fissions caused by neutrons with energies $\geq$100 keV
Intermediate: Majority of fissions caused by neutrons with energies between 0.625 eV and 100 keV
Thermal: Majority of fissions caused by neutrons with energies $\leq$ 0.625 eV

Overlap with Other Criticality Benchmark Sets

Fast benchmarks include ICSBEP specifications for 9 CSEWG fast benchmarks:

Jezebel, Jezebel-240, Jezebel-233, Godiva, BIG TEN, THOR, Flattop-Pu, Flattop-23, and Flattop-25

Thermal benchmarks include ICSBEP specifications for 19 CSEWG thermal benchmarks:

ORNL-1 through ORNL-4, ORNL-10, PNL-1, PNL-3 through PNL-6, PNL-11, PNL-12, PNL-30 through PNL-35, and HISS/HPG*

Suite contains 35 benchmarks that were studied by Steven van der Marck in his article, “Benchmarking ENDF/B-VII.0,” in the December 2006 issue of *Nuclear Data Sheets*

* Proposed but not yet accepted; epithermal spectrum

Fast Benchmarks

Principal Fuel	Number of Benchmarks by Reflector				
	None	Uranium	Heavy	Light	Total
^{233}U	1	5	2	2	10
HEU	4	9	5	11	29
IEU	5	2	2	1	10
Plutonium	4	5	5	7	21
Total	14	21	14	21	70

Uranium: HEU, normal uranium, or depleted uranium
Heavy: Aluminum, duralumin, steel, nickel, tungsten, or thorium
Light: Water, polyethylene, paraffin, beryllium, beryllium oxide, graphite, or tungsten carbide

Thermal Benchmarks

Principal Fuel	Number of Benchmarks		
	Lattice	Solution	Total
^{233}U	1	6	7
HEU	1	5	6
IEU	1	5	6
LEU	6	2	8
Plutonium	6	8	14
Total	15	26	41

Results for Metal Spheres Reflected by Tungsten or Tungsten Carbide

Fuel	Fuel Radius (cm)	Reflector Thickness (cm)	k_{eff}		
			Benchmark	ENDF/B-VII.0	ENDF/B-VI
^{233}U	5.0444	2.4384	1.0000 ± 0.0007	1.0051± 0.0003	1.0017 ± 0.0003
^{233}U	4.5999	5.7912	1.0000 ± 0.0008	1.0051± 0.0003	1.0040 ± 0.0003
HEU	6.6020	4.8260*	1.0000 ± 0.0050	1.0081± 0.0003	1.0048 ± 0.0003
HEU	6.2527	7.3660*	1.0000 ± 0.0050	1.0095 ± 0.0003	1.0063 ± 0.0003
HEU	6.0509	11.4300*	1.0000 ± 0.0050	1.0129 ± 0.0003	1.0093 ± 0.0003
HEU	6.0159	16.5100*	1.0000 ± 0.0050	1.0166 ± 0.0003	1.0136 ± 0.0003
Pu	5.0419	4.6990	1.0000 ± 0.0013	1.0092 ± 0.0003	1.0078 ± 0.0003

* Tungsten carbide reflector

Results for Metal Spheres Reflected by Graphite

Fuel	Fuel Radius (cm)	Reflector Thickness (cm)	k_{eff}		
			Benchmark	ENDF/B-VII.0	ENDF/B-VI
HEU	9.15*	3.45	1.0000 ± 0.0028	1.0074 ± 0.0003	1.0031 ± 0.0003
IEU	14.00**	3.20	1.0000 ± 0.0030	1.0075 ± 0.0003	1.0040 ± 0.0003
Pu	6.00***	5.65	1.0020 ± 0.0020	0.9993 ± 0.0003	0.9976 ± 0.0003

* Inner radius 4.029 cm
** Inner radius 2.788 cm
*** Inner radius 1.715 cm

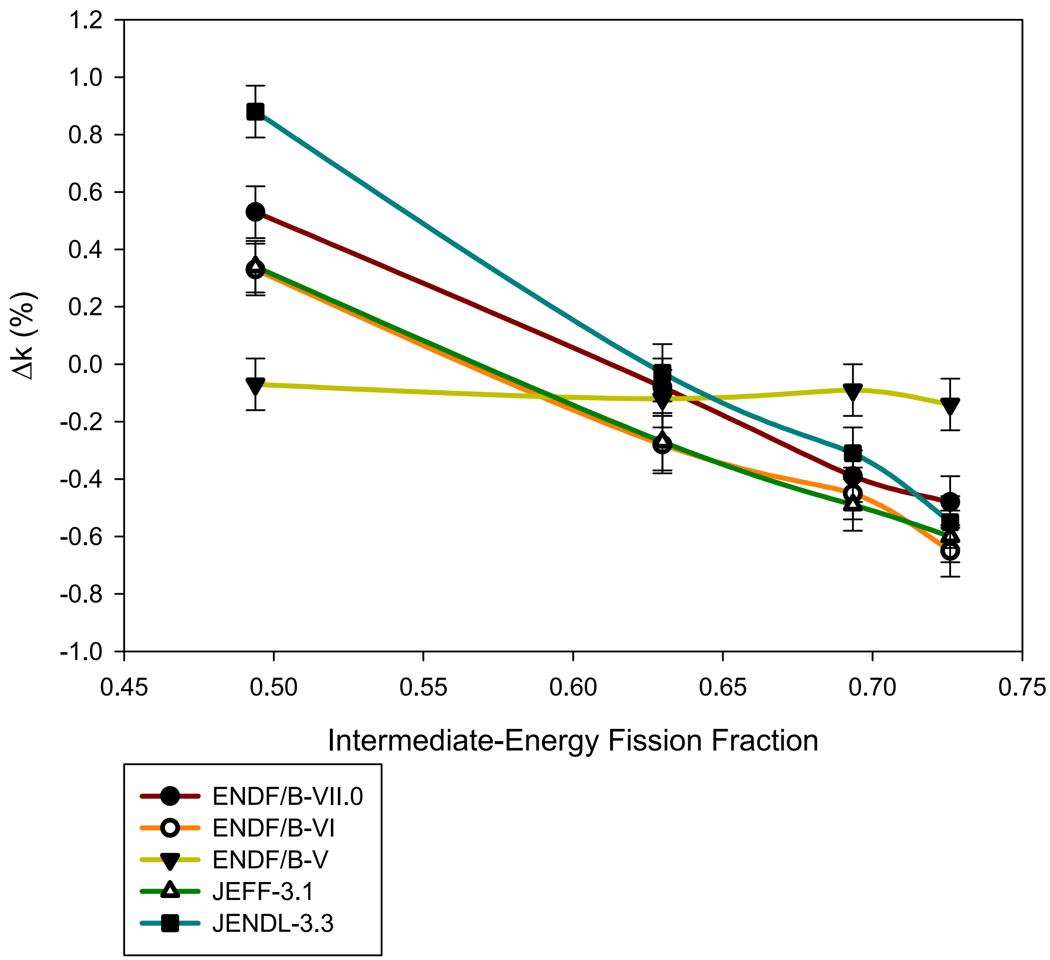
Results for Metal Spheres Reflected by Beryllium or Beryllium Oxide

Fuel	Fuel Radius (cm)	Reflector Thickness (cm)	k_{eff}		
			Benchmark	ENDF/B-VII.0	ENDF/B-VI
^{233}U	5.0444	2.0447	1.0000 ± 0.0030	0.9944 ± 0.0003	0.9950 ± 0.0003
^{233}U	4.5999	4.1961	1.0000 ± 0.0030	0.9925 ± 0.0003	0.9967 ± 0.0003
HEU	8.3500	2.6500	0.9992 ± 0.0015	0.9957 ± 0.0003	0.9952 ± 0.0003
HEU	8.3500*	2.6500**	0.9992 ± 0.0015	0.9955 ± 0.0003	0.9928 ± 0.0003
Pu	5.0419	3.6881	1.0000 ± 0.0030	0.9965 ± 0.0003	0.9990 ± 0.0003
Pu	5.3500*	5.6500	0.9992 ± 0.0015	0.9975 ± 0.0003	1.0011 ± 0.0003

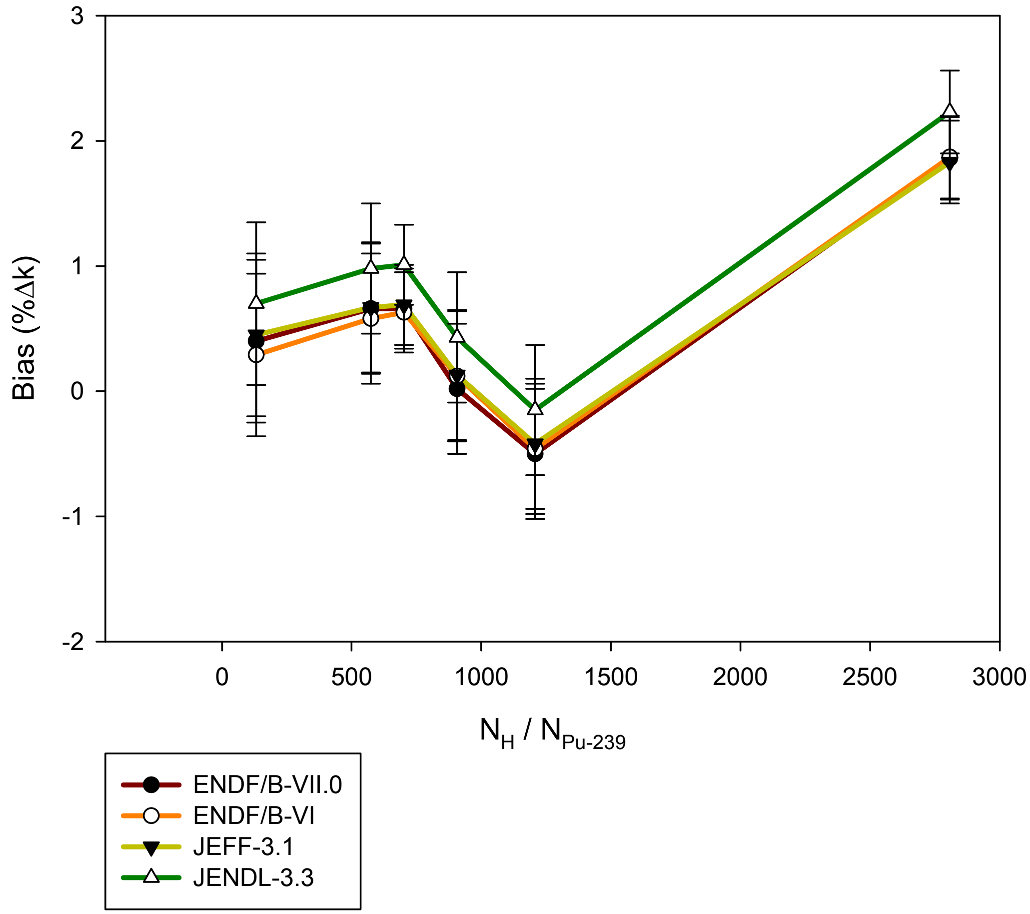
* Inner radius 1.4 cm

** Beryllium oxide reflector

Results for the Zeus Graphite Benchmarks



Reactivity Biases for Plutonium Solution Benchmarks



BIG TEN Critical Experiment

The BIG TEN critical assembly was constructed and operated at the Los Critical Experiments Facility at LANL in the 1970s

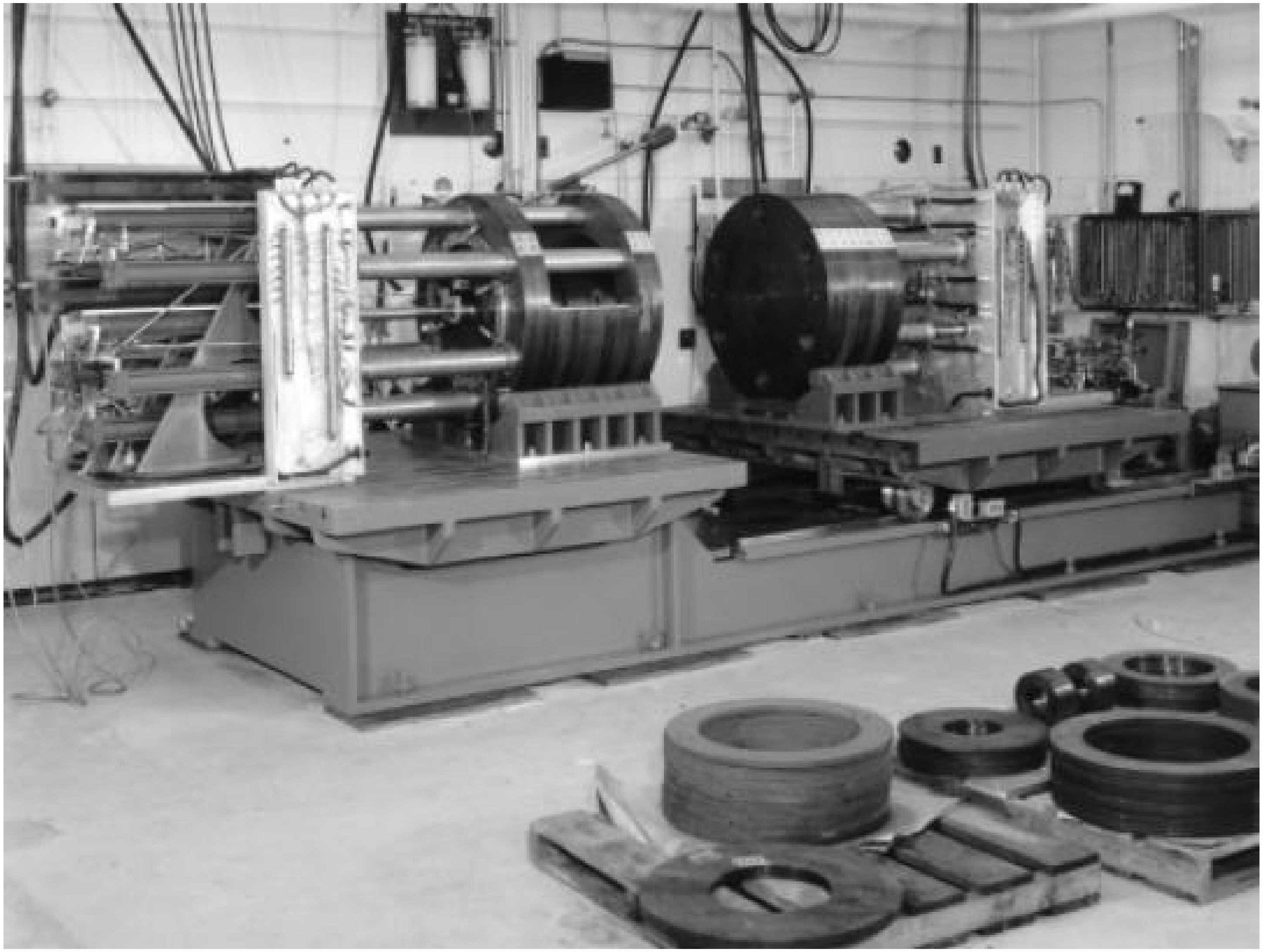
It was designed to allow measurements of nuclear data in a spectrum reasonably representative of a liquid-metal fast breeder reactor

BIG TEN was so named both because it was massive (~ 10 metric tons) and because its core contained an average enrichment of ~ 10 wt.%

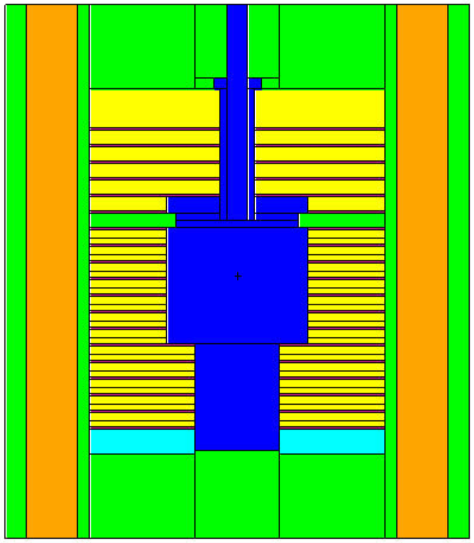
BIG TEN was reflected by an annulus of depleted uranium

Criticality was achieved by bringing the two subassemblies into contact (one of the subassemblies was mounted on rails)

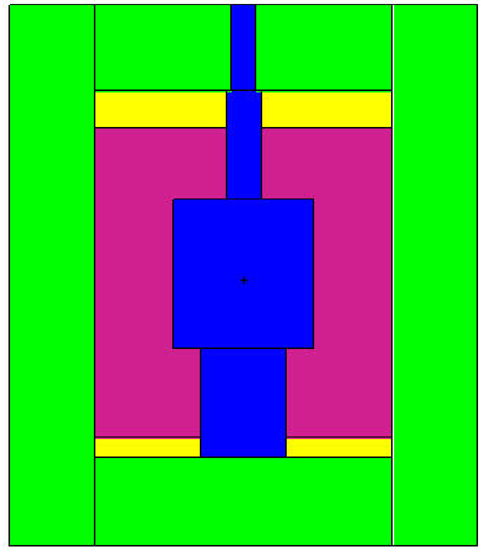
BIG TEN Assembly



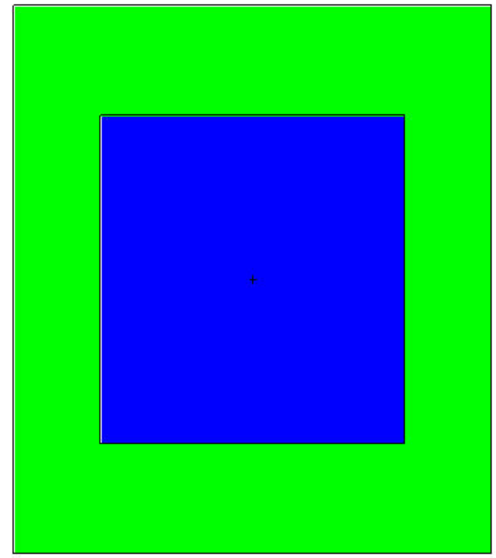
Comparison of BIG TEN Benchmark Models



"Simplified"



Improved



"Two-Zone"

- Blue: **10 wt.% U (nominal)**
- Red: **HEU**
- Orange: **Depleted U with Steel**
- Yellow: **Natural U**
- Cyan: **Natural U (Lower Density)**
- Magenta: **Homogenized HEU and Natural U**
- Green: **Depleted U**

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
Neutron leakage (%)		10.82	10.75	10.84
Fission, by Energy (%)	Fast	80.18	79.88	79.81
	Intermediate	19.82	20.12	20.19
	Thermal	0	0	0
Fission, by Isotope (%)	^{234}U	0.22	0.20	0.21
	^{235}U	74.39	73.90	73.60
	^{236}U	0.03	0.02	0.02
	^{238}U	25.36	25.88	26.17
Average Number of Neutrons per Fission		2.567	2.565	2.566

MCNP Calculations

Calculations were performed for the the three benchmark models with the MCNP5 Monte Carlo code, using ENDF/B-VII.0, ENDF/B-VI, JEFF-3.1, and JENDL-3.3 nuclear data libraries

Each calculation employed 550 generations of 10,000 neutrons each

Results from the first 50 generations were excluded from the statistics

⇒ Results for each case are based on 5,000,000 active neutron histories

MCNP5 Results for 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 ± 0.0002
	JEFF-3.1	0.9980 ± 0.0002	0.9979 ± 0.0002	0.9876 ± 0.0002
	JENDL-3.3	0.9952 ± 0.0002	0.9949 ± 0.0002	0.9851 ± 0.0002

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

ENDF/B-VII.0 produces very close agreement with the benchmark value of k_{eff} for all three models

JEFF-3.1 and JENDL-3.3 underpredict the benchmark value of k_{eff} by 0.5% to 1%, and ENDF/B-VI overpredicts it by more 1%

Summary and Conclusions

An expanded criticality validation suite has been created for MCNP

The 119 benchmarks in the expanded suite cover a broad range of fuels, spectra, and configurations

The expanded suite includes several sets of related benchmarks so that parameter studies can be conducted

One of the benchmarks in that suite is an improved benchmark model for the BIG TEN critical assembly, which will be submitted for approval by the ICSBEP at its meeting in May