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AN EXPANDED CRITICALITY VALIDATION SUITE FOR MCNP

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ABSTRACT

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*. The 119 benchmarks 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. The LEU category contains only thermal cases, since LEU can reach criticality only with a thermal spectrum. Succinct descriptions are provided for each benchmark, along with computed values for k_{eff} using nuclear data libraries based on ENDF/B-VI and ENDF/B-VII.0.

Key Words: MCNP, validation, suite, criticality, benchmarks

1 INTRODUCTION

Criticality safety practitioners are required to validate the computational tools they use. Validation of a computer code typically involves analyzing a set of benchmarks that cover the intended range of applicability and then assessing the accuracy of the computed results against the corresponding benchmark values. Computer code developers are faced with validation requirements to demonstrate that their code performs adequately for an even wider variety of applications.

The acceptability of a computer code usually is discussed in terms of verification and validation. Verification assesses the fidelity of the code to the theoretical models upon which it is based. It typically involves comparisons of computed results with closed-form analytic solutions or with reference results from a previously verified code. Validation assesses the accuracy with which the code predicts real-world behavior. It usually involves comparisons of computed results with real-world measurements, such as those from critical experiments or operating reactors. While developers can thoroughly verify their codes, validation is more problematic because of the wide range of potential applications and the variety of code options. Validation performed by code developers must necessarily be general, involving suites of benchmarks chosen to broadly represent and span the extent of anticipated applications.

The MCNP code developers have assembled more than a dozen verification and validation suites for testing general classes of problems, including installation, shielding, electrons, photons, variance reduction, reactor kinetics, and criticality. These suites provide a general indication of the overall performance of the code in conjunction with one or more specific nuclear data libraries. Furthermore, they can provide warnings of unexpected or unintended consequences that result from changes to nuclear data or to the code itself.

2 PREVIOUS MCNP CRITICALITY VALIDATION SUITES

Two criticality validation suites for the MCNP Monte Carlo code [1] have been used at Los Alamos National Laboratory (LANL) for nearly a decade. Those criticality validation suites were created by the nuclear data team and the Monte Carlo team. However, there is some overlap between them as well as some inconsistencies. In addition, neither of them adequately addresses certain areas of nuclear data. Consequently, an expanded criticality validation suite has been created that incorporates many of the benchmarks in those two suites, eliminates overlaps, resolves inconsistencies, and fills some of the gaps that neither of them addresses.

The nuclear data team's suite [2, 3] initially included 86 separate benchmarks but eventually expanded to 93 benchmarks. The suite is used primarily for nuclear data testing. Nearly all of the benchmarks in that suite are taken from the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* [4] or from the Cross Section Evaluation Working Group (CSEWG) benchmark book [5]. They include several sets of related benchmarks so that the effects of parameter variations such as enrichment, reflector thickness, or solution content can be evaluated. However, the suite contains only fast metal systems and thermal solution systems. It doesn't include any lattice benchmarks, any benchmarks with intermediate spectra, or any benchmarks with low enriched uranium (LEU) fuel.

The Monte Carlo team subsequently created a suite [6] of 27 criticality benchmarks to test changes to the MCNP Monte Carlo code and to its distributed nuclear data libraries. That suite eventually expanded to 31 benchmarks [7], although not all of the benchmarks in the initial version of the suite were retained in the later version. The objective was to have a wide representation of fissile materials, reflector materials, and spectra. The suite includes at least three fast, one intermediate, and two thermal benchmarks for ^{233}U systems, highly enriched uranium (HEU) systems, intermediate enriched uranium (IEU) systems, and plutonium systems. For LEU systems, it only includes thermal benchmarks, because they cannot reach criticality with intermediate or fast spectra. The three subcategories for fast systems are benchmarks that are unreflected, reflected by a heavy material, and reflected by a light material. The subcategories for thermal systems are lattice benchmarks and solution benchmarks. However, the suite does not include subsets of related benchmarks that would permit parameter variations to be studied. All of the benchmarks in the Monte Carlo team's suite are taken from the *Handbook*.

3 EXPANDED VALIDATION SUITE

All of the benchmarks in the expanded validation suite are taken from the *Handbook*. The name of each benchmark is the same as the identifier for the evaluation in the *Handbook* from which it is taken. In those cases where the evaluation includes more than one case, the benchmark name appends the case number to the identifier.

The benchmarks in the expanded validation suite are divided according to the isotope that produces the majority of fissions: ^{233}U, ^{235}U, or ^{239}Pu. The ^{235}U benchmarks are further subdivided by the fractional ^{235}U content in the uranium as HEU, IEU, or LEU. HEU contains 60 wt.% or more ^{235}U, and LEU contains 5 wt.% or less. IEU therefore contains between 5 wt.% and 60 wt.% ^{235}U. The ^{239}Pu category is generalized to include all plutonium isotopes and hereafter is referred to simply as plutonium. The number of cases in the expanded validation suite in each of these categories is shown in Table I, which also indicates the degree of overlap with the benchmarks in the two previous criticality validation suites.

Table I. Benchmarks in the expanded criticality validation suite

Principal Fuel	Number of Benchmarks			
	Data Team Suite	Monte Carlo Team Suite	Other	Expanded Suite
^{233}U	12	6		18
HEU	30	7	3	40
IEU	7	5	5	17
LEU		2	6	8
Plutonium	19	9	8	36
Total	68	29	22	119

It should be noted that the expanded validation suite uses 5 wt.% as the dividing line between LEU and IEU, whereas the *Handbook* uses 10 wt.%. The reason that 5 wt.% was chosen is that it is the current enrichment limit for fuel used in commercial nuclear reactors in the United States.

The expanded validation suite follows the guidelines from the *Handbook* in classifying spectra as fast, intermediate, or thermal. Fast benchmarks are those in which the majority of fissions is caused by neutrons with energy greater than 100 kev, and thermal benchmarks are those in which the majority of fissions is caused by neutrons with energies less than 0.625 eV. Benchmarks with intermediate spectra therefore are those in which the majority of fissions is caused by neutrons with energies between 0.625 eV and 100 keV. The spectral distribution of the benchmarks in the expanded validation suite is summarized in Table II.

Table II. Spectral distribution of benchmarks in the expanded criticality validation suite

Principal Fuel	Number of Benchmarks			
	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

The expanded suite is available for distribution to CSEWG data testers and currently is being used at LANL and at Brookhaven National Laboratory to test β versions of ENDF/B-VII.1 in order to assess the impact of proposed changes to nuclear data. Documentation [8] for the suite, including descriptions of and input files for each of the benchmarks, is publicly available through the CSEWG web page [9].

4 SUCCINCT DESCRIPTION OF BENCHMARKS

As previously stated, the name of each benchmark in the expanded criticality validation suite is the same as the identifier for the evaluation in the *Handbook* from which it is taken. In those cases where the evaluation includes more than one case, the benchmark name appends the case number to the identifier.

The ^{233}U benchmarks in the suite are characterized in Table III. The uranium in all of the ^{233}U benchmarks is highly enriched in ^{233}U, although it does contain small amounts of other uranium isotopes.

Table III. Characteristics of ^{233}U benchmarks

Spectrum	Form	Shape	Moderator and/or Reflector	Benchmark name(s)
Fast	Metal	Sphere	Unreflected	u233-met-fast-001
			HEU	u233-met-fast-002-case-1 u233-met-fast-002-case-2
			Normal uranium	u233-met-fast-003-case-1 u233-met-fast-003-case-2 u233-met-fast-006
			Tungsten	u233-met-fast-004-case-1 u233-met-fast-004-case-2
			Beryllium	u233-met-fast-005-case-1 u233-met-fast-005-case-2
Intermediate	Solution	Sphere	Beryllium	u233-sol-inter-001-case-1
Thermal	$UO_2 + ZrO_2$	Lattice	Water	u233-comp-therm-001-case-3
	Solution	Sphere	Unreflected	u233-sol-therm-001-case-1 u233-sol-therm-001-case-2 u233-sol-therm-001-case-3 u233-sol-therm-001-case-4 u233-sol-therm-001-case-5 u233-sol-therm-008

The uranium in all of the HEU benchmarks in the suite contains more than 88 wt.% ^{235}U. Those benchmarks are characterized in Tables IV-a and IV-b.

Table IV-a. Characteristics of HEU benchmarks, part 1

Spectrum	Form	Shape	Reflector	Benchmark(s)
Fast	Metal	Sphere	Unreflected	heu-met-fast-001 heu-met-fast-008 heu-met-fast-018-case-2
			Normal uranium	heu-met-fast-003-case-1 heu-met-fast-003-case-2 heu-met-fast-003-case-3 heu-met-fast-003-case-4 heu-met-fast-003-case-5 heu-met-fast-003-case-6 heu-met-fast-003-case-7 heu-met-fast-028
			Depleted uranium	heu-met-fast-014
			Tungsten carbide	heu-met-fast-003-case-8 heu-met-fast-003-case-9 heu-met-fast-003-case-10 heu-met-fast-003-case-11
			Nickel	heu-met-fast-003-case-12
			Steel	heu-met-fast-013 heu-met-fast-021-case-2
			Duralumin	heu-met-fast-022-case-2
			Aluminum	heu-met-fast-012
			Graphite	heu-met-fast-019-case-2
			Beryllium oxide	heu-met-fast-009-case-2
			Beryllium	heu-met-fast-009-case-1
			Polyethylene	heu-met-fast-011 heu-met-fast-020-case-2
			Water	heu-met-fast-004-case-1
		Cylinder	Unreflected	heu-met-fast-015
		Lattice	Paraffin	heu-met-fast-026-case-c-11

Table IV-b. Characteristics of HEU benchmarks, part 2

Spectrum	Form	Shape	Reflector, Moderator and/or Buffer	Benchmark(s)
Intermediate	UH_3	Cylinders	Natural uranium	heu-comp-inter-003, case-6
	Metal	Cylinders	Graphite, copper	heu-met-inter-006-case-1 heu-met-inter-006-case-2 heu-met-inter-006-case-3 heu-met-inter-006-case-4
Thermal	UO_2 + ZrO_2	Lattice	Water, ThO_2	u233-comp-therm-001-case-6
	Solution	Sphere	Unreflected	heu-sol-therm-013-case-1 heu-sol-therm-013-case-2 heu-sol-therm-013-case-3 heu-sol-therm-013-case-4 heu-sol-therm-032

The uranium in all of the IEU benchmarks in the suite contains between 9 and 38 wt.% ^{235}U, at least on average. A few of the IEU benchmarks contain alternating regions of HEU and normal uranium rather than a uniform enrichment. The IEU benchmarks in the expanded criticality validation suite are characterized in Table V.

The uranium in all of the LEU benchmarks in the suite contains between 2.4 and 5 wt.% ^{235}U. Those benchmarks are characterized in Table VI. All of them are thermal benchmarks, because LEU can only reach a critical condition with a thermal spectrum.

The plutonium benchmarks in the suite include benchmarks with both pu and mix identifiers. In addition to plutonium, the mix benchmarks also contain either HEU or normal uranium — i.e., mixed oxide (MOX). However, more than 60% of the fissions in the HEU-reflected benchmarks and more than 75% of the fissions in the MOX benchmarks occur in plutonium. The plutonium benchmarks are characterized in Tables VII-a and VII-b.

5 RESULTS FOR ENDF/B-VI AND ENDF/B-VII.0

MCNP results for k_{eff} for each of the benchmarks are presented in Tables VIII through XII. The results were obtained using ENDF/B-VII.0 and ENDF/B-VI nuclear data. The ENDF/B-VII.0 data are taken from the ENDF70 nuclear data library [10] distributed with MCNP5 1.51 and later. The ENDF/B-VI data are taken from the ACTI [11] and ENDF66 [12] nuclear data libraries included in the same distribution. In combination, those two libraries correspond to the final release of ENDF/B-VI for the cases in the suite.

Each of the calculations used a total of 600 generations with 10,000 histories per generation. The results from the first 100 generations were excluded from the statistics. Consequently, the reported result for each case is based on 5,000,000 active neutron histories.

Table V. Characteristics of IEU benchmarks

Spectrum	Form	Shape	Reflector and/or Buffer	Benchmark(s)
Fast	Metal	Sphere	Unreflected	ieu-met-fast-003-case-2
			Steel	ieu-met-fast-005-case-2
			Duralumin	ieu-met-fast-006-case-2
			Graphite	ieu-met-fast-004-case-2
		Cylinder	Unreflected	ieu-met-fast-001-case-1 ieu-met-fast-001-case-2 ieu-met-fast-001-case-3 ieu-met-fast-001-case-4
			Normal uranium	ieu-met-fast-002
			Depleted uranium	ieu-met-fast-007-case-4
Intermediate	Metal	Plate	Normal uranium, steel	mix-met-fast-008-case-7
Thermal	UO_2	Lattice	Water	ieu-comp-therm-002-case-3
	Solution	Cylinder	Unreflected	leu-sol-therm-007-case-14 leu-sol-therm-007-case-30 leu-sol-therm-007-case-32 leu-sol-therm-007-case-36 leu-sol-therm-007-case-49

Table VI. Characteristics of LEU benchmarks

Spectrum	Form	Shape	Buffer and/or Reflector	Benchmark(s)
Thermal	UO_2	Lattice	UO_2 Rods, Water	leu-comp-therm-008-case-1 leu-comp-therm-008-case-2 leu-comp-therm-008-case-5 leu-comp-therm-008-case-7 leu-comp-therm-008-case-8 leu-comp-therm-008-case-11
	Solution	Sphere	Water	leu-sol-therm-002-case-1
			Unreflected	leu-sol-therm-002-case-2

Table VII-a. Characteristics of plutonium benchmarks, part 1

Spectrum	Form	Shape	Reflector and/or Buffer	Benchmark(s)
Fast	Metal	Sphere	Unreflected	pu-met-fast-001 pu-met-fast-002 pu-met-fast-022-case-2
			HEU	mix-met-fast-001 mix-met-fast-003
			Normal uranium	pu-met-fast-006 pu-met-fast-010
			Depleted uranium	pu-met-fast-020
			Thorium	pu-met-fast-008-case-2
			Tungsten	pu-met-fast-005
			Steel	pu-met-fast-025-case-2 pu-met-fast-026-case-2
			Aluminum	pu-met-fast-009
			Graphite	pu-met-fast-023-case-2
			Beryllium	pu-met-fast-018 pu-met-fast-019
			Polyethylene	pu-met-fast-024-case-2
			Water	pu-met-fast-011
		Cylinder	Beryllium oxide	pu-met-fast-021-case-2
			Beryllium	pu-met-fast-021-case-1
		Lattice	Unreflected	pu-met-fast-003-case-103

Overall, ENDF/B-VII.0 produces noticeably better agreement with the benchmark values for k_{eff} than ENDF/B-VI does. The improvements are particularly noticeable for the fast unreflected and uranium-reflected ^{233}U metal spheres, most of the fast HEU metal spheres, the fast IEU cylinders, the thermal LEU lattices, most of the fast plutonium spheres, and the thermal MOX lattices. Both libraries tend to overpredict k_{eff} for fast cases reflected by tungsten and to underpredict k_{eff} for fast cases reflected by beryllium. However, results from β versions of ENDF/B-VII.1 show marked improvement for both reflectors.

Table VII-b. Characteristics of plutonium benchmarks, part 2

Spectrum	Form	Shape	Reflector and/or Moderator	Benchmark(s)
Intermediate	Mixture	Homogeneous	Hydrogen, graphite	pu-comp-inter-001
Thermal	MOX	Lattice	Water	mix-comp-therm-002-case-pnl30 mix-comp-therm-002-case-pnl31 mix-comp-therm-002-case-pnl32 mix-comp-therm-002-case-pnl33 mix-comp-therm-002-case-pnl34 mix-comp-therm-002-case-pnl35
	Solution	Sphere	Unreflected	pu-sol-therm-009-case-3a pu-sol-therm-011-case-16-5 pu-sol-therm-011-case-18-1 pu-sol-therm-011-case-18-6 pu-sol-therm-021-case-1 pu-sol-therm-021-case-3
		Cylinder	Water	pu-sol-therm-018-case-9 pu-sol-therm-034-case-1

6 SUMMARY AND CONCLUSIONS

The expanded validation suite provides a significant advance in the level of validation for the application of MCNP to criticality calculations. The careful selection of *Handbook* benchmarks that cover a wide range of materials, configurations, and spectra provides the required broad coverage of code applications. For practitioners, the suite also may serve as a starting point for validating MCNP and its various nuclear data libraries for their specific applications.

Results have been provided for each of the cases in the suite using nuclear data libraries based on ENDF/B-VI and ENDF/B-VII.0. Overall, ENDF/B-VII.0 produces noticeably better agreement with the benchmark values for k_{eff} than does ENDF/B-VI. In addition, the suite currently is being used at LANL and at Brookhaven National Laboratory to test β versions of ENDF/B-VII.1 in order to assess the impact of proposed changes to nuclear data.

7 REFERENCES

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Table VIII. MCNP results for ^{233}U benchmarks

Case Name	Benchmark k_{eff}	Calculated k_{eff}	
		ENDF/B-VII.0	ENDF/B-VI
u233-met-fast-001	1.0000 ± 0.0010	0.9993 ± 0.0003	0.9932 ± 0.0003
u233-met-fast-002-case-1	1.0000 ± 0.0010	0.9987 ± 0.0003	0.9950 ± 0.0003
u233-met-fast-002-case-2	1.0000 ± 0.0011	1.0005 ± 0.0003	0.9975 ± 0.0003
u233-met-fast-003-case-1	1.0000 ± 0.0010	0.9997 ± 0.0003	0.9958 ± 0.0003
u233-met-fast-003-case-2	1.0000 ± 0.0010	1.0001 ± 0.0003	0.9977 ± 0.0003
u233-met-fast-004-case-1	1.0000 ± 0.0007	1.0051 ± 0.0003	1.0017 ± 0.0003
u233-met-fast-004-case-2	1.0000 ± 0.0008	1.0051 ± 0.0003	1.0040 ± 0.0003
u233-met-fast-005-case-1	1.0000 ± 0.0030	0.9944 ± 0.0003	0.9950 ± 0.0003
u233-met-fast-005-case-2	1.0000 ± 0.0030	0.9925 ± 0.0003	0.9967 ± 0.0003
u233-met-fast-006	1.0000 ± 0.0014	0.9994 ± 0.0003	1.0002 ± 0.0003
u233-sol-inter-001-case-1	1.0000 ± 0.0083	0.9848 ± 0.0005	0.9903 ± 0.0005
u233-comp-therm-001-case-3	1.0000 ± 0.0024	1.0045 ± 0.0005	0.9968 ± 0.0005
u233-sol-therm-001-case-1	1.0000 ± 0.0031	1.0015 ± 0.0003	0.9991 ± 0.0003
u233-sol-therm-001-case-2	1.0000 ± 0.0033	1.0011 ± 0.0003	0.9988 ± 0.0003
u233-sol-therm-001-case-3	1.0000 ± 0.0033	1.0009 ± 0.0003	0.9982 ± 0.0003
u233-sol-therm-001-case-4	1.0000 ± 0.0033	1.0019 ± 0.0003	0.9976 ± 0.0003
u233-sol-therm-001-case-5	1.0000 ± 0.0033	0.9996 ± 0.0003	0.9972 ± 0.0003
u233-sol-therm-008	1.0000 ± 0.0029	1.0012 ± 0.0002	0.9975 ± 0.0002

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Table IX-a. MCNP results for HEU benchmarks, part 1

Case Name	Benchmark k_{eff}	Calculated k_{eff}	
		ENDF/B-VII.0	ENDF/B-VI
heu-met-fast-001	1.0000 ± 0.0010	0.9993 ± 0.0003	0.9962 ± 0.0003
heu-met-fast-003-case-1	1.0000 ± 0.0050	0.9954 ± 0.0003	0.9921 ± 0.0003
heu-met-fast-003-case-2	1.0000 ± 0.0050	0.9942 ± 0.0003	0.9912 ± 0.0003
heu-met-fast-003-case-3	1.0000 ± 0.0050	0.9994 ± 0.0003	0.9972 ± 0.0003
heu-met-fast-003-case-4	1.0000 ± 0.0030	0.9971 ± 0.0003	0.9952 ± 0.0003
heu-met-fast-003-case-5	1.0000 ± 0.0030	1.0008 ± 0.0003	1.0004 ± 0.0003
heu-met-fast-003-case-6	1.0000 ± 0.0030	1.0017 ± 0.0003	1.0004 ± 0.0003
heu-met-fast-003-case-7	1.0000 ± 0.0030	1.0027 ± 0.0003	1.0018 ± 0.0003
heu-met-fast-003-case-8	1.0000 ± 0.0050	1.0081 ± 0.0003	1.0048 ± 0.0003
heu-met-fast-003-case-9	1.0000 ± 0.0050	1.0095 ± 0.0003	1.0063 ± 0.0003
heu-met-fast-003-case-10	1.0000 ± 0.0050	1.0129 ± 0.0003	1.0093 ± 0.0003
heu-met-fast-003-case-11	1.0000 ± 0.0050	1.0166 ± 0.0003	1.0136 ± 0.0003
heu-met-fast-003-case-12	1.0000 ± 0.0030	1.0083 ± 0.0003	1.0043 ± 0.0003
heu-met-fast-004-case-1	1.0020 ± 0.0010	1.0028 ± 0.0003	0.9976 ± 0.0003
heu-met-fast-008	0.9989 ± 0.0016	0.9957 ± 0.0003	0.9924 ± 0.0003
heu-met-fast-009-case-1	0.9992 ± 0.0015	0.9957 ± 0.0003	0.9952 ± 0.0003
heu-met-fast-009-case-2	0.9992 ± 0.0015	0.9955 ± 0.0003	0.9928 ± 0.0003
heu-met-fast-011	0.9989 ± 0.0015	0.9989 ± 0.0003	0.9946 ± 0.0003
heu-met-fast-012	0.9992 ± 0.0018	0.9982 ± 0.0003	0.9933 ± 0.0003
heu-met-fast-013	0.9990 ± 0.0015	0.9975 ± 0.0003	0.9938 ± 0.0003
heu-met-fast-014	0.9989 ± 0.0017	0.9978 ± 0.0002	0.9939 ± 0.0002
heu-met-fast-015	0.9996 ± 0.0017	0.9943 ± 0.0003	0.9918 ± 0.0003

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Table IX-b. MCNP results for HEU benchmarks, part 2

Case Name	Benchmark k_{eff}	Calculated k_{eff}	
		ENDF/B-VII.0	ENDF/B-VI
heu-met-fast-018-case-2	1.0000 ± 0.0014	0.9999 ± 0.0003	0.9962 ± 0.0003
heu-met-fast-019-case-2	1.0000 ± 0.0028	1.0074 ± 0.0003	1.0031 ± 0.0003
heu-met-fast-020-case-2	1.0000 ± 0.0028	1.0008 ± 0.0003	0.9968 ± 0.0003
heu-met-fast-021-case-2	1.0000 ± 0.0024	0.9969 ± 0.0003	0.9943 ± 0.0003
heu-met-fast-022-case-2	1.0000 ± 0.0019	0.9977 ± 0.0003	0.9927 ± 0.0003
heu-met-fast-026-case-c-11	1.0000 ± 0.0038	1.0037 ± 0.0003	1.0002 ± 0.0004
heu-met-fast-028	1.0000 ± 0.0030	1.0032 ± 0.0003	1.0020 ± 0.0003
heu-comp-inter-003-case-6	1.0000 ± 0.0047	0.9951 ± 0.0003	0.9916 ± 0.0003
heu-met-inter-006-case-1	0.9977 ± 0.0008	0.9930 ± 0.0004	0.9914 ± 0.0003
heu-met-inter-006-case-2	0.9997 ± 0.0008	0.9960 ± 0.0004	0.9958 ± 0.0004
heu-met-inter-006-case-3	1.0015 ± 0.0009	1.0006 ± 0.0004	0.9993 ± 0.0003
heu-met-inter-006-case-4	1.0016 ± 0.0008	1.0075 ± 0.0003	1.0050 ± 0.0004
u233-comp-therm-001-case-6	1.0015 ± 0.0028	0.9991 ± 0.0004	0.9976 ± 0.0004
heu-sol-therm-013-case-1	1.0012 ± 0.0026	0.9985 ± 0.0003	0.9988 ± 0.0003
heu-sol-therm-013-case-2	1.0007 ± 0.0036	0.9975 ± 0.0003	0.9981 ± 0.0003
heu-sol-therm-013-case-3	1.0009 ± 0.0036	0.9942 ± 0.0003	0.9945 ± 0.0003
heu-sol-therm-013-case-4	1.0003 ± 0.0036	0.9957 ± 0.0003	0.9965 ± 0.0003
heu-sol-therm-032	1.0015 ± 0.0026	0.9991 ± 0.0002	0.9993 ± 0.0002

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Table X. MCNP results for IEU benchmarks

Case Name	Benchmark k_{eff}	Calculated k_{eff}	
		ENDF/B-VII.0	ENDF/B-VI
ieu-met-fast-001-case-1	0.9989 ± 0.0010	1.0009 ± 0.0003	0.9964 ± 0.0003
ieu-met-fast-001-case-2	0.9997 ± 0.0010	1.0013 ± 0.0003	0.9967 ± 0.0003
ieu-met-fast-001-case-3	0.9993 ± 0.0005	1.0014 ± 0.0003	0.9978 ± 0.0003
ieu-met-fast-001-case-4	1.0002 ± 0.0005	1.0015 ± 0.0003	0.9979 ± 0.0003
ieu-met-fast-002	1.0000 ± 0.0030	0.9991 ± 0.0003	1.0033 ± 0.0003
ieu-met-fast-003-case-2	1.0000 ± 0.0017	1.0029 ± 0.0003	0.9994 ± 0.0003
ieu-met-fast-004-case-2	1.0000 ± 0.0030	1.0075 ± 0.0003	1.0040 ± 0.0003
ieu-met-fast-005-case-2	1.0000 ± 0.0021	1.0018 ± 0.0003	0.9994 ± 0.0003
ieu-met-fast-006-case-2	1.0000 ± 0.0023	0.9957 ± 0.0003	0.9912 ± 0.0003
ieu-met-fast-007-case-4	1.0049 ± 0.0008	1.0049 ± 0.0002	1.0164 ± 0.0002
mix-met-fast-008-case-7	1.0030 ± 0.0025	1.0193 ± 0.0002	1.0402 ± 0.0002
ieu-comp-therm-002-case-3	1.0017 ± 0.0044	1.0045 ± 0.0004	1.0002 ± 0.0005
leu-sol-therm-007-case-14	0.9961 ± 0.0009	0.9950 ± 0.0003	0.9955 ± 0.0003
leu-sol-therm-007-case-30	0.9973 ± 0.0009	0.9977 ± 0.0003	0.9972 ± 0.0003
leu-sol-therm-007-case-32	0.9985 ± 0.0010	0.9958 ± 0.0003	0.9958 ± 0.0003
leu-sol-therm-007-case-36	0.9988 ± 0.0011	0.9986 ± 0.0003	0.9984 ± 0.0003
leu-sol-therm-007-case-49	0.9983 ± 0.0011	0.9975 ± 0.0003	0.9975 ± 0.0003

12. J. M. Campbell, S. C. Frankle, and R. C. Little, "ENDF66: A Continuous-Energy Neutron Data Library for MCNP4C," *Proceedings of the American Nuclear Society Radiation* Protection and Shielding Division 12th Biennial Topical Meeting, Santa Fe, New Mexico, USA (April 2002).

Table XI. MCNP results for LEU benchmarks

Case Name	Benchmark k_{eff}	Calculated k_{eff}	
		ENDF/B-VII.0	ENDF/B-VI
leu-comp-therm-008-case-1	1.0007 ± 0.0016	1.0012 ± 0.0003	0.9970 ± 0.0003
leu-comp-therm-008-case-2	1.0007 ± 0.0016	1.0013 ± 0.0003	0.9967 ± 0.0003
leu-comp-therm-008-case-5	1.0007 ± 0.0016	1.0007 ± 0.0003	0.9977 ± 0.0003
leu-comp-therm-008-case-7	1.0007 ± 0.0016	1.0003 ± 0.0003	0.9969 ± 0.0003
leu-comp-therm-008-case-8	1.0007 ± 0.0016	1.0007 ± 0.0003	0.9965 ± 0.0003
leu-comp-therm-008-case-11	1.0007 ± 0.0016	1.0020 ± 0.0003	0.9973 ± 0.0003
leu-sol-therm-002-case-1	1.0038 ± 0.0040	1.0000 ± 0.0003	0.9988 ± 0.0003
leu-sol-therm-002-case-2	1.0024 ± 0.0037	0.9959 ± 0.0003	0.9957 ± 0.0003

Table XII-a. MCNP results for plutonium benchmarks, part 1

Case Name	Benchmark k_{eff}	Calculated k_{eff}	
		ENDF/B-VII.0	ENDF/B-VI
pu-met-fast-001	1.0000 ± 0.0020	1.0000 ± 0.0003	0.9973 ± 0.0003
pu-met-fast-002	1.0000 ± 0.0020	0.9999 ± 0.0003	0.9979 ± 0.0003
pu-met-fast-003-case-103	1.0000 ± 0.0030	0.9981 ± 0.0003	0.9961 ± 0.0003
pu-met-fast-005	1.0000 ± 0.0013	1.0092 ± 0.0003	1.0078 ± 0.0003
pu-met-fast-006	1.0000 ± 0.0030	0.9995 ± 0.0003	1.0021 ± 0.0003
pu-met-fast-008-case-2	1.0000 ± 0.0006	0.9977 ± 0.0003	1.0039 ± 0.0003
pu-met-fast-009	1.0000 ± 0.0027	1.0053 ± 0.0003	1.0017 ± 0.0003
pu-met-fast-010	1.0000 ± 0.0018	1.0001 ± 0.0003	0.9986 ± 0.0003
pu-met-fast-011	1.0000 ± 0.0010	1.0002 ± 0.0003	0.9963 ± 0.0003
pu-met-fast-018	1.0000 ± 0.0030	0.9965 ± 0.0003	0.9990 ± 0.0003
pu-met-fast-019	0.9992 ± 0.0015	0.9975 ± 0.0003	1.0011 ± 0.0003
pu-met-fast-020	0.9993 ± 0.0017	0.9981 ± 0.0003	0.9978 ± 0.0003
pu-met-fast-021-case-1	1.0000 ± 0.0026	1.0021 ± 0.0003	1.0039 ± 0.0003
pu-met-fast-021-case-2	1.0000 ± 0.0026	0.9932 ± 0.0003	0.9927 ± 0.0003
pu-met-fast-022-case-2	1.0000 ± 0.0021	0.9983 ± 0.0003	0.9960 ± 0.0003
pu-met-fast-023-case-2	1.0000 ± 0.0020	0.9993 ± 0.0003	0.9976 ± 0.0003
pu-met-fast-024-case-2	1.0000 ± 0.0020	1.0019 ± 0.0003	1.0001 ± 0.0003
pu-met-fast-025-case-2	1.0000 ± 0.0020	0.9988 ± 0.0003	0.9966 ± 0.0003
pu-met-fast-026-case-2	1.0000 ± 0.0024	0.9985 ± 0.0003	0.9968 ± 0.0003
mix-met-fast-001	1.0000 ± 0.0016	0.9993 ± 0.0003	0.9969 ± 0.0003
mix-met-fast-003	0.9993 ± 0.0016	1.0008 ± 0.0003	0.9979 ± 0.0003
pu-comp-inter-001	1.0000 ± 0.0110	1.0116 ± 0.0002	1.0107 ± 0.0002

Table XII-b. MCNP results for plutonium benchmarks, part 2

Case Name	Benchmark k_{eff}	Calculated k_{eff}	
		ENDF/B-VII.0	ENDF/B-VI
mix-comp-therm-002-case-pnl30	1.0024 ± 0.0060	1.0010 ± 0.0003	0.9932 ± 0.0003
mix-comp-therm-002-case-pnl31	1.0009 ± 0.0047	1.0028 ± 0.0003	0.9967 ± 0.0003
mix-comp-therm-002-case-pnl32	1.0042 ± 0.0031	1.0032 ± 0.0003	0.9960 ± 0.0003
mix-comp-therm-002-case-pnl33	1.0024 ± 0.0021	1.0079 ± 0.0003	1.0032 ± 0.0003
mix-comp-therm-002-case-pnl34	1.0038 ± 0.0025	1.0046 ± 0.0003	0.9999 ± 0.0003
mix-comp-therm-002-case-pnl35	1.0029 ± 0.0027	1.0068 ± 0.0003	1.0026 ± 0.0003
pu-sol-therm-009-case-3a	1.0000 ± 0.0033	1.0190 ± 0.0002	1.0186 ± 0.0002
pu-sol-therm-011-case-16-5	1.0000 ± 0.0052	1.0060 ± 0.0004	1.0054 ± 0.0004
pu-sol-therm-011-case-18-1	1.0000 ± 0.0052	0.9944 ± 0.0004	0.9954 ± 0.0003
pu-sol-therm-011-case-18-6	1.0000 ± 0.0052	0.9996 ± 0.0004	1.0010 ± 0.0004
pu-sol-therm-018-case-9	1.0000 ± 0.0034	1.0031 ± 0.0003	1.0033 ± 0.0003
pu-sol-therm-021-case-1	1.0000 ± 0.0032	1.0043 ± 0.0004	1.0051 ± 0.0004
pu-sol-therm-021-case-3	1.0000 ± 0.0065	1.0044 ± 0.0005	1.0032 ± 0.0004
pu-sol-therm-034-case-1	1.0000 ± 0.0062	0.9999 ± 0.0004	0.9978 ± 0.0004