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MCNP CALCULATIONS FOR CRITICALITY-SAFETY BENCHMARKS WITH ENDF/B-V AND ENDF/B-VI LIBRARIES

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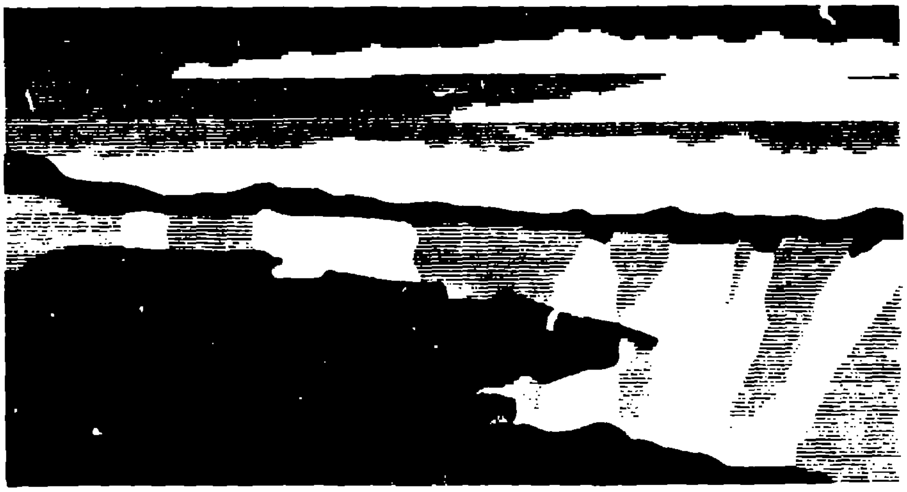

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MCNP CALCULATIONS FOR CRITICALITY-SAFETY BENCHMARKS WITH ENDF/B-V AND ENDF/B-VI LIBRARIES

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ABSTRACT

The MCNP Monte Carlo code, in conjunction with its continuous-energy ENDF/B-V and ENDF/B-VI cross-section libraries, has been benchmarked against results from 27 different critical experiments. The predicted values of k_{eff} are in excellent agreement with the benchmarks, except for the ENDF/B-V results for solutions of plutonium nitrate and, to a lesser degree, for the ENDF/B-V and ENDF/B-VI results for a bare sphere of ^{233}U.

INTRODUCTION

The MCNP Monte Carlo code [1] has been used for criticality-safety analyses for many years, and, in conjunction with its continuous-energy ENDF/B-V library, it has been benchmarked previously for criticality-safety applications [2]. However, a new set of continuous-energy cross-section libraries, based on Revision 2 of ENDF/B-VI, recently has become available for MCNP. This paper summarizes the results obtained using both libraries for a series of 27 benchmark experiments based on specifications and benchmark values of k_{eff} provided by the International Criticality Safety Benchmark Evaluation Project (ICSBEP) [3] and the Cross Section Evaluation Working Group (CSEWG) [4].

DESCRIPTION OF CASES

A large variety of cases was chosen for this study: metallic highly enriched uranium (HEU) and metallic plutonium systems (both bare and reflected), uranyl-nitrate solutions with HEU, uranium-dioxide (UO_2) fuel pins with and without poison pins in borated water, and plutonium-nitrate solutions.

Several fast-spectrum uranium systems were analyzed, including a bare HEU sphere (Godiva) [5, 6], an HEU sphere reflected with normal uranium (Topsy) [7], an HEU sphere reflected by water [8, 9], and an HEU cube reflected by water [10]. In addition, two systems with alternating platters of HEU and normal uranium were analyzed (Jemima) [11]. Platters of HEU and normal uranium were alternated in the first case ("pairs"), while two platters of normal uranium separated the platters of HEU in the second case ("triplets").

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Two types of thermal uranium systems were analyzed: uranyl nitrate solutions with HEU and lattices of fuel pins with low-enriched uranium (LEU). Five of the solution cases are based on experiments that were performed at Oak Ridge National Laboratory with spheres of uranyl nitrate (ORNL spheres) [12, 13]. The CSEWG specifications for these benchmarks represent them as bare spheres. The sixth case [14] is a concrete-reflected cylinder with a more highly concentrated solution of uranyl nitrate than the ORNL spheres. The lattice cases (B & W Core XI experiments) [15] each contain approximately 5,000 UO_2 fuel pins immersed in borated water. Load 1 is a uniform array of fuel pins, while Loads 2 and 8 contain water holes and/or Pyrex absorbing pins interspersed among the fuel pins.

The last uranium case is a bare sphere with 98 at.% ^{233}U (Jezebel-233) [5].

A brief summary of each of these uranium systems is given in Table I. The benchmark values for k_{eff} given in those tables are not all equal to unity; in such cases, they include standard deviations and/or adjustments that reflect the reactivity effect of uncertainties or idealizations identified by the experimenters or by the ICSBEP/CSEWG evaluators.

Three fast-spectrum plutonium systems were analyzed. Jezebel [16, 17] and Jezebel-240 [16] both are bare spheres of plutonium, but they contain different amounts of ^{240}Pu (4.5 at.% in Jezebel and 20.1 at.% in Jezebel-240). The isotopic composition of the water-reflected plutonium sphere [18] is similar to that of Jezebel.

Both bare and water-reflected plutonium-nitrate solutions were analyzed. All of these benchmarks are based on experiments performed at the Critical Mass Laboratory at Batelle Pacific Northwest Laboratories [19, 20].

The CSEWG benchmark specifications for the PNL spheres represent them as bare spheres with different concentrations of plutonium nitrate. However, the experiments that PNL-3 and PNL-4 are based on recently have been evaluated as part of the ICSBEP, and it has been suggested [21] that the CSEWG benchmarks for PNL-3 and PNL-4 should be revised to conform to the ICSBEP specifications (the ICSBEP specifications retain the stainless-steel sphere that encloses the solution and its cadmium cover, while the CSEWG bench-marks do not). Consequently, the ICSBEP specifications for those two cases have been used in this study, and the cases are denoted in Table II as PNL-3 (Rev.) and PNL-4 (Rev.) to indicate this distinction.

Three water-reflected spheres of plutonium-nitrate solutions also were analyzed. Two of the systems contain very different concentrations of plutonium nitrate, and ^{240}Pu constitutes a much lower atom fraction of the plutonium in the third case than in the other two.

A brief summary of each of these plutonium systems is given in Table II.

RESULTS

The MCNP calculations for most of these cases were performed with 440 generations of 2500 neutrons each, with the first 40 generations excluded from the statistics. The only exceptions are the B & W Core XI cases, which were run with 300 generations of 4000 neutrons each because of the large number of fuel pins present. The first 50 generations were excluded from the statistics for those cases. The results for each case, therefore, are based on 1 million active neutron histories. A brief summary of the results is given in Table III for the uranium systems and in Table IV for the plutonium systems.

Both ENDF/B-V and ENDF/B-VI predict excellent agreement with the benchmark values of k_{eff} for the metallic HEU experiments, with the exception of the ENDF/B-V results for the Jemima experiments. The differences for the solution experiments and for the lattices of UO_2 pins are more pronounced: ENDF/B-VI predicts values of k_{eff} for these experiments that are 0.002 to 0.006 Δk lower than those produced by ENDF/B-V. Neither library produces particularly good results for the ^{233}U Jezebel sphere. The agreement between the two results for this case is not surprising, because the ENDF/B-VI evaluation for ^{233}U is just a translation of the corresponding ENDF/B-V evaluation.

The lower reactivity for the Jemima experiments is due to a combination of changes to the ^{235}U and ^{238}U cross sections in the fast range, while the lower reactivity for the solution experiments is due primarily to changes in the thermal cross sections for ^{235}U. The slightly lower reactivity for the lattices of UO_2 pins is due primarily to changes in the ^{235}U and ^{238}U cross sections that do not quite compensate for each other. The lower reactivity improves the agreement with the Jemima experiments and the reflected cylinder of uranyl nitrate. On the other hand, it produces noticeably worse agreement for the ORNL spheres and slightly worse agreement with the lattices of UO_2 pins.

Both ENDF/B-V and ENDF/B-VI produce excellent agreement for the experiments involving metallic plutonium spheres. However, ENDF/B-VI produces dramatically improved agreement for the plutonium nitrate solutions. Previous versions of ENDF, not just ENDF/B-V, had consistently overestimated k_{eff} for the PNL experiments. The improvement is due to changes in the ^{239}Pu cross sections and, to a lesser extent, in the cross sections for ^{240}Pu and iron.

CONCLUSIONS

This study has benchmarked the MCNP code and its continuous-energy ENDF/B-V and ENDF/B-VI libraries against a variety of benchmark critical experiments. In general, there is excellent agreement between predicted values for k_{eff} and the benchmarks, with the exception of the ENDF/B-V results for plutonium-nitrate solutions and, to a lesser degree, the ENDF/B-V and ENDF/B-VI results for the bare sphere of ^{233}U. Relative to ENDF/B-V, ENDF/B-VI produces improved agreement with plutonium-nitrate solutions and the Jemima experiments. However, it produces slightly worse agreement for thermal uranium systems (spheres of uranyl nitrate and lattices of UO_2 fuel pins in borated water).

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Table I. Summary of Uranium Benchmark Cases

Case Title	Description	Source	Benchmark k_{eff}
Godiva	Bare HEU Sphere	ICSBEP	1.0010 ± 0.0010
Topsy Sphere	HEU Sphere in natural-U Sphere	ICSBEP	1.0000 ± 0.0030
Jemima Pairs	Pairs of platters of HEU and natural U	ICSBEP	0.9988 ± 0.0009
Jemima Triplets	Triplets of platters of HEU and natural U	ICSBEP	0.9987 ± 0.0009
HEU Sphere in Water	HEU sphere reflected by water	ICSBEP	0.9985
HEU Cube in Water	HEU cube reflected by water	ICSBEP	1.0000 ± 0.0010
ORNL-1	Bare sphere of uranyl nitrate (HEU)	CSEWG	1.0003
ORNL-2	Bare sphere of uranyl nitrate (HEU)	CSEWG	0.9998
ORNL-3	Bare sphere of uranyl nitrate (HEU)	CSEWG	0.9999
ORNL-4	Bare sphere of uranyl nitrate (HEU)	CSEWG	0.9992
ORNL-10	Bare sphere of uranyl nitrate (HEU)	CSEWG	1.0003
Uranyl Nitrate Cylinder	Cylinder of uranyl nitrate reflected by concrete (HEU)	ICSBEP	1.0000 ± 0.0019
B & W Core XI, Load 1	UO_2 pins in borated water (LEU)	ICSBEP	1.0007 ± 0.0005
B & W Core XI, Load 2	UO_2 pins and water holes in borated water (LEU)	ICSBEP	1.0007 ± 0.0005
B & W Core XI, Load 8	UO_2 and Pyrex pins in borated water (LEU)	ICSBEP	1.0007 ± 0.0005
Jezebel-233	Bare sphere of ^{233}U	ICSBEP	1.0000 ± 0.0010

Table II. Summary of Plutonium Benchmark Cases

Case Title	Description	Source	Benchmark k_{eff}
Jezebel	Bare plutonium sphere	ICSBEP	1.0000 ± 0.0020
Jezebel-240	Bare plutonium sphere (20 at.% ^{240}Pu)	ICSBEP	1.000 ± 0.0020
Pu Sphere in Water	Plutonium sphere reflected by water	ICSBEP	1.0000 ± 0.0010
PNL-1	Bare sphere of plutonium nitrate	CSEWG	1.0
PNL-2	Bare sphere of plutonium nitrate	CSEWG	1.0
PNL-3 (Rev.)	Sphere of plutonium nitrate with Cd Cover	ICSBEP	1.0
PNL-4 (Rev.)	Sphere of plutonium nitrate with Cd Cover	ICSBEP	1.0
PNL-5	Bare sphere of plutonium nitrate	CSEWG	1.0
Pu Nitrate Sphere	Sphere of plutonium nitrate reflected by water	ICSBEP	1.0000 ± 0.0055
Pu Nitrate Sphere, Low ^{240}Pu	Sphere of plutonium nitrate reflected by water	ICSBEP	1.0000 ± 0.0056
Pu Nitrate Sphere, Dilute	Sphere of plutonium nitrate reflected by water	ICSBEP	1.0000 ± 0.0055

Table III. Results for Uranium Benchmark Cases

Case Title	Benchmark k_{eff}	k_{eff}		Δk	
		ENDF/B-V	ENDF/B-VI	ENDF/B-V	ENDF/B-VI
Godiva	1.0000 ± 0.0010	0.9983 ± 0.0006	0.9967 ± 0.0006	-0.0017 ± 0.0012	-0.0033 ± 0.0012
Topsy Sphere	1.0000 ± 0.0030	1.0027 ± 0.0006	1.0013 ± 0.0006	0.0027 ± 0.0031	0.0013 ± 0.0031
Jemima Pairs	0.9988 ± 0.0009	1.0025 ± 0.0006	0.9982 ± 0.0006	0.0037 ± 0.0011	-0.0006 ± 0.0011
Jemima Triplets	0.9987 ± 0.0009	1.0053 ± 0.0006	0.9990 ± 0.0007	0.0066 ± 0.0011	0.0003 ± 0.0011
HEU Sphere in Water	0.9985	0.9965 ± 0.0008	0.9961 ± 0.0008	-0.0020 ± 0.0008	-0.0024 ± 0.0008
HEU Cube in Water	1.0000 ± 0.0010	1.0034 ± 0.0008	1.0026 ± 0.0008	0.0024 ± 0.0013	0.0026 ± 0.0013
ORNL-1	1.0003	1.0005 ± 0.0006	0.9951 ± 0.0005	0.0002 ± 0.0006	-0.0052 ± 0.0005
ORNL-2	0.9998	0.9981 ± 0.0006	0.9968 ± 0.0006	-0.0017 ± 0.0006	-0.0030 ± 0.0006
ORNL-3	0.9999	0.9961 ± 0.0006	0.9943 ± 0.0006	-0.0038 ± 0.0006	-0.0056 ± 0.0006
ORNL-4	0.9992	0.9964 ± 0.0006	0.9939 ± 0.0006	-0.0028 ± 0.0006	-0.0053 ± 0.0006
ORNL-10	1.0003	0.9996 ± 0.0004	0.9972 ± 0.0004	-0.0007 ± 0.0004	-0.0031 ± 0.0004
Uranyl Nitrate Cylinder	1.0000 ± 0.0019	1.0068 ± 0.0010	1.0016 ± 0.0010	0.0068 ± 0.0021	0.0016 ± 0.0021
B & W Core XI, Load 1	1.0007 ± 0.0005	0.9976 ± 0.0007	0.9987 ± 0.0007	-0.0031 ± 0.0009	-0.0020 ± 0.0009
B & W Core XI, Load 2	1.0007 ± 0.0005	1.0003 ± 0.0007	0.9973 ± 0.0006	-0.0004 ± 0.0009	-0.0034 ± 0.0008
B & W Core XI, Load 8	1.0007 ± 0.0005	0.9974 ± 0.0007	0.9943 ± 0.0006	-0.0033 ± 0.0009	-0.0064 ± 0.0008
Jezebel-233	1.0000 ± 0.0010	0.9932 ± 0.0006	0.9925 ± 0.0006	-0.0068 ± 0.0012	-0.0075 ± 0.0012

Table IV. Results for Plutonium Benchmark Cases

Case Title	Benchmark k_{eff}	k_{eff}		Δk	
		ENDF/B-V	ENDF/B-VI	ENDF/B-V	ENDF/B-VI
Jezebel	1.0000 ± 0.0020	0.9975 ± 0.0006	0.9975 ± 0.0006	-0.0025 ± 0.0021	-0.0025 ± 0.0021
Jezebel-240	1.0000 ± 0.0020	0.9994 ± 0.0006	0.9996 ± 0.0006	-0.0006 ± 0.0021	-0.0004 ± 0.0021
Pu Sphere in Water	1.0000 ± 0.0010	0.9999 ± 0.0006	0.9978 ± 0.0006	-0.0001 ± 0.0012	-0.0022 ± 0.0012
PNL-1	1.0	1.0146 ± 0.0010	1.0077 ± 0.0009	0.0146 ± 0.0010	0.0077 ± 0.0009
PNL-2	1.0	1.0060 ± 0.0010	0.9999 ± 0.0010	0.0060 ± 0.0010	-0.0001 ± 0.0010
PNL-3 (Rev.)	1.0000 ± 0.0052	1.0021 ± 0.0008	0.9953 ± 0.0008	0.0021 ± 0.0053	-0.0047 ± 0.0053
PNL-4 (Rev.)	1.0000 ± 0.0052	1.0094 ± 0.0008	0.9994 ± 0.0008	0.0094 ± 0.0053	-0.0006 ± 0.0053
PNL-5	1.0	1.0088 ± 0.0009	1.0001 ± 0.0009	0.0088 ± 0.0009	0.0001 ± 0.0009
Pu Nitrate Sphere	1.0000 ± 0.0055	1.0126 ± 0.0009	1.0043 ± 0.0009	0.0126 ± 0.0056	0.0043 ± 0.0056
Pu Nitrate Sphere, Low ^{240}Pu	1.0000 ± 0.0056	1.0116 ± 0.0009	1.0017 ± 0.0008	0.0116 ± 0.0057	0.0017 ± 0.0057
Pu Nitrate Sphere, Dilute	1.0000 ± 0.0055	1.0104 ± 0.0007	1.0027 ± 0.0007	0.0104 ± 0.0056	0.0027 ± 0.0056