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Development and Validation of the New Continuous Energy Capability in the Criticality Safety Code KENO

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Abstract

The continuous energy cross sections that are used in KENO V.a and KENO-VI are generated using the latest AMPX cross-section processing system. ENDF/B-VI Release 8 and ENDF/B-VII Release 0 data have recently been processed through AMPX to generate continuous energy cross-section data. Continuous energy versions of KENO and these newly generated data have been tested using various problem sets, including SCALE sample problems and critical benchmark cases. Analysis of the results from continuous energy KENO V.a and continuous energy KENO-VI using the latest AMPX-generated ENDF/B-VII Release 0 cross sections are presented for benchmark problems that represent a wide range of critical fissile systems.

1. Introduction

Oak Ridge National Laboratory (ORNL) has incorporated continuous energy capability in the KENO V.a and KENO VI codes that are maintained as part of the Standardized Computer Analyses for Licensing Evaluation (SCALE) code system (SCALE, 2006). Both codes can perform the neutron transport calculations in either multigroup or continuous energy mode. The energy treatment mode is automatically selected based on the cross-section library name if the problem is initiated by one of the corresponding control modules. For KENO V.a the control module is CSAS5; for KENO-VI the control module is CSAS6. In the remainder of this paper, when the KENO code is referenced, calculation in the continuous energy mode is implied.

As part of this development, ORNL has developed a continuous energy cross-section format and the continuous energy cross-section processing software needed to prepare data libraries for KENO. The processing software has been added to the AMPX (Dunn and Greene, 2002) code system that is used to prepare nuclear data libraries for SCALE. Production continuous energy libraries based on ENDF/B-VI Release 8 and ENDF/B-VII Release 0 evaluations have been prepared using the AMPX code system. Both sets of cross sections have been generated at multiple temperatures: 300, 600, 900, 1200, and 2400 K. In addition, the cross sections for the nuclides with thermal scattering data have been generated at the temperatures that are provided in the corresponding ENDF/B evaluation files. Although temperature interpolation of the cross sections is not yet available in the continuous energy

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mode of KENO, having multiple temperature cross sections available allows more accurate (albeit possibly approximate) analysis of high-temperature systems. As part of the benchmarking effort, critical benchmark experiments that include a wide variety of fissile systems in various moderator and reflector configurations have been selected.

This paper provides the results of initial validation efforts for KENO and the corresponding continuous energy cross-section data that are based on the ENDF/B-VII Release 0 evaluations for more than 500 benchmark problems. These benchmark problems provide a comprehensive validation suite. Goluoglu et al. (2007) have previously reported the performance of the code and continuous energy cross sections based on ENDF/B-VI Release 8 for a limited number of benchmarks.

2. Benchmark Problems

Benchmark problems that have been used in this study have been selected to provide a validation suite from a wide range of fissile systems. The benchmark problems have been divided into six groups: High enriched uranium systems (HEU), intermediate enriched uranium systems (IEU), low enriched uranium systems (LEU), mixed oxide systems (MOX), plutonium systems (Pu), and ^{233}U systems (U-233). The benchmark problems are from the *International Handbook of Evaluated Criticality Safety Benchmark Experiments* (*IHECSBE*) (2007). The case filenames in the following sections are based on the *IHECSBE* naming conventions with minor changes. Since the benchmark problems are from the *IHECSBE*, detailed model descriptions have not been provided in this paper. Rather, the reader is referred to the documentation provided with the *IHECSBE*.

3. Validation and Results

A total of 515 benchmark problems have been modeled and analyzed in six groups. The following sections provide detailed analysis results for these benchmark groups. All KENO calculations used continuous energy cross sections based on ENDF/B-VII Release 0 evaluations and have been run with a sufficient total number of histories to achieve a standard deviation of k_{eff} of 0.0005 or less. In the following sections, the percent differences have been adjusted to account for the uncertainty in the calculated k_{eff} values and the uncertainty in the benchmark k_{eff} values.

3.1. HEU

This group consists of 184 HEU systems. The calculated k_{eff} values and percent differences are shown in Fig. 1 to identify cases that show poor agreement. Table 1 lists the benchmark filenames, k_{eff} values, and KENO calculated k_{eff} values.

The vast majority of the benchmarks in this group are calculated very accurately.

The hci005 series benchmarks show poor agreement. Three of the cases that show poor agreement are noted below. These benchmarks also have unusually high benchmark k_{eff} values (greater than 1.0). Clearly, the values were extrapolated; a benchmark k_{eff} value of even 1.03 (for hci005.1) implies a super prompt critical configuration that would not be possible for a critical benchmark experiment in a laboratory. A review of the corresponding evaluation document from the *IHECSBE* has been performed to determine the cause of these large discrepancies. The evaluators of the hci005 series experiments report similar large discrepancies with various codes and cross-section data sets and believe that the problem is with the cross sections for the structural materials such as iron, chromium, nickel, and zirconium.

The next set of benchmarks that show large discrepancies is from the hmf007 series (cases 32, 33, and 34). These three cases are the only cases from the hmf007 series that contain a Teflon (CF_2) moderator. Sample calculations that have been provided by the evaluators also show large discrepancies between the calculated and measured benchmark k_{eff} values for these cases. Therefore, it is likely that fluorine cross sections are the reason for overestimating their k_{eff} values.

The benchmark hmf060 is also poorly calculated. Evaluators for this benchmark report similarly high calculated values for this configuration, which is a cylindrical assembly of U metal (93% ^{235}U) and tungsten with aluminum reflectors (also identified as ZPR-9, assembly 4).

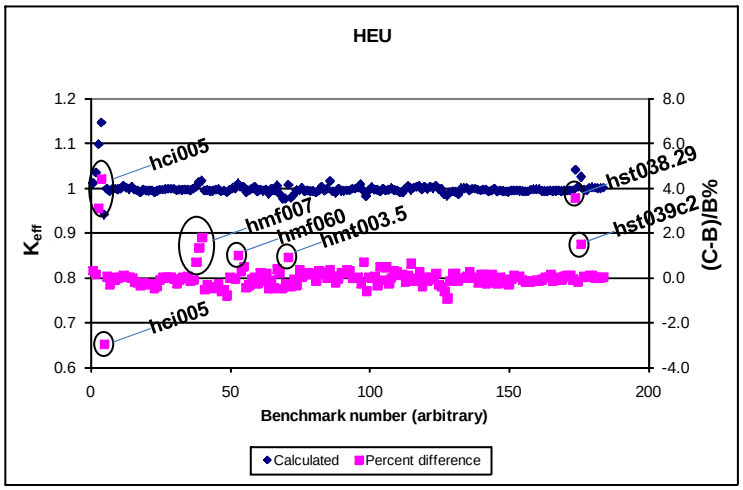

Fig. 1. Calculated k_{eff} values and percent differences for HEU benchmarks.

Table 1
Calculated k_{eff} values and percent differences for HEU benchmarks

Benchmark				KENO-CE	Benchmark				KENO-CE
No.	Name	k_{eff}	Uncertainty	k_{eff}	No.	Name	k_{eff}	Uncertainty	k_{eff}
1	hci004	1.0000	0.0040	1.0110	36	hmf007-30	0.9981	0.0002	0.9955
2	hci005.1	1.0320	0.0040	1.0343	37	hmf007-31	1.0013	0.0002	0.9989
3	hci005.2	1.0500	0.0080	1.0984	38	hmf007-32	0.9959	0.0001	1.0038
4	hci005.4	1.0640	0.0180	1.1466	39	hmf007-33	0.9995	0.0001	1.0135
5	hci005.5	0.9970	0.0130	0.9413	40	hmf007-34	0.9977	0.0001	1.0165
6	hmf001.bare	1.0000	0.0010	0.9993	41	hmf007-35	1.0011	0.0001	0.9946
7	hmf007-01	0.9971	0.0001	0.9929	42	hmf007-36	0.9999	0.0001	0.9956
8	hmf007-02	0.9986	0.0001	0.9983	43	hmf007-37	0.9988	0.0001	0.9935
9	hmf007-03	1.0012	0.0001	0.9988	44	hmf007-38	1.0000	0.0001	0.9940
10	hmf007-04	0.9970	0.0001	0.9976	45	hmf007-39	1.0018	0.0001	0.9967
11	hmf007-05	1.0000	0.0001	0.9991	46	hmf007-40	1.0013	0.0001	0.9975
12	hmf007-06	1.0028	0.0001	1.0047	47	hmf007-41	0.9994	0.0001	0.9923
13	hmf007-07	0.9996	0.0001	1.0008	48	hmf007-42	1.0016	0.0001	0.9949
14	hmf007-08	0.9992	0.0001	0.9981	49	hmf007-43	0.9998	0.0001	0.9906
15	hmf007-09	1.0017	0.0008	1.0022	50	hmf022	1.0000	0.0019	0.9959
16	hmf007-10	1.0000	0.0001	0.9969	51	hmf027	1.0000	0.0025	0.9997
17	hmf007-11	0.9982	0.0001	0.9949	52	hmf028	1.0000	0.0030	0.9982
18	hmf007-12	0.9951	0.0001	0.9905	53	hmf060	0.9955	0.0024	1.0102
19	hmf007-13	1.0009	0.0001	0.9974	54	hmf067.1	0.9959	0.0024	1.0032
20	hmf007-14	0.9983	0.0001	0.9941	55	hmf067.2	0.9938	0.0024	1.0034
21	hmf007-15	0.9978	0.0001	0.9938	56	hmi006.1	0.9977	0.0008	0.9912
22	hmf007-16	0.9988	0.0001	0.9949	57	hmi006.2	1.0001	0.0008	0.9947
23	hmf007-17	0.9972	0.0001	0.9913	58	hmi006.3	1.0015	0.0009	0.9987
24	hmf007-18	0.9991	0.0001	0.9939	59	hmi006.4	1.0016	0.0008	1.0030
25	hmf007-19	0.9983	0.0001	0.9962	60	hmm005.1	1.0007	0.0027	0.9922
26	hmf007-20	0.9981	0.0001	0.9971	61	hmm005.2	1.0003	0.0028	0.9967
27	hmf007-21	0.9987	0.0001	0.9978	62	hmm005.3	1.0012	0.0029	0.9938
28	hmf007-22	0.9994	0.0001	0.9983	63	hmm005.4	1.0016	0.0030	0.9973
29	hmf007-23	0.9993	0.0001	0.9982	64	hmm005.5	1.0005	0.0040	0.9874
30	hmf007-24	1.0001	0.0001	0.9982	65	hmt001detail	1.0010	0.0060	0.9988
31	hmf007-25	0.9990	0.0001	0.9952	66	hmt001simple	1.0010	0.0060	0.9952
32	hmf007-26	0.9997	0.0001	0.9974	67	hmt003.1	1.0000	0.0010	1.0059
33	hmf007-27	0.9965	0.0002	0.9960	68	hmt003.2	0.9910	0.0030	0.9869
34	hmf007-28	0.9987	0.0002	0.9974	69	hmt003.3	0.9826	0.0060	0.9768
35	hmf007-29	0.9978	0.0002	0.9971	70	hmt003.4	0.9876	0.0040	0.9768

Table 1
Calculated k_{eff} values and percent differences for HEU benchmarks (continued)

Benchmark				KENO-CE
No.	Name	k_{eff}	Uncertainty	k_{eff}
71	hmt003.5	0.9930	0.0030	1.0078
72	hmt003.6	0.9889	0.0030	0.9787
73	hmt003.7	0.9919	0.0030	0.9849
74	hmt006.01	1.0000	0.0044	0.9954
75	hmt006.02	1.0000	0.0040	0.9952
76	hmt006.03	1.0000	0.0040	1.0000
77	hmt006.04	1.0000	0.0040	0.9935
78	hmt006.05	1.0000	0.0040	0.9940
79	hmt006.06	1.0000	0.0040	0.9933
80	hmt006.07	1.0000	0.0040	0.9935
81	hmt006.08	1.0000	0.0040	0.9903
82	hmt006.09	1.0000	0.0040	0.9951
83	hmt006.10	1.0000	0.0040	1.0024
84	hmt006.11	1.0000	0.0040	0.9941
85	hmt006.12	1.0000	0.0040	0.9987
86	hmt006.13	1.0000	0.0061	1.0157
87	hmt006.14	1.0000	0.0040	0.9922
88	hmt006.15	1.0000	0.0040	0.9895
89	hmt006.16	1.0000	0.0040	0.9984
90	hmt006.17	1.0000	0.0040	0.9939
91	hmt006.18	1.0000	0.0040	0.9939
92	hmt006.19	1.0000	0.0040	0.9952
93	hmt006.20	1.0000	0.0040	0.9950
94	hmt006.21	1.0000	0.0040	0.9986
95	hmt006.22	1.0000	0.0040	0.9987
96	hmt006.23	1.0000	0.0040	1.0008
97	hmt008detail	1.0009	0.0052	1.0085
98	hmt010.15mil	1.0026	0.0072	0.9949
99	hmt010.7.5mil	1.0030	0.0072	0.9825
100	hmt013.15mil	0.9983	0.0020	0.9944
101	hmt013.625in	1.0021	0.0022	1.0017
102	hmt014simple	0.9939	0.0015	0.9973
103	hst001.01	1.0004	0.0060	0.9958
104	hst001.02	1.0021	0.0072	0.9925
105	hst001.03	1.0003	0.0035	0.9982
106	hst001.04	1.0008	0.0053	0.9946
107	hst001.05	1.0001	0.0049	0.9963
108	hst001.06	1.0002	0.0046	0.9997
109	hst001.07	1.0008	0.0040	0.9957
110	hst001.08	0.9998	0.0038	0.9946
111	hst001.09	1.0008	0.0054	0.9908
112	hst001.10	0.9993	0.0054	0.9899
113	hst002.01	1.0025	0.0058	0.9994
114	hst002.02	1.0028	0.0058	1.0044
115	hst002.03	1.0033	0.0068	0.9958
116	hst002.04	1.0034	0.0069	1.0007
117	hst002.05	1.0018	0.0044	1.0025
118	hst002.06	1.0023	0.0041	1.0058
119	hst002.07	1.0025	0.0050	0.9974
120	hst002.08	1.0030	0.0055	1.0032
121	hst002.09	1.0012	0.0046	0.9985
122	hst002.10	1.0024	0.0050	1.0036
123	hst002.11	1.0017	0.0038	1.0002
124	hst002.12	1.0027	0.0050	1.0053
125	hst002.13	1.0025	0.0055	0.9981
126	hst002.14	1.0031	0.0066	0.9981
127	hst004.1	1.0000	0.0033	0.9870
128	hst004.2	1.0000	0.0036	0.9833
129	hst004.3	1.0000	0.0039	0.9905
130	hst004.4	1.0000	0.0046	0.9924
131	hst004.5	1.0000	0.0052	0.9912
132	hst004.6	1.0000	0.0059	0.9867
133	hst009.1	0.9990	0.0043	0.9996
134	hst009.2	1.0000	0.0039	0.9997
135	hst009.3	1.0000	0.0036	1.0005
136	hst009.4	0.9986	0.0035	0.9940
137	hst010.1	1.0000	0.0029	0.9986
138	hst010.2	1.0000	0.0029	0.9990
139	hst010.3	1.0000	0.0029	0.9967
140	hst010.4	0.9992	0.0029	0.9944
141	hst013.1	1.0012	0.0026	0.9973
142	hst013.2	1.0007	0.0036	0.9969
143	hst013.3	1.0009	0.0036	0.9924
144	hst013.4	1.0003	0.0036	0.9942
145	hst032.1	1.0015	0.0026	0.9987
146	hst038.01	1.0000	0.0025	0.9921
147	hst038.02	1.0000	0.0025	0.9950
148	hst038.03	1.0000	0.0025	0.9935
149	hst038.04	1.0000	0.0025	0.9926
150	hst038.05	1.0000	0.0025	0.9918
151	hst038.06	1.0000	0.0025	0.9941
152	hst038.07	1.0000	0.0032	0.9946
153	hst038.08	1.0000	0.0026	0.9947
154	hst038.09	1.0000	0.0033	0.9939
155	hst038.10	1.0000	0.0026	0.9934
156	hst038.11	1.0000	0.0025	0.9929
157	hst038.12	1.0000	0.0025	0.9931
158	hst038.13	1.0000	0.0050	0.9971
159	hst038.14	1.0000	0.0050	0.9975
160	hst038.15	1.0000	0.0050	0.9976
161	hst038.16	1.0000	0.0050	0.9976
162	hst038.17	1.0000	0.0026	0.9937
163	hst038.18	1.0000	0.0032	0.9935
164	hst038.19	1.0000	0.0032	0.9935
165	hst038.20	1.0000	0.0032	0.9949
166	hst038.21	1.0000	0.0025	0.9933
167	hst038.22	1.0000	0.0027	0.9937
168	hst038.23	1.0000	0.0027	0.9945
169	hst038.24	1.0000	0.0026	0.9934
170	hst038.25	1.0000	0.0032	0.9938
171	hst038.26	1.0000	0.0032	0.9943
172	hst038.27	1.0000	0.0032	0.9943
173	hst038.28	1.0000	0.0025	0.9939
174	hst038.29	1.0000	0.0025	1.0406
175	hst038.30	1.0000	0.0027	1.0033
176	hst039c2	1.0000	0.0051	1.0251
177	hst042.1	0.9957	0.0039	0.9960
178	hst042.2	0.9965	0.0036	0.9956
179	hst042.3	0.9994	0.0028	1.0012
180	hst042.4	1.0000	0.0034	1.0017
181	hst042.5	1.0000	0.0034	1.0008
182	hst042.6	1.0000	0.0037	0.9997
183	hst042.7	1.0000	0.0036	0.9998
184	hst042.8	1.0000	0.0035	1.0011

Case 5 of the hmt003 series benchmarks calculates high. For this case, the evaluators report about 0.9% difference between calculated and measured values as well.

The benchmark case hst038 case 29 exhibits a large difference between the measured and calculated k_{eff} values. Evaluators of this series also obtain very large discrepancies and indicate that the cause of this large difference for case 29 is unknown.

The benchmark case hst039 case 2 also exhibits a large difference between the measured and calculated k_{eff} values. Sample calculation results provided by the evaluators show similar large deviations for hst039 series benchmarks.

3.2. IEU

This group consists of 18 IEU systems. The calculated k_{eff} values and percent differences are shown in Fig. 2 to identify cases that show poor agreement. Table 2 lists the benchmark filenames, k_{eff} values, and KENO calculated k_{eff} values.

The agreement for all benchmark problems in this group is very good with an average percent difference of 0.04.

3.3. LEU

This group consists of 225 LEU systems. The calculated k_{eff} values and percent differences are shown in Fig. 3 to identify cases that show poor agreement. Table 3 lists the benchmark filenames, k_{eff} values, and KENO calculated k_{eff} values.

The agreement for all benchmark problems in this group is good; the average percent difference of –0.13. It is worth noting that the lct003 series benchmarks are underestimated. For this series of benchmarks, the evaluators also note that all cases are underpredicted by as much as 1% using various codes and data sets.

3.4. MOX

This group consists of 45 MOX systems. The calculated k_{eff} values and percent differences are shown in Fig. 4 to identify cases that show poor agreement. Table 4 lists the benchmark filenames, k_{eff} values, and KENO calculated k_{eff} values.

Cases 1 through 6 of the mct012 series benchmarks are poorly calculated. A review of the evaluations for these benchmarks revealed that evaluators also observed large differences between expected and calculated k_{eff} values for this set (cases 1 through 6 are in set I of mct012 series of benchmarks). The reason for large deviations for this set of benchmarks is not known. However, evaluators believe it may be due to the plutonium isotopics. Cases 31 through 33 also exhibit large differences. This behavior is not observed by the evaluators. Although the differences are large, the k_{eff} values are within 3σ of each other. Large differences in cases 31 through 33 are attributed to the large benchmark uncertainties.

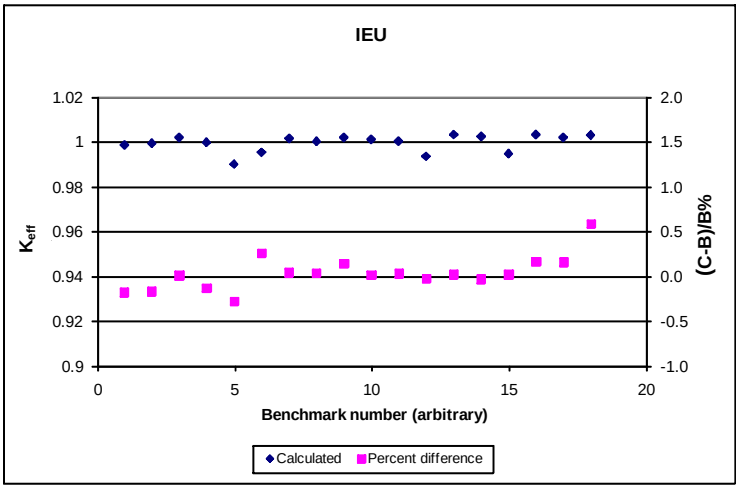

Fig. 2. Calculated k_{eff} values and percent differences for IEU benchmarks.

Table 2
Calculated k_{eff} values and percent differences for IEU benchmarks

Benchmark				KENO-CE
No.	Name	k_{eff}	Uncertainty	k_{eff}
1	ict002.1	1.0014	0.0039	0.9986
2	ict002.2	1.0019	0.0040	0.9993
3	ict002.3	1.0017	0.0044	1.0018
4	ict002.4	1.0019	0.0044	0.9997
5	ict002.5	1.0014	0.0043	0.9900
6	ict002.6	1.0016	0.0044	0.9954
7	imf001.1i	0.9989	0.0009	1.0014
8	imf001.2i	0.9997	0.0009	1.0001
9	imf001.3i	0.9993	0.0003	1.0019
10	imf001.4i	1.0002	0.0003	1.0010

Benchmark				KENO-CE
No.	Name	k_{eff}	Uncertainty	k_{eff}
11	imf002.1	1.0000	0.0030	1.0003
12	imf007.twozone	0.9948	0.0013	0.9936
13	imf-007 detail	1.0045	0.0007	1.0033
14	imf-007 simple	1.0045	0.0007	1.0025
15	imf010.1	0.9954	0.0024	0.9946
16	imf012.1	1.0007	0.0027	1.0033
17	imf014.1	0.9958	0.0022	1.0019
18	imf014.2	0.9927	0.0022	1.0030

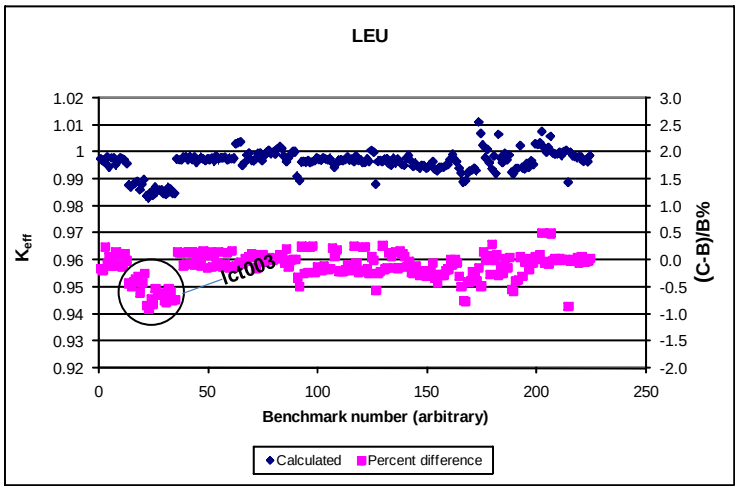

Fig. 3. Calculated k_{eff} values and percent differences for LEU benchmarks.

Table 3
Calculated k_{eff} values and percent differences for LEU benchmarks

Benchmark				KENO-CE
No.	Name	k_{eff}	Uncertainty	k_{eff}
1	lct001.1	1.0000	0.0031	0.9974
2	lct001.2	0.9998	0.0030	0.9968
3	lct001.3	0.9998	0.0030	0.9961
4	lct001.4	0.9998	0.0030	0.9980
5	lct001.5	0.9998	0.0030	0.9944
6	lct001.6	0.9998	0.0030	0.9977
7	lct001.7	0.9998	0.0031	0.9977
8	lct001.8	0.9998	0.0030	0.9952
9	lct002.1	0.9997	0.0020	0.9964
10	lct002.2	0.9997	0.0020	0.9978
11	lct002.3	0.9997	0.0020	0.9974
12	lct002.4	0.9997	0.0018	0.9971
13	lct002.5	0.9997	0.0019	0.9956
14	lct003.01	1.0000	0.0039	0.9877
15	lct003.02	1.0000	0.0039	0.9871

Benchmark				KENO-CE
No.	Name	k_{eff}	Uncertainty	k_{eff}
16	lct003.03	1.0000	0.0039	0.9880
17	lct003.04	1.0000	0.0039	0.9886
18	lct003.05	1.0000	0.0039	0.9890
19	lct003.06	1.0000	0.0039	0.9860
20	lct003.07	1.0000	0.0039	0.9879
21	lct003.08	1.0000	0.0039	0.9896
22	lct003.09	1.0000	0.0039	0.9837
23	lct003.10	1.0000	0.0039	0.9830
24	lct003.11	1.0000	0.0039	0.9849
25	lct003.12	1.0000	0.0039	0.9838
26	lct003.13	1.0000	0.0039	0.9868
27	lct003.14	1.0000	0.0039	0.9856
28	lct003.15	1.0000	0.0039	0.9859
29	lct003.16	1.0000	0.0039	0.9858
30	lct003.17	1.0000	0.0039	0.9846

Table 3
Calculated k_{eff} values and percent differences for LEU benchmarks (continued)

Benchmark				KENO-CE
No.	Name	k_{eff}	Uncertainty	k_{eff}
31	lct003.18	1.0000	0.0039	0.9842
32	lct003.19	1.0000	0.0039	0.9868
33	lct003.20	1.0000	0.0039	0.9863
34	lct003.21	1.0000	0.0039	0.9846
35	lct003.22	1.0000	0.0039	0.9847
36	lct009-01	1.0000	0.0021	0.9973
37	lct009-02	1.0000	0.0021	0.9970
38	lct009-03	1.0000	0.0021	0.9971
39	lct009-04	1.0000	0.0021	0.9980
40	lct009-05	1.0000	0.0021	0.9982
41	lct009-06	1.0000	0.0021	0.9972
42	lct009-07	1.0000	0.0021	0.9982
43	lct009-08	1.0000	0.0021	0.9972
44	lct009-09	1.0000	0.0021	0.9981
45	lct009-10	1.0000	0.0021	0.9962
46	lct009-11	1.0000	0.0021	0.9970
47	lct009-12	1.0000	0.0021	0.9979
48	lct009-13	1.0000	0.0021	0.9974
49	lct009-14	1.0000	0.0021	0.9966
50	lct009-15	1.0000	0.0021	0.9975
51	lct009-16	1.0000	0.0021	0.9972
52	lct009-17	1.0000	0.0021	0.9977
53	lct009-18	1.0000	0.0021	0.9965
54	lct009-19	1.0000	0.0021	0.9984
55	lct009-20	1.0000	0.0021	0.9973
56	lct009-21	1.0000	0.0021	0.9978
57	lct009-22	1.0000	0.0021	0.9978
58	lct009-23	1.0000	0.0021	0.9981
59	lct009-24	1.0000	0.0021	0.9970
60	lct009-25	1.0000	0.0021	0.9975
61	lct009-26	1.0000	0.0021	0.9974
62	lct009-27	1.0000	0.0021	0.9976
63	lct010-01	1.0000	0.0021	1.0029
64	lct010-02	1.0000	0.0021	1.0034
65	lct010-03	1.0000	0.0021	1.0037
66	lct010-04	1.0000	0.0021	0.9950
67	lct010-05	1.0000	0.0021	0.9961
68	lct010-06	1.0000	0.0021	0.9988
69	lct010-07	1.0000	0.0021	0.9995
70	lct010-08	1.0000	0.0021	0.9969
71	lct010-09	1.0000	0.0021	0.9966
72	lct010-10	1.0000	0.0021	0.9974
73	lct010-11	1.0000	0.0021	0.9994
74	lct010-12	1.0000	0.0021	0.9995
75	lct010-13	1.0000	0.0021	0.9967
76	lct010-14	1.0000	0.0028	0.9985
77	lct010-15	1.0000	0.0028	0.9999
78	lct010-16	1.0000	0.0028	1.0004
79	lct010-17	1.0000	0.0028	0.9993
80	lct010-18	1.0000	0.0028	0.9999
81	lct010-19	1.0000	0.0028	0.9992
82	lct010-20	1.0000	0.0028	1.0012
83	lct010-21	1.0000	0.0028	1.0018
84	lct010-22	1.0000	0.0028	1.0013
85	lct010-23	1.0000	0.0028	0.9984
86	lct010-24	1.0000	0.0028	0.9964
87	lct010-25	1.0000	0.0028	0.9977
88	lct010-26	1.0000	0.0028	0.9989
89	lct010-27	1.0000	0.0028	1.0001
90	lct010-28	1.0000	0.0028	1.0000
91	lct010-29	1.0000	0.0028	0.9910
92	lct010-30	1.0000	0.0028	0.9893
93	lct016.01	1.0000	0.0031	0.9962
94	lct016.02	1.0000	0.0031	0.9964
95	lct016.03	1.0000	0.0031	0.9962
96	lct016.04	1.0000	0.0031	0.9966
97	lct016.05	1.0000	0.0031	0.9961
98	lct016.06	1.0000	0.0031	0.9963
99	lct016.07	1.0000	0.0031	0.9967
100	lct016.08	1.0000	0.0031	0.9976
101	lct016.09	1.0000	0.0031	0.9972
102	lct016.10	1.0000	0.0031	0.9970
103	lct016.11	1.0000	0.0031	0.9978
104	lct016.12	1.0000	0.0031	0.9973
105	lct016.13	1.0000	0.0031	0.9972
106	lct016.14	1.0000	0.0031	0.9975
107	lct016.15	1.0000	0.0031	0.9960
108	lct016.16	1.0000	0.0031	0.9943
109	lct016.17	1.0000	0.0031	0.9956
110	lct016.18	1.0000	0.0031	0.9969
111	lct016.19	1.0000	0.0031	0.9969
112	lct016.20	1.0000	0.0031	0.9968
113	lct016.21	1.0000	0.0031	0.9972
114	lct016.22	1.0000	0.0031	0.9980
115	lct016.23	1.0000	0.0031	0.9970
116	lct016.24	1.0000	0.0031	0.9973
117	lct016.25	1.0000	0.0031	0.9963
118	lct016.26	1.0000	0.0031	0.9984
119	lct016.27	1.0000	0.0031	0.9967
120	lct016.28	1.0000	0.0031	0.9969
121	lct016.29	1.0000	0.0031	0.9962
122	lct016.30	1.0000	0.0031	0.9961
123	lct016.31	1.0000	0.0031	0.9973
124	lct016.32	1.0000	0.0031	0.9965
125	lct017-01	1.0000	0.0031	1.0005
126	lct017-02	1.0000	0.0031	0.9999
127	lct017-03	1.0000	0.0031	0.9880
128	lct017-10	1.0000	0.0031	0.9965
129	lct017-11	1.0000	0.0031	0.9968
130	lct017-12	1.0000	0.0031	0.9964
131	lct017-13	1.0000	0.0031	0.9972
132	lct017-14	1.0000	0.0031	0.9975

Table 3
Calculated k_{eff} values and percent differences for LEU benchmarks (continued)

Benchmark				KENO-CE
No.	Name	k_{eff}	Uncertainty	k_{eff}
133	lct017-15	1.0000	0.0028	0.9957
134	lct017-16	1.0000	0.0028	0.9951
135	lct017-17	1.0000	0.0028	0.9976
136	lct017-18	1.0000	0.0028	0.9959
137	lct017-19	1.0000	0.0028	0.9974
138	lct017-20	1.0000	0.0028	0.9959
139	lct017-21	1.0000	0.0028	0.9954
140	lct017-22	1.0000	0.0028	0.9949
141	lct017-23	1.0000	0.0028	0.9976
142	lct017-24	1.0000	0.0028	0.9987
143	lct017-25	1.0000	0.0028	0.9968
144	lct039.01	1.0000	0.0014	0.9946
145	lct039.02	1.0000	0.0014	0.9958
146	lct039.03	1.0000	0.0014	0.9946
147	lct039.04	1.0000	0.0014	0.9941
148	lct039.05	1.0000	0.0014	0.9950
149	lct039.06	1.0000	0.0014	0.9948
150	lct039.07	1.0000	0.0014	0.9939
151	lct039.08	1.0000	0.0014	0.9945
152	lct039.09	1.0000	0.0014	0.9949
153	lct039.10	1.0000	0.0014	0.9964
154	lct039.11	1.0000	0.0014	0.9936
155	lct039.12	1.0000	0.0014	0.9928
156	lct039.13	1.0000	0.0014	0.9943
157	lct039.14	1.0000	0.0014	0.9942
158	lct039.15	1.0000	0.0014	0.9942
159	lct039.16	1.0000	0.0014	0.9950
160	lct039.17	1.0000	0.0014	0.9953
161	lct051.01	1.0010	0.0020	0.9969
162	lct051.02	1.0010	0.0024	0.9990
163	lct051.09	1.0010	0.0019	0.9973
164	lct051.10	1.0010	0.0019	0.9964
165	lct051.11	1.0010	0.0019	0.9940
166	lct051.12	1.0010	0.0019	0.9921
167	lct051.13	1.0010	0.0022	0.9889
168	lct051.14	1.0010	0.0019	0.9892
169	lct051.15	1.0010	0.0024	0.9920
170	lct051.16	1.0010	0.0020	0.9928
171	lct051.17	1.0010	0.0027	0.9932
172	lct051.18	1.0010	0.0021	0.9939
173	lct051.19	1.0010	0.0019	0.9931
174	lct019c1	1.0000	0.0063	1.0111
175	lct019c2	1.0000	0.0058	1.0067
176	lct019c3	1.0000	0.0061	1.0025
177	lmt001.1	0.9990	0.0057	0.9979
178	lst001	0.9991	0.0029	1.0008
179	lst03c1	0.9997	0.0039	0.9960
180	lst03c2	0.9993	0.0042	0.9937
181	lst03c3	0.9995	0.0042	0.9984
182	lst03c4	0.9995	0.0042	0.9920
183	lst03c5	0.9997	0.0048	1.0065
184	lst03c6	0.9999	0.0049	0.9977
185	lst03c7	0.9994	0.0049	0.9960
186	lst03c8	0.9993	0.0052	0.9995
187	lst03c9	0.9996	0.0052	0.9971
188	lst04-R01	0.9994	0.0008	0.9988
189	lst04-R29	0.9999	0.0009	0.9924
190	lst04-R33	0.9999	0.0009	0.9920
191	lst04-R34	0.9999	0.0010	0.9937
192	lst04-R46	0.9999	0.0010	0.9939
193	lst04-R51	0.9994	0.0011	1.0023
194	lst04-R54	0.9996	0.0011	0.9941
195	lst07-R14	0.9961	0.0009	0.9936
196	lst07-R30	0.9973	0.0009	0.9957
197	lst07-R32	0.9985	0.0010	0.9944
198	lst07-R36	0.9988	0.0011	0.9966
199	lst07-R49	0.9983	0.0011	0.9952
200	lst16-R105	0.9996	0.0013	1.0029
201	lst16-R113	0.9999	0.0013	1.0027
202	lst16-R125	0.9994	0.0014	1.0033
203	lst16-R129	0.9996	0.0014	1.0075
204	lst16-R131	0.9995	0.0014	1.0016
205	lst16-R140	0.9992	0.0015	0.9998
206	lst16-R196	0.9994	0.0015	1.0016
207	lst17-R104	0.9981	0.0013	1.0057
208	lst17-R122	0.9986	0.0013	0.9995
209	lst17-R123	0.9989	0.0014	0.9992
210	lst17-R126	0.9992	0.0014	0.9992
211	lst17-R130	0.9987	0.0015	0.9998
212	lst17-R147	0.9996	0.0015	0.9986
213	lst18c1	0.9992	0.0010	1.0001
214	lst18c3	0.9996	0.0010	1.0006
215	lst18c4	0.9997	0.0010	0.9888
216	lst18c5	0.9992	0.0010	0.9999
217	lst18c6	0.9996	0.0010	0.9986
218	lst20-R216	0.9995	0.0010	0.9983
219	lst20-R217	0.9996	0.0010	0.9980
220	lst20-R220	0.9997	0.0012	0.9982
221	lst20-R226	0.9998	0.0012	0.9980
222	lst21-R215	0.9983	0.0009	0.9964
223	lst21-R218	0.9985	0.0010	0.9970
224	lst21-R221	0.9989	0.0011	0.9963
225	lst21-R223	0.9993	0.0012	0.9986

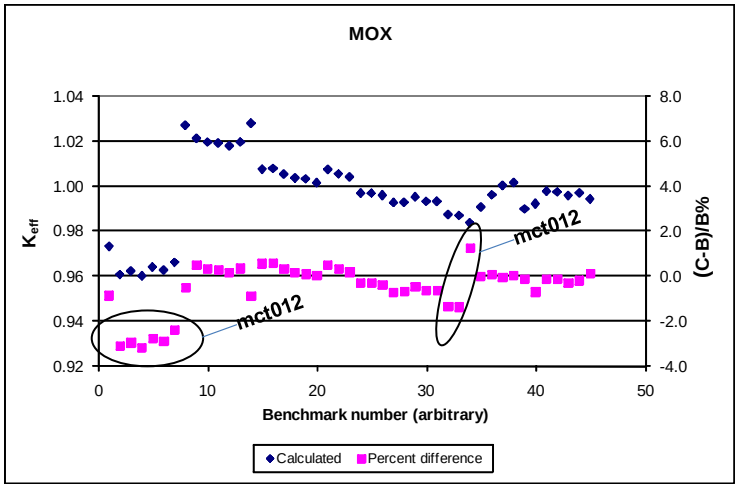

Fig. 4. Calculated k_{eff} values and percent differences for MOX benchmarks.

Table 4
Calculated k_{eff} values and percent differences for MOX benchmarks

Benchmark				KENO-CE	Benchmark				KENO-CE
No.	Name	k_{eff}	Uncertainty	k_{eff}	No.	Name	k_{eff}	Uncertainty	k_{eff}
1	mcf001	0.9866	0.0023	0.9733	24	mct012.23	1.0007	0.0114	0.9968
2	mct012.01	1.0052	0.0067	0.9608	25	mct012.24	1.0007	0.0114	0.9968
3	mct012.02	1.0052	0.0067	0.9623	26	mct012.25	1.0007	0.0114	0.9959
4	mct012.03	1.0052	0.0067	0.9600	27	mct012.26	1.0007	0.0114	0.9926
5	mct012.04	1.0052	0.0067	0.9641	28	mct012.27	1.0007	0.0114	0.9928
6	mct012.05	1.0052	0.0067	0.9627	29	mct012.28	1.0007	0.0114	0.9951
7	mct012.06	1.0052	0.0075	0.9662	30	mct012.29	1.0007	0.0114	0.9933
8	mct012.07	1.0053	0.0134	1.0270	31	mct012.30	1.0007	0.0114	0.9933
9	mct012.08	1.0053	0.0055	1.0213	32	mct012.31	1.0017	0.0151	0.9873
10	mct012.09	1.0053	0.0055	1.0196	33	mct012.32	1.0017	0.0151	0.9870
11	mct012.10	1.0053	0.0055	1.0192	34	mct012.33	1.0017	0.0151	0.9837
12	mct012.11	1.0053	0.0055	1.0179	35	mmf011.1	0.9897	0.0023	0.9906
13	mct012.12	1.0053	0.0055	1.0197	36	mmf011.2	0.9998	0.0023	0.9960
14	mct012.13	1.0053	0.0158	1.0280	37	mmf011.3	1.0018	0.0024	1.0002
15	mct012.14	1.0012	0.0086	1.0076	38	mmf011.4	1.0012	0.0024	1.0016
16	mct012.15	1.0012	0.0086	1.0078	39	mst007.1	1.0000	0.0043	0.9899
17	mct012.16	1.0012	0.0086	1.0053	40	mst007.2	1.0000	0.0077	0.9922
18	mct012.17	1.0012	0.0086	1.0036	41	mst007.3	1.0000	0.0046	0.9976
19	mct012.18	1.0012	0.0086	1.0031	42	mst007.4	1.0000	0.0046	0.9975
20	mct012.19	1.0012	0.0086	1.0014	43	mst007.5	1.0000	0.0091	0.9959
21	mct012.20	1.0014	0.0114	1.0073	44	mst007.6	1.0000	0.0043	0.9969
22	mct012.21	1.0014	0.0120	1.0055	45	mst007.7	1.0000	0.0034	0.9943
23	mct012.22	1.0014	0.0152	1.0040					

3.5. Pu

This group consists of 30 Pu systems. The calculated k_{eff} values and percent differences are shown in Fig. 5 to identify cases that show poor agreement. Table 5 lists the benchmark filenames, k_{eff} values, and KENO calculated k_{eff} values.

Case pci001 is underpredicted by 1%, which is slightly less than the experimental uncertainty. However, the calculated and benchmark k_{eff} values are within 3σ of each other.

Case pmi002.1 shows the largest discrepancy in this group. Similar large differences are also noted by the evaluators of this benchmark using various codes and data sets. It is speculated that the differences are due to the iron cross sections for this case (experiment name ZPR-6/10).

Case pst008.10 is overpredicted by more than 1%. Evaluators of the pst008 series benchmarks also report similar trends with various code and data sets.

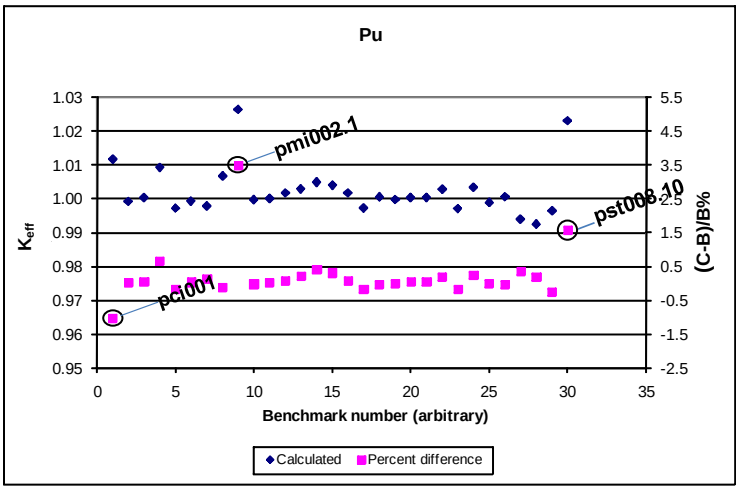

Fig. 5. Calculated k_{eff} values and percent differences for Pu benchmarks.

Table 5
Calculated k_{eff} values and percent differences for Pu benchmarks

Benchmark				KENO-CE	Benchmark				KENO-CE
No.	Name	k_{eff}	Uncertainty	k_{eff}	No.	Name	k_{eff}	Uncertainty	k_{eff}
1	pci001	1.0000	0.0110	1.0116	16	pst005.7	1.0000	0.0047	1.0018
2	pmf001bare	1.0000	0.0020	0.9992	17	pst005.8	1.0000	0.0047	0.9972
3	pmf002	1.0000	0.0020	1.0004	18	pst005.9	1.0000	0.0047	1.0005
4	pmf005	1.0000	0.0013	1.0093	19	pst006.1	1.0000	0.0035	0.9998
5	pmf006	1.0000	0.0030	0.9972	20	pst006.2	1.0000	0.0035	1.0004
6	pmf008.1	1.0000	0.0006	0.9993	21	pst006.3	1.0000	0.0035	1.0005
7	pmf012	1.0009	0.0021	0.9979	22	pst007.02	1.0000	0.0047	1.0028
8	pmf013	1.0034	0.0023	1.0068	23	pst007.03	1.0000	0.0047	0.9971
9	pmi002.1	0.9869	0.0026	1.0265	24	pst007.05	1.0000	0.0047	1.0034
10	pst005.1	1.0000	0.0047	0.9997	25	pst007.06	1.0000	0.0047	0.9988
11	pst005.2	1.0000	0.0047	1.0002	26	pst007.07	1.0000	0.0047	1.0006
12	pst005.3	1.0000	0.0047	1.0017	27	pst007.08	1.0000	0.0047	0.9940
13	pst005.4	1.0000	0.0047	1.0030	28	pst007.09	1.0000	0.0047	0.9925
14	pst005.5	1.0000	0.0047	1.0049	29	pst007.10	1.0000	0.0047	0.9964
15	pst005.6	1.0000	0.0047	1.0041	30	pst008.10	1.0000	0.0037	1.0231

3.6. U-233

This group consists of 13 U-233 systems. The calculated k_{eff} values and percent differences are shown in Fig. 6 to identify cases that show poor agreement. Table 6 lists the benchmark filenames, k_{eff} values, and KENO calculated k_{eff} values.

For this group of benchmarks, the agreement between the benchmark and calculated values is excellent.

4. Summary

More than 500 benchmark problems have been modeled and analyzed in this validation study. The benchmark problems have been divided into six groups: HEU, IEU, LEU, MOX, Pu, and U-233. The average percent difference between the calculated and benchmark k_{eff} values for the HEU group is 0.0. Although there are some benchmark cases in this group that are calculated poorly, calculations reported by the evaluators of these benchmarks using other code and data sets show similar poor agreement. Therefore, the performance of KENO and the associated ENDF/B-VII Release 0 continuous energy cross sections for HEU systems is deemed very good.

The average percent difference between the calculated and benchmark k_{eff} values for the IEU group is 0.04. The performance of KENO and the associated ENDF/B-VII Release 0 continuous energy cross sections for IEU systems is deemed very good.

The average percent difference between the calculated and benchmark k_{eff} values for the LEU group is –0.13. The performance of KENO and the associated ENDF/B-VII Release 0 continuous energy cross sections for LEU systems is deemed very good.

The average percent difference between the calculated and benchmark k_{eff} values for the MOX group is –0.5. The reason for this large average value is set I of the mct012 series benchmarks. Calculations using other code and data sets reported by the evaluators of these benchmarks show similar poor agreement. Therefore, the performance of KENO and the associated ENDF/B-VII Release 0 continuous energy cross sections for MOX systems is deemed very good.

The average percent difference between the calculated and benchmark k_{eff} values for the Pu group is 0.2. Although there are some benchmark cases in this group that calculate poorly, calculations using other code and data sets reported by the evaluators of these benchmarks show similar poor agreement. Therefore, the performance of KENO and the associated ENDF/B-VII Release 0 continuous energy cross sections for Pu systems is deemed very good.

Finally, the average percent difference between the calculated and benchmark k_{eff} values for the U-233 group is 0.0. The performance of KENO and the associated ENDF/B-VII Release 0 continuous energy cross sections for U-233 systems is deemed excellent.

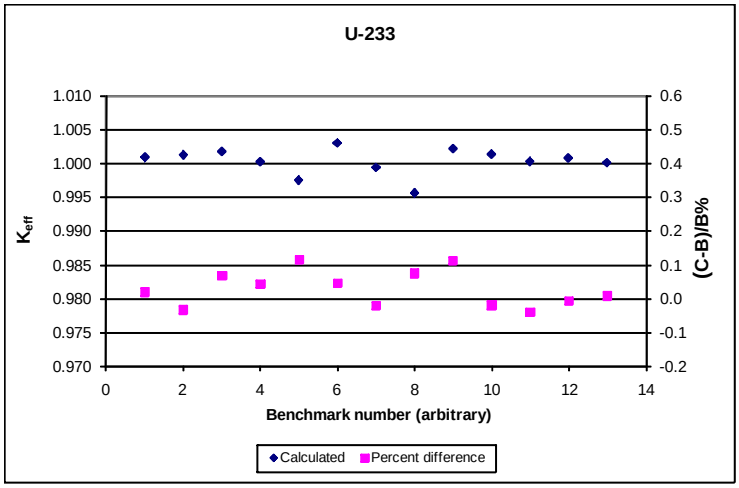

Fig. 6. Calculated k_{eff} values and percent differences for U-233 benchmarks.

Table 6
Calculated k_{eff} values and percent differences for U-233 benchmarks

Benchmark				KENO-CE
No.	Name	k_{eff}	Uncertainty	k_{eff}
1	uct001.1	1.0006	0.0027	1.0008
2	uct001.2	1.0015	0.0025	1.0012
3	uct001.3	1.0000	0.0024	1.0016
4	uct001.4	1.0007	0.0025	1.0001
5	uct001.5	1.0015	0.0026	0.9974
6	uct001.6	1.0015	0.0028	1.0029
7	uct001.7	0.9995	0.0027	0.9993
8	uct001.8	1.0004	0.0028	0.9955
9	ust001.1	1.0000	0.0031	1.0021
10	ust001.2	1.0005	0.0033	1.0013
11	ust001.3	1.0006	0.0033	1.0002
12	ust001.4	0.9998	0.0033	1.0007
13	ust001.5	0.9999	0.0033	1.0000

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