NUCL SCI TECH (2022) 33:8
https://doi.org/10.1007/s41365-022-00994-3

Performance of the CENDL-3.2 and other major neutron data libraries for criticality calculations

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Received: 5 July 2021 / Revised: 15 November 2021 / Accepted: 19 November 2021 / Published online: 18 January 2022

Abstract Nuclear data are the cornerstones of reactor physics and shielding calculations. Recently, China released CENDL-3.2 in 2020, and the US released ENDF/B-VIII.0 in 2018. Therefore, it is necessary to comprehensively evaluate the criticality computing performance of these newly released evaluated nuclear libraries. In this study, we used the NJOY2016 code to generate ACE format libraries based on the latest neutron data libraries (including CENDL-3.2, JEFF3.3, ENDF/B-VIII.0, and JENDL4.0). The MCNP code was used to conduct a detailed analysis of fission nuclides, including ^{235}U, ^{233}U, and ^{239}Pu, in different evaluated nuclear data libraries based on 100 benchmarks. The criticality calculation performance of each library was evaluated using three statistical parameters: $\delta k/\sigma$, χ^2, and $\langle|\Delta|\rangle$. Analysis of the $\delta k/\sigma$ parameter showed that CENDL-3.1 and JENDL-4.0 both had > 10 benchmarks that exceeded 3σ, whereas CENDL-3.2, ENDFB-VIII.0, and JEFF-3.3 had, 7, 5, and 4 benchmarks, respectively, exceeding 3σ. The ENDF/B-VII.1 library performed best, with only two benchmarks exceeding 3σ. Compared to CENDL-3.1, CENDL-3.2 offers an improvement in criticality calculations. Compared to the JEFF-3.3 and ENDF/B-VIII.0 libraries, CENDL3.2 performs better in the calculation of the ^{233}U assemblies, but it performs poorly in the pusl11 series case calculation of the ^{239}Pu assemblies, and thus further improvement is needed.

Keywords Criticality calculations · CENDL-3.2 · ENDF/B-VIII.0 · Neutron · ACE library

This work was supported by the National Natural Science Foundation of China (No. 11875128).

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1 Introduction

Evaluated nuclear data libraries are the basis of reactor physics and shielding calculations. Currently, there are five major evaluated nuclear libraries in the world. Recently, the world's major nuclear data libraries have successively released their latest versions. In 2020, the China Institute of Atomic Energy released CENDL-3.2 [1]. Data for most of the key nuclides in nuclear applications (e.g., U, Pu, Th, and Fe) have been revised and updated in CENDL-3.2. In 2018, the Brookhaven National Laboratory in the US released ENDF/B-VIII.0 [2]. ENDF/B-VIII.0 fully incorporates the new International Atomic Energy Agency standards, includes improved thermal neutron scattering data, and uses newly evaluated data from the CIELO project [3] for neutron reactions on ^{1}H, ^{16}O, ^{56}Fe, ^{235}U, ^{238}U, and ^{239}Pu. In 2017, the Nuclear Energy Agency officially released JEFF-3.3 [4], which thoroughly updated the neutron, decay data, fission yields, and neutron activation libraries in EAF format and provided neutron thermal scattering files for 20 compounds. In 2010, the Japan Atomic Energy Agency released JENDL4.0 [5]. In this new library, much emphasis is placed on the improvement of fission products and minor actinoid data. As of 2016, the ENDF files of some nuclides in JENDL4.0 have been updated. In addition, China's nuclear data measurement technology has also progressed, providing effective support for the evaluation of the CENDL library. Researchers at the Chinese Academy of Sciences [6] measured the neutron capture cross section of ^{197}Au using the time-of-flight technique at the Back-n facility of the China Spallation Neutron Source in the 1 eV to 100 keV range. The results are in good agreement with the ENDF/BVIII.0, CENDL-3.1, and other libraries in the resonance region and in agreement with both neutron time-of-flight and GELINA experimental data in the 5–100 keV range. In addition, researchers at Lanzhou University [7] measured cross sections of the (n,2n) reactions for Nd isotopes induced by 14-MeV neutrons using activation and relative methods. The present results are generally consistent with the ENDF/B-VII.1, CENDL-3.1, and JENDL-4.0 data at neutron energies of 14.2 and 14.9 MeV.

An evaluated nuclear data library cannot be used directly and needs to be processed into a working nuclear library using a nuclear data processing code (such as NJOY [8] or NECP-Atlas [9]). In general, working nuclear libraries are divided into multi-group cross-section libraries for deterministic codes and continuous point-wise cross-section libraries for stochastic codes. The ACE format [10] is a common continuous point-wise cross-section library storage format used in stochastic codes for reactor physics and shielding calculations.

From civil nuclear power plants to space reactors for aerospace and power reactors for submarines, many applications have high requirements for nuclear data libraries. Different evaluated nuclear data libraries employ different evaluations for some important reaction channels of key nuclides. Therefore, it is necessary to conduct detailed tests on the quality of nuclear data from different nuclear data libraries. The validation of nuclear data libraries generally includes criticality, shielding, and depletion tests. The criticality benchmark test is an important form of acceptance testing that can effectively test the data accuracy of key fission nuclides and provide effective guidance for thermal and fast reactor designs. In addition, a more detailed understanding of the criticality calculation performance of the newly released evaluated nuclear data libraries is needed to provide a reference for the choice of nuclear data libraries in thermal and fast reactor designs. Hence, it is very important to evaluate the quality of the newly released nuclear library through criticality benchmark testing.

In this study, the MCNP [11] code was used to evaluate the performance of the newly released evaluated nuclear data libraries for criticality calculations. Several criticality benchmarks from the ICSBEP manual [12] were selected to verify the performance of criticality calculations. The criticality calculation performance of each library was evaluated using three statistical parameters: $\delta k/\sigma$, χ^2, and $\langle|\Delta|\rangle$ [13, 14]. The remainder of this paper is organized as follows: Sect. 2 introduces the methods for the development of the ACE libraries, Sect. 3 describes the numerical verification of the newly released libraries, and Sect. 4 presents our conclusions.

2 Methodology

To study the criticality calculation performance of the newly released evaluated nuclear data libraries, the ACE-formatted libraries for Monte Carlo code calculations based on the CENDL-3.1 [15], CENDL-3.2, ENDF/B-VIII.0, ENDF/B-VII.1 [16], JEFF-3.3, and JENDL-4.0 were created using the NJOY2016 code [8]. Based on the criticality benchmarks in the ICSBEP manual, the criticality calculation performance of different evaluated nuclear data libraries was studied in detail using statistical analysis methods. Section 2.1 describes the methods used to develop the ACE-formatted libraries. Section 2.2 describes the ICSBEP benchmark suite. Section 2.3 describes the details of the statistical analysis methods.

2.1 ACE-formatted libraries and MCNP simulation details

The ACE library production and MCNP simulation processes are shown in Fig. 1. The NJOY program is a popular nuclear data processing program that can generate nuclear data in multiple formats for shielding and criticality calculations based on the evaluated nuclear data library. The JOYPI code can generate NJOY inputs for the development of the ACE library. The ACE format library is a continuous point section library for Monte Carlo program calculations and can be processed by using the NJOY program. The main NJOY modules used to make the ACE library include RECONR, BROASDR, THERMR, PURR, and ACER. The RECONR module performs the point cross-section resonance reconstruction function based on the ENDF file data. The BROADR module performs the temperature-related Doppler broadening function. The THERMR module generates the cross sections for free scatters in the thermal energy range. The PURR module calculates the unresolved resonance probability tables, and the ACER module converts the previously generated data into a c-type ACE file for use in MCNP.

In the benchmark suite of the ICSBEP manual, some benchmarks contain thermal neutron scattering materials, and the corresponding thermal neutron scattering sub-library (TSL library) needs to be processed for calculation. For the new versions of ENDF/B-VIII.0, JENDL-4.0, and JEFF-3.3, there are corresponding TSL libraries, but for CENDL-3.2 and CENDL-3.1, no TSL library is provided.

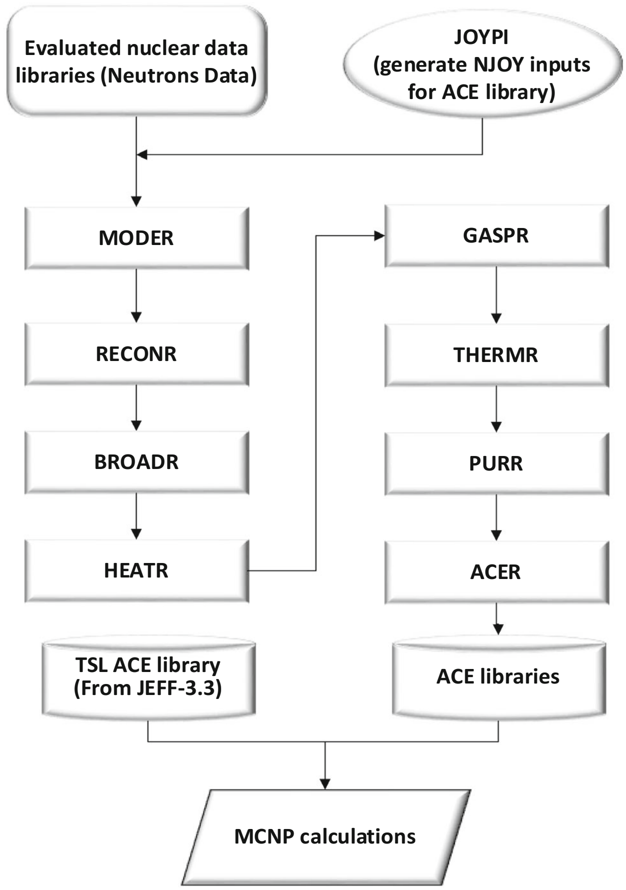


Fig. 1 Production and verification process for the ACE-formatted libraries. MODER, RECONR, BROADR, HEATR, GASPR, THERMR, PURR, ACER are the modules of the NJOY 2016 code. JOYPI is an automatic NJOY input card generating program

Therefore, to maintain the consistency of verification for different evaluated nuclear data libraries, we used the verified and publicly available data of the ACE thermal scattering library of JEFF-3.3 to perform criticality calculations for the benchmarks with thermal neutron scattering materials. The purpose of this study is to verify the overall criticality calculation performance of neutron data libraries. The standard neutron ACE library used in this study was based on different data libraries and was produced using the NJOY2016 program. If there are moderators in the benchmark facilities, the TSL library must be considered in the calculations. The TSL library used for the benchmark with moderators was from the JEFF3.3 ACE library.

For all assemblies calculated by MCNP, 3000 source neutrons were run per kcode cycle. For all metal assembly benchmarks, 40 inactive cycles and 360 active cycles were run. For the solution assemblies, 40 inactive cycles and 760 active cycles were run. These numbers ensure that sufficient active cycles are run to obtain good statistics for k_{eff} calculations [17]. All these benchmarks use the total nubar data in the MCNP input. Eigenvalue uncertainties were < 70 pcm, which is approximately an order of magnitude lower than most benchmark uncertainties.

2.2 Description for the criticality benchmarks suite

A set of 100 criticality safety benchmarks was selected and established for the MCNP code. Benchmarks were obtained from two reports: a suite of criticality benchmarks for validating nuclear data [17] and an expanded criticality validation suite for MCNP [18]. Among the 100 benchmark cases, 88 were from the first report and 12 were from the second one. Although all benchmark cases have standard ICSBEP names, the names are too long to be displayed in the chart when describing them; therefore, they are usually represented by abbreviations. The abbreviations of the benchmark cases used in this study are consistent with those of the above two reports.

The fission nuclides ^{233}U, ^{235}U, and ^{239}Pu produce the majority of fission products in the reactor. The criticality benchmark suite in this study is made up of five major categories based on the major fission nuclides: critical assemblies utilizing ^{233}U, intermediate-enriched ^{235}U (IEU), highly enriched ^{235}U (HEU), ^{239}Pu, and mixed metal (MIX) assemblies. Within each category, there were bare, reflected, and solution assemblies. The classification of the assembly and the number of each classification are listed in Table 1. The ICSBEP benchmarks and their abbreviations and the benchmark k_{eff} reference values used in this study are listed in Table 8 in Appendix , and the calculated k_{eff} values and statistical errors of each data library are listed in Table 9.

2.3 Statistical analysis methods

The benchmark results were analyzed using the statistical parameters $\delta k/\sigma$, χ^2, and $\langle|\Delta|\rangle$.

χ^2 is a statistical parameter used to determine which evaluated nuclear data library is the most suitable for criticality calculations. $\langle|\Delta|\rangle$ is the measure of the average difference between the calculated and benchmark k_{eff} eigenvalues. $\delta k/\sigma$ indicates the consistency of the evaluated library and benchmark value in each benchmark case.

We use the 3σ rule to evaluate the calculation results of the benchmark. In statistics, the 3σ rule is a shorthand used

Table 1 Start this caption with a short description of your table

Assembly	^{233}U	IEU	HEU	^{239}Pu	MIX	Total
Case numbers	17	14	37	21	11	100

to remember the percentage of values that lie within an interval estimate in a normal distribution: 68%, 95%, and 99.7% of the values lie within one, two, and three standard deviations of the mean, respectively. In empirical sciences, the 3σ rule expresses a conventional heuristic that nearly all values are taken to lie within three standard deviations of the mean, and thus it is empirically useful to treat 99.7% probability as near certainty. The results can be considered identical if the relative difference between the k_{eff} eigenvalues and the benchmark values was within the ± 3σ interval. Note that we have bolded the values exceeding ± 3σ in each benchmark to facilitate identification in the table.

$\langle|\Delta|\rangle$ and χ^2 are defined by

$$\langle|\Delta|\rangle = \sum_{i=1}^{n} \frac{\left|k_{\mathrm{eff}\,i}^{\mathrm{calculation}} - k_{\mathrm{eff}\,i}^{\mathrm{benchmark}}\right|}{n}, \tag{1}$$

$$\chi^2 = \sum_{i=1}^{n} \frac{\left(\left(k_{\mathrm{eff}_i}^{\mathrm{calculation}} - k_{\mathrm{eff}_i}^{\mathrm{benchmark}}\right)/\sigma_i^{\mathrm{benchmark}}\right)^2}{n}, \tag{2}$$

where n is the benchmark number, $\sigma^{\mathrm{benchmark}}$ is the benchmark experimental uncertainty, $k_{\mathrm{eff}}^{\mathrm{calculation}}$ and $k_{\mathrm{eff}}^{\mathrm{benchmark}}$ are the simulated k_{eff} eigenvalue and benchmark k_{eff} eigenvalue, respectively, and i and n are the specific benchmark and total number of benchmark cases, respectively. $\delta k/\sigma$ was used to provide a confidence level for the benchmarks. The relative difference δk and the relative combined statistical uncertainty σ are defined by

$$\delta k = \frac{k_{\mathrm{eff}}^{\mathrm{calculation}} - k_{\mathrm{eff}}^{\mathrm{benchmark}}}{k_{\mathrm{eff}}^{\mathrm{benchmark}}}, \tag{3}$$

$$\sigma = \sqrt{\left(\sigma^{\mathrm{benchmark}} \cdot k_{\mathrm{eff}}^{\mathrm{benchmark}}\right)^2 + \left(\sigma^{\mathrm{calculation}} \cdot k_{\mathrm{eff}}^{\mathrm{calculation}}\right)^2}. \tag{4}$$

χ^2 and $\langle|\Delta|\rangle$ are lumped parameters that can describe the overall performance of the data library in the corresponding types of benchmarks. $\delta k/\sigma$ can locate the performance of each data library in each benchmark.

3 Results and discussion

3.1 *Comparison of the* k_{eff} *calculation results*

The calculated values were compared to the reference value (Figs. 2, 3, 4, 5, 6). Most of the calculated values were close to the allowable error interval of the experimental value. The analysis and discussion of each benchmark type are as follows:

(1) For the ^{233}U assemblies (Fig. 2), the calculated values in most cases were in good agreement with the experimental values. The calculated values of the benchmarks of 23umt4b deviated significantly from the experimental values.
(2) For the IEU assemblies (Fig. 3), the calculated values in most cases were in good agreement with the experimental values. For the ieumt4 benchmark, all the calculated results except JENDL-4.0 were overestimated compared to the experimental value, and, for the ieumt6 benchmark, all the calculated results were underestimated compared to the experimental value.
(3) For the HEU assemblies (Fig. 4), all calculated values were overestimated compared to the experimental values in the umet3k benchmark. For the umet9b, usol13c, umet8, and umet15 benchmarks, all calculated values were underestimated compared to the experimental values.
(4) For the ^{239}Pu assemblies (Fig. 5), the calculated values in most cases were in good agreement with the experimental values. For the four benchmarks of the pusl cases (pusl11a, pusl11b, pusl11c, and pusl11d), the calculation results of CENDL-3.2 and CENDL-3.1 were overestimated compared to those of other data libraries. After comparing individual nuclides to each other, we found that ^{239}Pu of CENDL-3.2 caused the overestimation of pusl11 series cases.
(5) For the MIX assemblies (Fig. 6), the calculated values in most cases were in good agreement with the experimental values. The calculated values of mix-met8-7 deviate greatly from the experimental values.

3.2 Discussion of the statistical results

The results of the three statistical parameters of each data library (Tables 2, 3, 4, 5, 6) were compared in this study. The analysis and discussion are as follows:

(1) For the ^{233}U assemblies (Table 2), CENDL-3.1 exceeded 3σ in the four benchmarks of 23umt4a, 23umt4b, 23umt5a, and 23umt5b. JEFF-3.3 exceeded 3σ in the flat23 benchmark. For the 23umt4b benchmark, all databases exceeded 3σ. By analyzing the values of χ^2 and $\langle|\Delta|\rangle$, it can be concluded that CENDL-3.2 offers significant improvement compared to CENDL-3.1.
(2) For the IEU assemblies (Table 3), CENDL-3.1 exceeded 3σ in the benchmarks of lst7-14 and ieumt1c. Six benchmarks exceeded 3σ in the JENDL-4.0 library. Analysis of the values of χ^2 and $\langle|\Delta|\rangle$ showed that ENDFB-VIII.0 and JEFF-3.3 performed better than the other libraries.
(3) For the HEU assemblies (Table 4), CENDL-3.1 exceeded 3σ in the benchmarks of umet19 and

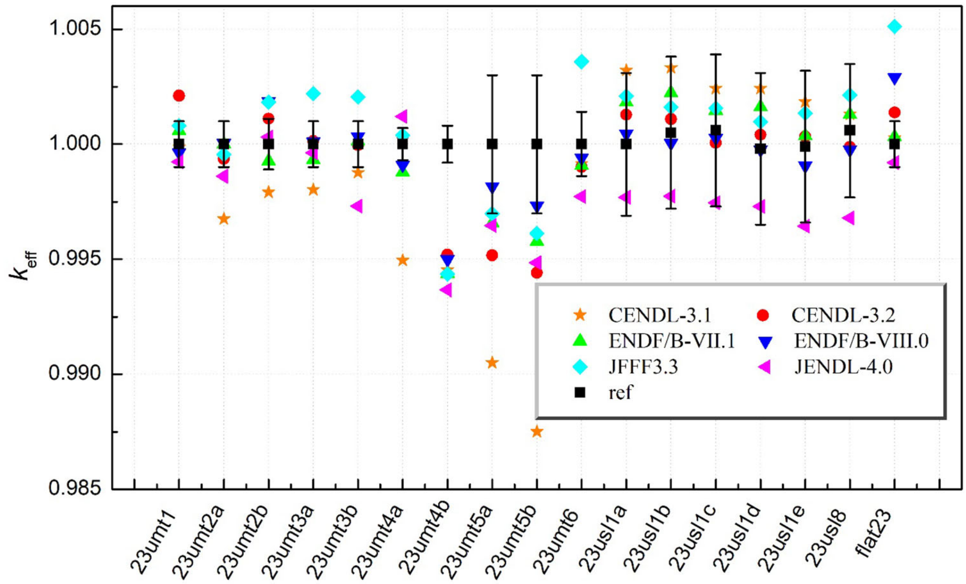


Fig. 2 (Color online) k_{eff} comparison for ^{233}U assemblies

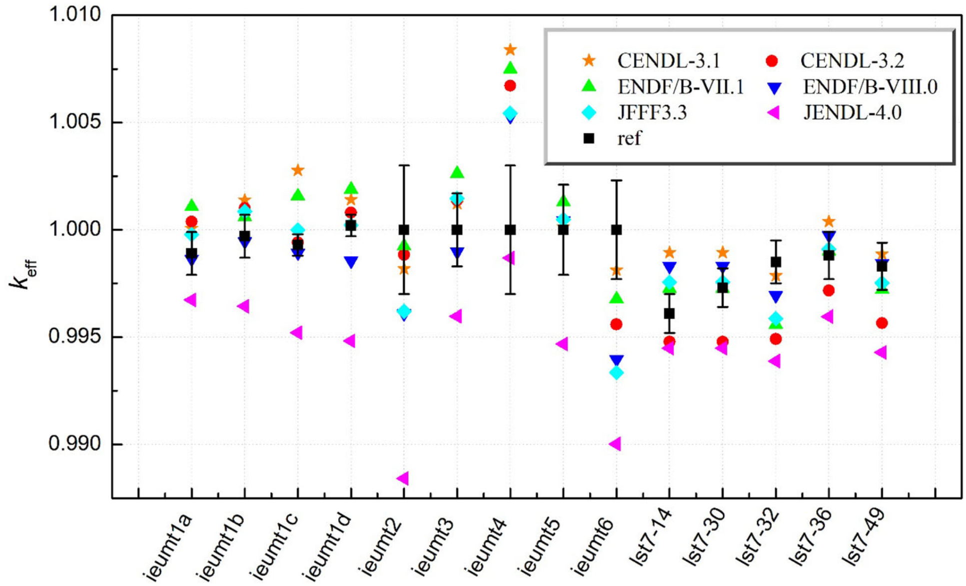


Fig. 3 (Color online) k_{eff} comparison for IEU assemblies

ieumt1c. JEFF-3.3 exceeded 3σ in the umet4b benchmark. Five benchmarks exceeded 3σ in the JENDL-4.0 library. Analysis of the values of χ^2 and $\langle|\Delta|\rangle$ showed that CENDL-3.2 is not significantly improved compared to CENDL-3.1.

(4) For the ^{239}Pu assemblies (Table 5), CENDL-3.1, and CENDL-3.2 both exceeded 3σ in the benchmarks of pusl11c and pusl11d. For the pumet8b benchmark, except for ENDF/B-VII.1, all other data libraries exceeded 3σ. Analyzing the values of χ^2 and $\langle|\Delta|\rangle$ showed that the ENDF/B-VII.1 library performs better than the other data libraries.

(5) For the MIX assemblies (Table 6), all libraries exceeded 3σ in the benchmark mixmet8-7. The ENDF/B-VII.1 library performs better than the other data libraries. Analysis of the values of χ^2 and $\langle|\Delta|\rangle$ shows that CENDL-3.2 performs better than CENDL-3.1.

Based on the calculated values of all benchmarks, we used chi-square and average errors to analyze the overall performance of all data libraries in criticality calculations (Table 7). From the perspective of the calculation results of the new and old updates of the library, CENDL-3.2 has smaller chi-square and average deviations for all

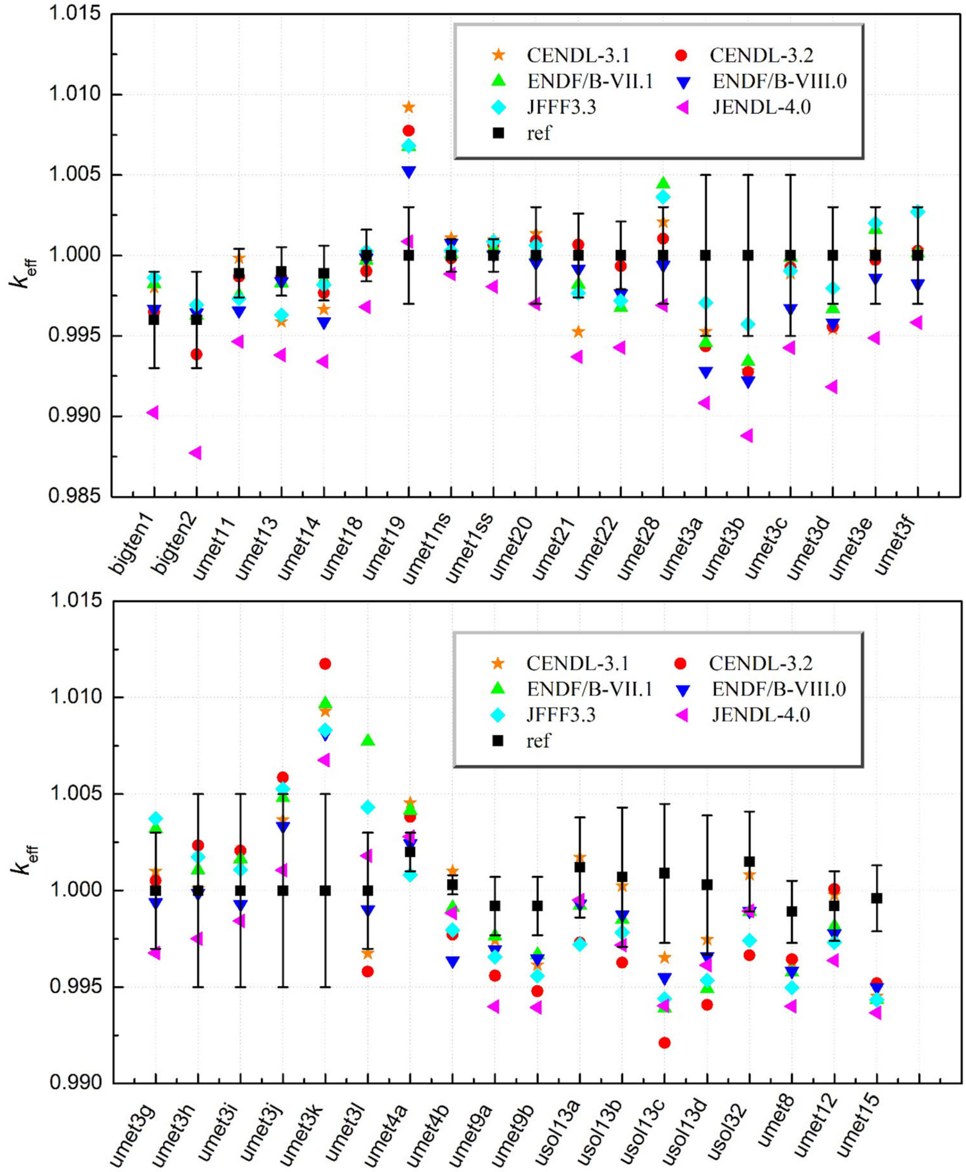


Fig. 4 (Color online) k_{eff} comparison for HEU assemblies

benchmarks than CENDL-3.1, which reflects that, for the type of benchmarks involved, CENDL-3.2 is superior to the previous version. The average deviation of ENDF/B-VIII.0 for all benchmarks is similar to that of ENDF/B-VII.1, both being near 230, and the chi-square is larger than that of ENDF/B-VII.1. By counting the number of benchmarks exceeding 3σ, it can be seen that the number of benchmarks exceeding 3σ for JENDL-4.0 and CENDL-3.1 is > 10 and the number of benchmarks exceeding 3σ for ENDF/B-VIII.0 and JEFF-3.3 is ∼ 5.

In general, based on the above 100 criticality benchmark calculation results, we can conclude that the criticality calculation performance of CENDL-3.2 is better than that of CENDL-3.1. Analysis of the chi-square and average deviations and the number of benchmarks exceeding 3σ demonstrates that the overall criticality calculation performance of ENDF/B-VIII.0 and JEFF3.3 is equivalent. The ENDF/B-VII.1 library performed the best. Compared with the JEFF-3.3 and ENDF/B-VIII.0 libraries, CENDL3.2 performs better in the calculation of ^{233}U devices and performs poorly in the pusl11 series case calculation of Pu devices, and thus further improvement is needed.

Compared to CENDL-3.1, CENDL-3.2 [1] has more materials (272), of which the data of 134 nuclides are new or updated evaluations in the energy region of 10^{-5} eV to 20 MeV. Data for most of the key nuclides in nuclear applications (e.g., U, Pu, Th, and Fe) have been revised. Covariance data for the main reactions were added for 70 fission product nuclides in CENDL-3.2. Compared to

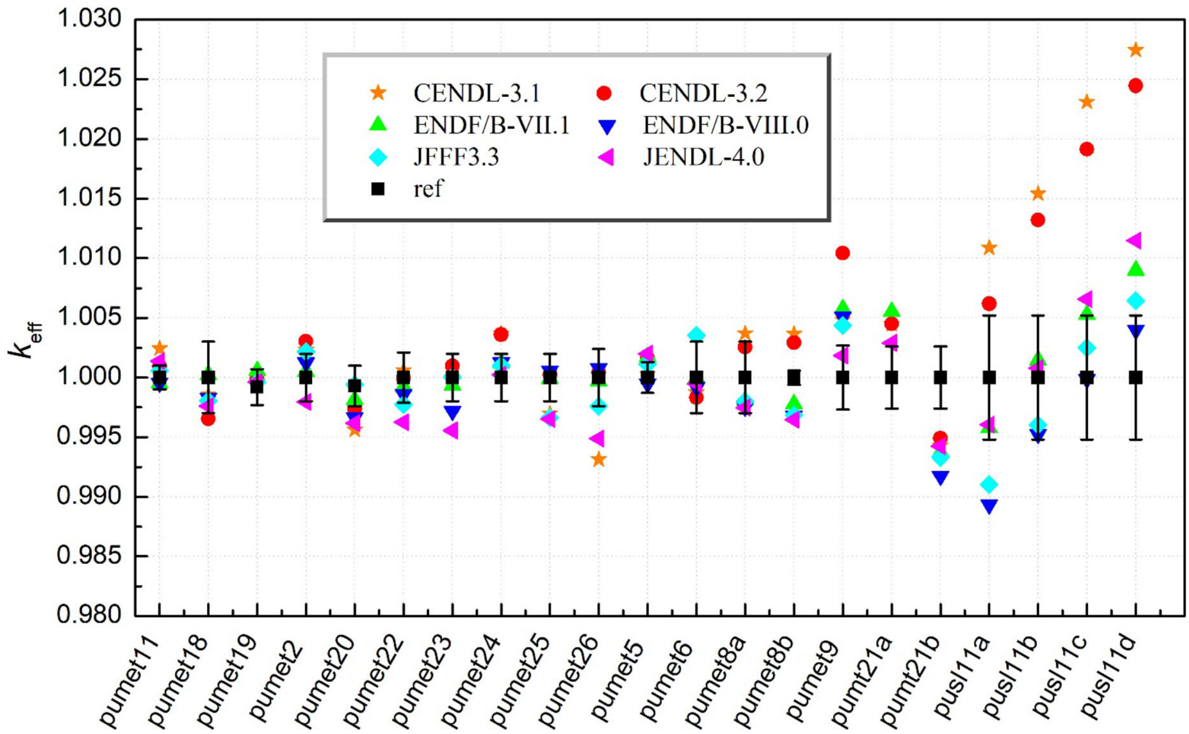
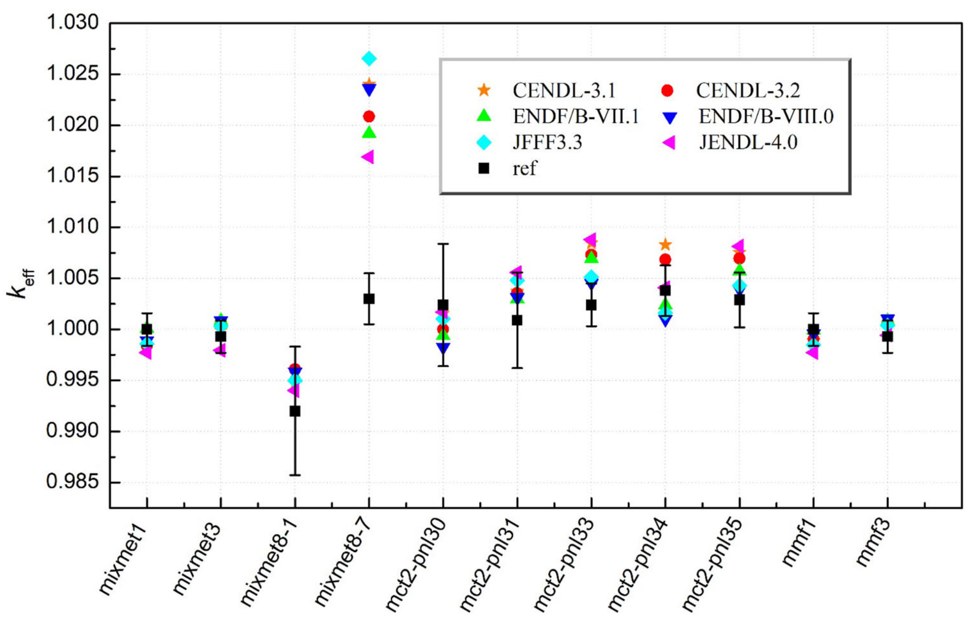


Fig. 5 (Color online) k_{eff} comparison for ^{239}Pu assemblies

Fig. 6 (Color online) k_{eff} comparison for MIX assemblies



ENDF/B-VII.1, ENDF/B-VIII.0 [2] employs major changes for neutron reactions on the important isotopes ^{1}H, ^{16}O, ^{56}Fe, ^{235}U, ^{238}U, and ^{239}Pu and other nuclides that impact simulations of nuclear criticality. The number of materials increased from 423 to 557. In addition, neutron reactions on light nuclei, structural materials, minor actinides, fission energy release, decay data, and charged particle reactions and thermal neutron scattering data have been notably updated.

Therefore, we expect that the criticality calculation performance of ENDF/B-VIII.0 is better than that of ENDF/B-VII.1. However, for different benchmark experiments, the calculation results of the new evaluated library ENDF/B-VIII.0 are not all better than those of the previous

Table 2 The statistic metrics for ^{233}U assemblies

Case	CENDL-3.1 $\delta k/\sigma$	CENDL-3.2	ENDF/B-VII.1	ENDF/B-VIII.0	JEFF-3.3	JENDL-4.0
23umt1	− 0.11	1.82	0.52	–0.33	0.70	–0.67
23umt2a	− 2.84	− 0.55	0.00	0.03	− 0.39	− 1.22
23umt2b	− 1.69	0.90	− 0.58	1.50	1.45	0.25
23umt3a	− 1.70	0.12	− 0.58	0.10	1.89	− 0.33
23umt3b	− 1.05	− 0.03	0.12	0.28	1.77	− 2.28
23umt4a	− **5.57**	0.37	− 1.33	− 1.03	0.41	1.28
23umt4b	− **5.64**	− **4.84**	− **5.75**	− **5.26**	− **5.76**	− **6.38**
23umt5a	− **3.10**	− 1.58	− 1.11	− 0.60	− 0.99	− 1.15
23umt5b	− 4.07	− 1.82	− 1.38	− 0.87	− 1.26	− 1.68
23umt6	− 0.55	− 0.63	− 0.62	− 0.39	2.31	− 1.46
23usl1a	1.03	0.41	0.59	0.14	0.67	− 0.74
23usl1b	0.85	0.18	0.52	− 0.14	0.34	− 0.83
23usl1c	0.55	− 0.16	0.26	− 0.10	0.29	− 0.94
23usl1d	0.79	0.18	0.55	− 0.01	0.35	− 0.75
23usl1e	0.59	0.13	0.14	− 0.25	0.44	− 1.04
23usl8	0.24	− 0.25	0.24	− 0.29	0.53	− 1.30
flat23	0.23	1.16	0.27	2.44	**4.25**	− 0.67
χ^2	14.88	1.65	2.71	3.29	3.22	1.85
$\langle\lvert\Delta\rvert\rangle$	351.8	142.5	144.3	115.9	196.9	225.4

The values in bold indicate that the values of $\delta k/\sigma$ have exceeded ±3, indicating that the calculated result of this benchmark are in poor consistency with the experimental value

Table 3 The statistic metrics for IEU assemblies

Case	CENDL-3.1 $\delta k/\sigma$	CENDL-3.2	ENDF/B-VII.1	ENDF/B-VIII.0	JEFF-3.3	JENDL-4.0
lst7-14	**3.02**	− 1.39	1.24	2.34	1.56	− 1.70
lst7-30	1.74	− 2.65	− 0.04	1.07	0.28	− 2.97
lst7-32	− 0.61	− **3.45**	− 2.80	− 1.50	− 2.55	− **4.42**
lst7-36	1.41	− 1.44	0.18	0.84	0.27	− 2.51
lst7-49	0.50	− 2.33	− 0.97	0.12	− 0.69	− **3.56**
ieumt1a	1.00	1.27	1.91	− 0.23	0.76	− 1.88
ieumt1b	1.45	1.13	0.79	− 0.21	1.00	− 2.80
ieumt1c	**4.40**	0.14	2.92	− 0.48	0.92	− **5.26**
ieumt1d	1.53	0.79	2.19	− 2.04	0.03	− **7.03**
ieumt2	–0.60	− 0.38	− 0.25	− 1.28	− 1.25	− **3.79**
ieumt3	0.68	0.77	1.44	− 0.56	0.82	− 2.23
ieumt4	2.74	2.20	2.45	1.73	1.77	− 0.43
ieumt5	0.07	2.13	0.60	0.20	0.22	− 2.45
ieumt6	− 0.79	− 1.86	− 1.36	− 2.55	− 2.80	− **4.21**
χ^2	5.98	3.61	4.28	2.43	2.02	21.26
$\langle\lvert\Delta\rvert\rangle$	202.1	239.5	198.9	179.0	185.9	449.7

The values in bold indicate that the values of $\delta k/\sigma$ have exceeded ±3, indicating that the calculated result of this benchmark are in poor consistency with the experimental value

version, such as the three benchmarks of pusl11a, pusl11b, and pumet21b in the Pu assemblies. In the criticality calculation of these three benchmarks, compared with the experimental value, the k_{eff} results of ENDF/B-VIII.0 are 200–500 pcm smaller than the calculation results of ENDF/B-VII.1. This is also one of the goals of our work, that is, to find benchmarks that are not sensitive to the newly evaluated library and provide a reference for subsequent

Table 4 The statistic metrics for HEU assemblies

Case	CENDL-3.1 $\delta k/\sigma$	CENDL-3.2	ENDF/B-VII.1	ENDF/B-VIII.0	JEFF-3.3	JENDL-4.0
umet11	0.57	− 0.13	− 0.83	− 1.41	− 0.95	− 2.53
bigten1	0.67	0.16	0.74	0.22	0.87	− 1.92
bigten2	0.04	− 0.71	0.09	0.15	0.31	− 2.75
umet13	− 1.93	− 0.22	− 0.44	− 0.38	− 1.68	− **3.22**
umet14	− 1.25	− 0.68	− 0.27	− 1.67	− 0.40	− **3.06**
umet18	− 0.25	− 0.57	− 0.17	− 0.09	0.15	− 1.89
umet19	**3.01**	2.53	2.20	1.72	2.23	0.28
umet1ns	0.93	–0.15	0.08	0.65	0.24	− 0.99
umet1ss	0.85	0.56	0.37	0.03	0.74	− 1.70
umet20	0.44	0.29	0.00	− 0.15	0.20	− 0.98
umet21	− 1.78	0.25	− 0.67	− 0.31	− 0.88	− 2.37
umet22	− 1.02	− 0.30	− 1.48	− 1.09	− 1.29	− 2.63
umet28	0.68	0.34	1.45	− 0.20	1.19	− 1.01
umet3a	− 0.94	− 1.12	− 1.08	− 1.43	− 0.58	− 1.82
umet3b	− 1.43	− 1.44	− 1.31	− 1.55	− 0.85	− 2.22
umet3c	− 0.22	− 0.14	− 0.02	− 0.65	− 0.19	− 1.14
umet3d	− 1.49	− 1.45	− 1.08	− 1.37	− 0.66	− 2.67
umet3e	0.07	− 0.09	0.52	− 0.45	0.65	− 1.67
umet3f	0.10	0.09	0.05	− 0.57	0.88	− 1.36
umet3g	0.32	0.17	1.05	− 0.20	1.22	− 1.05
umet3h	0.02	0.46	0.21	− 0.03	0.35	− 0.49
umet3i	0.29	0.41	0.32	− 0.14	0.21	− 0.31
umet3j	0.73	1.16	0.96	0.66	1.05	0.21
umet3k	1.84	2.33	1.92	1.62	1.65	1.34
umet3l	− 1.06	− 1.37	2.51	− 0.32	1.41	0.59
umet4a	2.07	1.46	1.74	0.34	− 0.97	0.64
umet4b	0.81	− 2.96	− 1.36	− **4.29**	− 2.62	− 1.68
umet9a	− 1.09	− 2.22	− 0.96	− 1.40	− 1.60	− **3.23**
umet9b	− 1.88	− 2.72	− 1.54	− 1.67	− 2.25	− **3.26**
usol13a	0.20	− 1.48	− 0.75	− 0.72	− 1.51	− 0.64
usol13b	− 0.13	− 1.22	− 0.61	− 0.54	− 0.79	− 0.97
usol13c	− 1.20	− 2.42	− 1.93	− 1.49	− 1.79	− 1.89
usol13d	− 0.78	− 1.71	− 1.48	− 1.02	− 1.36	− 1.15
usol32	− 0.26	− 1.85	− 0.99	− 0.98	− 1.56	− 0.98
umet8	− 1.53	− 1.43	− 1.84	− 1.81	− 2.31	− 2.90
umet12	0.30	0.46	− 0.56	− 0.75	− 0.98	− 1.49
umet15	− 2.84	− 2.45	− 2.93	− 2.60	− 2.93	− **3.30**
χ^2	1.68	2.53	1.75	2.86	2.31	4.23
$\langle\|\Delta\|\rangle$	250.1	299.5	279.5	245.9	293. 8	432

The values in bold indicate that the values of $\delta k/\sigma$ have exceeded ±3, indicating that the calculated result of this benchmark are in poor consistency with the experimental value

evaluation work. The calculation results of Table 7 list only the statistical performance of the current benchmark cases. The results in Table 7 cannot explain that the calculation result of ENDF/B-VIII.0 must be better than the calculation result of ENDF/B-VII.1. This requires a specific analysis based on specific issues.

3.3 Discussion of the anomalous benchmarks

From the discussion in Sect. 3.2, the $\delta k/\sigma$ value of all data libraries exceeded 3σ in the three benchmarks of 23umt4b, pumet8b, and mixmet8-7, which indicates that there is a large deviation between the experimental and

Table 5 The statistic metrics for ^{239}Pu assemblies

Case	CENDL-3.1 $\delta k/\sigma$	CENDL-3.2	ENDF/B-VII.1	ENDF/B-VIII.0	JEFF-3.3	JENDL-4.0
pumet1	1.22	1.05	0.15	0.04	− 0.23	− 0.58
pumet10	− 0.78	− 0.80	− 0.18	− 1.07	0.01	− 1.96
pumet11	1.90	0.76	− 0.38	− 0.37	0.45	1.12
pumet18	− 0.48	− 1.14	0.08	− 0.56	− 0.64	− 0.78
pumet2	1.12	1.46	0.24	0.61	1.04	− 0.99
pumet20	− 2.04	− 1.06	− 0.64	− 1.48	0.07	− 1.74
pumet22	0.28	− 0.02	− 0.35	− 0.65	− 1.05	− 1.73
pumet23	0.00	0.47	− 0.31	− 1.36	0.01	− 2.12
pumet24	1.75	1.72	0.59	0.61	0.48	0.11
pumet25	− 1.46	0.11	− 0.04	0.27	− 1.62	− 1.67
pumet26	− 2.79	0.17	− 0.13	0.31	− 0.97	− 2.07
pumet5	0.17	1.15	1.22	− 0.36	0.78	1.39
pumet6	− 0.40	− 0.55	− 0.01	− 0.27	1.15	− 0.17
pumet8a	1.21	0.83	− 0.63	− 0.81	− 0.65	− 0.83
pumet8b	**4.25**	**3.41**	− 2.55	− **4.01**	− **3.74**	− **4.13**
pumet9	1.75	**3.76**	2.08	1.84	1.58	0.66
pumt21b	− 2.14	− 1.91	− 2.35	− **3.08**	− 2.50	− 2.16
pusl11a	2.08	1.18	− 0.81	− 2.04	− 1.72	− 0.76
pusl11b	2.95	2.53	0.28	− 0.91	− 0.76	0.15
pusl11c	**4.41**	**3.65**	1.01	− 0.02	0.48	1.26
pusl11d	**5.24**	**4.67**	2.98	0.59	1.54	2.19
χ^2	6.50	4.75	1.55	2.71	2.49	3.72
$\langle\lvert\Delta\rvert\rangle$	592.3	503.2	209.6	261.9	272.2	333.3

The values in bold indicate that the values of $\delta k/\sigma$ have exceeded ±3, indicating that the calculated result of this benchmark are in poor consistency with the experimental value

Table 6 The statistic metrics for MIX assemblies

Case	CENDL-3.1 $\delta k/\sigma$	CENDL-3.2	ENDF/B-VII.1	ENDF/B-VIII.0	JEFF-3.3	JENDL-4.0
mct2-pnl30	− 0.14	− 0.40	− 0.50	− 0.69	− 0.23	− 0.12
mixmet1	− 0.56	− 0.94	0.05	− 0.64	− 0.84	− 1.33
mixmet3	0.35	0.84	0.89	0.91	0.58	− 0.79
mixmet8-1	0.45	0.65	0.52	0.62	0.48	0.32
mixmet8-7	**8.33**	**7.09**	**6.42**	**8.17**	**9.33**	**5.52**
mct2-pnl31	0.59	0.56	0.43	0.47	0.82	0.98
mct2-pnl33	2.83	2.31	2.12	1.01	1.28	2.98
mct2-pnl34	1.78	1.21	− 0.55	− 1.10	− 0.86	0.11
mct2-pnl35	1.70	1.49	1.03	0.38	0.52	1.92
mmf1	− 0.69	− 0.59	− 0.04	− 0.24	− 0.94	− 1.40
mmf3	0.78	0.85	0.94	1.07	0.67	0.08
χ^2	7.94	5.83	4.60	6.74	8.62	4.53
$\langle\lvert\Delta\rvert\rangle$	423.6	404.0	332.1	378.5	392. 4	356.7

The values in bold indicate that the values of $\delta k/\sigma$ have exceeded ±3, indicating that the calculated result of this benchmark are in poor consistency with the experimental value

calculated values. This question needs to be addressed separately.

The 23umt4b (u233-fast-met-004) benchmark is a spherical device, divided into two layers: The inner layer contains ^{233}U fuel and the outer layer is a reflective layer

Table 7 The comparison of $\langle|\Delta|\rangle$ values (in pcm) and χ^2 for total benchmark cases

Metrics	CENDL-3.2	CENDL-3.1	ENDF/B-VIII.0	ENDF/B-VII.1	JEFF-3.3	JENDL-4.0
χ^2	3.59	5.19	3.25	2.67	3.61	6.71
$\langle\|\Delta\|\rangle$	320.6	347.3	232.3	237.12	272.4	374.8
Numbers exceed 3σ	7	11	5	2	4	13

dominated by tungsten. The pumet8b (pu-met-fast-008b) benchmark is a spherical device, divided into two layers: The inner layer contains Pu fuel and the outer layer is a reflection layer of ^{232}Th. The mixmet8-7 (mix-met-inter-008-case-7) benchmark is based on a k_∞ measurement. The configuration consists of a rectangular plate with three rectangular normal-uranium plates above it and the other three below it. The plates were enclosed on all sides of a rectangular steel sheath.

Physically, k_{eff} is mainly dominated by fission nuclides, but the reflective layer also has an important influence on k_{eff}. The average deviation between the pumet8b and 23umt4b benchmarks and the experimental values was $\sim$ 600 pcm. In fact, there are benchmarks that have a deviation of >600 pcm from the experimental value, such as the JEFF-3.3calculation result for pumt21b. For the mixmet8-7 benchmark, the k_{eff} deviation between the calculated value of all libraries and the experimental value was within 1000–2000 pcm. In addition, the k_{eff} results of the reference values from ENDF/B-VII.0 and ENDF/B-VI also deviate from the experimental values by >1000 pcm. The k_{eff} result of MCNP6.2 based on ENDF/B-VII.1, found in the LA-UR-17–25,040 report [19], is 1.0192, which has a deviation of 1620 pcm from the experimental value. At present, no report has been published to explain the reason for the large deviation between the calculated and experimental values for mixmet8-7, and further research is needed.

From the point of view of nuclear data, because the benchmark involves many nuclides, it is impossible to determine which nuclides that have a greater impact on k_{eff} through qualitative analysis. The commonly used method is to determine the important reaction channels of key nuclides that have a greater impact on k_{eff} through sensitivity and uncertainty analyses. This part of the work has not been done yet, and the sensitivity and uncertainty analysis will be further studied in our future work.

4 Conclusion

A comprehensive suite of 100 criticality benchmarks has been established for validating nuclear data, including CENDL-3.2, ENDF/B-VIII.0, JEFF3.3, JENDL-4.0, CENDL-3.1, and ENDF/B-VII.1. The suite contains benchmarks for five major categories: critical assemblies utilizing ^{233}U, IEU, HEU, ^{239}Pu, and MIX assemblies.

(1) In these 100 calculation benchmark cases, the calculated values for most of the cases were in good agreement with the experimental values.

(2) Considering all devices comprehensively and analyzing the values of χ^2 and $\langle|\Delta|\rangle$ demonstrates that the overall criticality calculation performance of ENDF/B-VIII.0 and JEFF3.3 is basically equivalent. The ENDF/B-VII.1 library offers the best performance in criticality calculations. In addition, CENDL-3.2 is improved compared to the CENDL-3.1 library and is better than JENDL-4.0. CENDL-3.2 performed better in the calculations of ^{233}U assemblies. However, for the pusl11 series of Pu devices, CENDL-3.2 has poor performance in criticality calculations and needs further improvement.

(3) The $\delta k/\sigma$ values of most benchmark cases in different data libraries were in the 3σ interval with a confidence of 99.7%. A few benchmark cases (e.g., 23umet4b, pumet8b, and mixmet8-7) have $\delta k/\sigma$ values higher than the 3σ interval for all libraries. The reason for the large deviation between the calculated value of mixmet8-7 and the experimental value requires further study.

Appendix

See Tables 8 and 9

Table 8 ICSBEP benchmark abbreviation and reference k_{eff} value

Type	Abbreviation	ICSBEP reference	Benchmark k_{eff}
233U	23umt1	233U-MET-FAST-001	1.0000 ± 0.00100
233U	23umt2a	233U-MET-FAST-002 Case 1	1.0000 ± 0.00100
233U	23umt2b	233U-MET-FAST-002 Case 2	1.0000 ± 0.00110
233U	23umt3a	233U-MET-FAST-003 Case 1	1.0000 ± 0.00100
233U	23umt3b	233U-MET-FAST-003 Case 2	1.0000 ± 0.00100
233U	23umt4a	233U-MET-FAST-004 Case 1	1.0000 ± 0.00070
233U	23umt4b	233U-MET-FAST-004 Case 2	1.0000 ± 0.00080
233U	23umt5a	233U-MET-FAST-005 Case 1	1.0000 ± 0.00300
233U	23umt5b	233U-MET-FAST-005 Case 2	1.0000 ± 0.00300
233U	23umt6	233U-MET-FAST-006	1.0000 ± 0.00140
233U	23usl1a	233U-SOL-THERM-001 Case 1	1.0000 ± 0.00310
233U	23usl1b	233U-SOL-THERM-001 Case 2	1.0005 ± 0.00330
233U	23usl1c	233U-SOL-THERM-001 Case 3	1.0006 ± 0.00330
233U	23usl1d	233U-SOL-THERM-001 Case 4	0.9998 ± 0.00330
233U	23usl1e	233U-SOL-THERM-001 Case 5	0.9999 ± 0.00330
233U	23usl8	233U-SOL-THERM-008	1.0006 ± 0.00290
HEU	bigten1	F-10–1 (In CSEWG)	0.9960 ± 0.00300
HEU	bigten2	F-10–2 (In CSEWG)	0.9960 ± 0.00300
233U	flat23	F-24 (In CSEWG)	1.0000 ± 0.00100
IEU	ieumt1a	IEU-MET-FAST-001 Case 1	0.9989 ± 0.00100
IEU	ieumt1b	IEU-MET-FAST-001 Case 2	0.9997 ± 0.00100
IEU	ieumt1c	IEU-MET-FAST-001 Case 3	0.9993 ± 0.00050
IEU	ieumt1d	IEU-MET-FAST-001 Case 4	1.0002 ± 0.00050
IEU	ieumt2	IEU-MET-FAST-002	1.0000 ± 0.00300
IEU	ieumt3	IEU-MET-FAST-003	1.0000 ± 0.00170
IEU	ieumt4	IEU-MET-FAST-004	1.0000 ± 0.00300
IEU	ieumt5	IEU-MET-FAST-005	1.0000 ± 0.00210
IEU	ieumt6	IEU-MET-FAST-006	1.0000 ± 0.00230
MIX	mixmet1	MIX-MET-FAST-001	1.0000 ± 0.00160
MIX	mixmet3	MIX-MET-FAST-001	0.9993 ± 0.00160
239U	pumet1	PU-MET-FAST-001	1.0000 ± 0.00200
239U	pumet10	PU-MET-FAST-010	1.0000 ± 0.00180
239U	pumet11	PU-MET-FAST-011	1.0000 ± 0.00100
239U	pumet18	PU-MET-FAST-018	1.0000 ± 0.00300
239U	pumet19	PU-MET-FAST-019	0.9992 ± 0.00150
239U	pumet2	PU-MET-FAST-002	1.0000 ± 0.00200
239U	pumet20	PU-MET-FAST-020	0.9993 ± 0.00170
239U	pumet22	PU-MET-FAST-022	1.0000 ± 0.00210
239U	pumet23	PU-MET-FAST-023	1.0000 ± 0.00200
239U	pumet24	PU-MET-FAST-024	1.0000 ± 0.00200
239U	pumet25	PU-MET-FAST-025	1.0000 ± 0.00200
239U	pumet26	PU-MET-FAST-026	1.0000 ± 0.00240
239U	pumet5	PU-MET-FAST-005	1.0000 ± 0.00130
239U	pumet6	PU-MET-FAST-006	1.0000 ± 0.00300
239U	pumet8a	PU-MET-FAST-008 Case 1	1.0000 ± 0.00300
239U	pumet8b	PU-MET-FAST-008 Case 2	1.0000 ± 0.00060
239U	pumet9	PU-MET-FAST-009	1.0000 ± 0.00270
239U	pumt21a	PU-MET-FAST-021 Case 1	1.0000 ± 0.00260

Table 8 continued

Type	Abbreviation	ICSBEP reference	Benchmark k_{eff}
239U	pumt21b	PU-MET-FAST-021 Case 2	1.0000 ± 0.00260
239U	pusl11a	PU-SOL-THERM-011 Case 18–1	1.0000 ± 0.00520
239U	pusl11b	PU-SOL-THERM-011 Case 18–6	1.0000 ± 0.00520
239U	pusl11c	PU-SOL-THERM-011 Case 16–5	1.0000 ± 0.00520
239U	pusl11d	PU-SOL-THERM-011 Case 16–1	1.0000 ± 0.00520
HEU	umet11	HEU-MET-FAST-011	0.9989 ± 0.00150
HEU	umet13	HEU-MET-FAST-013	0.9990 ± 0.00150
HEU	umet14	HEU-MET-FAST-014	0.9989 ± 0.00170
HEU	umet18	HEU-MET-FAST-018	1.0000 ± 0.00160
HEU	umet19	HEU-MET-FAST-019	1.0000 ± 0.00300
HEU	umet1ns	HEU-MET-FAST-001 Case b	1.0000 ± 0.00100
HEU	umet1ss	HEU-MET-FAST-001 Case a	1.0000 ± 0.00100
HEU	umet20	HEU-MET-FAST-020	1.0000 ± 0.00300
HEU	umet21	HEU-MET-FAST-021	1.0000 ± 0.00260
HEU	umet22	HEU-MET-FAST-022	1.0000 ± 0.00210
HEU	umet28	HEU-MET-FAST-028	1.0000 ± 0.00300
HEU	umet3a	HEU-MET-FAST-003 Case 1	1.0000 ± 0.00500
HEU	umet3b	HEU-MET-FAST-003 Case 2	1.0000 ± 0.00500
HEU	umet3c	HEU-MET-FAST-003 Case 3	1.0000 ± 0.00500
HEU	umet3d	HEU-MET-FAST-003 Case 4	1.0000 ± 0.00300
HEU	umet3e	HEU-MET-FAST-003 Case 5	1.0000 ± 0.00300
HEU	umet3f	HEU-MET-FAST-003 Case 6	1.0000 ± 0.00300
HEU	umet3g	HEU-MET-FAST-003 Case 7	1.0000 ± 0.00300
HEU	umet3h	HEU-MET-FAST-003 Case 8	1.0000 ± 0.00500
HEU	umet3i	HEU-MET-FAST-003 Case 9	1.0000 ± 0.00500
HEU	umet3j	HEU-MET-FAST-003 Case 10	1.0000 ± 0.00500
HEU	umet3k	HEU-MET-FAST-003 Case 11	1.0000 ± 0.00500
HEU	umet3l	HEU-MET-FAST-003 Case 12	1.0000 ± 0.00300
HEU	umet4a	HEU-MET-FAST-004 Case 2	1.0020 ± 0.00100
HEU	umet4b	HEU-MET-FAST-004 Case 1	1.0003 ± 0.00050
HEU	umet9a	HEU-MET-FAST-009 Case 1	0.9992 ± 0.00150
HEU	umet9b	HEU-MET-FAST-009 Case 2	0.9992 ± 0.00150
HEU	usol13a	HEU-SOL-THERM-003 Case 1	1.0012 ± 0.00260
HEU	usol13b	HEU-SOL-THERM-003 Case 2	1.0007 ± 0.00360
HEU	usol13c	HEU-SOL-THERM-003 Case 3	1.0009 ± 0.00360
HEU	usol13d	HEU-SOL-THERM-003 Case 4	1.0003 ± 0.00360
HEU	usol32	HEU-SOL-THERM-032	1.0015 ± 0.00260
HEU	umet8	HEU-MET-FAST-008	0.9989 ± 0.00160
HEU	umet12	HEU-MET-FAST-012	0.9992 ± 0.00180
HEU	umet15	HEU-MET-FAST-015	0.9996 ± 0.00170
MIX	mixmet8-1	MIX-MET-FAST-008 Case 1	0.9920 ± 0.00630
MIX	mixmet8-7	MIX-MET-FAST-008 Case 7	1.0030 ± 0.00250
IEU	lst7-14	leu-sol-therm-007-case-14	0.9961 ± 0.00090
IEU	lst7-30	leu-sol-therm-007-case-30	0.9973 ± 0.00090
IEU	lst7-32	leu-sol-therm-007-case-32	0.9985 ± 0.00100
IEU	lst7-36	leu-sol-therm-007-case-36	0.9988 ± 0.00110
IEU	lst7-49	leu-sol-therm-007-case-49	0.9983 ± 0.00110
MIX	mct2-pnl30	mix-comp-therm-002-case-pnl30	1.0024 ± 0.00600

Table 8 continued

Type	Abbreviation	ICSBEP reference	Benchmark k_{eff}
MIX	mct2-pnl31	mix-comp-therm-002-case-pnl31	1.0009 ± 0.00470
MIX	mct2-pnl33	mix-comp-therm-002-case-pnl33	1.0024 ± 0.00210
MIX	mct2-pnl34	mix-comp-therm-002-case-pnl34	1.0038 ± 0.00250
MIX	mct2-pnl35	mix-comp-therm-002-case-pnl35	1.0029 ± 0.00270
MIX	mmf1	mix-met-fast-001	1.0000 ± 0.00160
MIX	mmf3	mix-met-fast-003	0.9993 ± 0.00160

Table 9 k_{eff} values and statistical errors of different libraries

Case	CENDL-3.1	CENDL-3.2	ENDF/B-VII.1	ENDF/B-VIII.0	JEFF-3.3	JENDL-4.0
23umt1	0.99987 ± 0.00055	1.00211 ± 0.00058	1.00059 ± 0.00055	0.99963 ± 0.00053	1.00080 ± 0.00056	0.99923 ± 0.00056
23umt2a	0.99676 ± 0.00055	0.99936 ± 0.00059	1.00000 ± 0.00056	1.00004 ± 0.00059	0.99955 ± 0.00057	0.99861 ± 0.00055
23umt2b	0.99792 ± 0.00056	1.00111 ± 0.00056	0.99927 ± 0.00060	1.00186 ± 0.00058	1.00183 ± 0.00061	1.00031 ± 0.00057
23umt3a	0.99803 ± 0.00058	1.00014 ± 0.00060	0.99932 ± 0.00060	1.00011 ± 0.00057	1.0022 ± 0.00060	0.99962 ± 0.00059
23umt3b	0.99876 ± 0.00062	0.99996 ± 0.00059	1.00014 ± 0.00057	1.00033 ± 0.00060	1.00206 ± 0.0006	0.99731 ± 0.00063
23umt4a	0.99495 ± 0.00058	1.00034 ± 0.00058	0.99878 ± 0.00059	0.99909 ± 0.00054	1.00038 ± 0.00060	1.00121 ± 0.00063
23umt4b	0.99019 ± 0.00063	0.99711 ± 0.00061	0.99514 ± 0.00063	0.99487 ± 0.00062	0.9982 ± 0.00063	0.99814 ± 0.00063
23umt5a	0.99050 ± 0.00061	0.99517 ± 0.00061	0.99659 ± 0.00064	0.99817 ± 0.00060	0.99698 ± 0.00062	0.99646 ± 0.00063
23umt5b	0.98751 ± 0.00064	0.99441 ± 0.00063	0.99577 ± 0.00065	0.99733 ± 0.00065	0.99612 ± 0.00065	0.99485 ± 0.00066
23umt6	0.99915 ± 0.00067	0.99901 ± 0.00070	0.99907 ± 0.00057	0.99940 ± 0.00066	1.00359 ± 0.00068	0.99773 ± 0.00067
23usl1a	1.00322 ± 0.00038	1.00128 ± 0.00036	1.00183 ± 0.00038	1.00045 ± 0.00038	1.00209 ± 0.00038	0.99770 ± 0.00039
23usl1b	1.00333 ± 0.00039	1.00109 ± 0.00037	1.00224 ± 0.00039	1.00005 ± 0.00037	1.00162 ± 0.00040	0.99775 ± 0.00038
23usl1c	1.00243 ± 0.00038	1.00006 ± 0.00039	1.00147 ± 0.00040	1.00027 ± 0.00038	1.00157 ± 0.00039	0.99746 ± 0.00039
23usl1d	1.00243 ± 0.00039	1.00041 ± 0.00039	1.00162 ± 0.00037	0.99976 ± 0.00039	1.00098 ± 0.00042	0.99730 ± 0.00040
23usl1e	1.00185 ± 0.00040	1.00033 ± 0.00042	1.00037 ± 0.00041	0.99906 ± 0.00039	1.00135 ± 0.00042	0.99644 ± 0.00040
23usl8	1.00131 ± 0.00026	0.99988 ± 0.00025	1.00129 ± 0.00025	0.99976 ± 0.00026	1.00214 ± 0.00025	0.99680 ± 0.00026
bigten1	0.99801 ± 0.00048	0.99649 ± 0.00052	0.99823 ± 0.00047	0.99667 ± 0.00048	0.99862 ± 0.00051	0.99023 ± 0.00047
bigten2	0.99613 ± 0.00047	0.99385 ± 0.00049	0.99628 ± 0.00048	0.99644 ± 0.00049	0.99693 ± 0.00049	0.98773 ± 0.00044
flat23	1.00027 ± 0.00064	1.00138 ± 0.00064	1.00032 ± 0.00066	1.00291 ± 0.00065	1.00512 ± 0.00067	0.99920 ± 0.00066
ieumt1a	1.00007 ± 0.00061	1.00039 ± 0.00061	1.00109 ± 0.00056	0.99864 ± 0.00057	0.99978 ± 0.00058	0.99673 ± 0.00058
ieumt1b	1.00140 ± 0.00061	1.00102 ± 0.00061	1.00061 ± 0.00056	0.99946 ± 0.00060	1.00086 ± 0.00058	0.99644 ± 0.00060
ieumt1c	1.00277 ± 0.00061	0.99941 ± 0.00058	1.00158 ± 0.00060	0.99893 ± 0.00059	1.00000 ± 0.00058	0.99521 ± 0.00060
ieumt1d	1.00141 ± 0.00061	1.00081 ± 0.00059	1.00188 ± 0.00058	0.99856 ± 0.00063	1.00022 ± 0.00061	0.99483 ± 0.00058
ieumt2	0.99818 ± 0.00059	0.99884 ± 0.00052	0.99925 ± 0.00058	0.99610 ± 0.00052	0.99620 ± 0.00055	0.98842 ± 0.00057
ieumt3	1.00123 ± 0.00060	1.00138 ± 0.00057	1.00261 ± 0.00062	0.99898 ± 0.00061	1.00147 ± 0.00057	0.99598 ± 0.00061
ieumt4	1.00838 ± 0.00060	1.00672 ± 0.00059	1.00749 ± 0.00059	1.00529 ± 0.00061	1.00543 ± 0.00062	0.99869 ± 0.00061
ieumt5	1.00015 ± 0.00055	1.00467 ± 0.00061	1.00131 ± 0.00056	1.00044 ± 0.00065	1.00048 ± 0.00060	0.99469 ± 0.00054
ieumt6	0.99812 ± 0.00060	0.99560 ± 0.00054	0.99677 ± 0.00059	0.99397 ± 0.00055	0.99335 ± 0.00058	0.99003 ± 0.00058
mixmet1	0.99905 ± 0.00059	0.9984 ± 0.00058	1.00009 ± 0.00058	0.99891 ± 0.00057	0.99858 ± 0.00055	0.99774 ± 0.00056
mixmet3	0.9999 ± 0.000610	1.00074 ± 0.00062	1.00084 ± 0.00064	1.00087 ± 0.00066	1.00030 ± 0.00062	0.99795 ± 0.00058
pumet1	1.00253 ± 0.00055	1.00218 ± 0.00058	1.00031 ± 0.00056	1.00008 ± 0.00058	0.99953 ± 0.00058	0.99878 ± 0.00060
pumet10	0.99852 ± 0.00060	0.99848 ± 0.00060	0.99966 ± 0.00060	0.99797 ± 0.00060	1.00002 ± 0.00062	0.99628 ± 0.00059
pumet11	1.00243 ± 0.00079	1.00094 ± 0.00074	0.99953 ± 0.00071	0.99955 ± 0.00068	1.00056 ± 0.00073	1.00137 ± 0.00070
pumet18	0.99854 ± 0.00061	0.99652 ± 0.00061	1.00024 ± 0.00065	0.99828 ± 0.00061	0.99804 ± 0.00061	0.99760 ± 0.00060
pumet2	1.00234 ± 0.00058	1.00304 ± 0.00059	1.00050 ± 0.00057	1.00126 ± 0.00057	1.00216 ± 0.00058	0.99794 ± 0.00059
pumet20	0.99561 ± 0.00064	0.99738 ± 0.00064	0.99814 ± 0.00061	0.99664 ± 0.00061	0.99942 ± 0.00056	0.99616 ± 0.00063
pumet22	1.00061 ± 0.00057	0.99995 ± 0.00054	0.99924 ± 0.00057	0.99859 ± 0.00057	0.99772 ± 0.00056	0.99624 ± 0.00054

Table 9 continued

Case	CENDL-3.1	CENDL-3.2	ENDF/B-VII.1	ENDF/B-VIII.0	JEFF-3.3	JENDL-4.0
pumet23	1.00001 ± 0.00061	1.00098 ± 0.00057	0.99935 ± 0.00058	0.99717 ± 0.00059	1.00003 ± 0.00054	0.99556 ± 0.00061
pumet24	1.00367 ± 0.00064	1.00362 ± 0.00065	1.00124 ± 0.00063	1.00128 ± 0.00064	1.00100 ± 0.00061	1.00023 ± 0.00062
pumet25	0.99696 ± 0.00058	1.00024 ± 0.00060	0.99992 ± 0.00057	1.00056 ± 0.00062	0.99662 ± 0.00060	0.99651 ± 0.00059
pumet26	0.99313 ± 0.00057	1.00042 ± 0.00061	0.99969 ± 0.00060	1.00077 ± 0.00058	0.99759 ± 0.00064	0.99486 ± 0.00062
pumet5	1.00024 ± 0.00057	1.00165 ± 0.00061	1.00176 ± 0.00063	0.99948 ± 0.00061	1.00113 ± 0.00064	1.00200 ± 0.00061
pumet6	0.99877 ± 0.00061	0.99832 ± 0.00070	0.99996 ± 0.00071	0.99918 ± 0.00074	1.00354 ± 0.00067	0.99947 ± 0.00069
pumet8a	1.00371 ± 0.00059	1.00254 ± 0.00059	0.99807 ± 0.00061	0.99753 ± 0.00061	0.99801 ± 0.00062	0.99747 ± 0.00062
pumet8b	1.00367 ± 0.00062	1.00292 ± 0.00061	0.99778 ± 0.00063	0.99677 ± 0.00054	0.99683 ± 0.00060	0.99644 ± 0.00062
pumet9	1.00483 ± 0.00058	1.01041 ± 0.00061	1.00577 ± 0.00063	1.00511 ± 0.00063	1.00437 ± 0.00059	1.00183 ± 0.00057
pumt21b	0.99428 ± 0.00060	0.99490 ± 0.00062	0.99372 ± 0.00064	0.99176 ± 0.00063	0.99332 ± 0.00064	0.99422 ± 0.00066
pusl11a	1.01086 ± 0.00052	1.00619 ± 0.00054	0.99577 ± 0.00051	0.98934 ± 0.00055	0.99104 ± 0.0005	0.99605 ± 0.00052
pusl11b	1.01542 ± 0.00053	1.01321 ± 0.00054	1.00147 ± 0.00055	0.99524 ± 0.00054	0.99601 ± 0.00055	1.00078 ± 0.00055
pusl11c	1.02311 ± 0.00062	1.01914 ± 0.00062	1.00528 ± 0.00063	0.99987 ± 0.00062	1.0025 ± 0.00060	1.00659 ± 0.00060
pusl11d	1.02745 ± 0.00061	1.02445 ± 0.00059	1.00898 ± 0.00060	1.00400 ± 0.00060	1.00645 ± 0.00058	1.01147 ± 0.00061
umet11	0.99985 ± 0.00072	0.99868 ± 0.00069	0.99752 ± 0.00074	0.99657 ± 0.00070	0.99732 ± 0.00073	0.99465 ± 0.00077
umet13	0.99589 ± 0.00060	0.99865 ± 0.00063	0.99829 ± 0.00059	0.99839 ± 0.00058	0.99630 ± 0.00059	0.99381 ± 0.00060
umet14	0.99665 ± 0.00060	0.99767 ± 0.00062	0.99842 ± 0.00057	0.99588 ± 0.00063	0.99818 ± 0.00063	0.99341 ± 0.00058
umet18	0.99958 ± 0.00059	0.99902 ± 0.00059	0.99972 ± 0.00054	0.99985 ± 0.00059	1.00025 ± 0.00062	0.99680 ± 0.00056
umet19	1.00921 ± 0.00061	1.00776 ± 0.00065	1.00676 ± 0.00063	1.00526 ± 0.00060	1.00683 ± 0.0006	1.00086 ± 0.00061
umet1ns	1.00107 ± 0.00057	0.99983 ± 0.00054	1.00009 ± 0.00060	1.00075 ± 0.00056	1.00028 ± 0.00058	0.99886 ± 0.00057
umet1ss	1.00098 ± 0.00057	1.00064 ± 0.00054	1.00043 ± 0.00057	1.00004 ± 0.00057	1.00085 ± 0.00055	0.99806 ± 0.00055
umet20	1.00135 ± 0.00063	1.00088 ± 0.00066	0.99999 ± 0.00066	0.99955 ± 0.00065	1.00062 ± 0.00063	0.99699 ± 0.00063
umet21	0.99525 ± 0.00061	1.00066 ± 0.00062	0.99820 ± 0.00063	0.99916 ± 0.00065	0.99765 ± 0.00058	0.99370 ± 0.00057
umet22	0.99777 ± 0.00057	0.99934 ± 0.00059	0.99677 ± 0.00057	0.99763 ± 0.00058	0.99719 ± 0.00060	0.99428 ± 0.00056
umet28	1.00207 ± 0.00061	1.00103 ± 0.00064	1.00443 ± 0.00062	0.99940 ± 0.00061	1.00363 ± 0.00058	0.99690 ± 0.00063
umet3a	0.99528 ± 0.00062	0.99435 ± 0.00062	0.99457 ± 0.00065	0.99281 ± 0.00055	0.99706 ± 0.00058	0.99083 ± 0.00062
umet3b	0.99281 ± 0.00060	0.99275 ± 0.00058	0.99341 ± 0.00058	0.99221 ± 0.00061	0.99574 ± 0.00059	0.98881 ± 0.00058
umet3c	0.99888 ± 0.00061	0.99928 ± 0.00062	0.99988 ± 0.00062	0.99672 ± 0.00062	0.99905 ± 0.00062	0.99427 ± 0.00064
umet3d	0.99544 ± 0.00063	0.99557 ± 0.00060	0.99668 ± 0.00061	0.99581 ± 0.00065	0.99797 ± 0.00066	0.99183 ± 0.00062
umet3e	1.00020 ± 0.00064	0.99973 ± 0.00063	1.00160 ± 0.00060	0.99861 ± 0.00064	1.00200 ± 0.00059	0.99487 ± 0.00062
umet3f	1.0003 ± 0.00067	1.00028 ± 0.00062	1.00016 ± 0.00059	0.99824 ± 0.00061	1.0027 ± 0.00065	0.99583 ± 0.00065
umet3g	1.00099 ± 0.00063	1.00051 ± 0.00065	1.00320 ± 0.00061	0.99938 ± 0.00065	1.00373 ± 0.00058	0.99678 ± 0.00066
umet3h	1.00010 ± 0.00057	1.00234 ± 0.00061	1.00107 ± 0.00064	0.99986 ± 0.00062	1.00175 ± 0.00063	0.99751 ± 0.00064
umet3i	1.00145 ± 0.00060	1.00207 ± 0.00063	1.00162 ± 0.00060	0.99928 ± 0.00063	1.00108 ± 0.00063	0.99842 ± 0.00060
umet3j	1.00367 ± 0.00064	1.00586 ± 0.00063	1.00482 ± 0.00061	1.00333 ± 0.00064	1.00527 ± 0.00062	1.00106 ± 0.00059
umet3k	1.00929 ± 0.00065	1.01174 ± 0.00059	1.00967 ± 0.00061	1.00814 ± 0.00059	1.00831 ± 0.00057	1.00676 ± 0.00066
umet3l	0.99675 ± 0.00062	0.99581 ± 0.00058	1.00772 ± 0.00065	0.99902 ± 0.00061	1.00432 ± 0.00060	1.00180 ± 0.00061
umet4a	1.00455 ± 0.00071	1.00382 ± 0.00074	1.00416 ± 0.00073	1.00243 ± 0.00074	1.00081 ± 0.00071	1.00280 ± 0.00074
umet4b	1.00101 ± 0.00072	0.99773 ± 0.00071	0.99912 ± 0.00071	0.99637 ± 0.00077	0.99796 ± 0.00074	0.99884 ± 0.00071
umet9a	0.99743 ± 0.00064	0.99560 ± 0.00062	0.99765 ± 0.00060	0.99695 ± 0.00060	0.99657 ± 0.00068	0.99400 ± 0.00060
umet9b	0.99616 ± 0.00061	0.99479 ± 0.00062	0.99669 ± 0.00065	0.99649 ± 0.00062	0.99558 ± 0.00060	0.99395 ± 0.00060
usol13a	1.00173 ± 0.00038	0.99731 ± 0.00039	0.99923 ± 0.00039	0.99930 ± 0.00037	0.99722 ± 0.00037	0.99951 ± 0.00037
usol13b	1.00024 ± 0.00041	0.99628 ± 0.00040	0.99850 ± 0.00039	0.99873 ± 0.00042	0.99784 ± 0.00040	0.99718 ± 0.00040
usol13c	0.99653 ± 0.00043	0.99211 ± 0.00043	0.99390 ± 0.00041	0.99550 ± 0.00040	0.99440 ± 0.00042	0.99404 ± 0.00043
usol13d	0.99747 ± 0.00041	0.99408 ± 0.00045	0.99492 ± 0.00044	0.99660 ± 0.00044	0.99536 ± 0.00041	0.99614 ± 0.00042
usol32	1.00082 ± 0.00025	0.99666 ± 0.00024	0.99890 ± 0.00025	0.99893 ± 0.00024	0.99742 ± 0.00025	0.99894 ± 0.00025
umet8	0.99632 ± 0.00054	0.99645 ± 0.00061	0.99577 ± 0.00059	0.99584 ± 0.00057	0.99497 ± 0.00059	0.99401 ± 0.00054

Table 9 continued

Case	CENDL-3.1	CENDL-3.2	ENDF/B-VII.1	ENDF/B-VIII.0	JEFF-3.3	JENDL-4.0
umet12	0.99977 ± 0.00057	1.00007 ± 0.00054	0.99814 ± 0.00062	0.99779 ± 0.00057	0.99733 ± 0.00062	0.99639 ± 0.00059
umet15	0.99453 ± 0.00055	0.99520 ± 0.00059	0.99436 ± 0.00057	0.99499 ± 0.00052	0.99435 ± 0.00057	0.99367 ± 0.00059
mixmet8-1	0.99477 ± 0.00048	0.99607 ± 0.00047	0.99526 ± 0.00048	0.99584 ± 0.00057	0.99497 ± 0.00059	0.99401 ± 0.00054
mixmet8-7	1.02400 ± 0.00016	1.02087 ± 0.00018	1.01920 ± 0.00018	1.02361 ± 0.00020	1.02653 ± 0.00017	1.01691 ± 0.00017
lst7-14	0.99894 ± 0.00030	0.99479 ± 0.00031	0.99726 ± 0.00029	0.99831 ± 0.00031	0.99756 ± 0.00029	0.99449 ± 0.00031
lst7-30	0.99894 ± 0.00030	0.99479 ± 0.00031	0.99726 ± 0.00029	0.99831 ± 0.00031	0.99756 ± 0.00029	0.99449 ± 0.00031
lst7-32	0.99786 ± 0.00030	0.99492 ± 0.00029	0.99559 ± 0.00029	0.99694 ± 0.00029	0.99587 ± 0.00027	0.99389 ± 0.00031
lst7-36	1.00039 ± 0.00026	0.99717 ± 0.00028	0.99900 ± 0.00027	0.99975 ± 0.00027	0.99910 ± 0.00026	0.99596 ± 0.00027
lst7-49	0.99887 ± 0.00028	0.99566 ± 0.00028	0.99721 ± 0.00027	0.99844 ± 0.00027	0.99752 ± 0.00027	0.99429 ± 0.00026
mct2-pnl30	1.00157 ± 0.00034	1.00000 ± 0.00035	0.99939 ± 0.00034	0.99825 ± 0.00032	1.00103 ± 0.00033	1.00170 ± 0.00034
mct2-pnl31	1.00374 ± 0.00078	1.00357 ± 0.00079	1.00296 ± 0.00084	1.00315 ± 0.00071	1.00482 ± 0.00076	1.00558 ± 0.00078
mct2-pnl33	1.00846 ± 0.00034	1.00733 ± 0.00034	1.00694 ± 0.00035	1.00455 ± 0.00032	1.00514 ± 0.00032	1.00878 ± 0.00036
mct2-pnl34	1.00831 ± 0.00031	1.00686 ± 0.00031	1.00239 ± 0.00033	1.00101 ± 0.00032	1.00161 ± 0.00033	1.00409 ± 0.00034
mct2-pnl35	1.00756 ± 0.00034	1.00697 ± 0.00033	1.00572 ± 0.00033	1.00395 ± 0.00032	1.00431 ± 0.00033	1.00816 ± 0.00031
mmf1	0.99888 ± 0.00027	0.99905 ± 0.00026	0.99993 ± 0.00026	0.99961 ± 0.00026	0.99848 ± 0.00026	0.99773 ± 0.00027
mmf3	1.00056 ± 0.00028	1.00068 ± 0.00027	1.00083 ± 0.00029	1.00104 ± 0.00027	1.00039 ± 0.00027	0.99943 ± 0.00028

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Xu-Bo Ma, Kui Hu and Teng Zhang. The first draft of the manuscript was written by Bin Zhang and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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