

Criticality Validation of SuperMC with ICSBEP

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Abstract

Super Monte Carlo Simulation Program for Nuclear and Radiation Process (SuperMC) is a CAD based Monte Carlo program for integrated simulation of nuclear system by making use of hybrid MC and deterministic methods and advanced computer technologies, developed by FDS Team in China. The effective neutron multiplication factor k_{eff} is a key parameter for criticality calculation in safety design and analysis of reactors. In order to validate the correctness of criticality calculation of the latest version SuperMC 2.3, Handbook of International Evaluated Criticality Safety Benchmark Experiments (ICSBEP) was used for validation the code. Then 117 representative benchmarks from ICSBEP were selected as a validation suite which gave a broad coverage of fissile materials, reflector materials and energy spectrum for criticality safety applications. All the calculation results of SuperMC were compared with the experimental values and 78% of the results were within one or two σ of the experimental values. The average deviation between the results of SuperMC and MCNP was 7.034pcm by using the same nuclear data library. All the comparisons indicated that SuperMC2.3 worked correctly in the criticality safety calculations.

Key Words: SuperMC, criticality, k_{eff} , ICSBEP.

1. Background

Monte Carlo (MC) neutron transport codes are widely used in various applications of reactor physics, criticality safety analysis, radiation shielding problems and detector modeling. The development of advanced nuclear energy system brings great challenges to current simulation methods and tools of nuclear energy system on neutronics, fluids and heat transfer, materials, fuels, geometrical modeling, data visualization, etc. To support these studies, a new Monte Carlo code named Super Monte Carlo Simulation Program for Nuclear and Radiation Process (SuperMC) is under development by the FDS Team in China [1-4]. The latest version SuperMC 2.3 can perform neutron and photon transport calculation, and integrates geometry and physics automatic modeling, and visualization and virtual simulation, assisted with own developed nuclear data library. Various fixed source and criticality parameters of reactors can also be calculated. It adopts complete and concrete physics model of 10^{-11} MeV to 150 MeV neutron and 1keV to 100GeV photon.

The effective neutron multiplication factor k_{eff} which determines how a nuclear chain reaction proceeds is an important parameter for criticality calculation in reactor safety design and analysis of reactors. Criticality safety practitioners are required to validate the computational tools used in

their work, and so are code developers. Code validation is necessary for evaluating the reliability of the simulation system. For criticality safety validation, several MC codes have tested with the validation suite chosen from Handbook of International Evaluated Criticality Safety Benchmark Experiments (ICSBEP) [5-6], such as MCNP [7], Serpent [8], McCARD [9] and TRIPOLI-4 [10]. For criticality safety applications, 117 representative benchmarks from ICSBEP were used to validate the code. The calculation results were compared with experimental values and MCNP results. In Sections 2 and 3, validation suite, simulation methods were respectively introduced in detail. The calculation results and comparison of SuperMC with experiments and MCNP were presented in Section 4.

2. Validation Suite

The handbook is intended to validate calculational techniques that are used to establish minimum subcritical margins for operations with fissile materials and determine criticality alarm requirements and placements. The data in the handbook are frequently used for validating codes and cross section libraries used for reactor physics simulation, especially for criticality safety analyses.

In order to validate the code for criticality safety applications, a set of 117 representative benchmarks has been selected from ICSBEP. The cases of the validation suite were chosen to include a wide variety of fissile materials, reflector materials and energy spectrum. The selected benchmarks in the validation suite are divided into three categories by major isotopes: ^{233}U , ^{235}U , and ^{239}Pu . The benchmarks in the ^{235}U category are further divided into three categories according to the enrichment of ^{235}U in fuel: highly enriched uranium (HEU ≥ 60 wt.%), intermediate enriched uranium (10 wt.% $< \text{IEU} < 60$ wt.%) and low enriched uranium (LEU ≤ 10 wt.%). The suite also covers a wide range of neutron energy spectra and is categorized by fast, intermediate and thermal spectrum. The fast spectrum benchmarks are those the majority of fissions are caused by neutrons with energy greater than 100keV. Thermal spectrum benchmarks are those the majority of fissions are caused by neutrons with energy lower than 0.625eV. The intermediate spectrum benchmarks are those in which more than half of the fissions are caused by neutrons with energy between 0.625eV and 100keV. It is noted that the LEU category only contains thermal cases because the systems cannot reach criticality with intermediate and fast spectrum. The cases in the validation suite in each of these categories were shown in Table I.

Table I Criticality validation suite from ICSBEP.

Principal Fuel	Number of benchmarks by spectrum			
	Fast	Intermediate	Thermal	Total
LEU	0	0	8	8
IEU	10	0	6	16
HEU	29	5	6	40
^{233}U	10	1	7	18
Plutonium	21	1	13	35
Total	70	7	40	117

3. Simulation and Analysis Method

Each benchmark from ICSBEP has all of the evaluated experimental data, benchmark specifications which contain geometry model, material data, temperature data and etc. The automatic functions of the models conversion and construction of SuperMC were used to greatly reduce the human power and enhance the reliability of the calculation models [11-15]. In the validation suite, there are a series of low enriched uranium reactor benchmarks with large amount of repeat structure description in the geometry model. The automatic converting function of SuperMC from MCNP input files to SuperMC input files was used to effectively enhance the benchmarking efficiency. Repeat structure construction of reactor cores based on the assigned parameters and the conversion between CAD models and MC calculation geometry models were also adopted in the validation process. Besides, physics attributes including materials, sources, tallies, and temperature data were assigned graphically to form complete calculation input files.

The calculations used more than total of 30000 generations with 3000 histories per generation. The results from the first 100 generations were excluded from the statistics. The calculation was run in the k-eigenvalue criticality mode. The nuclear data library named Hybrid Evaluated Nuclear Data Library (HENDL) in SuperMC for nuclear analysis which can provide fine-group, coarse-group and point-wise nuclear data to fulfill the requirements of advanced reactor design and the relevant studies (Xu et al., 2010) was used for validation the code. The evaluated data in the nuclear library were selected from international evaluated nuclear data source, such as ENDF, JENDL, and JEFF. The data library had also been extensively tested [17]. All contrast simulation was done with the same nuclear data library and under the same computing configuration.

With using the same ACE format library files, it significantly reduced the uncertainties between the two codes by eliminating all discrepancies originating from the fundamental interaction data. The calculation results reflected discrepancies between two codes directly. Comparing with the benchmark experimental measurement data, following equations were used to evaluate the deviations between the calculation results and experimental data.

The relative difference was defined by [10]:

$$X = (X^{\text{benchmark or mcnp}} - X^{\text{SuperMC}}) / X^{\text{benchmark or mcnp}}$$

Where X was the analyzed parameter. The relative combined statistical uncertainty (σ), was defined by:

$$\sigma = \sqrt{(\sigma^{\text{benchmark or mcnp}})^2 + (\sigma^{\text{SuperMC}})^2}$$

Where $\sigma_i^{\text{benchmark or mcnp}}$ and $\sigma_i^{\text{SuperMC}}$ were benchmark experimental uncertainties and statistical uncertainties of SuperMC results.

4. Calculation Results and Analysis

The results of k_{eff} and its statistics uncertainty in each case were collected and presented in Figs. 2-6. The average statistical error for SuperMC and MCNP were 25pcm (from 20 to 33pcm) and 26pcm (from 22 to 35pcm) respectively. The statistical error was much smaller than the errors of benchmark value which the average value was 502pcm. So the statistical error for MCNP and SuperMC were not presented in Figs.

We also compared and analyzed the calculation results as well as the benchmark experimental measurements to determine whether the code works well for a wide range of problems. The benchmark name is abbreviated to use the first letter of ICSBEP name, which gives HEU-MET-FAST-001 for hmf1.

The difference of k_{eff} between SuperMC and MCNP for this suite using the same data library was shown in Fig. 1. While interfacing the same nuclear data library, the differences of results were due to the differences of codes. The average deviations between SuperMC and MCNP were 7.034pcm (from 0 to 28pcm) by using the same data library. There was a good agreement between the results of two codes. According to the equations in section 3, compared with the experimental data, about 78% of the cases simulated by SuperMC were within one or two σ of the experimental data.

The Figs. 2-6 showed a comparison of k_{eff} between the experimental data and calculation results. It was noted that also the calculation results of MCNP using the ENDF/B-VII.0 data library were presented in Figs. 2-6 [6]. The aim was to confirm whether the different data libraries would have a greater impact on calculation results with using one code. The average deviation calculated by MCNP with using two data libraries was about 0.0037.

By analyzing the distribution of k_{eff} in the results, some k_{eff} from the calculation results were higher than experimental data: umf04, pmf05 and pmf08 were 300-400 pcm above the experimental data, and the results for pst09 were even higher. On the other hand, some results were relatively lower than experimental data: mct02-case-pnl-30, pnl-31, pnl-32, pnl-33, and pnl-35 which had large amount of repeat structure description in the geometry model. The benchmark pst09 calculated by SuperMC owned the maximum deviation which was 2118pcm compared with the experimental data while the previous data calculated by MCNP which interfaced to ENDF/B-VII.0 data library was 1900pcm from the experimental data. The isotopes of data library in these cases might influence the final results: an absorber such as Gd, a moderator such as C, or structural materials such as Ni, stainless steel, Mo, Cr, Zr in between fuel plates. The reason of the discrepancies may be due to the elements' data that were specific to these cases. More cases were needed to be simulated to find the specific reasons.

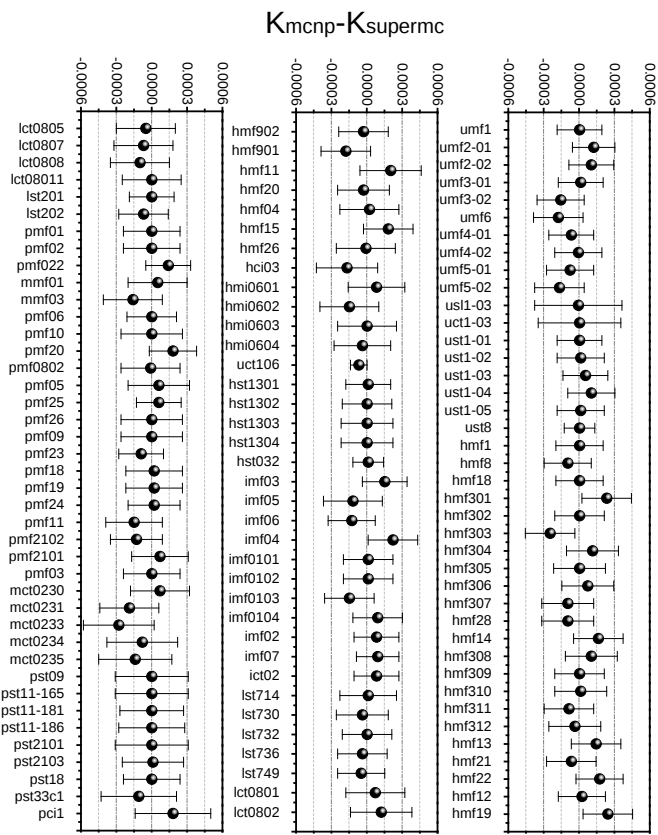


Figure1 Comparison between SuperMC and MCNP with the same data library.

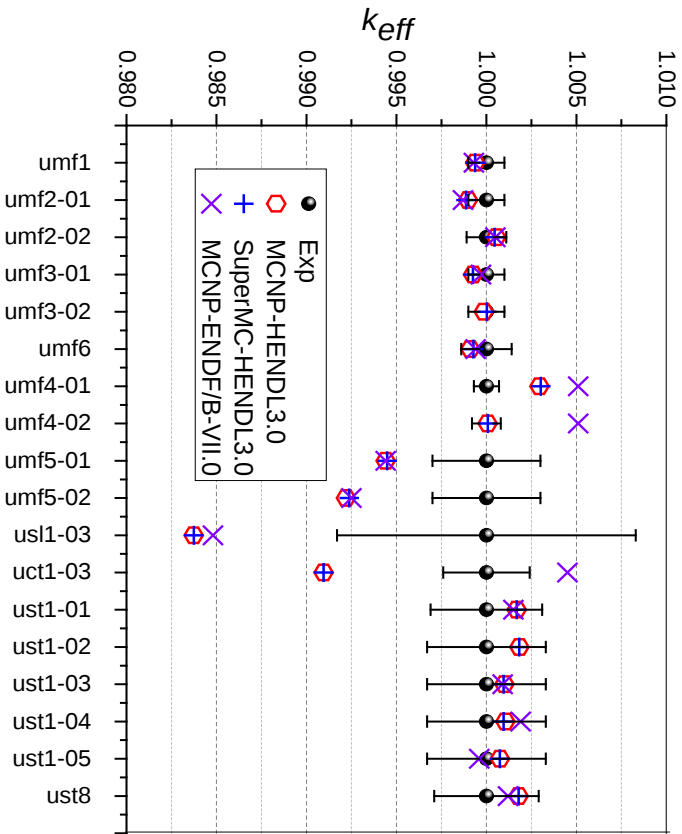


Figure2 Results for the ^{233}U benchmarks

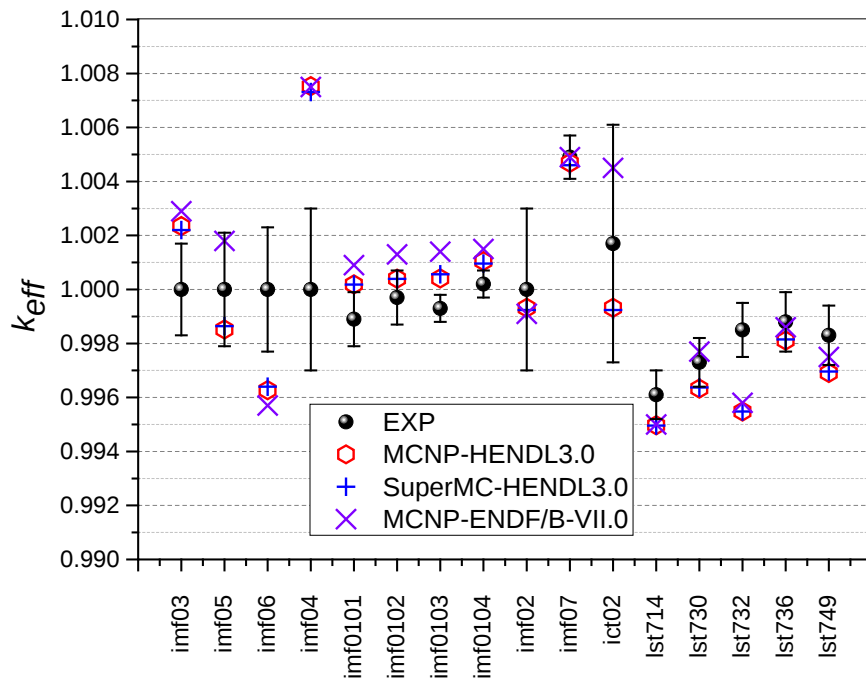


Figure3 Results for the HEU benchmarks.

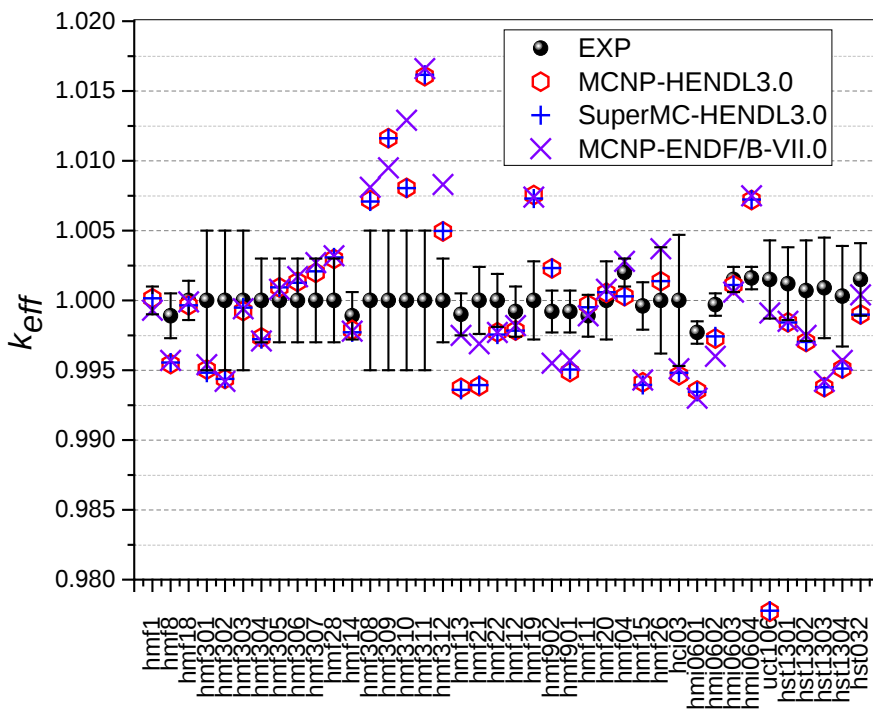


Figure4 Results for the IEU benchmarks.

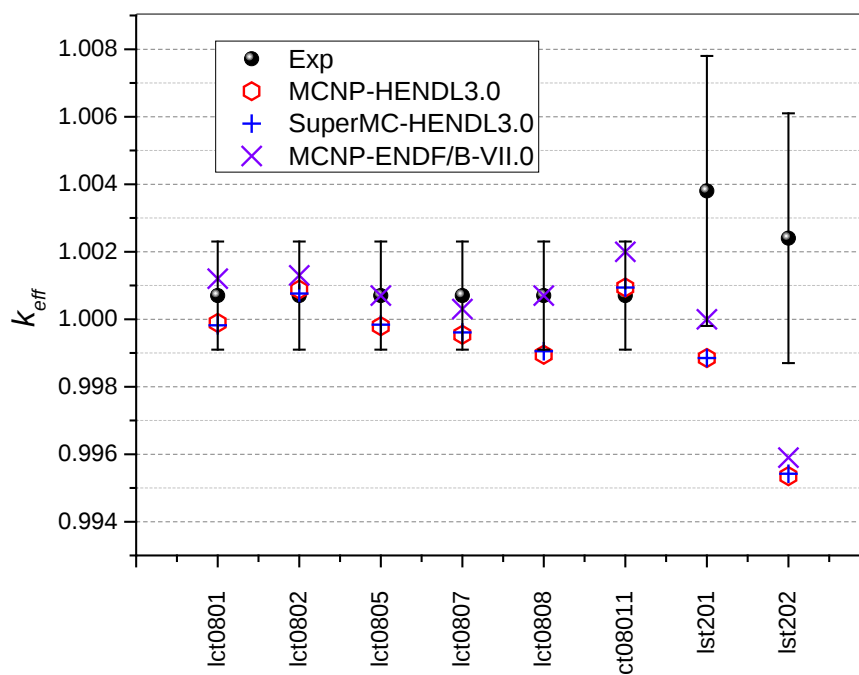


Figure5 Results for the LEU benchmarks

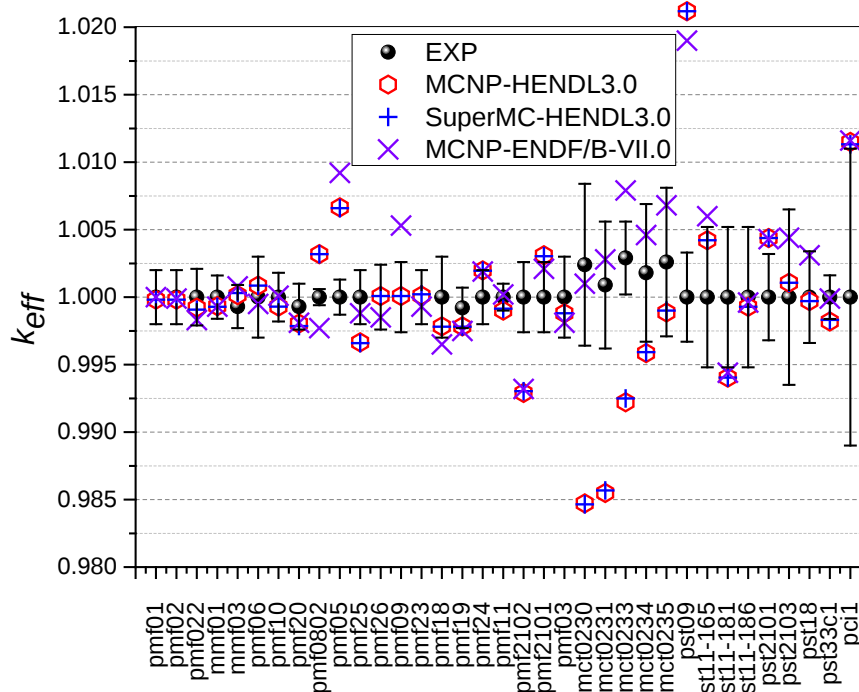


Figure6 Results for the Pu benchmark

5. Conclusions

ICSBEP was adopted to validate the criticality calculations of SuperMC and 117 representative benchmarks were selected to present the calculation results. All the calculation results of SuperMC were compared with the experimental values and 78% of the results were within one or two σ of the experimental values. The average deviation between the results of SuperMC and MCNP using the same nuclear data library was 7.034pcm (from 0 to 28pcm). The conclusion can be drawn that the criticality safety calculation capacity and correctness of SuperMC2.3 were proved in a manner.

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7. References

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