Verification of Shielding Benchmark Problems Based on the MagicMC Program

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Abstract

A verification study of shielding benchmarks was conducted based on MagicMC, a multifunctional digital-intelligent Monte Carlo program platform independently developed by the Nuclear Energy and Application Laboratory (NEAL) at the University of South China, aiming to evaluate its reliability for engineering applications. The Winfrith Water shielding benchmark and the NUREG/CR-6115 pressurized water reactor (PWR) shielding benchmark were selected as verification objects. MagicMC was employed to perform high-fidelity modeling and neutron transport calculations for both types of benchmarks, and the results were compared and analyzed against the calculation results of the international mainstream Monte Carlo program MCNP.

The results indicate that the calculation results of MagicMC for both types of benchmarks are in good agreement with those of MCNP. In the Winfrith Water shielding benchmark, the calculated neutron energy spectra at various measurement positions agree well, with overall small statistical errors. In the PWR pressure vessel benchmark, the azimuthal distribution of fast neutron flux calculated by MagicMC is consistent with the MCNP results, with an average relative deviation of approximately 4.35%, and the maximum relative deviation remains within the acceptable range for engineering. The verification results demonstrate that the MagicMC program possesses the capability to handle deep-penetration shielding problems and particle transport analysis for complex reactor systems, providing reliable computational support for reactor shielding design and safety analysis.

Full Text

Validation of MagicMC Program Using Shielding Benchmark Problems

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1. Introduction

Radiation shielding calculation is a core component in the design, operation, and safety analysis of nuclear energy systems [**?**]. During the operation of a nuclear reactor, the behavior of high-energy neutrons—specifically their flux attenuation and material activation—directly relates to radiation protection for personnel and environmental safety. Furthermore, these factors influence the lifetime assessment and maintenance cycles of critical equipment, such as the reactor pressure vessel (RPV), thereby exerting a profound impact on the overall economic efficiency and safety margins of nuclear power plants. Consequently, the development of high-efficiency particle transport calculation tools to achieve precise radiation field analysis in complex nuclear systems remains a primary focus in the field of nuclear engineering [**?**].

The Monte Carlo (MC) method solves the particle transport equation through statistical sampling, enabling the tracking of full-energy particle behavior within arbitrary complex structures. It is considered an ideal tool for high-precision shielding analysis. However, high statistical errors and low computational efficiency caused by deep penetration problems remain core challenges in Monte Carlo simulations. To overcome these bottlenecks, researchers have developed various advanced variance reduction techniques, such as importance sampling and weight window methods, to ensure computational accuracy and efficiency in low-flux regions.

To further promote the engineering application of China' s independent Monte Carlo calculation platforms, the Nuclear Energy Application Laboratory (NEAL) at the University of South China has developed the Multi-function Generalized Intelligent Code-bench based on the Monte Carlo method (MagicMC). This program utilizes a dynamic transport algorithm as its core, integrating functional modules for radiation shielding calculation, material activation analysis, and dose calculation, while supporting heterogeneous parallel computing and global weight-window adaptive optimization. This study focuses on the shielding calculation module of MagicMC, conducting validation of its accuracy and reliability using two typical international standard benchmarks: the Winfrith Water shielding benchmark and the NUREG/CR-6115 Pressurized Water Reactor (PWR) shielding benchmark.

Figure 1

Figure 1: Figure 1

2. MagicMC Methodology

2.1 Overall Program Architecture MagicMC is a multifunctional digital-intelligent computing software featuring a modular and hierarchical structural design. Its particle transport module incorporates a variance reduction module, supporting the combined invocation of various functional modules for tasks demanding high precision and computational efficiency. The design pays particular attention to the efficiency challenges inherent in deep penetration problems, leveraging robust geometric modeling and global variance reduction to perform efficient shielding calculations.

2.2 Radiation Shielding Calculation Methods The core of radiation shielding design lies in establishing accurate source terms and calculating transport processes through shielding materials to obtain dose distributions. MagicMC employs a global variance reduction technique based on mesh weight windows. This method performs an initial simulation to obtain a spatial flux distribution, which is then used to construct a mesh importance distribution. This guides and iteratively updates the weight window parameters until convergence.

The workflow is based on a forward-coupled MC-MC global variance reduction framework. To suppress excessive gradients in the lower bound of the weight window in deep penetration regions, MagicMC utilizes an adaptive smoothing factor $[0, 1]$ to maintain steady transitions in the weight window, enhancing the stability and computational efficiency of the variance reduction strategy.

3. Numerical Validation

3.1 Winfrith Water Shielding Benchmark To verify the accuracy of MagicMC in deep-penetration scenarios, this study applied it to the Winfrith Water shielding benchmark from the Shielding Integral Benchmark Archive and Database (SINBAD).

3.1.1 Experimental Configuration and Geometry The experiment was conducted in a large aluminum water tank (dimensions: 300 cm $\times$ 300 cm $\times$ 300 cm), as illustrated in

. The benchmark utilizes a ^{252}Cf fission neutron source. Neutron fluence rate measurements were performed within an air-filled aluminum tube at five measurement points located at the source plane as well as above and below it (at 0 cm, 10 cm, 20 cm, 30 cm, and 50 cm) to obtain neutron energy spectrum data at various depths.

3.1.2 Computational Results and Analysis Calculations were performed using the ENDF/B-VII.1 library. The results demonstrate strong overall consistency with reference data, particularly in the low-energy region where particle statistics are robust. The statistical error for the total flux in each counting region was maintained within acceptable limits; for energy groups with higher neutron flux, the maximum statistical error remained below 1%, while for lower flux regions, it was controlled within 5%. As the distance between the source and detection region increases, the statistical error shows an upward trend but remains well within the range for engineering applications.

3.2 NUREG/CR-6115 PWR Shielding Benchmark The NUREG/CR-6115 PWR shielding benchmark was used to verify the computational accuracy of MagicMC in the context of reactor pressure vessel (RPV) fluence analysis.

3.2.1 Model Description The model corresponds to a PWR core with an axial height equivalent to 12 fuel assemblies. Proceeding outward from the core, the materials include core materials, the thermal shield, pressure vessel cladding, and the RPV itself. The radial dimensions and materials are detailed in .

3.2.2 Source Term Modeling The model employs a probabilistic sampling construction based on the relative power density of the lattice. For peripheral fuel regions, which contribute the dominant share of the radiation dose, the model utilizes a refined approach defining geometry at the fuel rod level. For internal regions, an equivalent assembly-level source description is applied. Axial power evolution is characterized through piecewise discrete sampling probabilities along the z-axis.

3.2.3 Results and Statistical Error Evaluation The primary objective was to calculate the fast neutron flux ($E > 1.0$ MeV) on the RPV. Using global variance reduction, the statistical errors across all counting regions were effectively controlled. The neutron flux distribution calculated by MagicMC demonstrates good consistency with reference results. The average relative deviation across all counting regions is 4.35%, with a maximum deviation of 10.1% in specific tally regions. These deviations are attributed to differences in variance reduction strategies (importance-based vs. weight-window-based) but remain within the ideal range for engineering applications.

4. Conclusion

This study presents a systematic benchmark validation of MagicMC. The results from the Winfrith and NUREG/CR-6115 benchmarks confirm the reliability of the code for deep-penetration shielding and complex reactor system analysis. MagicMC demonstrates the accuracy and stability required for engineering applications, such as reactor shielding design and pressure vessel lifetime assessment. Future research will focus on extending these capabilities to transient conditions and multi-physics collaborative analysis involving thermal-hydraulics and material damage processes.

Figure 2

Figure 2: Figure 2

Figure 3

Figure 3: Figure 3

Keywords

Monte Carlo method; Shielding benchmark problems; Deep penetration; Pressurized water reactor

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Figures

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Figure 4

Figure 4: Figure 4

Figure 5

Figure 5: Figure 5

Figure 6

Figure 6: Figure 6

Figure 7

Figure 7: Figure 7

Figure 13

Figure 8: Figure 13