Research on Shutdown Dose Safety Algorithm for Advanced Solid-State Modular Small Nuclear Energy Systems

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Abstract. Nuclear energy, as one of the crucial high-energy-density clean energy sources, is inherently associated with safety concerns regarding radiation dose throughout its development and application. The evolution of distributed power markets has rendered the calculation of dose rates for small reactors a focal point of research. This study employs uncertainty-based particle transport calculations and burnup calculations using the matrix exponential method. A Rigorous 2-Step (R2S) program is developed for the coupled neutron-high-energy gamma-ray transport in a multi-physics framework involving criticality, burnup, and activation processes. The correctness and accuracy of the algorithm are verified against the internationally recognized ITER shutdown dose rate benchmark. The research findings demonstrate that the R2S program aligns well with numerical solutions provided by various authoritative international institutions for FDS, SWIP, Jakhar and CCFE programs in benchmark calculations. Consequently, the R2S algorithm developed in this study proves applicable for dose rate numerical calculations in small modular solid-state nuclear energy systems, offering robust data support for the safety assessment of advanced nuclear power systems.

Keywords: Renewable Energy, Nuclear Energy, Radiation Safety; Rigorous 2-Step Method; Monte Carlo Simulation.

1 Introduction

The development of distributed power markets has created a broader space for the application of advanced small modular mobile nuclear power sources. Due to the closer proximity of personnel workstations to the reactor core and the increased susceptibility of all solid-state components to radiation penetration, safety challenges during emergency repairs and routine maintenance are more severe for small reactors. The internal components of the reactor undergo long-term neutron irradiation, leading to activation reactions, making them the most significant radiation source affecting the shutdown safety of advanced nuclear systems.

Before the widespread discussion of activation issues in small reactors, similar problems were extensively studied and discussed in Tokamak fusion systems. In 1998, the

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ITER project proposed the use of conversion factor methods for dose rate estimation in shield design [1]. Subsequently, researchers from relevant organizations introduced a Monte Carlo direct one-step method based on coupled neutron-photon transport information memory and pointer-based vectors (Direct 1-Step, D1S) [2], as well as an Advanced Direct 1-Step Method [3]. Building upon this, the Rigorous 2-Step (R2S) method for activation dose rate calculation was developed by coupling the transport processes of neutrons and photons through program interfaces, automatically accumulating statistics on numerical values. This non-conversion factor full Monte Carlo method exhibits excellent capabilities in handling complex geometry and conducting large-scale burnup calculations in various regions, making it applicable to a wider range of scenarios [3]. While these three methods have been proposed for a considerable amount of time, as safety research on solid modular reactors progresses, the activation algorithms for plasma-constrained fusion systems fail to meet the diverse and complex design requirements of fusion systems. The utilization of activation-prone structural materials such as industrial-grade 304 stainless steel introduces significant photon penetration effects in compact spatial designs. In the operational environment of mobile reactors on the road, the effectiveness of shadow shielding is limited, and the emergence of prominent voids and scattering effects within the entire solid-state space poses new challenges for advanced small reactors in biologically shielded dose rate calculations.

Therefore, this paper, in conjunction with the dose shielding requirements of advanced small nuclear power sources, develops a Rigorous 2-Step calculation program with automatic coupling of "criticality-burnup-activation" based on Monte Carlo simulation and burnup calculation. To validate the effectiveness and correctness of the algorithm, the program is applied to benchmark tests for ITER shutdown dose rate calculations. The numerical results are compared with solutions provided by FDS, SWIP, Jakhar, and CCFE institutions to verify the program's computational capabilities and accuracy in modular geometry conditions for solid-state reactors.

2 Program Design

2.1 Physical algorithm

Under neutron irradiation conditions, nuclear structural materials undergo activation reactions, releasing a significant amount of decay photons, which become a crucial source for shutdown dose rates. From the perspective of actual physical processes, a comprehensive estimation of biological dose rates typically involves the following three steps [2-4]:

1. Neutron Transport Calculation: Based on a given three-dimensional model, neutron transport calculations are performed to obtain the energy and flux distribution of neutrons in specific spatial regions during reactor operation.

2. Activation Calculation: Using the data from step 1, activation calculations are carried out for each component to determine the distribution of decay gamma sources on a specified isotope list.

3. Photon Transport Calculation: Utilizing the gamma ray source distribution data obtained in step 2, photon transport calculations are conducted to derive the static distribution of shutdown dose rates.

While these steps can theoretically be achieved through deterministic methods like the Discrete Ordinates (Sn) method and corresponding activation programs, in practical energy engineering, advanced reactor systems often feature highly complex geometric structures. Moreover, in small solid-state reactors, irregular geometries such as heat pipe heat exchangers, turbines, and shell structures need to be considered for activation. Therefore, the limited geometric adaptability of the Sn method may lead to significant uncertainties in radiation transport calculations, especially when modeling shielding accurately. To ensure reliable results, the Monte Carlo method based on uncertainty theory is chosen for neutron transport (Step 1) and photon transport (Step 3) due to its excellent geometric description capabilities through probabilistic sampling [5]. Additionally, for Step 2, a point-burnup calculation code is employed, relying on decay databases and single-group cross-section databases applicable to various reactor types [6].

2.2 Core Components of the Calculation Scheme

The central components of the calculation scheme consist of two main parts: the RMC Monte Carlo program and the DEPTH burnup code. The execution involves calling interface programs to facilitate free communication between the two components. This includes importing neutron spectra and flux data from RMC into DEPTH and exporting secondary photon source distribution data from DEPTH to RMC. The entire process is illustrated in Figure 1.

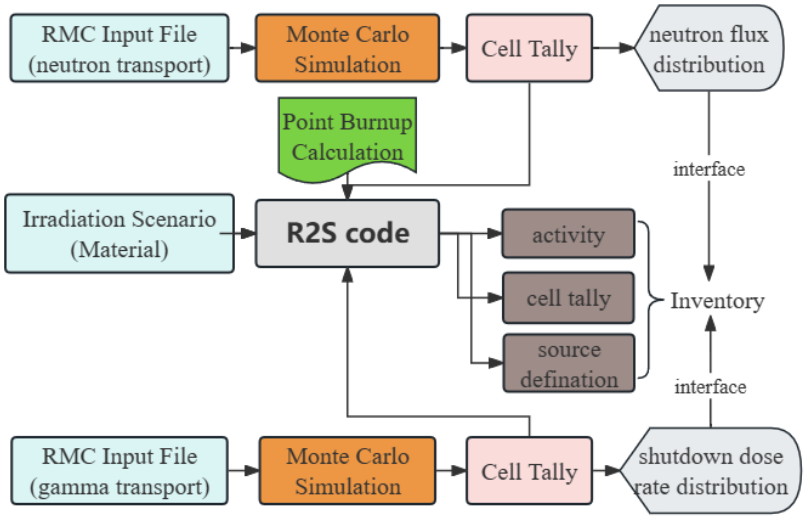

Fig. 1. Flow scheme of the R2S coupling procedure system

The calculation begins with the RMC criticality calculation based on a specific three-dimensional geometric model. After the transport phase, a multigroup structure of neutron energy spectra distribution is obtained. The calculated neutron flux spectra are stored in a standardized format in the output file. The interface program normalizes these values to real values and passes them to the activation module DEPTH through the first call.

Using the multigroup spectra data, the provided activation cross-sections are collapsed into single-group cross-sections for the subsequent activation calculations. During the detailed and large-scale burnup process in fine-partitioned regions, the energy spectra and intensity of decay gamma sources for the considered materials and geometric grid elements are statistically calculated. Through the second call, this data is passed back to the transport module. Finally, the spatial distribution of shutdown dose rates is obtained through photon transport calculations.

3 ITER Shutdown Dose Rate Benchmark Validation

3.1 Problem Description

The schematic geometry of the benchmark is illustrated in Figure 2. The entire model has a length of 7m, with the central cylindrical sleeve section being 5.5m long, representing the activation region in the problem. An isotropic fixed neutron source is placed to the left of the sleeve, and a counting plate is positioned to the right. The outermost layer of the activation region is a 550cm-long hollow composite steel cylinder with inner and outer radii of 50cm and 100cm, respectively. The front section of the sleeve contains an internally placed cylindrical steel-water mixture, with a length of 210cm and inner and outer radii of 48cm and 15cm, respectively. The rear end is sealed by a 15cm-thick, 48cm-radius steel disk, with a 2cm gap between it and the outer steel cylinder. The neutron source is a cylinder with a radius of 100cm, aligned with the outer steel cylinder, located 100cm from the front of the components, with a width of 10cm, emitting isotropic neutrons. The counter grid consists of concentric disks with a thickness of 10cm, positioned 30cm from the back of the components, and the radii of the concentric circles are 15cm, 30cm, 45cm, and 60cm [7].

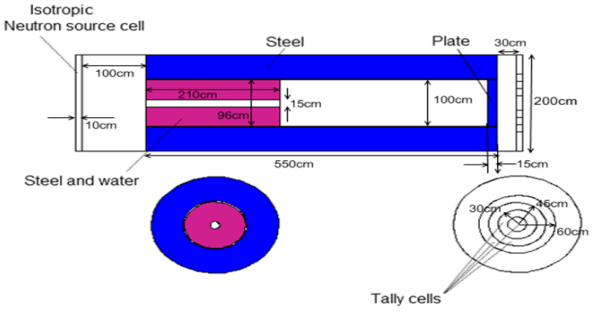

Fig. 2. ITER SDDR benchmark problem geometry.

The benchmark calculation involves two problems:

1. Calculate the neutron flux on four surfaces (front and back of the inner steel-water mixture cylinder, front and back of the sealing steel disk) of the cylinder and disk components.

2. Calculate the photon dose values on four Tally locations on the rightmost plate due to activation of the cylindrical sleeve material.

Throughout the simulation, the neutron source strength is set to 2.0×10^19 n/second, with an energy of 14MeV. The neutron spectrum is divided into 18 groups, with upper limits at 1.00E-10,1.00E-09,1.00E-08,1.00E-07,1.00E-06,1.00E-05,1.00E-04,1.00E-03,1.00E-02,0.1,1,10,13,14,15,16,20MeV. The decay gamma source spectrum is defined in 16 bins, with upper limits at 0.1, 0.4, 0.6, 0.8, 1.0, 1.22, 1.44, 1.66, 2.0, 2.5, 3.0, 4.0, 5.0, 8.0, 10.0MeV. The neutron irradiation scheme is provided in Table 1.

Table 1. Neutron irradiation scheme.

Source Strength (neutron/s)	Time Period	Number of repetitions
1.0714×10^{17}	2y	1
8.25×10^{17}	10y	1
0	0.667y	1
1.6607×10^{18}	1.33 y	1
0	3920s	17
2.0×10^{19}	400s	17
0	3920s	4
2.8×10^{19}	400s	4

3.2 Calculation Results and Analysis

Figure 3 depicts the normalized neutron flux statistics on four planes for Problem 1, illustrating the approximate transport of neutron flux along the axis. A comparison of RMC results with four other calculations reveals that, as the distance between the statistical region and the neutron source increases, the computational discrepancies slightly grow, consistent with the deep-penetration characteristics of Monte Carlo transport. Deviations among 66.7% of reference solutions are within 10%, while 87.5% of solutions exhibit deviations within 20%, falling within the acceptable range for shielding calculations. This validates the accuracy of the geometric model construction and particle transport sampling processes[8].

Figure 4 displays the results for Problem 2. The initial neutron source is located on the leftmost disk. In such cases, the isotopes activated by neutron irradiation will inevitably show a trend of more activation on the left and less on the right. Therefore, a fine partitioning of the grid elements in the activation region is necessary. Additionally, since photons emitted from the rear of the geometric unit contribute significantly to the dose at the counting locations, uniform sampling of the decay photon sources within the segmented units is selected to ensure computational efficiency.

Upon comparing with other reference solutions, it can be observed that the computed results of the current coupled program generally follow the expected numerical trend. Considering the differences in decay photon databases used in activation calculations, the partitioning of geometric units, and the burnup equation-solving methods, some deviations in dose results may exist among different programs. However, the discrepancies between the results generated by the current coupled program and those from FDS, SWIP, CCFE and other programs are controlled within 15% at each location, maintaining a certain level of convergence. This indicates that the designed coupling program possesses a certain level of correctness and accuracy in its workflow design.

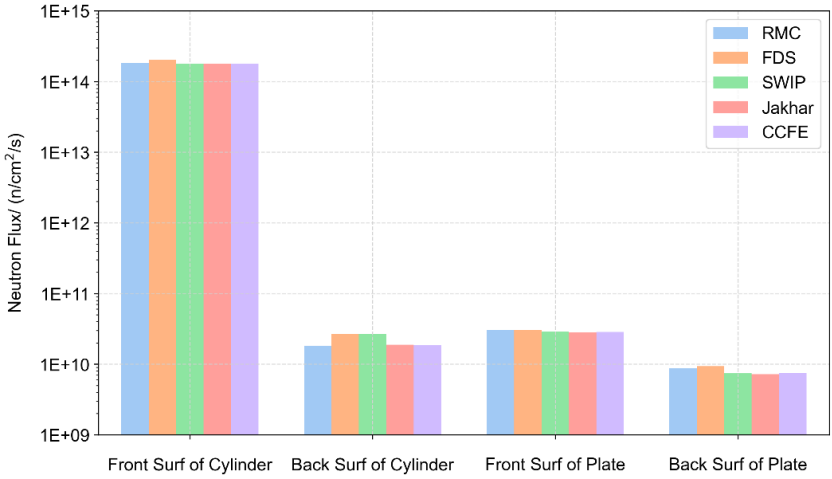

Fig. 3. Comparison of flux calculation results.

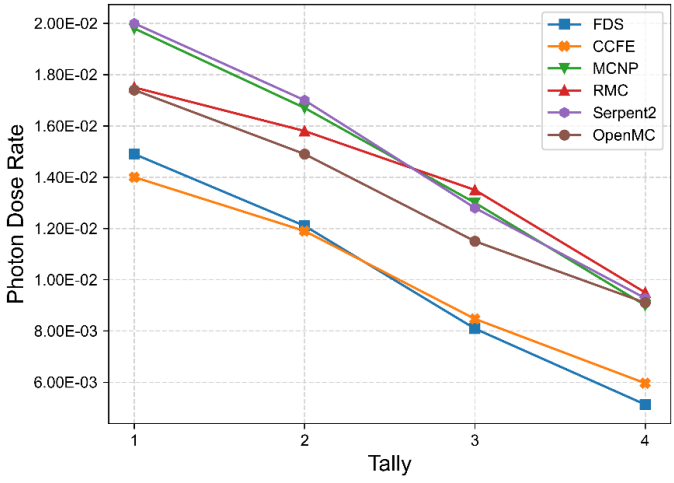

Fig. 4. Comparison of calculation results of shutdown dose rate.

4 Conclusion

This study employs the Rigorous 2-Step (R2S) algorithm and establishes a large-scale parallel coupled criticality-burnup calculation program based on RMC (Monte Carlo program) and DEPTH (burnup code). This program achieves a fully automatic coupling of criticality and burnup, enabling detailed activation analysis of shutdown dose rates for small reactor loop components.

The implementation process begins with the design of the program workflow and the development of relevant interface scripts. Subsequently, numerical calculations are conducted using the ITER shutdown dose rate benchmark under simplified geometric conditions. The program's results are then compared and analyzed against existing Monte Carlo program results.

The findings demonstrate that the proposed coupling scheme exhibits a certain level of correctness and reliability. By successfully applying the R2S algorithm, this study provides a comprehensive analysis of shutdown dose rates for small reactor loop components, offering valuable insights for the safety assessment of advanced nuclear power systems.

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