A Fast Variance Reduction Technique for Efficient Radiation Shielding Calculations in Nuclear Reactors

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INTRODUCTION

Topic

- This study focuses on developing a faster Variance Reduction Technique (VRT) for radiation shielding calculations in deep penetration problem for Small Modular Reactors (SMRs).

Conventional Radiological emergency response modeling

- The primary sources from the reactor are neutrons and photons, and the radiation dose in the target area is calculated using the MCNP6 program
- A conventional method uses SSW/SSR to record particle energy, direction, and position on the reactor vessel surface to generate a source.
- However, it does not support multi-threading, resulting in slower computation.

Objective

- The aim of this study is to develop a new VRT that improves computational speed by proportionally increasing it with the number of threads through multi-threading. This is achieved by calculating radiation transport starting from outside the reactor vessel, allowing for design modifications of the geometry without the need for criticality calculations or radiation transport inside the vessel.

Reference Reactor description

- The reference reactor is a 40 MW(thermal) lead-bismuth-Eutectic (LBE)-cooled fast reactor, surrounded by concrete shielding.

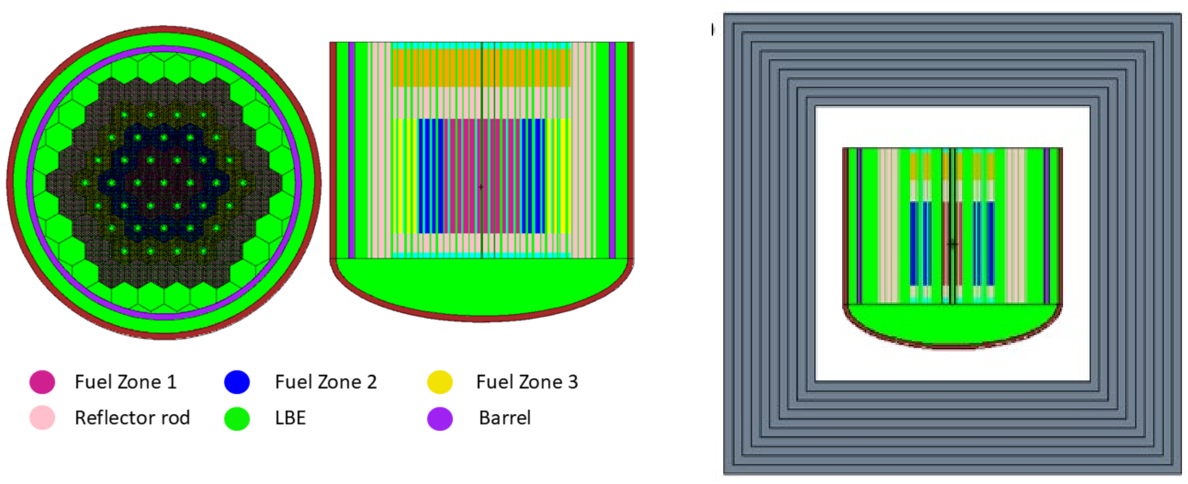

Fig 1. Reactor core configuration and Shielding model

Methodology

Two-step method

- In the first step, the energy and polar direction of particles are recorded in a spherical tally surrounding the reactor. The energy ranges and polar angle intervals of the particles recorded on the sphere are divided into multiple segments to increase accuracy.
- In the second step, these recorded values are used to define a fixed source for radiation shielding analysis.

Direct gamma-ray approximation

- Primary gamma rays are generated from prompt fission, gamma rays from fission products, and gamma rays from radiative capture by various isotopes in reactor. secondary gamma rays are produced by interactions between neutrons that escape the vessel and the shielding material. As seen in Figure 3, Radiation dose from direct gamma rays can be negligible In deep penetration problems as it decreases while passing through the shielding, allowing us to define the two-step source based on neutrons only

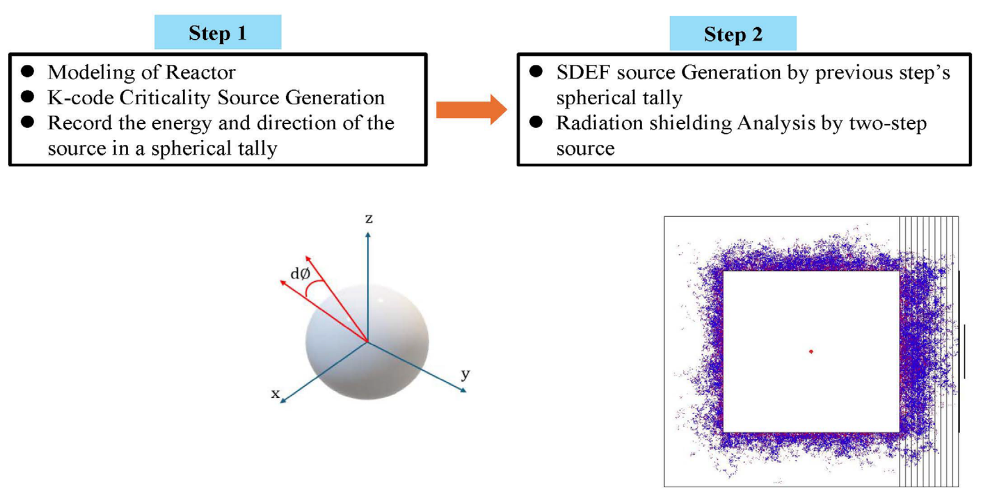

Fig 2. Two-step method flow chart

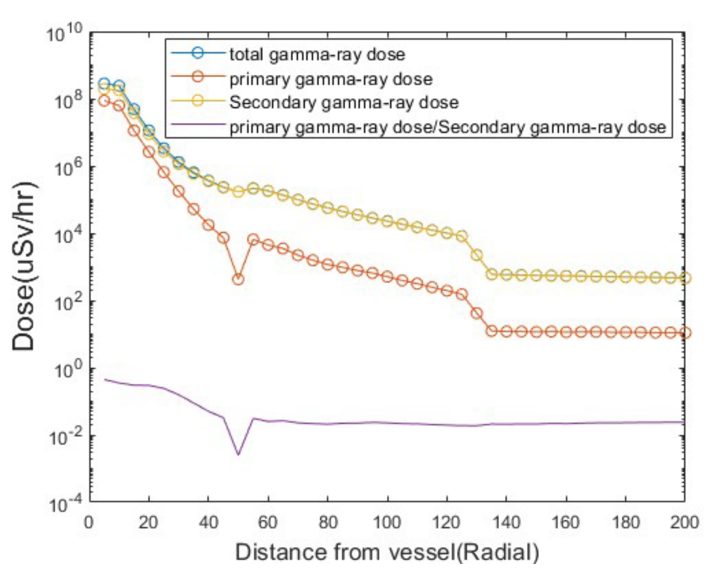

Fig 3. The behavior of Primary and Secondary gamma ray

Result

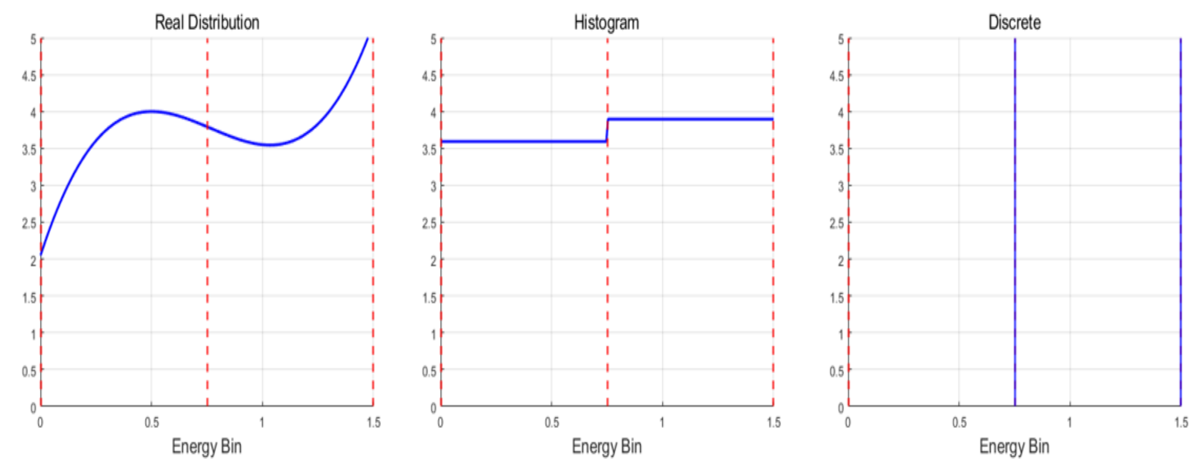

Fig 4. Direction and Energy sampling method-discrete and histogram

Best approximation finding

- Dose ratio=(Two-step source dose rate)/(original source dose rate)
- The dose ratios between the direct source and the two-step source are compared based on concrete thickness. The dose ratios measured on the concrete surface are compared at 10 cm intervals.
- The closer the dose ratio is to 1, the more accurate the VRT is.

Sensitivity analysis

- (a) in fig5, the energy division is fixed at 101 segments, while the direction is divided into 64, 128, 256, and 500 segments.
- As seen in (a) and (b) in fig5, when energy is sufficiently divided, there is little difference between dividing the direction using the discrete method or the histogram method.
- When Comparing (a) and (c) shows that when the energy is divided using the histogram method, underestimation occurs, resulting in doses lower than those from the original source.
- When comparing Figure (a) and (d), Dividing into fewer energy groups reduces accuracy
- (e) shows that the best approximation is achieved when the energy is divided into 202 discrete groups and the direction into 128 segments. This configuration provided the most accurate results. The average dose rate error was the lowest at 12.32%.

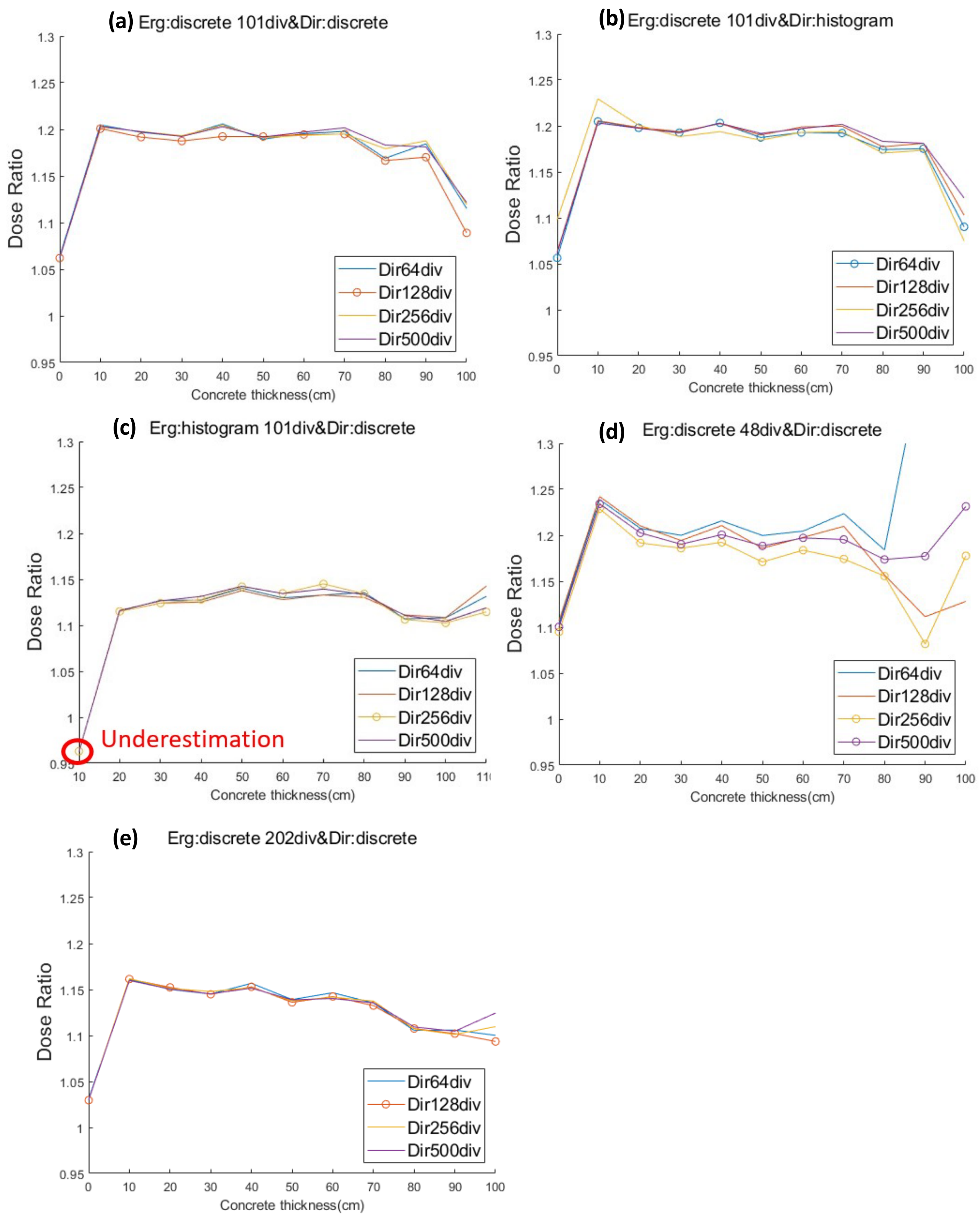

Fig 5. Sensitivity analysis on direction and energy division

[Reference]

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