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Application and Analysis of the Revised Accurate Weight Method for Fusion Facilities

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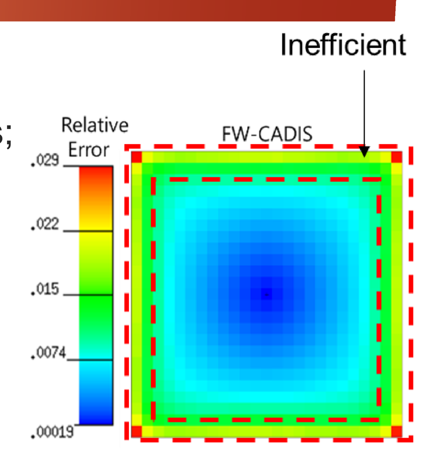
ABSTRACT : Monte Carlo (MC) methods are widely used for nuclear analysis in fusion facilities. However, their computational cost is high. Hybrid MC methods such as CADIS and FW-CADIS, which are implemented in ADVANTG, address this issue by generating variance-reduction parameters deterministically and then running MC simulations. In our previous work, the Revising Accurate Weight (RAW) method was proposed, which corrects weight windows using relative errors obtained from MC simulations for problems involving multiple tallies. In this study, the RAW method was applied to a fusion experimental facility at the conceptual design stage and compared with FW-CADIS. In the IBTF test cell model, the average figure of merit increased by about 3.5 times, while the maximum figure of merit decreased by 65 percent. Errors at the outer boundary, which were high under the FW-CADIS method, were reduced when the RAW method was applied. On the other hand, errors in near pipes increased. To investigate this behavior, a penetration model was analyzed. The model consisted of a concrete block with a square-shaped penetration modeled as a void, with a point source placed at the center. The RAW method showed a more uniform error distribution in regions without penetration. However, the relative error increased at the bends and at the end of the penetration. This was attributed to weight increases near the bends, which reduced the number of MC particles, and to larger variations in particle weights reaching the terminal region. These results indicate that in geometries with gaps or penetrations, it is necessary to consider not only the high-RE regions but also the neighboring regions that influence them.

Introduction

- MC simulation and Variance Reduction
  - The Monte Carlo (MC) method provides accurate analysis for complex geometries; however, it requires long computation time
  - Variance reduction (VR) techniques have been developed and are used to improve computational efficiency; however, the efficiency varies depending on how the VR parameters are applied
  - To determine VR parameters, the Hybrid MC method has been developed; it determines VR parameters through a deterministic approach and then performs MC simulations using them



  - Among Hybrid MC methods for global responses such as dose maps, the FW-CADIS method is known to be the most efficient
  - However, the relative errors are still not uniform due to the methodology of the hybrid MC method and the assumptions of the deterministic method (space, angle, energy, etc.)
  - In our previous study, the Revising Accurate Weight (RAW) method was proposed to refine variance reduction parameters using relative errors (RE)
  - In this study, the RAW method was applied to a fusion experimental facility in the conceptual design phase to identify potential issues
  - After identifying these issues, representative model was constructed to reproduce the problems, and the underlying causes were analyzed

Background

- RAW method
  - MC Particle: $m(P) \approx n(P)/\overline{w}(P)$

    $n(P)$: Analog Particle Density in Phase Space; $\overline{w}$: Average Weight
    - MC particles do not represent real radiation particles; rather, they are artificial particles created in simulations to apply VR
    - This relation represents the concept proposed by Cooper and Larson: if MC particles are uniformly distributed throughout the system, each response will have a similar variance
  - Weight for Uniformly Low RE

$$\overline{w}(P) \propto n(P)\ or\ \phi(P)$$

    $\phi(P)$: Particle Flux
  - Relative Error for Analog MC Simulation

$$RE(P) \propto 1/\sqrt{\mathrm{n}(P)}\ \ or\ \ 1/\sqrt{\phi(P)}$$

  - Weight and Relative Error

$$\overline{w}(P) \propto\ 1/RE(P)^2$$

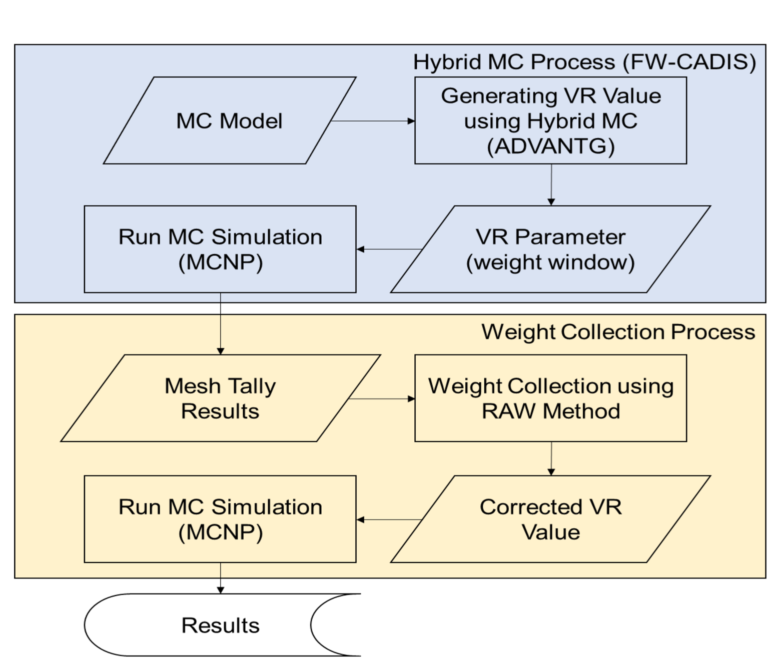
  - Weight Equation for Correction (RAW method)

$$\boxed{\overline{\mathrm{w}}_{\mathrm{raw}}(\vec{r},E) = \overline{w}_{hy}(\vec{r},E) \times Min\,[RE]^2/RE^2(\vec{r})}$$

    $\overline{w}_{hy}$: Weight from Hybrid MC Method

    $RE^2(\vec{r})$: Relative Error of MC Simulation in mesh tally

- Process for RAW method
  1. Make Weight Window using Hybrid MC Method
  2. Run MC Simulation with Mesh Tally (same size of weight window mesh)
  3. Update Weight Window using RAW Method
  4. Re-run MC Simulation with updated weight window



Application in Fusion Facility

- Estimation of Efficiency
  - Average Figure Of Merit (FOM)

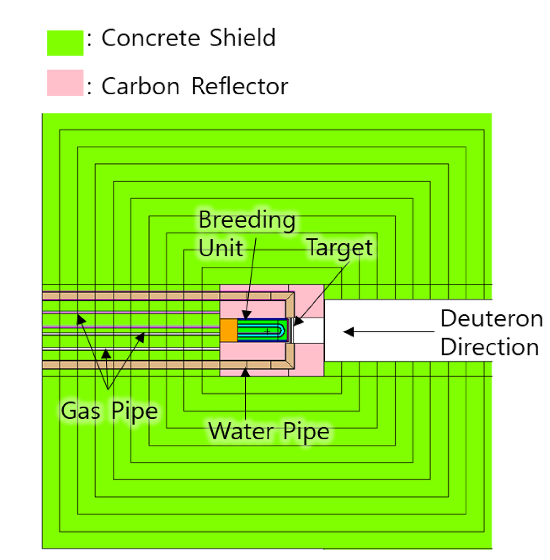
$$FOM_{ave} = \frac{1}{\frac{1}{N}\sum_{i=1}^{N} RE_i \times T}$$

  - Maximum FOM

$$FOM_{max} = \frac{1}{Max[RE_i] \times T}$$

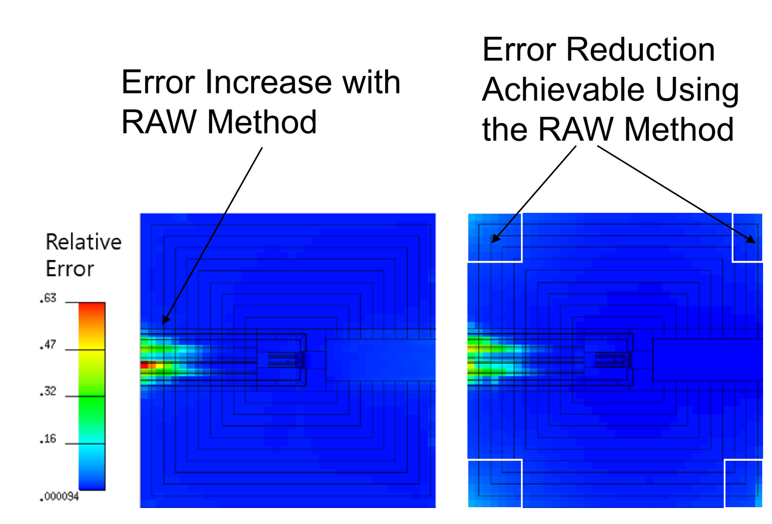
  N indicate the number of response, and RE_i is the RE for the i^th response

- Test Cell for Breeding Unit Model
  - At the center is the tritium breeding unit, which consists of Li_2TiO_3 pebbles, $Be_{12}Ti$ beryllide, and structural materials
  - Breeding unit is surrounded by a carbon reflector
  - For radiation shielding, the outer region is enclosed by concrete
  - Behind the breeding unit, water pipes for target cooling as well as pipes for breeding unit cooling and tritium extraction are located
  - Except for the water pipes, the other pipes were assumed to be filled with void



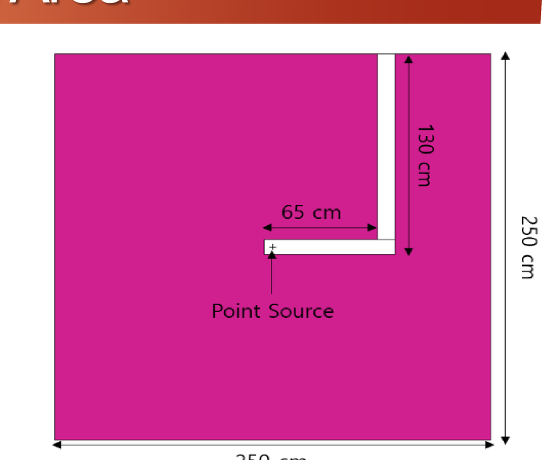
- Results
  - FOM_{ave} increased by approximately 3.5 times
  - FOM_{max} decreased by 65%
  - RE at the outer boundary calculated using the FW-CADIS method were reduced
  - in the pipe regions where errors were already high in the FW-CADIS method, the RAW method resulted in even higher errors

Method	Total MC time [Min]	FOM_{ave}	FOM_{max}
RAW Method	32634	0.565	4.48×10^{-5}
FW-CADIS	29985	0.163	6.90×10^{-5}

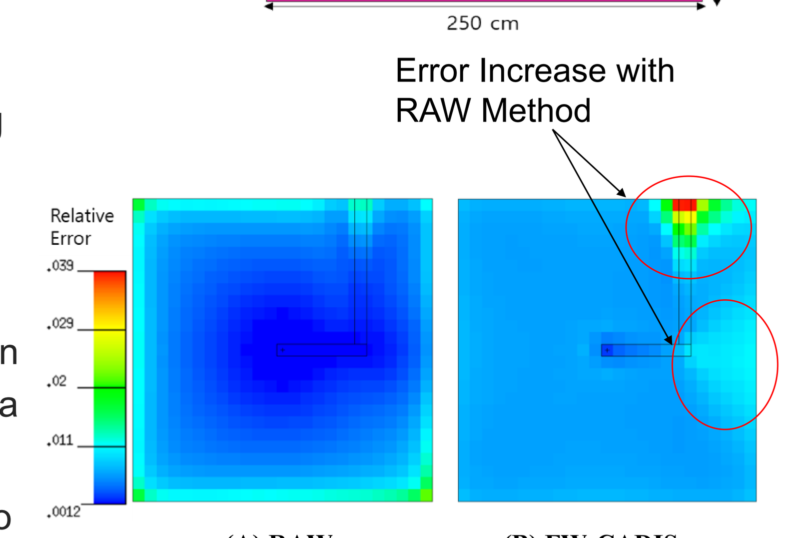


Analysis for RE Near Penetration Area

- Evaluation of a model with a 1 MeV point source at the center of a concrete block and a penetration, as shown in the figure on the right



- all errors were constrained to within 5% to ensure reliable results
- It was confirmed that the RAW method provides a more uniform RE distribution in regions without penetration
- However, at the end of the penetration and at the bending region, the RE increases
  - At the bending location, where particles can reach relatively easily, the RE is originally low
  - Nevertheless, since the RAW method increases the weight in such regions, the number of particles decreases, leading to a slight increase in RE
  - At the end of the penetration, the elevated RE is attributed to the larger weight assigned at the bending part compared to FW-CADIS, which results in greater variation in particle weights arriving at the final penetration region



- it is necessary to consider not only the high RE locations but also the regions that influence those locations

Conclusion and Future Works

- In this study, the RAW method was applied to a conceptual fusion facility model and compared with the FW-CADIS method
  - the RAW method reduced the REs at the outer boundary, which were pronounced under the FW-CADIS method. However, an increase in RE around the empty pipe was observed.
- To investigate the underlying cause of this behavior, A model with a penetration was created to analyze the phenomenon of increased RE
  - When the RAW method was applied, REs increased at the bends and at the end of the penetration due to the redistribution of MC particle weights and the resulting variation in particle transport
  - These results suggest that in geometries containing gaps or penetrations, attention must be paid not only to the locations with high RE but also to the regions associated with them
- ***Future Works***: a method will be developed to reduce the RE in regions associated with locations where REs are large.

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