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Development of a Variance Reduction Scheme in the MCS Monte Carlo Code

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1. Introduction

The MCS Monte Carlo (MC) code has been developed in Ulsan National Institute of Science and Technology (UNIST) for large-scale whole core high-fidelity simulation since 2013. The neutron transport simulation of criticality eigenvalue problem has been the main concern of the MCS development, even though MCS has the capability to simulate the fixed source problem. Recently, effort has been spent on extending the application of MCS code to shielding analysis, which requires the development of photon transport module, coupled neutron/photon transport module and various variance reduction (VR) techniques. This paper will report current developing status of the VR scheme in the MCS code, with the focus on the weight window (WW) technique.

2. Methods

2.1 The WW concept

The WW [1] has been one of the most widely used VR techniques and has been implemented in many MC codes like MCNP [2] and Serpent [3]. For each space-phase-energy volume/mesh, a WW as shown in Fig. 1 is applied [4]. Particles with weights lower than the WW lower boundary W_L are rouletted, particles with weights higher than the WW upper boundary W_U are split, while particles with weights between W_L and W_U are not affected.

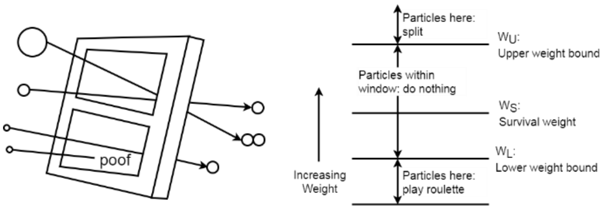

Fig. 1. The WW concept [4].

2.2 The WW generator

The application of the WW is straightforward. However, WW generator (WWG) is the key for the performance of the WW and there are many approaches for WWG.

A group of methods utilize deterministic codes to calculate the forward/adjoint flux and then generate the WW for corresponding MC simulations, like AVATAR [5], CADIS and FW-CADIS [6, 7]. These methods require the deterministic modeling of the system and is not considered now for MCS development.

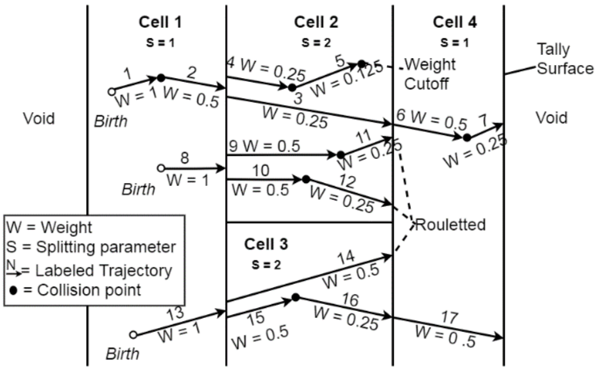

Fig. 2. The sample problem used to explain WWG in MCNP [4].

Table I: Importance estimation process for sample problem shown in Fig. 2 [4]

Row	Description	Cell 1	Cell 2	Cell 3	Cell 4
	Weight				
1	Trajectories entering	1,8,13	3,4,9,10	14,15	6,17
2	Weight associated with above trajectories	1,1,1	0.25,0.25,0.5,0.5	0.5,0.5	0.5,0.5
3	Total weight entering	3	1.5	1	1
	Score				
4	Trajectories entering resulted in score	7,17	7	17	7,17
5	Scores associated with above trajectories	0.25,0.5	0.25	0.5	0.25,0.5
6	Total score	0.75	0.25	0.5	0.75
	Estimate				
7	Estimated importance Row 6/Row 3	0.25	0.167	0.5	0.75

The original WWG method proposed together with the WW technique by the MCNP group (WWG_MCNP) is to use MC simulation to tally the importance of each cell [1, 4]. The example problem shown in Fig. 2 is used to explain the idea [4]. The corresponding importance estimation process is shown in Table I. Two additional tallies are required during the simulation, the total weight entering each cell and the total score due to the trajectories entering each cell.

The WWG_MCNP has been implemented in the MCS code. However, several key issues need to be considered for the application of this WWG. First, if the target detector tally is a rare event tally, the score would be zero even with large number of histories, in which case the importance is very difficult to obtain. Second, even if there are non-zero score tallies for some cells, most cells would have zero scores, in which case the importance for most cells cannot be obtained. This latter case usually implies lower performance for the MC simulation with the generated WW.

2.3 A new Response Matrix based WWG

To resolve the aforementioned issues about the WWG_MCNP, the concept of WW iteration can be applied, meaning that a previously generated WW is employed in a MC simulation with WWG to hopefully generate a better WW. Many iteration strategies can be applied, but they are all user-dependent, that is, the experience of the user would affect the performance significantly.

A new WWG has been implemented in the MCS code that utilizes a response matrix (WWG_RM) to solve the importance. The basic idea of WWG_RM is that, if one cell cannot contribute to the detector score directly, particles in this cell have some probability to go into another cell that contribute to the detector score directly.

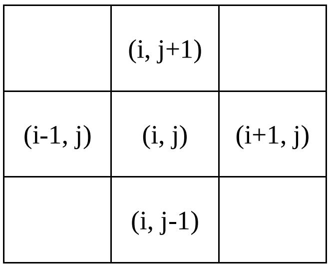

Fig. 3. The schematic diagram of a 2D mesh.

As shown in Fig. 3, the expected score of cell (i,j) can be calculated as:

$$s_{i,j} = p_{-1,0}s_{i-1,j} + p_{1,0}s_{i+1,j} + p_{0,-1}s_{i,j-1} + p_{0,1}s_{i,j+1}, \quad (1)$$

$$\left(1, -p_{-1,0}, -p_{1,0}, -p_{0,-1}, -p_{0,1}\right)\begin{pmatrix} s_{i,j} \\ s_{i-1,j} \\ s_{i+1,j} \\ s_{i,j-1} \\ s_{i,j+1} \end{pmatrix} = 0, \quad (2)$$

where $s_{i,j}$ is the expected score of one particle in cell (i,j), $p_{-1,0}$ is the probability of particles in cell (i,j) to go into the neighbor cell (i-1,j) and the other s and p terms are defined similarly. The 0 on the right-hand side of Eq. (2) means that the direct score due to particles in cell (i,j) is 0.

In the same way, the example problem shown in Fig. 2 can be also illustrated with the WWG_RM, as shown in Table II. Eq. (3) is the equation used to calculate the expected score (the importance) of each cell. The solution is (s_1, s_2, s_3, s_4) = (0.25, 0.25, 0.375, 0.75), which is a little different from those by WWG_MCNP, (0.25, 0.167, 0.5, 0.75). However, the difference may be due to the insufficient number of histories used for this example. If enough number of histories are used, it can be expected that the two WWG methods would produce the same result.

$$\begin{pmatrix} 3.0 & -1.5 & -1.0 & 0 \\ 0 & 1.5 & 0 & -0.5 \\ 0 & 0 & 1.0 & -0.5 \\ 0 & 0 & 0 & 1.0 \end{pmatrix}\begin{pmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0.75 \end{pmatrix}. \quad (3)$$

Table II: Illustration of the WWG_RM

Particle tracks Particle weight Total weight Sign*	To cell 1	To cell 2	To cell 3	To cell 4	Direct Score
From cell 1	1,8,13 1,1,1 3.0 +	3,4,9,10 0.25,0.25,0.5,0.5 1.5 -	14,15 0.5,0.5 1.0 -	0 0 0 -	0 0 0 +
From cell 2	0 0 0 -	3,4,9,10 0.25,0.25,0.5,0.5 1.5 +	0 0 0 -	6 0.5 0.5 -	0 0 0 +
From cell 3	0 0 0 -	0 0 0 -	14,15 0.5,0.5 1.0 +	17 0.5 0.5 -	0 0 0 +
From cell 4	0 0 0 -	0 0 0 -	0 0 0 -	6,17 0.5,0.5 1.0 +	7,17 0.25,0.5 0.75 +

*: The signs of the track in the same cell/mesh and the direct scores are positive (+), while signs for tracks entering other cells are negative (-).

3. Numerical Results

The KN12 spent nuclear fuel cask has been modeled using the MCS code to estimate the neutron flux in a 10x10x10 cm cubic box located on the axial mid-plane of the cask, 1 m away from the outer surface of the cask, as shown in Fig. 4. Twelve typical 17x17 PWR fuel assemblies in total are loaded in the cask. The cask is filled with water (water between the fuel lattices), and all materials are assumed at room temperature. The source term calculation has been done for each spent nuclear fuel assembly with a burnup of 60 GWD/MTU to get the depleted fuel compositions and the neutron source for this cask modeling. The spatial distribution and energy spectrum of the modelled neutron source are shown in Figs. 5 and 6, respectively.

At first, 5 million histories are used for the simulation without WW. A 3D cylindrical mesh (20x8x48 uniform meshes in RTZ coordinate system covering all the system space) is used for the WWG. Only one history reaches the tally box and produces a non-zero score. The WWs generated by the WWG_MCNP and WWG_RM approaches for this case are shown in Figs. 7 and 8, where T means theta, the angular mesh index.

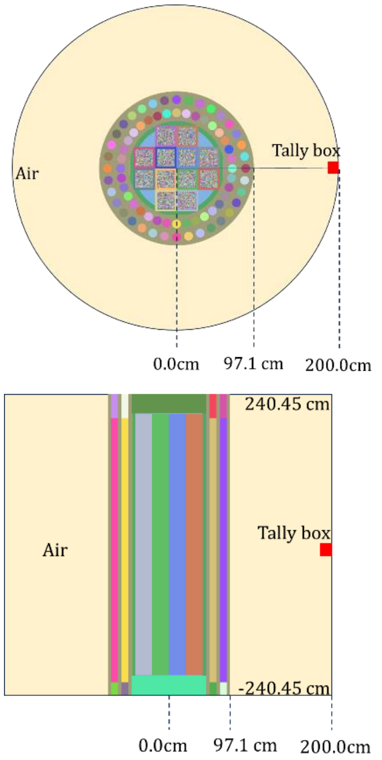

Fig. 4. The KN12 cask model by MCS: radial (upper), axial (lower).

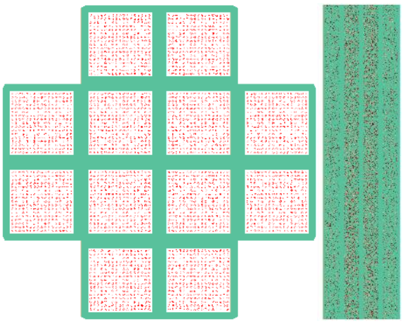

Fig. 5. The initial neutron source (red points) distribution by MCS: radial (left), axial (right).

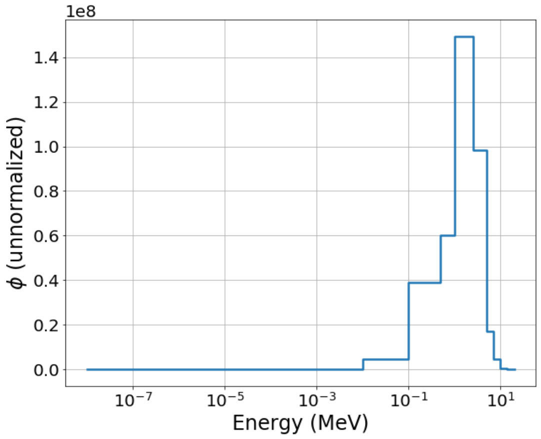

Fig. 6. The initial neutron source spectrum.

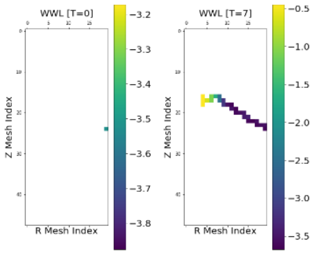

Fig. 7. The WW generated by WWG_MCNP (the log10 values are plotted).

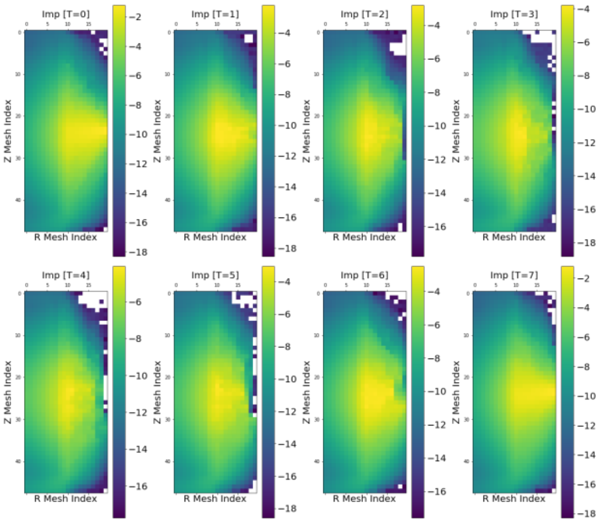

Fig. 8. The importance map generated by WWG_RM (the log10 values are plotted and unnormalized).

Using the WWs generated by the two methods, the simulation is rerun separately with the same number of histories. The results are listed in Table III for comparison. Without WW, it is very difficult to get non-zero tally scores and it is also difficult for the WWG_MCNP to generate good WWs. The results are totally unreliable. On the contrary, the WWG_RM can produce good WW with higher performance, with 3,714 non-zero-score histories instead of only 1 to 3 non-zero scores and an increase of FOM by around 2 orders of magnitude.

Table III: The box tally results

WW by	Tally Score				
	# of non-zero scores	Mean	Std	VOV	FOM
No WW	1	1.82E-06	1.00	1.00	0.013
WWG_MCNP	3	3.17E-09	0.77	0.78	0.030
WWG_RM	3714	9.21E-07	0.071	0.19	2.260

It is well known that the WW iteration can be conducted to generate better and better WWs. In addition, various modifications of the model can be made to lead the particles to regions of higher importance. However, for cases with different detector locations, separate simulations are required for each case when using the WWG_MCNP, whereas for WWG_RM, the same RM may be used to generate the importance maps for different detector tallies. As shown in Figs. 9 and 10, the RM tallied during the first simulation without WW can also generate importance map for tally boxes located on the top and bottom axial planes.

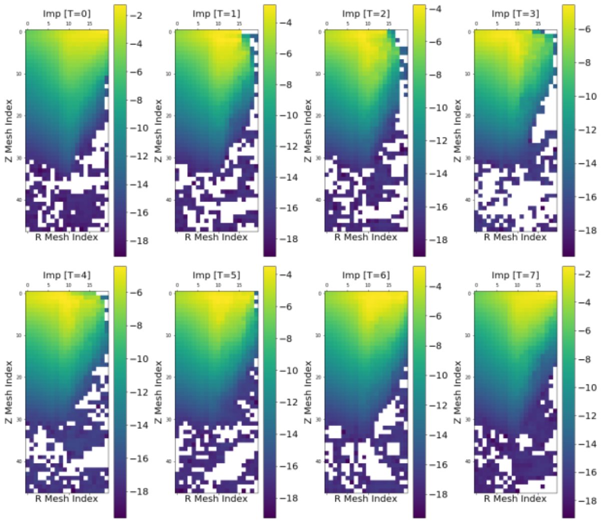

Fig. 9. The importance map generated by WWG_RM for tally box on top axial plane (the log10 values are plotted and unnormalized).

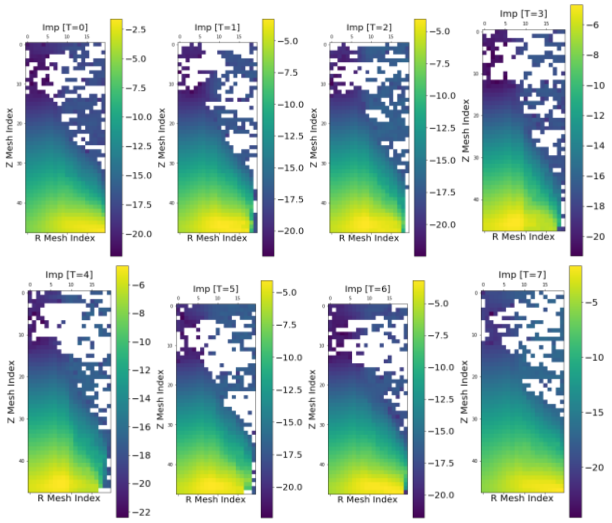

Fig. 10. The importance map generated by WWG_RM for tally box on bottom axial plane (the log10 values are plotted and unnormalized).

4. Summary

A new variance reduction scheme based on the WW technique, WWG_RM, has been developed and implemented in the MCS code. The method utilizes a response matrix that is tallied during the forward MC simulation to generate the importance of each cell/mesh. This scheme has the potential to generate good WW while simplifying or eliminating the need for WW iteration strategies. The preliminary results on the KN12 spent nuclear fuel cask problem demonstrate the performance of this method. More investigations and tests will be conducted to further improve this method for shielding analysis.

ACKNOWLEDGEMENT

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