Application of A^{3}MCNP^{TM} to Radiation Shielding Problems

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Abstract. This paper briefly discusses the theory of the A^{3}MCNP^{TM} code and its application to three real-world shielding/fixed-source problems; including PWR cavity dosimetry, DPA estimation at a BWR core-shroud weld, and dose estimation at the surface of a storage cask. These problems all address major concerns of nuclear utilities and are very important for the continued safe and economical operation of nuclear power plants. The paper demonstrates that A^{3}MCNP^{TM}, with its automated variance reduction capability, is able to solve these problems in a relatively short time with modest computational resources, while significantly reducing the engineer's time and effort for performing these calculations.

1 Introduction

The Monte Carlo (MC) method is considered to be one of the most accurate techniques for simulation of radiation transport. The major drawback associated with using the MC method for simulation of real-world problems is its exorbitant computational expense. To overcome this shortcoming, numerous variance reduction (VR) techniques have been devised and implemented in production codes such as MCNP^{TM} [1]. Effective use of VR techniques for large/complex problems, however, is not straightforward and can be very time consuming. To surmount this difficulty, we have developed a new automatic VR methodology, CADIS (Consistent Adjoint Driven Importance Sampling) [2,3], that formulates both source and transport biasing in a consistent manner based on importance sampling. The space- and energy-dependent source and transport biasing parameters are generated by deterministic transport calculations and used with the weight window technique. The CADIS methodology, along with capabilities for automatic mesh generation and input preparation for a deterministic transport code, has been implemented into the MCNP^{TM} code. This new version of MCNP^{TM} is referred to as A^{3}MCNP^{TM} (Automated Adjoint Accelerated MCNP) [3].

In this paper, we briefly discuss the performance of A^{3}MCNP^{TM} for three major problems of interest to the nuclear industry; including PWR cavity dosimetry [4], DPA estimation at a BWR core-shroud weld [5], and gamma dose estimation over a storage cask.

2 Description of A^{3}MCNP^{TM}

A^{3}MCNP^{TM} (Automated Adjoint Accelerated MCNP) automatically generates a deterministic "importance" function that is used within the CADIS (Consistent Adjoint Driven Importance Sampling) methodology. CADIS performs source and transport biasing using a space-energy dependent weight-window technique. It determines the biased source and weight-window lower bounds via a deterministic adjoint function. Below, we summarize functions performed by A^{3}MCNP^{TM}

1. Generation of a mesh distribution for the deterministic S$_N$ calculation.
2. Preparation of input file for the TORT S$_N$ code [6].
3. Determination of material compositions and preparation of the necessary input files for the GIP code [6] for generation of multi-group mixture cross-sections.
4. Reads the adjoint "importance" function and prepares a biased source as

$$\hat{q}(P) \;=\; \frac{\Psi^{\dagger}(P)q(P)}{\int_P \Psi^{\dagger}(P)q(P)dP} \tag{1}$$

   and the corresponding formulation for particle statistical weight as

$$W(P) \;=\; \frac{\int_P \Psi^{\dagger}(P)q(P)dP}{\Psi^{\dagger}(P)} \;=\; \frac{R}{\Psi^{\dagger}(P)} \tag{2}$$

   where, R is the response, P refers to the independent variables, e.g., space (r), energy (E), and direction (Ω), and $\Psi^{\dagger}$, q, and $\hat{q}$ are the importance function, "unbiased" source, and "biased" source, respectively.
5. Superimposes the deterministic S$_N$ spatial-mesh distribution and energy-group structure onto the MC model in a "transparent" manner.
6. Calculates space- and energy-dependent weight-window lower bounds (W_l) for the "transparent" space-energy mesh according to

$$W_l(r,E) \;=\; \frac{W}{(\frac{C_u+1}{2})} \;=\; \frac{R}{\phi^{\dagger}(r,E)}\frac{1}{(\frac{C_u+1}{2})} \tag{3}$$

   where $\phi^{\dagger}$ is the scalar adjoint function and $C_u = \frac{W_u}{W_l}$ is the ratio of upper and lower weight window values.
7. Updates the particle weight, as each particle is transported through the "transparent" mesh using the following formulation:

$$W(r,E) \;=\; W(r',E')\,\frac{\phi^{\dagger}(r',E')}{\phi^{\dagger}(r,E)}. \tag{4}$$

3 Performance of A^{3}MCNP^{TM}

In this section, the performance of A^{3}MCNP^{TM} for three different problems that are important for nuclear safety and operation is discussed.

3.1 Cavity Dosimetry for a PWR

Problem Description - The embrittlement of a reactor pressure vessel (RPV) is primarily due to the bombardment of high-energy neutrons and cannot be directly determined from measured quantities. Cavity dosimetry calculations attempt to estimate high-energy reaction rates in a small volume outside of the RPV at a distance of ~350 cm from the core centerline. These reaction rates are used to validate methods/models that are subsequently used to estimate RPV neutron fluence. The problem is illustrated in Fig. 1 , which shows one octant of the Three Mile Island Unit 1 (TMI-1) reactor.

Performance - Without the use of VR techniques, one could allow MCNP^{TM} to run this problem continuously for weeks and still not obtain statistically significant/reliable results [3]. Before the CADIS methodology and the A^{3}MCNP^{TM} code were developed, this problem was manually optimized with existing VR methods [2]; including, source biasing, weight windows, exponential transformation, and energy cutoff. This manual optimization required a great deal of time and effort to develop, but proved to be very successful in terms of both computational performance and calculational reliability (i.e., enabled problem objectives to be accomplished with available computational resources). Upon completion and implementation of the automated VR methodology, the problem was used to evaluate the efficiency of the automated VR approach. Application of the CADIS methodology increased the calculational efficiency by a factor of more than 4 with respect to our best manually optimized model and by a factor of ~50,000 with respect to the analog case. Furthermore, the automatic VR approach required very little user time, effort, or experience.

We have performed [2] a number of studies to evaluate the relationship between the accuracy of the adjoint function and its effectiveness for VR of the MC calculation. The effectiveness of the adjoint function for VR was found to be rather insensitive to the accuracy of the adjoint function, and in some cases, due

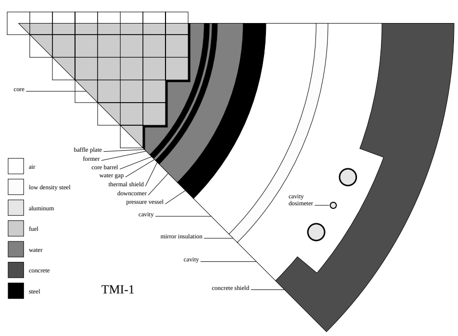


Fig. 1. One octant of TMI-1

to the reduction in data volume and CPU time required for the S_N calculation, less detailed adjoint functions actually yielded greater effectiveness.

3.2 Estimation of DPA at a BWR Core Shroud Weld

Problem Description - The core shroud is an ~5 cm thick stainless steel annulus located between the core and the pressure vessel of a BWR reactor. Fig. 2 depicts the axial locations of the core-shroud welds (H1 to H8) relative to the reactor core and other structural components. We have developed a model of size 300×300×381 cm^3 and estimated the DPA at a small segment (2×2×2 cm^3) of the H4 weld, which is located ~63.5 cm above the core mid-plane.

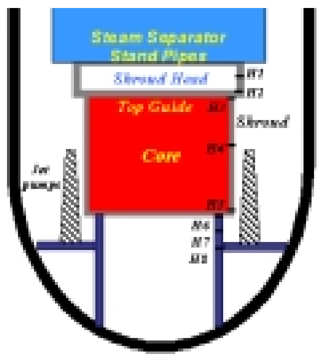
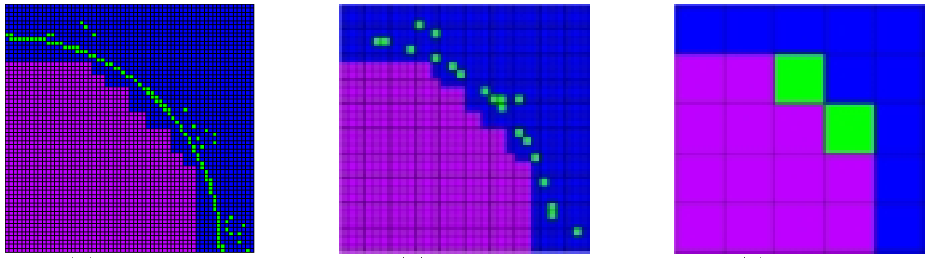


Fig. 2. Schematic of a BWR core shroud and its welds

Performance - We examined the performance of A^3MCNP^{TM} for different mesh distributions (uniform and variable) that are used for the deterministic S_N calculation. Here, for brevity, we present only three cases with uniform meshes of 86,400, 10,800, and 300. Fig. 3 shows a sample mesh distribution for each case. The xy mesh intervals for cases 1 to 3 are 5, 10, and 60 cm, and z-mesh intervals are 15.875, 31.75, and 31.75 cm, respectively. As expected, due to the coarse meshing, large (> several orders of magnitude) differences are observed in the calculated adjoint function distributions for the different cases.

The estimated FOM of the unbiased case after 2000 CPU-min with a relative error of 14.97% is only 0.022, while cases 1 to 3 show significantly higher FOMs, which are larger by factors of 4123, 2945, and 131, respectively. As expected, case 1, with the finest TORT mesh distribution, achieves the best FOM, but requires the longest CPU time among the three cases. For example, to achieve a 1σ statistical uncertainty of 1.0%, case 1 requires a total CPU of 534.9 min, from which 424.6 min is consumed by TORT. Our estimated total CPU times, for 1.0% uncertainty, for the unbiased case and cases 2 and 3 are 448,201, 223.5, and 3462.7 min, respectively. This means that case 2 yields the largest CPU speedup of 2005, and even case 3 with its very inaccurate "importance" function yields a speedup of 129.

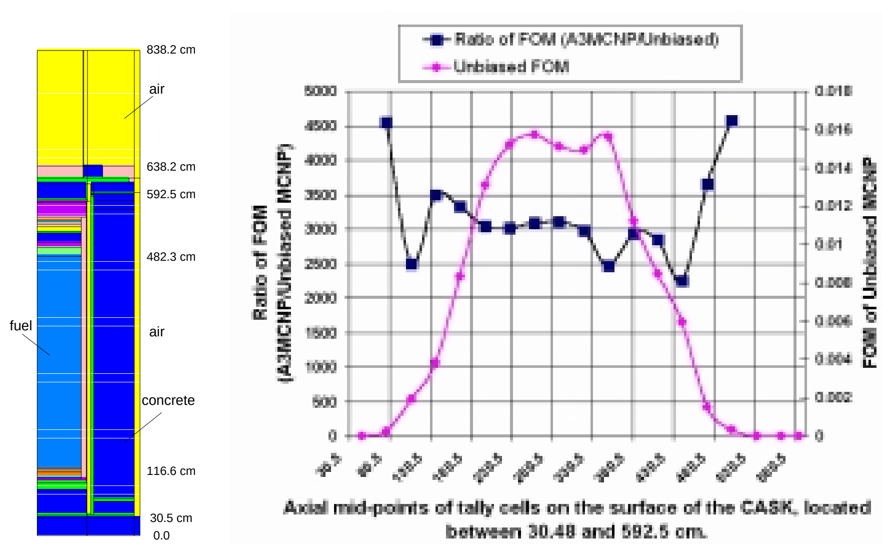


(a) Case 1 (b) Case 2 (c) Case 3

Fig. 3. Mesh distributions from A^{3}MCNP^{TM} for the TORT adjoint calculations

3.3 Storage Cask

Problem Description - To expand storage capacity and prevent premature plant shutdown, utilities are storing their Spent Nuclear Fuel (SNF) on-site in dry casks. Multidimensional MC codes such as MCNP^{TM} are used for this application. Because of the large size of the physical model (∼3.3 m diameter and ∼6 m height) and the need for detailed information with high precision, VR methods are necessary. Here, we consider a concrete cask of size 178.3×178.3×838.2 cm^3, and evaluate the gamma dose on the outer surface, as a whole and over axial segments. Fig. 4a shows an axial cross section of the MCNP^{TM} model [7] (developed by Holtec Int.), which represents one quarter of a 24-assembly PWR storage cask, used for this study.



(a) Geometric model (b) Comparison of FOMs versus axial location

Fig. 4. Storage cask geometry and FOM comparison

Performance - For the unbiased case, a 1σ uncertainty of 0.0376 and FOM of 0.12 are achieved after 6000 CPU-min. For the A^{3}MCNP^{TM} run, after 180 min, we achieve a 1σ uncertainty of 0.0047 with a FOM of 254. This means that to evaluate the dose over the surface, as a whole, A^{3}MCNP^{TM} performs ~2117 times faster than the unbiased MCNP^{TM}. For this, besides the CPU for MC simulation, we have used ~20 CPU-min for determination of the 3-D "importance" function distribution using the TORT code. We have also examined the performance of A^{3}MCNP^{TM} for evaluation of dose along axial segments. Fig. 4b shows the ratio of FOMs (A^{3}MCNP^{TM} to unbiased MCNP^{TM}) and the FOM of the unbiased MCNP^{TM} as a function of axial position. As expected, the performance of A^{3}MCNP^{TM} improves significantly as one moves away from the fuel assembly mid-plane; this is specially evident at the regions above and below the fuel assemblies, i.e., $<$116.55 cm and $>$482.3 cm.

4 Conclusions

This paper briefly described the A^{3}MCNP^{TM} code and its automated VR, based on the CADIS methodology. We examined the performance of A^{3}MCNP^{TM} for several real-world problems and demonstrated significant improvements in computational efficiency. Perhaps more important than its ability to increase the calculational efficiency, is the fact that A^{3}MCNP^{TM} does so in a way that requires very little time or experience on the part of the user.

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