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Comparison of ADVANTG Simulations to Simple Shielding Measurements

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INTRODUCTION

Monte Carlo (MC) radiation transport simulations, like those performed using Monte Carlo N-Particle (MCNP) [1], can be highly accurate but require time to reduce the statistical uncertainties in the calculated detector response(s). Many different "variance reduction" techniques devised over the years increase the efficiency of MC calculations, but these methods can be more art than science. Many of these methods are problem specific or require careful tuning of parameters for good performance. One of the best variance reduction methods, in terms of both reliable performance increases and ease of use, is the use of weight windows. Weight windows are derived from an importance map in space and energy that allows the transport code to focus more simulation time on particles that have a higher likelihood of being important to the final detector response. Less time is spent simulating particles that have little chance of making a contribution to the detector response. MCNP already includes the abilities to generate and use weight windows. Unfortunately, generating weight windows can take a very long time, perhaps longer than the original problem.

Oak Ridge National Laboratory has led the development of hybrid methods using a discrete ordinates adjoint calculation to quickly develop an importance map (weight windows) for use in a Monte Carlo code. The Consistent Adjoint Driven Importance Sampling (CADIS) [2] method uses an adjoint calculation to develop both an importance map and a biased source distribution that work together. This method is reasonably automatic, is easy to use, and has been implemented in the AutomateD VAriaNce reducTion Generator (ADVANTG) [3] package that works with MCNP5. ADVANTG reads an MCNP input file and a small amount of extra user information and then runs an adjoint deterministic calculation using Denovo [4]. The importance map and biased source distribution derived from the CADIS method can then be incorporated back into the original MCNP input file to enhance the figure-of-merit (FOM) of the calculation. The FOM is a measure of the efficiency of the calculation using the amount of run time and corresponding level of statistical uncertainty in the detector result. ADVANTG-enhanced MCNP input files have been shown to increase the FOM of many types of problems, obtaining the same level of statistical uncertainty in a shorter time compared to standard MCNP. ADVANTG can also generate variance reduction parameters (importance map and biased source) using the Forward-Weighted CADIS (FW-CADIS) method [5] for optimizing mesh tallies. The CADIS method creates variance reduction parameters that optimize a tally's total quantity (flux, dose rate, interaction rate, etc.) and will not generally increase performance for all parts of a segmented tally. To optimize a segmented tally, the FW-CADIS method uses two discrete ordinates calculations to make variance reduction parameters that help compute a segmented tally with uniform relative uncertainties in each bin.

This report will demonstrate that using ADVANTG for neutron and photon radiation shielding problems will (1) preserve the standard MCNP results and (2) obtain those results either with less statistical uncertainty or in shorter times than the standard MCNP calculation. The four demonstration problems in this report are based on simple neutron or photon transmission measurements through different materials. All of the problems here used the CADIS method and still saw improvement across the flux tallies segmented by particle energy.

SIMULATION OF EXPERIMENTS

Iron Sphere Neutron Leakage

In the early 1990s, several experiments measuring the energy spectrum of ^{252}Cf neutrons leaking from a sphere of iron were performed to benchmark Evaluated Nuclear Data File B-VI (ENDF/B-VI) cross-section data [6]. Two sets of measurements of the flux at 1 m were made—one by the Czechoslovakian National Research Institute (NRI) and the other by the Skoda Company. Measurement values from the experiments were tabulated as flux per unit energy as a function of neutron energy. The results were normalized by $4\pi(100\text{ cm})^2$ so that the total flux at the detector with no shielding would have been 1.

An MCNP model of the experiment, shown in Fig. 1, included the source capsule and the insertion tube into the iron sphere. The source was modeled with a Watt spectrum. A point detector tally 1 m from the center of the sphere collected flux information with energy bins matching the experimental results.

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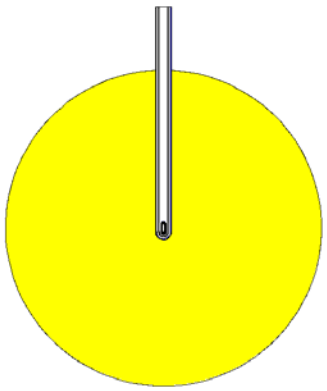

Fig. 1. Iron sphere with source insertion tube.

For ADVANTG, a uniform 25 × 25 × 30 mesh (2 cm) was used over the iron sphere and the tubes extending out of the top of the sphere. An extra mesh cell containing the position of the point detector was also included. The importance map and biased source took about 1 min to compute for each MCNP input file (NRI and Skoda), and the MCNP runs took 60 minutes.

The predicted fluxes at the detector from standard MCNP and the ADVANTG-accelerated MCNP match the experimentally measured values well. The ADVANTG-accelerated MCNP flux values match the standard MCNP values well, but with better uncertainties. The ratios of the figures-of-merit (FOM) of the two simulations for the Skoda experiment, shown in Fig. 2, demonstrate that ADVANTG does indeed speed up the calculation. As expected with CADIS, some parts of the energy range perform better than others. The FOM ratio for the NRI experiment is slightly higher. In computing the total flux at the point detector (the real goal of CADIS), the FOM was 1.9 times higher for ADVANTG compared to standard MCNP for the Skoda simulations. For the NRI simulations, the FOM for total flux was 2.25 times higher.

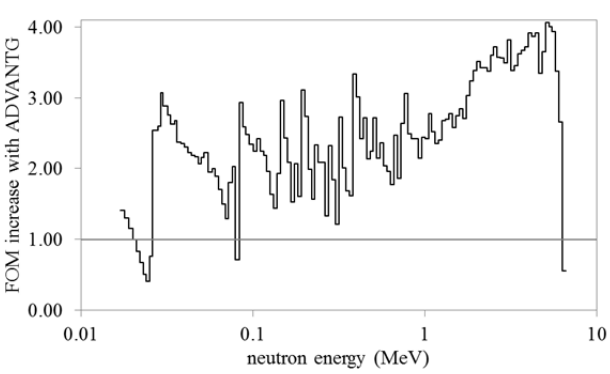

Fig. 2. ADVANTG speed up for the iron sphere.

Heavy Water Neutron Leakage

The leakage spectrum of ^{252}Cf neutrons through a 15 cm radius sphere filled with heavy water was measured in several experiments in Prague in the mid 1990s [7] to evaluate ENDF/B-IV and ENDF/B-VI nuclear data. A proton recoil spectrometer was used to measure neutron flux values from 0.1 MeV to 10 MeV.

To account for room scatter, each experiment consisted of two measurements. The first measurement recorded the neutron flux in a detector 75 cm from the center of the source, which was at the center of the heavy water sphere. This measurement included some amount of scatter from the walls and floor of the experimental hall. The second measurement used a "shadow cone" made of four disc-shaped shields between the sphere and the detector, shown in Fig. 3, to block the direct contribution and measure only the scatter from the floor and walls of the experimental hall.

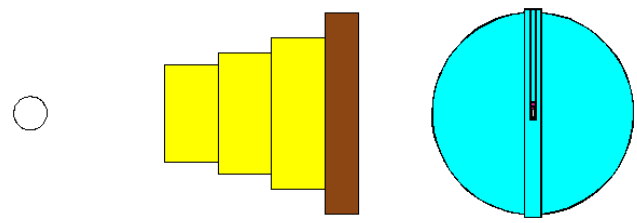

Fig. 3. Geometry of the D_2O leakage experiment with the shadow cone in place. The detector volume is on the left.

Four simulations with MCNP were completed using the different insertion tubes (A8 or A25) with and without the shields. Each was allowed 18 h of execution time to tightly converge the results in all 96 tally energy bins. The difference between the simulations with and without the shields was computed and compared to the experimental measurements. Agreement between MCNP and the experiments is very good.

Many of the lower energy neutrons do not escape the heavy water shield. Of the neutrons that do escape, only a few are emitted towards the detector. Significant improvement in simulation times should be achievable with the ADVANTG-created biased sources and importance maps. The discrete ordinates adjoint calculation used the following: the 27-group energy library; S_8/P_3 quadrature and Legendre scattering expansion; and a mesh of 109 × 77 × 82 over the experimental hall, with more detail in the heavy water sphere, in the shields, near the detector, and along the inner surface of the floor and walls. For each of the four MCNP cases above, the adjoint calculation time was 35–40 minutes.

Results from the MCNP calculations using the ADVANTG variance reduction parameters were compared to those from standard MCNP simulations. The leakage spectrum computed using the ADVANTG variance reduction parameters compared well with standard MCNP values. The FOM increase using ADVANTG was typically 5 or higher, except in the

energy range above 5 MeV where the leakage flux is very low. Figure 4 shows the ratio of the FOM for the final leakage spectrum values (the difference of two simulations). The simulations with the shields in place saw a larger speed-up than the simulations without the shields, which is quite typical—more difficult problems require more variance reduction and see higher benefits from ADVANTG.

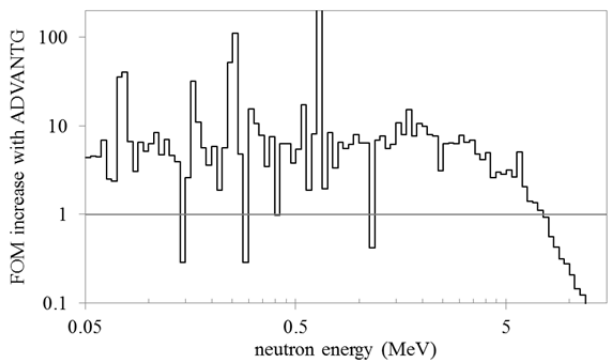

Fig. 4. ADVANTG speed up for the heavy water sphere.

Iron Spheres Neutron and Photon Leakage

During the 1980s, several experiments [8] measuring the neutron and photon leakage spectra outside iron spheres of various sizes were performed at the Institute of Physics and Power Engineering in Obninsk, Russia. Measurements of the neutron and photon leakage spectra were taken for six different sizes of iron spheres, ranging in size from 20 to 70 cm in diameter. Neutron and photon spectra from the bare source were also taken. Each of the iron spheres contained a small cavity in the center of the sphere to hold the ^{252}Cf source assembly. For an iron sphere of radius R, the active detector region was at a distance of $3R$ from the center of the sphere. In addition to the source/sphere combination and detector, a large removable cone of either borated polyethylene (for neutron measurements) or lead (for photon measurements) was mounted on a tripod between the sphere and detector to measure the background radiation.

MCNP inputs were constructed for the bare source and iron spheres of six diameters, and all used a single point detector tally. For each of these seven cases, three inputs were constructed: (1) the neutron source with a neutron tally, (2) the neutron source with a photon tally, and (3) the photon source with a photon tally. The photon leakage spectra are the sum of the second and third cases. ADVANTG inputs were made for each of these analog MCNP inputs. The Denovo deterministic adjoint transport calculations used a 27n/19g cross section library, a P_3 Legendre scattering expansion, a quadruple-range angular quadrature with four polar cones and four azimuthal angles per cone and a spatial mesh of 2 cm in the x-, y-, and z-dimensions.

The 21 input files were run for 1 h each using analog MCNP. Each was also run with ADVANTG, using a 0.2–11 minute Denovo calculation and a 1 h MCNP calculation. For the neutron leakage cases, the calculated leakages compared very well to the measured neutron leakages. For the photon cases, the calculated leakages did not compare well to the measurements. The measured leakage flux is higher than the calculated leakage over the entire energy range, and the discrepancy between measurement and calculation is worse for larger diameter spheres.

ADVANTG leakage results matched the analog MCNP results quite well for both neutrons and photons and for all of the sphere sizes. The effective speed-ups—the ratio of the FOM of ADVANTG to the analog FOM—for the 60 cm iron sphere are shown in Figs. 5 and 6.

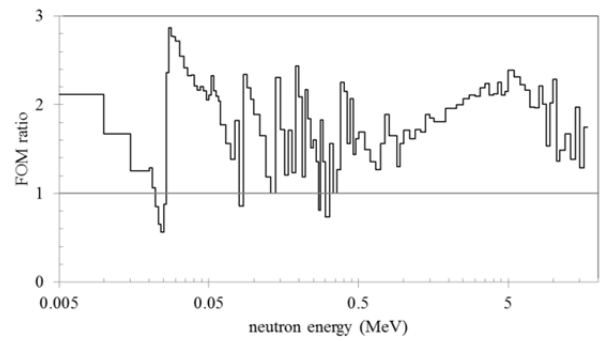

Fig. 5. ADVANTG speed up for neutrons through iron.

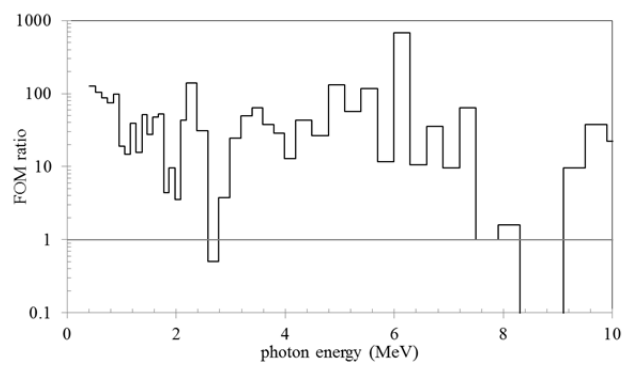

Fig. 6. ADVANTG speed up for photons through iron.

Lead Spheres Neutron and Photon Leakage

Similar to the above measurements, a series of leakage measurements using lead spheres [9] was also conducted in Obninsk, Russia. This series of experiments measured the leakage fluxes of neutrons and photons from a ^{252}Cf source inside of lead spheres of diameter 20, 40, and 60 cm. Analog MCNP inputs and ADVANTG inputs were similar to the previous experiment as well.

For the neutron experiments, the calculated leakage fluxes compared well to the measurements above 50 keV. From 5 keV to 50 keV, the measured fluxes are higher

than the calculated fluxes. Overall, the measured fluxes do not show the level of detail observed in the calculated data. The ADVANTG-enhanced MNCP calculations compared very well to analog MCNP.

The FOM of the neutron ADVANTG calculations was only slightly better than for analog MCNP. The speed-up from ADVANTG is significant for the photon leakage fluxes, especially for the larger spheres. The ratio of the ADVANTG FOM to the analog FOM is shown in Figs. 7 and 8 for the 60 cm lead sphere.

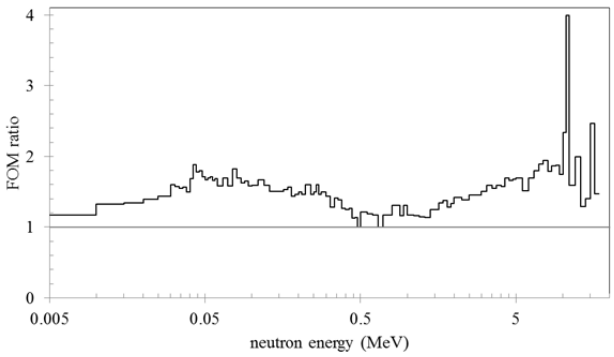

Fig. 7. ADVANTG speed up for neutrons through lead.

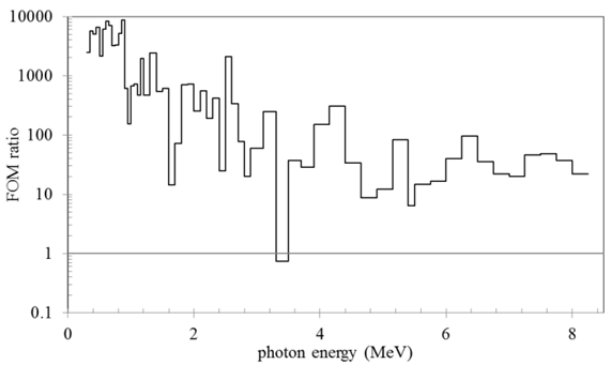

Fig. 8. ADVANTG speed up for photons through lead.

SUMMARY

The ADVANTG tool uses a quick adjoint deterministic calculation to develop variance reduction parameters (a weight windows map and consistent biased source sampling distribution) to increase the efficiency of an MCNP Monte Carlo radiation transport code. Four well-documented experiments have been simulated with standard analog MCNP and ADVANTG-enhanced MCNP. Results using ADVANTG match the standard MCNP results well—showing that the use of the variance reduction parameters has not changed the answers. Modest gains in speed were observed for neutron problems, and significant gains were observed for photon problems. Note that these experiments are all simple—for deep penetration problems, the FOM improvements from ADVANTG are much more dramatic [2].

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