Duct Streaming Validation Benchmark Calculations with a Global Importance Map

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INTRODUCTION

The Monte Carlo N-Particle (MCNP) transport code is a standard in the field of computational Monte Carlo radiation transport [1]. One reason MCNP has become such a standard is the extensive benchmark testing and validation it has undergone (see `http://mcnp-green.lanl.gov/publication/mcnp_publications.html`). This work presents benchmark comparisons of MCNP to a set of duct streaming benchmark experiments performed in the late 1960s [2].

The benchmark experiments consist of a neutron beam from Oak Ridge National Laboratory's Tower Shielding Facility's TSR-II nuclear reactor incident on the side walls of three different concrete duct geometries. The duct geometries include a straight duct, a two-legged duct with a single 90° bend, and a three legged duct with two 90° bends. All three duct cross sections are square. The experiment reports the subcadmium (below 0.5 eV) neutron fluxes along the duct centerline resulting from subcadmium neutrons incident on the duct wall at various distances from the duct opening.

To reduce the Monte Carlo uncertainties, a modified version of MCNP5 (RSICC version 1.40) that includes the capability of combining tallies with linear multipliers and passing the combination to the weight window generator, thereby weighting the adjoint source of each tally, is used (see reference [3]). Calculations performed using this linear tally combination (LTC) are compared to the traditional (unmodified) MCNP5 weight window capabilities. This work reports both the computational figure of merits and compares the accuracy of the computed results to the experiment.

BENCHMARK PROBLEMS AND METHODOLOGY

Computational Method and Procedure

Weight-window variance reduction is a combination particle splitting and rouletting game that depends on the particle's weight (see [1] for further details). Parameters for the weight window must be nontrivially supplied by the user but is simplified by means of the weight-window generator [4]. The weight-window generator estimates weighted adjoint values for phase space regions and converts these adjoint values to the parameters needed for the weight window. In this work, weight windows are used to reduce the statiscital uncertainties associated with the centerline flux tallies. Three different methods of generating the weight window are used: 1. generating a "global" weight window optimized for a linear combination of mesh tally voxels encompassing the entire problem, 2. generating a weight windows for a linear combination of the centerline flux tallies, and 3. generating traditional weight windows with a single tally.

The authors have demonstrated global weight-window generation using the LTC capability of the modified MCNP5 with a mesh tally in [3], where it was shown that the linear multipliers weight the contribution of each tally, or adjoint source strength, to the weight window. In the case of the mesh tally, each voxel is treated as an individual tally. The process of weighting the adjoint source strength of each tally via the LTC and weight-window generation is iterative. The iterative weighting first requires the calculation of linear multipliers in one simulation; in a second simulation, those multipliers are used to generate weight windows. Generating multipliers and then weight windows is repeated until a global weight-window map is generated for the entire geometry.

An alternative method of generating the weight-window map with the LTC is to combine the tallies of interest (the centerline neutron fluxes) with the LTC and then iterate as discussed above to produce a weight-window map based only on the tallies of interest, the so-called "LTC-tally" weight-window map. The primary difference between the two weight-window maps is that the global map optimizes for the combination of mesh tally voxels over the entire problem while the LTC-tally map only optimizes for the combination of point detectors along the centerline where the flux measurements are made. Both of the weight-window maps are then individually used to compute the centerline neutron fluxes in the ducts.

For the global and LTC-tally weight-window generation, ten full (generate multipliers and then weight windows) iterations of 10^6 histories are run. For the traditional weight-window generation, ten iterations of 2×10^6 histories are used, and the tally used to generate the weight windows is moved incrementally from the source to the final tally. In all cases, 2×10^7 total histories are used to generate weight windows. Attention was given to ensuring the same amount of computational effort was applied to each of the three weight-window generation techniques and production runs. Once the weight-window map, either global, LTC-tally, or traditional, is generated, the production run
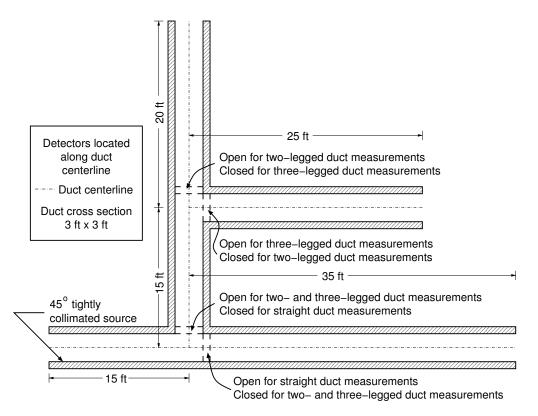
Fig. 1. Three duct problem geometry–specific paths are closed off to create the desired duct shape (adapted from [2])

can be performed to compute the centerline neutron flux tallies using weight-window variance reduction. The results using all three weight-window maps are compared.

Benchmark Problem Geometry

The neutron beam from the TSR-II reactor impinges on the sidewall of the duct in a "tightly collimated" beam at an angle of 45°. The walls of the concrete duct are 22.86 cm (9 in) thick and composed of steel reinforced concrete [2, 5]. The geometry of each of the three ducts is shown in Fig. 1, although, each duct was modeled individually because that is how the experiment was performed. Experimental measurements were taken at various distances along each duct. The experimentally quantified value is the subcadmium neutron flux arising from subcadmium neutrons incident on the duct wall.

The assumed incident subcadmium neutron energy distribution was determined by obtaining the modeled neutron spectrum from the light-water moderated Godiva reactor and passing it through 0.0762 cm (0.030 in) of cadmium [6]. The difference between the spectrum incident on the cadmium and the spectrum passing through the cadmium was considered to be the subcadmium spectrum and is not significantly different from a thermal Maxwellian spectrum. A light-water $S(\alpha, \beta)$ treatment was applied to the concrete material to properly account for thermal neutron scattering.

MCNP5 point detectors were placed along the geometry in the same locations that measurements were reported in the experiments. The point detectors each had a constant flux approximation radius of 1 cm and were located in air where few collisions near the point detector are expected. All contributions to the point detectors were deemed to have originated from the incident subcadmium spectrum, and the resulting Monte Carlo flux estimates normalized per history were scaled by the reported source strength of 1.65×10^4 n s^{-1} W^{-1}. Once the weight-window map was generated as discussed above, a production run using 10^8 histories was performed to compute the flux at each point detector.

RESULTS

Benchmark Accuracy Comparison

The results for the three-legged duct are presented in Fig. 2. The global and LTC-tally results have relative errors less than 1%, and the traditional case has errors less than 6%. All calculations used the same total number of histories (weight-window generation and production calculation). Figure 2(a) shows that the calculations (global, LTC-tally, and traditional) produce the same flux estimates, as expected, and are consistently less than the experimen-
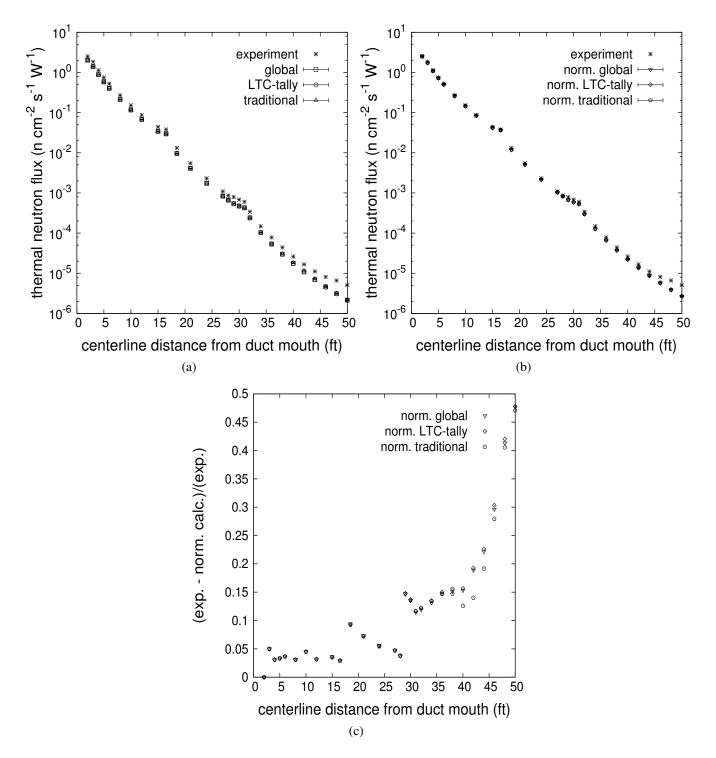
Fig. 2. (a) Comparison of three-legged duct computed results to experimental results, (b) comparison of three-legged duct normalized results to experimental, and (c) relative error in normalized computed results

tally reported results. This indicates a systematic error in the model. The calculated results for each case were also normalized, such that, the first calculated datum exactly matched the experimental result. This normalization, shown in Fig. 2(b), attempts to correct for systematic errors in the modeling. Before normalizaton, the relative error between the first calculated datum and the first experimental datum was 20%.

Also shown in Fig. 2(c) is the relative difference between the normalized calculation and the experimentally determined fluxes. For the straight duct (not shown), the relative deviation from the experiment is on the order of 5%, and, for the two-legged duct (also not shown), the same 5% relative deviation is observed for the first leg and then around 10% for the second leg. The three-legged duct exhibits around 5% deviation for the first leg, 10% for the second leg, and then 15% for the closest detectors in the third leg. The calculations showed deviations around 50% at the farthest tally locations for the third leg, even for the normalized data.

The authors noticed from the simulations that two factors significantly affected the calculated results. The first factor is the concrete composition. The concrete composition reported by Maerker and Muckenthaler contains lower concentrations of hydrogen and oxygen, but higher concentrations of carbon, than other typical concretes [5, 7]. Despite this difference between the reported experimental composition and other common concrete compositions, the composition reported by Maerker and Muckenthaler was used in the simulation.

The second factor affecting the calculation is the source beam radius. Maerker and Muckenthaler state that "[t]he cross-sectional area of the beam was *approximately* one-eighth that of the duct mouth," or having a radius of 18.24 cm, that originates from a 3.81 cm collimator, which was not modeled. It was observed in the computation that, as the beam was narrowed, the resulting fluxes increased, and possible errors may exist in the modeling of the source, which was assumed to be monodirectional and uniform over the 18.24 cm radius. Furthermore, the incident subcadmium neutron energy spectrum was developed from a moderated Godiva reactor core passing through cadmium and my not exactly represent the subcadmium spectrum originating from the TSR-II reactor, though the primary component of the spectrum is the thermal region from scattering in water and is presumably comparable.

The three-legged duct geometry was previously reported on by Brockhoff and Shultis as a test problem for an albedo approximation [8]. Brockhoff and Shultis observed similar large deviations in the MCNP calculation for the three-legged problem at the distant detector locations. Furthermore, simulation results for the three-legged duct problem were also generated by Maerker and Muckenthaler in the same work as the experimental data [2]. Their simu-

lation results also underestimated the experimental data at the far detector locations.

Calculation Efficiency Comparison

The calculated figure of merit (FOM) for each of the three weight-window generation methods is shown in Fig. 3 for the three-legged duct geometry. The efficiencies for the straight duct and two-legged duct were computed but are not shown. In the case of the straight duct, both the global and LTC-tally methods exhibit approximately a factor of two higher FOMs than iteratively generating weight windows by moving the tally from the source to the farthest detector point. For the two-legged duct, again the global and LTC-tally methods are superior to the traditional methods, but the global generation method is more efficient than either the LTC-tally or traditional methods for detectors down the second leg.

The three-legged duct tallies' FOMs exhibit extreme fluctuation down the third leg for the traditional weight-window-generation method. This extreme fluctuation is possibly due to poor sampling of the phase space around the third-leg detectors during weight-window generation. Still, the global weight window performs better than either the LTC-tally or traditional weight windows, and, furthermore, the global weight-window calculations produce a much smoother efficiency calculation than do the other weight windows.
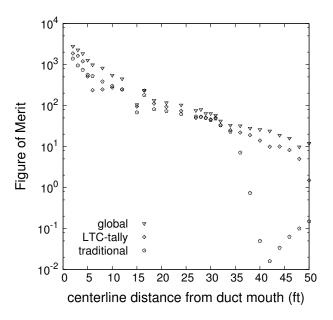

Fig. 3. Tally figure-of-merit comparisons for the three-legged duct

CONCLUSION

MCNP produces an excellent comparison of computed to experimental centerline fluxes for the straight and two-legged ducts. The calculated three-legged duct results compare excellently to the measured values up to far detector points down the third leg. The systematic bias that seems to exist between the unnormalized computed results and the experimental data is thought to be due to inaccurate modeling of the source or concrete composition.

The global weight window produces higher FOMs than both of the other weight-window-generation methods, though the LTC-tally method faired well. It is possible one could develop a better method to generate weight windows with the traditional MCNP capabilities than the one employed in this work, e.g., combining variance reduction methods or using different tallies for the weight-window generation than for the production run. However, the process of generating the global windows is straight forward and is easily scripted into an automatic process.

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