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A WEIGHTED ADJOINT SOURCE FOR WEIGHT-WINDOW GENERATION BY MEANS OF A LINEAR TALLY COMBINATION

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ABSTRACT

A technique has been developed to aid in weight-window parameter estimation in problems with multiple tallies using a linear combination of tallies. This technique has been implemented as a patch to MCNP5 RSICC version 1.40 and effectively weights the adjoint source term for each tally in the combination. Optimizing weight-window parameters for the linear tally combination allows the user to optimize weight windows for multiple regions at once and optimize globally by using a mesh tally. In this work, the authors present results of solutions to verification problems, test and challenge problems, and a global calculation of a 1e5 voxel oil-well logging tool problem.

Key words: Monte Carlo, linear combination, weight window, variance reduction, global importance

1. INTRODUCTION

Current research in accelerating Monte Carlo radiation transport calculations uses deterministic calculations (diffusion or transport) to estimate weight windows [1] or importances to be used in a second Monte Carlo calculation [2, 3]. These hybrid techniques avoid some of the problems with Monte Carlo weight-window generators[4] such as failing to fully populate the weight windows, even with multiple iterations, because of the weight-window generator's statistical nature.

This work uses existing Monte Carlo methods and focuses on the development of a techniques to estimate importances. A linear tally combination has been added to a research version of MCNP5. The linear tally combination is a linear sum of tallies with multipliers specified by the user. Using that combination with the existing weight-window generator in MCNP allows weight-window parameters to be estimated for difficult problems, where weight-window parameters would have been difficult to obtain previously. Initial findings of this work were presented in [5, 6]. Results of the initial test problems were promising in that weight-window generation for the linear combination produced a more efficient calculations than other techniques investigated.

Herein, the linear tally combination and weight-window generation is applied to test problems and verification problems. Additional focus is placed on the use of the linear tally combination with a mesh tally for global problem optimization.

2. BACKGROUND

2.1. Importance Estimation

With good variance reduction, the weight and importance of a particle typically vary inversely to each other. As a particle is transported it may, while undergoing variance reduction games, gain or lose weight and, in general, loses weight as it moves farther from the source. As the particle moves farther from the source toward the tally it becomes increasingly important, thus establishing the inverse relation between weight and importance.

The importance need not depend on all of phase space $\mathbf{P} = (\mathbf{r}, \hat{\mathbf{\Omega}}, E, t)$, but may also depend on a subset of the phase space variables. For example, the average importance at $\mathbf{r}$ is given by

$$I(\mathbf{r}) = \frac{\displaystyle\int_{4\pi}\int_0^\infty \int_0^\infty N(\mathbf{r}, \hat{\mathbf{\Omega}}, E, t) I(\mathbf{r}, \hat{\mathbf{\Omega}}, E, t)\, dt\, dE\, d\Omega}{\displaystyle\int_{4\pi}\int_0^\infty \int_0^\infty N(\mathbf{r}, \hat{\mathbf{\Omega}}, E, t)\, dt\, dE\, d\Omega}. \tag{1}$$

Here, $N(\mathbf{r}, \hat{\mathbf{\Omega}}, E, t)$ is a weighting function, typically the forward particle density. Similarly, the average importance in a region of space S is given by

$$I_S = \int_S N(\mathbf{P}) I(\mathbf{P})\, d\mathbf{P} \Big/ \int_S N(\mathbf{P})\, d\mathbf{P}\ , \quad S \in \mathbf{P}. \tag{2}$$

Booth [7] realized that, with some bookkeeping, the average importance in a region I_S can be calculated in a forward Monte Carlo calculation as

$$I_S = \sum_i T_i \Big/ \sum_i w_i\ , \tag{3}$$

where T_i is the score due to particle i (and any of its progeny) after particle i's *first* entry into S, and w_i is the weight of particle i upon its *first* entry into S. In other words, $N(\mathbf{P})$ of Eq. (2) is taken to be the forward particle densisty entering region S the *first* time. This statistical technique of estimating the importance has become known as the "weight-window generator" [1].

The weight-window generator produces an estimate of the importances, given the score definition and weights required in Eq. (3), *for any score definition*. The weight-window generator keeps track of where the particles are and their eventual scores; it does not matter how that score is defined (surface flux or current, volume flux, reaction rate, etc.), hence, its functionality with multiple tally types. Equation (3) indicates that it is possible to generate weight windows for a linear combination of tallies, not just single tallies. The linear tally combination simply defines a new score which the generator tries to optimize. It is an important distinction that use of the weight-window generator and the linear tally combination *is not* generating an importance function for multiple tallies; rather, it is generating an importance function for a single tally that happens to be composed of other tallies.

2.2. Adjoint Sources

When a forward calculation is performed, particles are emitted from a source and tallies of those particles are made as they transport through the geometry. Often, the desired tallies are modified by a response function. One defines the total detector/tally response R as

$$R = \int_S \int_{4\pi} \int_0^\infty \mathcal{R}(\mathbf{r}, \hat{\mathbf{\Omega}}, E)\phi(\mathbf{r}, \hat{\mathbf{\Omega}}, E) dE\, d\Omega\, dS, \tag{4}$$

where S is some spatial region and $\mathcal{R}$ is the detector/tally response function, which in general could depend on position, direction, and energy of the particles. Fundamentally, $\mathcal{R}$ does two things: (1) it determines what particles are "accepted" as part of the response, and (2) it scales the response for incoming particles.

In an adjoint calculation, adjoint particles are emitted from an adjoint source (at the forward tally location) and tallies of the adjoint particles (at the forward source location) are made as they transport through the geometry. The adjoint source is determined by the forward response function.

As an example of determining the response or adjoint source distribution, consider a tally of surface current (an MCNP F1 tally) where the response R_C is given by

$$R_C = \int_S \int_{4\pi} \int_0^\infty \phi(\mathbf{r}, \hat{\mathbf{\Omega}}, E) \left| \hat{\mathbf{\Omega}} \cdot \hat{\mathbf{n}} \right| \, dE\, d\Omega\, dS, \tag{5}$$

where S is now the area of the surface, and $\hat{\mathbf{n}}$ is the unit normal vector to the surface. If one then lets $\mu = \hat{\mathbf{\Omega}} \cdot \hat{\mathbf{n}} = |\hat{\mathbf{\Omega}}||\hat{\mathbf{n}}| \cos(\theta) = \cos(\theta)$, where θ is measured from the normal of the surface, then the response becomes

$$R_C = \int_S \int_{4\pi} \int_0^\infty |\mu| \phi(\mathbf{r}, \hat{\mathbf{\Omega}}, E) \, dE\, d\Omega\, dS, \tag{6}$$

so the response function is $\mathcal{R} = |\mu|$[1]. For the response of Eq. (6), the adjoint source emits uniformly in all energies but not uniformly in all directions. The directional distribution of particle emission is proportional to the absolute value of the cosine between the direction of emission and the surface normal vector.

If the flux, either surface (F2 in MCNP) or volume (F4 in MCNP), is the response, then the adjoint source emits particles of all energies isotropically over the detector region. This can be seen by observing that the flux response R_F is

$$R_F = \int_S \int_{4\pi} \int_0^\infty \phi(\mathbf{r}, \hat{\mathbf{\Omega}}, E) \, dE\, d\Omega\, dS, \tag{7}$$

so that $\mathcal{R} = 1$, a uniform distribution of all adjoint source variables.

For the verification problems discussed below, it is necessary to create MCNP models using Eq. (6) to compute the adjoint flux. The adjoint sources for these models are constructed by considering what the response $\mathcal{R}$ is in the forward calculation. Once $\mathcal{R}$ is defined, the correct adjoint source distribution is then a normalized form of $\mathcal{R}$ over the source emission variables.

[1] $|\mu|$ is used because particles contribute a positive value regardless of the direction they are crossing the surface. MCNP's "current tally" is really more of a particle density tally and not a *net current* tally as the name might imply.

3. METHOD

A linear tally combination was recently added to a research version of MCNP (patch to RSICC MCNP5 1.40) to test the generation of weight-window parameters for the combined tally T_{LC} [5, 6]

$$T_{LC} = m_1 T_1 + m_2 T_2 + \ldots + m_k T_k, \tag{8}$$

where m_i represents the multiplier for tally T_i, $1 \leq i \leq k$. All MCNP tallies, except the pulse height tallies, may be used in the linear tally combination. The mesh tally may also be used with the linear tally combination, where, each individual voxel of the mesh tally is treated as a volume flux tally having its own multiplier. The resulting scores from each of the tallies can then be passed to the generator as the numerator of Eq. (3).

3.1. Selection of Multipliers

The selection of multipliers is crucial to generating efficient weight-window lower bounds. Consider a source with a near tally and a far tally and the importance functions shown in Fig. 1. The importance functions shown are representative of what would be produced by the weight-window generator for each tally alone. If one desires a importance function for both detectors in single calculation and chooses a simple sum of the individual importance functions, a particle in between the two tallies moving away from the near tally and toward the far tally will likely be rouletted because the importance along its current direction is dropping. This rouletting is less than ideal if one is interested in scores to the far detector as well.

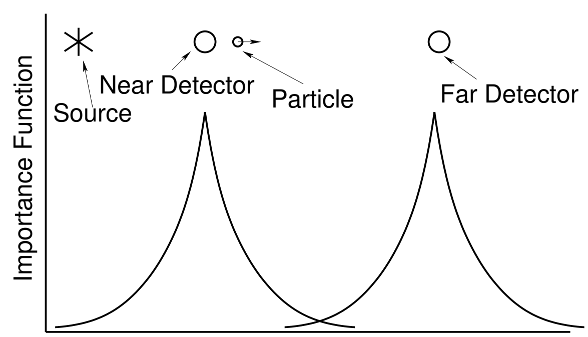


Figure 1. Importance splitting example.

If the importance function were not to drop so dramatically after passing the first detector, then more of the particles would survive to reach the second detector. The large drop in importance after the first detector is a result of the lower scores from lower weight particles contributing to the far detector instead of the near detector. If larger scores contribute to the far detector from the same lower weight particles then the importance will be higher, as exhibited by Eq. (3). The linear tally combination's multipliers provide a method of weighting the contribution of individual tallies to obtain a desired higher importance. If each detector is included in the linear tally combination, the tallies over those detectors become a single tally with its own importance function. If both of the tallies in this example are used in the linear tally combination and the far detector's multiplier is selected such that, on average, it contributes the same score as the near detector, the resulting importance produced by the generator will be higher toward the far detector. Selecting multipliers in the manner above minimizes variation in the average scores for the linear tally combination.

One way to minimize each average score variation is to select all the tally multipliers inversely to the respective tally mean, namely

$$m_i \propto 1 \Big/ \overline{T_i} \,. \tag{9}$$

By choosing multipliers that are inversely proportional to the tally mean, then on average the contribution C_i to the linear tally combination from the ith tally on the jth history is

$$C_i^j = m_i T_i^j = \frac{k}{\overline{T_i}} T_i^j, \tag{10}$$

where k is a constant of proportionality. The Monte Carlo estimate of the expected value of the contribution is then

$$\overline{C_i} = \frac{k}{\overline{T_i} N} \sum_{j=1}^{N} T_i^j. \tag{11}$$

As $N \to \infty$ the summation approaches the mean of the tally $\overline{T_i}$, which gives as the contribution

$$\overline{C_i} = k. \tag{12}$$

One finds that, by selecting the multipliers inversely to the tally mean, the ith tally's contribution to the linear combination is constant in the limit of large N, thereby, minimizing fluctuations in the combination's score. For the purposes of this research, k is chosen to be the largest tally mean so that the multiplier for the largest tally is one and all others are greater than one.

The process of obtaining multipliers and generating weight windows is almost always iterative. It has been observed from repeated application of weight window generation using the linear tally combination that a short calculation to obtain initial "order of magnitude" multipliers should be performed first. Then, the multipliers obtained should be used for an initial generation of weight windows. Those weight windows should then be used to refine the multiplier estimates, which in turn should be used to further refine the weight windows. This process should be repeated until multipliers and weight window stop improving, followed by hand adjustement if necessary.

3.2. Multiplier Effect on Generated Weight Windows

The weight-window generator, based on Eq. (3), estimates a normalized average adjoint flux of the problem because $\phi^\dagger(\mathbf{P}) = I(\mathbf{P})$. The weight-window generator performs well given adequate sampling of the phase space regions important to the tally. The adjoint flux scales linearly with an increase in the adjoint source strength, thus, the adjoint flux resulting from the linear tally combination given in Eq. (8) is

$$\phi^\dagger_{T_{LC}} = m_1 \phi^\dagger_{T_1} + m_2 \phi^\dagger_{T_2} + \ldots + m_k \phi^\dagger_{T_k}, \tag{13}$$

where $\phi^\dagger_{T_{LC}}$ represents the adjoint flux for the linear combination and $\phi^\dagger_{T_i}$ is the adjoint flux for tally T_i. It is the adjoint flux of Eq. (13) that the weight-window generator is estimating.

The multiplier in front of the individual tally adjoint fluxes in Eq. (13) effectively scales the adjoint source because of the linearity of the adjoint Boltzmann transport equation. Thus, using the linear multipliers as a weighting for the linear-tally-combination tallies and generating weight-window parameters based on that linear combination is essentially estimating the importance/adjoint flux resulting from multiple adjoint sources, each scaled by its respective multiplier. Put differently, it is weighting each of the adjoint sources' flux contributions to the combined adjoint flux at a given phase space location.

4. ONE GROUP VERIFICATION PROBLEMS

Two one-group verification problems are used to demonstrate the weighting of the adjoint source via the multipliers. One of the problems is a purely-absorbing infinite medium with infinite plane source, which has a closed form analytic solution that can be compared to the liner-tally-combination method. The other problem is a scattering and absorbing media problem. Both of these problems are run using MCNP's multigroup transport mode [8].

4.1. Geometry

The geometry of these two verification problems is the same and is illustrated in Fig. 2. The geometry simulates an infinite slab as a specularly reflecting cylinder bounded by non-reflecting planes at the ends of the cylinder. The end surfaces are positioned at $x = -10$ cm and $x = 24$ cm and are placed sufficiently many mean free paths away to account for any backscattering into the regions of interest (in and around the source and tallies). The source for the forward calculation is a plane located at $x = 1$ cm sampled uniformly over area. The source emits isotropically into only the single group.

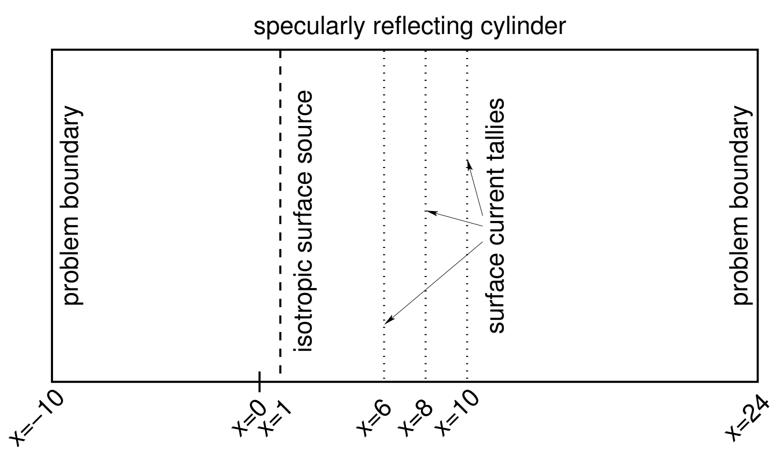


Figure 2. One dimensional geometry used in all verification problems.

The adjoint source must be correctly described to make a fair comparison to the weight-window results from the forward calculation. In the forward calculation, the responses are current tallies located at 6 cm, 8 cm, and 10 cm. The response, integrating over energy, to an MCNP current tally is, from Eq. (6),

$$R = \int_S \int_{-1}^{1} |\mu| \phi(x, \mu) \, d\mu \, dS \quad x \in S. \tag{14}$$

From this response one finds that the adjoint source must be angularly distributed as $|\mu|$. More specifically, the direction of adjoint particle emission must be distributed as μ about both the positive and negative surface normal directions.

4.2. One-Group Pure Absorber

Our research version of MCNP5 was used to generate spatial weight windows for the linear combination of the three tallies as well as to compute the adjoint flux density. The multipliers for the linear combination were selected inversely to the tally means so as to minimize the variation to the linear combination, as discussed above. The analytic adjoint solution, continuous in space and direction,

$$I(x, \mu) = e^{-(x - x_d)/\mu} \tag{15}$$

was weighted by the forward particle density

$$N(x, \mu) = \frac{1}{2} e^{-(x - x_s)/\mu} \tag{16}$$

and numerically integrated over direction to find the importance and adjoint flux as a function of position as specified by Eq. (2), namely,

$$I_{analytic} = \int_0^1 N(x, \mu) I(x, \mu) d\mu \Bigg/ \int_0^1 N(x, \mu) d\mu \; . \tag{17}$$

Only the contribution from $0 \leq \mu \leq 1$ needed to be considered because particles are incapable of backscattering in the pure absorber.

Figure 3(a) compares the results of the weight-window generation using the linear tally combination to the analytic solution for the simulated infinite medium problem. The line labeled “fltc-wwg importance” is the importance generated using the linear tally combination in MCNP5 with the linear-tally-combination patch. The histogram structure arises from the fact that importances estimated in MCNP5 are averaged over spatial regions. The agreement between the analytic importance and linear tally combination weight-window generation importance is excellent.

Fig. 3(b) shows the calculated adjoint fluxes (normalized to unity at the physical source location) for the weighted adjoint sources discussed above using MCNP5, the analytic solution, and PARTISN. The adjoint calculation using MCNP is performed in multigroup mode. Because only one energy group is considered and the forward transport process is the same as the adjoint transport process for one group, the problem may be run as a forward calculation with the correct adjoint source [9, chapter 4]. Technical difficulties running MCNP in adjoint mode with a purely absorbing medium prevented running the problem using actual multigroup transport. The MCNP adjoint calculation is therefore labeled “f-adjoint” to denote that it is the adjoint computed using a forward calculation. The agreement between all of these solutions is excellent, thus indicating that, because the calculated importance is dependent on the adjoint flux, the importance being calculated is indeed the importance for the weighted adjoint source.

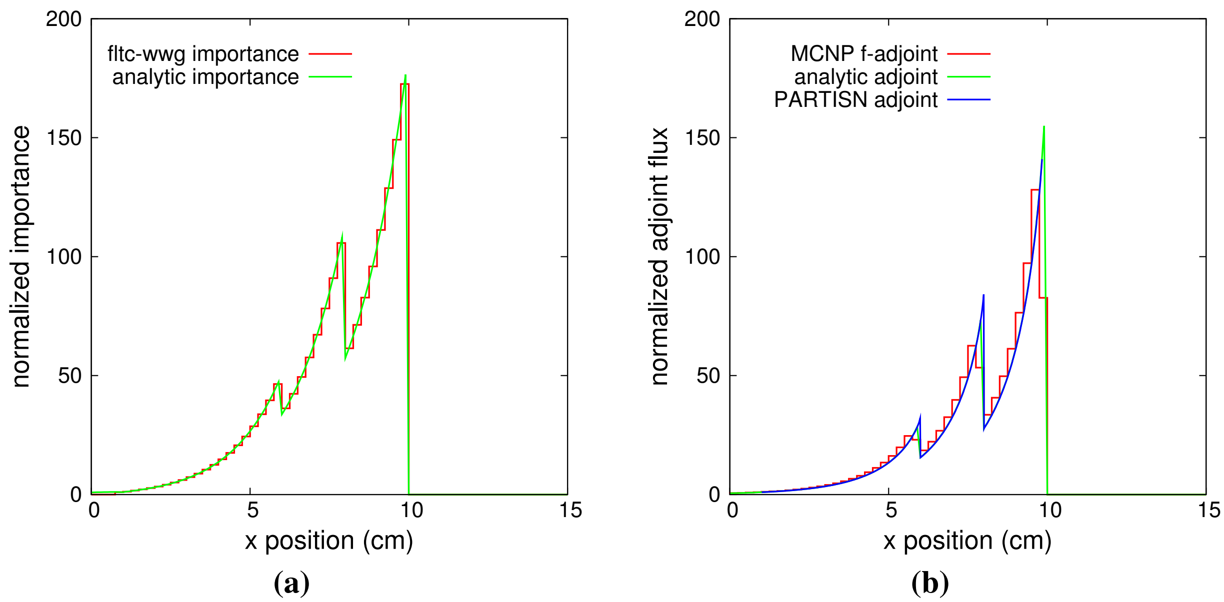


Figure 3. (a) Comparison of the spatial analytic importance function to the importance function generated using MCNP's weight-window generator and the linear tally combination, and (b) a similar comparison of the adjoint fluxes. All results are normalized to unity in the cell containing the physical source.

4.3. One-Group Absorbing and Scattering Medium

The one-group absorption and scattering medium calculation was performed with MCNP to compare the weight windows generated using a linear-tally-combination tally to those obtained by weighting the adjoint flux by the forward particle density, as in Eq. (2). The total cross section for the one-group medium is $\Sigma_t = 1$ cm^{-1}, and the absorption and scattering cross sections are $\Sigma_a = \Sigma_s = 0.5$ cm^{-1}.

The one-dimensional geometry was subdivided into multiple smaller cells with planes parallel to the source and tallies and at the same positions as the planes of the weight-window mesh. The weight-window generation using the linear tally combination was performed, thereby determining the appropriate multipliers. Each of the dividing planes was used as surface current tallies and binned by the cosine of the direction the particle crosses the surface for both an adjoint calculation and a forward calculation. Both calculations were performed using multigroup transport in MCNP with adjoint sources appropriately weighted by the multiplier values. [For a discussion of why and how to appropriately weight the adjoint calculation see 8]. The adjoint response (or expected score) at each of the dividing surfaces, as a finely histogrammed function of particle direction, was then calculated. For this calculation Eq. (2) was used with $N(\mathbf{P})$ equal to the density of particles crossing surface S for the *first* time.

MCNP does not have a obvious method of determining what crosses a surface the first time, so to obtain the desired first crossing score to each surface a non-standard calculation is performed for each surface. For each calculation, the importances of all cells on the opposite side of the surface to the source are given zero importances. In this way, when a particle crosses the surface for the first time it is counted and then immediately killed because of the zero importance on the other side.

The adjoint particle density computed using MCNP was weighted by the forward particle density computed using MCNP with a external script to obtain an average importance using Eq. (2). The importance obtained using this averaging was compared to that produced using the weight-window generator and the linear tally combination. A comparison of the importance calculated from the adjoint (labeled "calculated") and that from the weight-window generator (labeled "fltc+wwg") are presented in Fig. 4, and excellent agreement exists between the two sets of data.

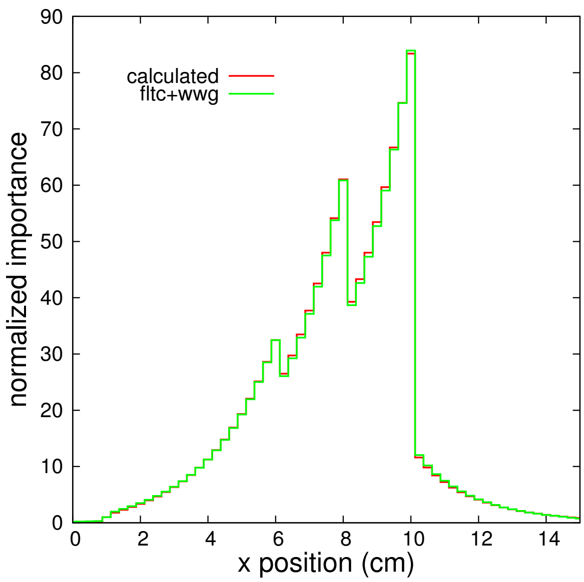


Figure 4. Comparison of the spatial importance function generated by the MCNP weight-window generator and linear tally combination and the spatial importance obtained by computing the forward particle density and adjoint response and combining them via Eq. (2).

5. TEST AND CHALLENGE PROBLEMS

The linear tally combination and weight-window generation was applied to a set of problems to test its capabilities. Specifically, a plain water cube geometry was used to test simultaneously generating neutron and photon weight windows. A concrete sphere problem with high optical thickness was chosen to test the capabilities of the method applied to deep penetration problems. For this sphere problem, weight windows are generated with the linear tally combination in one case using a set of intermediate surfaces and in another case using a mesh tally over the entire problem. Additionally, the technique is applied to a gamma-gamma density probe problem to obtain a global flux solution throughout the geometry using a mesh tally with the linear tally combination. For all of these problems the iterative method described in Section 3.1 is used to generate multipliers and weight windows.

5.1. Concrete Sphere Deep Penetration Problem

This problem is designed to be a difficult deep penetration problem. The tally and source are sufficiently separated, such that, using the weight-window generator on the single tally does not produce a weight-window estimate because very few particles contribute to the tally.

5.1.1. Problem geometry

The problem consists of a concrete sphere with 1-MeV neutrons nearly tangentially incident on one end. The desired surface current tally is located on the opposite end of the sphere, approximately 80 mfp away at the source energy.

Weight windows are generated in one case using a linear tally combination of the intermediate surface current tallies and in another case using a mesh tally overlayed on the problem. The initial goal was to obtain a well converged result of the surface current tally. However, using the mesh tally over the entire problem with the linear tally combination provides a global solution for the flux in addition to the initially desired tally. When the mesh tally is used, it has the same 8000-voxel mesh geometry as the weight-window mesh.

5.1.2. Deep penetration results

Fig. 5 shows the weight windows produced when intermediate surfaces and the mesh tally are used for weight-window generation. When the linear combination of surface current tallies through the sphere are used for weight-window generation, the weight windows decrease predominantly toward the tally. However, when the mesh tally is used the generated weight-window lower bounds decrease in all directions from the region particles enter the sphere.

Using the linear tally combination for weight-window generation makes it possible to generate weight windows for a difficult problem in 5 iterations of 2e6 particles for the linear tally combination of intermediate surface tallies and 4 iterations of 2e6 particles for the linear combination of the mesh tally. Table I shows the tally results for the two different methods of weight window generation and the analog case, which required 5e8 histories to get even an initial estimate of the tally. Using the weight windows generated by the linear combination of intermediate surfaces produces the highest figure of merit.

Use of the linear tally combination with the mesh tally optimizes the flux calculation throughout the problem geometry. Fig. 6 presents the mesh tally values and relative errors for the yz-plane at $x = 0$ cm. All of the relative errors in the mesh tally calculation are less than 0.10 and predominantly less that 0.05. The mesh tally in combination with the linear tally combination and weight-window generator produces a weight window that optimizes the calculation for a “global” combination of voxels not only for the individual tally.

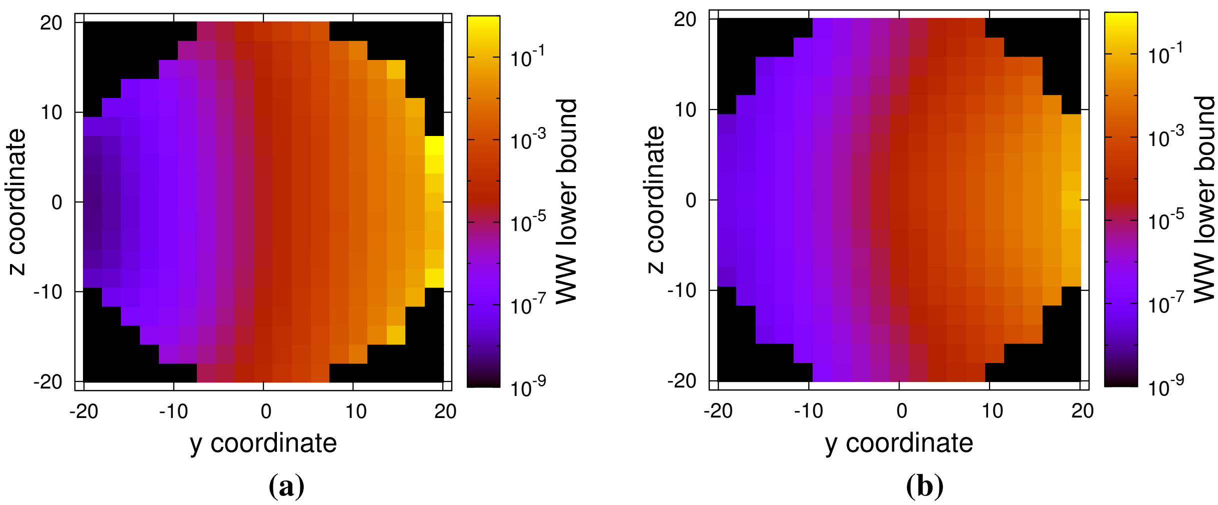


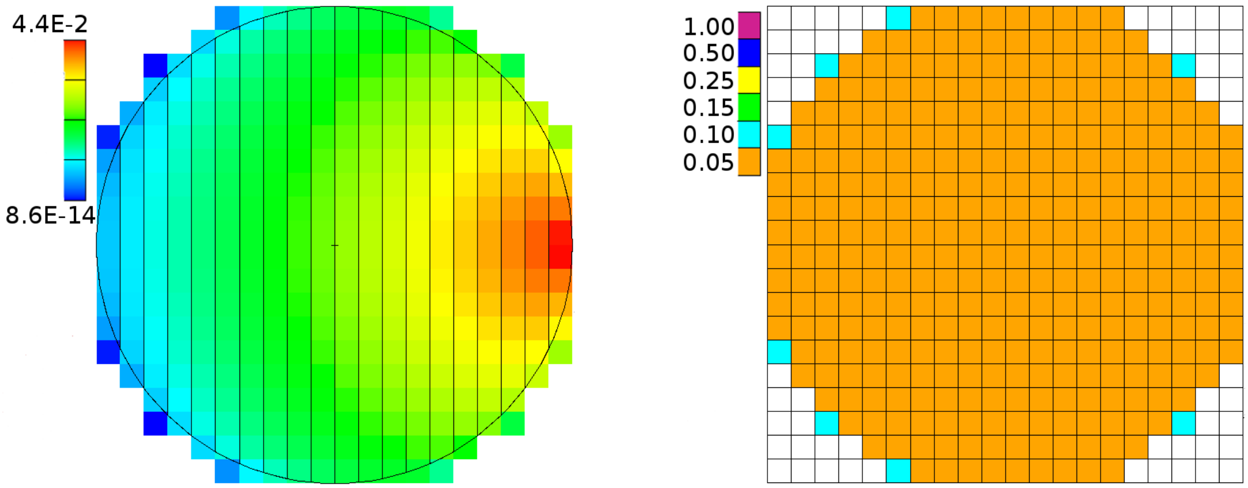
Figure 5. Linear tally combination lower weight-window bounds in concrete sphere for (a) plane tallies through sphere, and (b) a mesh tally.

Table I. Resulting tally values, relative errors, and figures of merit for the concrete sphere problem.

	Analog	
Mean	**Rel. Err.**	**FOM**
5.5142E-09	0.9119	4.4E-03

	LTC+WWG with Surface Tallies	
Mean	**Rel. Err.**	**FOM**
1.8459E-09	0.0045	381

	LTC+WWG with Mesh Tally	
Mean	**Rel. Err.**	**FOM**
1.8491E-09	0.0068	125



(a) **(b)**

Figure 6. Mesh tally (a) values and (b) relative error after generation of weight windows using the mesh tally on the linear tally combination.

5.2. Simultaneous Neutron and Gamma Generated Windows

Typically in a Monte Carlo calculation only a weight window optimized for a tally of a single particle type can be used. For example, a tally for gamma flux may be influenced by neutrons through (n,γ) reactions, which will be optimized by a neutron weight window and a gamma weight window. However, only the single tally for gamma flux is being optimized even though a neutron weight window is generated and used. This problem includes a gamma tally and a neutron tally in the linear tally combination in attempt to generate a weight window that favors both tallies.

5.2.1. Problem geometry

The problem geometry is a 30 cm $\times$ 30 cm $\times$ 30 cm water cube with a 1-MeV point isotropic neutron source at its center. A gamma surface flux tally is performed across the surface perpendicular to the y-axis in the positive direction and a neutron flux tally is performed across the surface perpendicular to the y-axis in the negative direction. The problem is subdivided into a series a cells in the y direction by planes perpendicular to the y-axis. A 1-MeV point isotropic source is located at the center of the cube and cell-based weight windows are generated for a linear tally combination containing both the gamma-flux tally and the neutron-flux tally.

5.2.2. Simultaneous weight-window results

Figure 7 presents the resulting weight windows for this problem in the case that only the neutron tally is optimized, only the photon tally is optimized, and the linear tally combination is optimized.

When only the neutron tally is optimized, the generated weight windows favor neutrons moving in the negative y direction, and, even after multiple iterations of weight-window generation, an estimate of the neutron weight window for the cells near the photon tally is not obtained.

Fig. 7(b) shows that the photon weight window favors photons moving in the positive y direction. The neutron weight window also favors neutrons moving in the positive y direction except in the cells at the problem boundaries. The neutron weight window preferentially move neutrons toward the photon tally because (n,γ) reactions are the source of the photons and as the neutron move nearer the photon tally, photons produced in those locations are more likely to contribute to the tally.

When the linear tally combination is use to generate weight windows a very different neutron weight window is obtained. Figure 7(a) shows that, for the linear tally combination, the neutrons are favored to move in the negative y direction toward the neutron tally but are not as strongly discouraged from moving in the positive y direction as in the case of optimizing only the neutron tally. Little difference is observed in the behavior of the photon weight windows for optimization of the linear tally combination.

Table II shows the tally results for the neutron and photon tallies in the problem for three different cases. The resulting figures of merits are 1031 for the neutron tally and 53 for the photon tally when only the weight window generated with the neutron tally is used. Interestingly, the photon tally does well even though no photon weight window is uses as a result of the simplistic problem and the low photon attenuation. The weight window produced using only the photon tally with the weight-window generator gives a fugure of merit of 20547 for the photon tally and 3.3 for the neutron tally. The weight window produced generating with the linear tally combination gives figures of merit of 3242 for the neutron tally and 6861 for the photon tally, which is less efficient than either calculation alone but requiring less weight-window generation time.

Table II. Resulting tally values, relative errors, and figures of merit for the simultaneous weight window generation problem.

Neutron Tally Alone WWG			
Tally	**Mean**	**Rel. Err.**	**FOM**
Neutron	1.6699E-06	0.0013	1031
Photon	2.1298E-04	0.0058	53

Photon Tally Alone WWG			
Tally	**Mean**	**Rel. Err.**	**FOM**
Neutron	1.6412E-06	0.0671	3.3
Photon	2.1344E-04	0.0009	20547

Neutron & Photon Tallies LTC+WWG			
Tally	**Mean**	**Rel. Err.**	**FOM**
Neutron	1.6696E-06	0.0017	3242
Photon	2.1290E-04	0.0012	6861

5.3. Application To A Gamma-Gamma Density Tool Problem

Weight-window generation using a linear tally combination was also applied to a gamma-gamma density well-logging tool model [10] (Fig. 8). In this study, the technique generates weight-window parameters for the combination of both the near and far detectors and a mesh tally over the entire problem for a global importance map. A flux tally mesh (with over 100,000 mesh cells) is overlaid on the entire problem with the goal of obtaining a well converged flux estimate in each voxel. An iterative process is used to determine the weight-window parameters for each voxel where each iteration consists of refining the estimate of not only the weight-window parameters but also the multipliers. Five iterations of 5e7 histories were needed to obtain weight-window estimates throughout the problem.

Figure 9(a) shows the voxel relative error for an MCNP calculation using default variance reduction and 1×10^8 histories. Note that only the region directly around the source has well converged flux estimates. Using the linear tally combination and weight-window generation with the mesh tally, one finds (Fig. 9(b)) that it is possible to obtain values throughout the problem and that the relative errors are dramatically reduced compared to the default case. Previously in MCNP5 it was not possible to generate weight-window parameters for a mesh tally; but this new technique allows weight-window parameters to be generated that work with the mesh tally on a global basis. Figure 10 shows the fraction of voxels having less that a specified relative error for the gamma-gamma density tool problem as a function of the number of histories run. As expected, the more histories used the more voxels having low relative errors produced.

6. CONCLUSIONS

A new technique has been devised by implementing a linear tally combination in MCNP, which, in conjunction with MCNP's weight-window generator, is capable of optimizing a linear combination of tallies. This technique is shown to be equivalent to increasing the adjoint source strengths of detectors by means of the linear multiplier. A comparison to two verifications problems is made to demonstrate that the linear multiplier is equivalent to increasing the adjoint source-strength. The results of the comparison problem show excellent agreement between the analytic or calculated importances and the computed importances using the weight-window generator with the linear tally combination.

In addition, the technique has been employed to generating global importances in conjunction with MCNP's mesh tally capabilities. In the oil-well logging problem considered, it is possible to obtain a flux throughout the problem domain with relative errors less than 10% in the majority of voxels.

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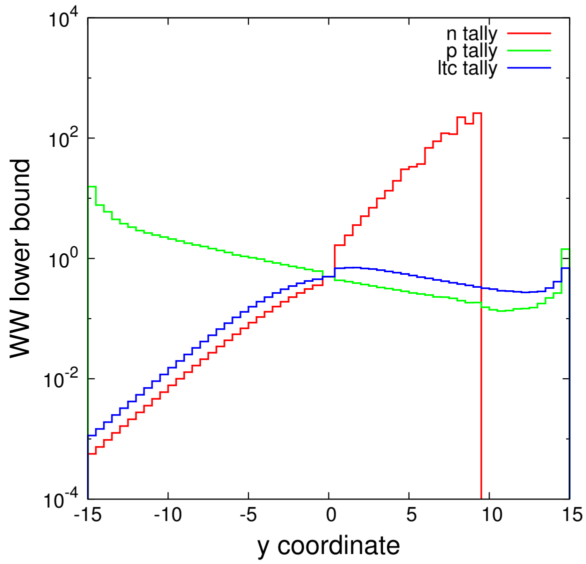
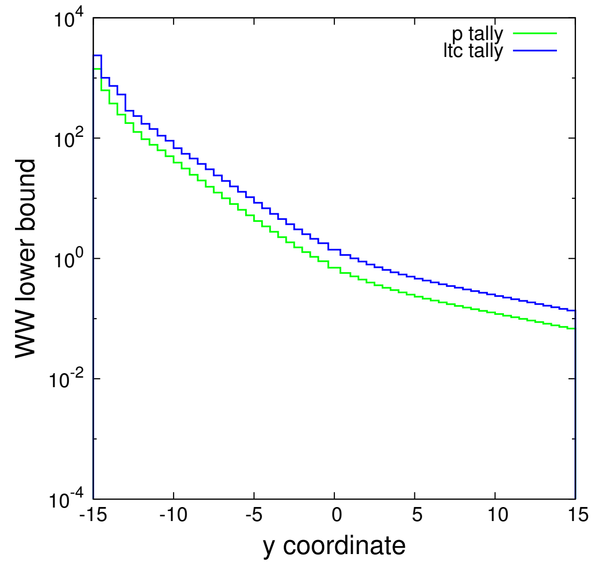


(a)



(b)

Figure 7. (a) neutron and (b) photon weight windows as a function of the tally being optimized.

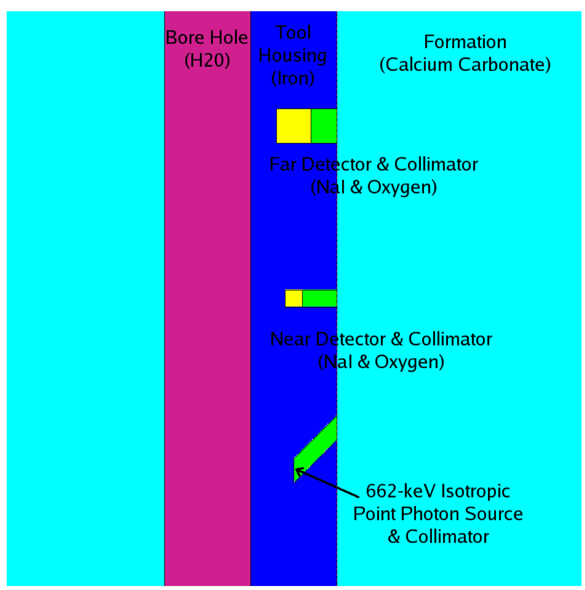


Figure 8. gamma-gamma density oil-well logging tool model geometry.

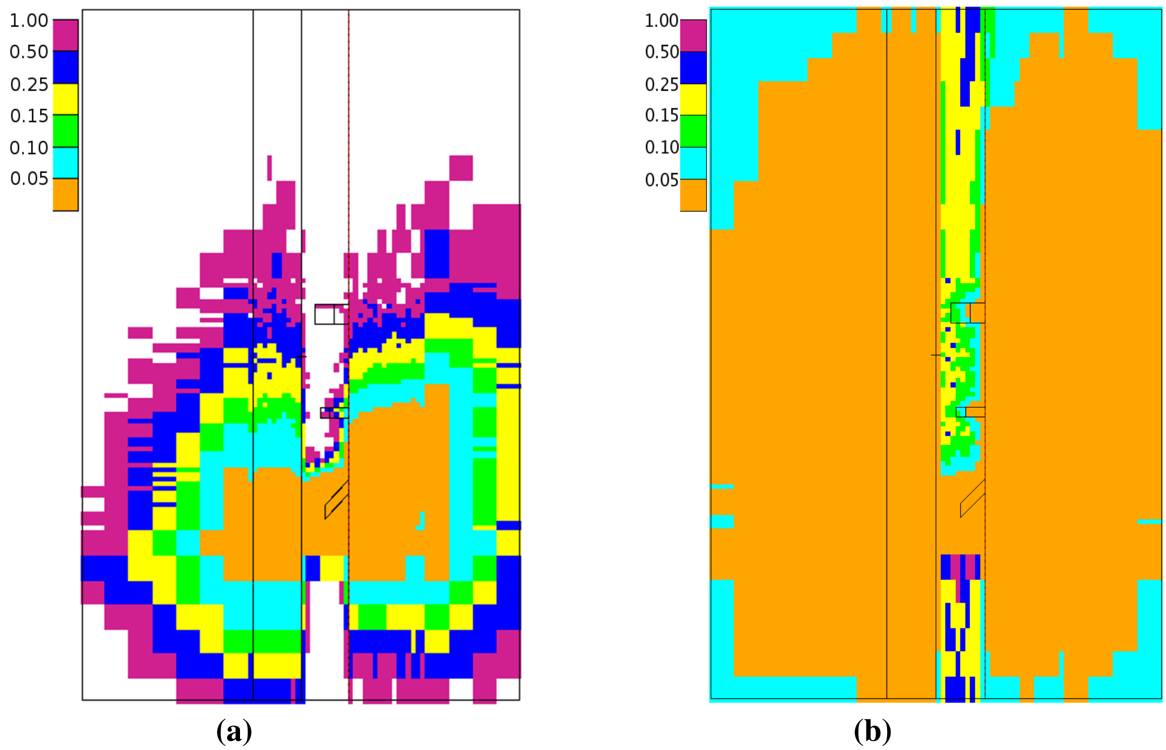


Figure 9. (a) Voxel relative error after default mesh tally production run of 1×10^8 histories, and (b) voxel relative error after mesh tally weight-window generation using linear tally combination and production run of 5×10^7 histories.

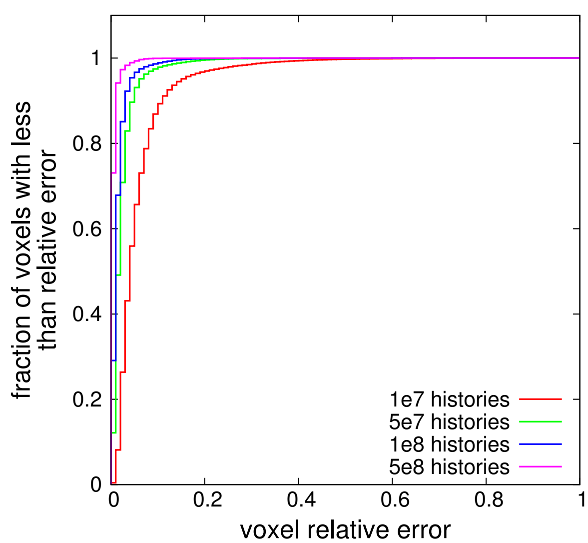


Figure 10. Fraction of voxels having less than given relative error as a function of number of histories.

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