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by Means of a Linear Tally Combination

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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 new importance estimation technique has been developed that allows weight-window optimization for a linear combination of tallies. This technique has been implemented in a local version of MCNP 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. In this work, we present our results of solutions to an analytic three-tally-region test problem and a flux calculation on a 100,000 voxel oil-well logging tool problem.

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

1. INTRODUCTION

The linear tally combination addition to MCNP was used to generate results for simple test problems and other, more difficult, problems that strain the capabilities of the importance splitting technique [1, 2]. Results of the test problems were very promising in that weight window generation for the linear combination worked and in most cases produced a calculation requiring substantially less user time than running each tally as a separate problem. At this point, it was clear to the authors that their conceptual idea of how the linear tally combination and weight window generator work together was correct but lacking a more in depth explanation, which is the focus of this work.

2. BACKGROUND

2.1. Basic Importance Concepts

When performing radiation transport calculations using Monte Carlo simulation, if variance reduction is used, then inevitably certain variance reduction terms arise in the discussion. Two of the more common terms are a particle's importance and weight, which are defined by the following:

1. importance – the expected score/response from a unit weight particle,
2. weight – a value representing the particles relative contribution to a tally [3].

Using good variance reduction, the weight and importance of a particle typically vary inversely to each other. As the 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, then it becomes increasingly important, thus establishing the inverse relation between weight and importance.

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

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

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

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

In Monte Carlo radiation transport calculations the importances are used to split a particle into many equivalent particles with appropriately reduced weights as they move toward higher importances or to roulette particles thereby terminating the history or appropriately increasing the particles' weights as they move toward lower importances. By playing this "importance game" one seeks to maximize the computational time spent tracking particles that will contribute to tallies and minimize time spent following particles that will be useless to the calculation.

Booth [4], 1984 realized that, with some bookkeeping, the average importance in a region I_S can be calculated in a forward Monte Carlo calculation as

$$I_S = \frac{\left\{ \begin{array}{l} \text{score resulting from all particles and progeny} \\ \text{passing through phase-space region } S \end{array} \right\}}{\left\{ \begin{array}{l} \text{total weight entering} \\ \text{phase-space region } S \end{array} \right\}}. \quad (3)$$

This statistical technique of estimating the importance has become known as the "weight window generator." The weight window variance reduction technique is a weight dependent technique that depends on user input of lower weight bounds for the window. Conceptually, particles having weights in excess of the upper weight bound are split so that they fit within the window, while those with weights below the lower bound are either killed or promoted into the window with appropriate frequency. The weight window technique is very similar to the importance splitting discussed above, but depends on the particles weight. The crux of using the weight window technique is the user being able to provide the weight window lower bounds, a task quite difficult by hand but relatively easily done with the weight window generator by means of Eq. (3).

The mechanics of the weight window generator are such that it produces an estimate of the importances given the score definition and weights required in Eq. (3), *for any score definition*. This

is to say, that the weight window generator need keep track only of where the particles are and the eventual scores, but it does not matter how that score is defined, hence its functionality with multiple tally types. This behavior of the generator 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 a important distinction that using 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 Flux and Sources

Another concept commonly discussed with particle importance is the adjoint flux $\phi^\dagger$, because the two are synonymous. Where the flux describes the behavior of physical particles moving outward from the source, the adjoint flux describes the behavior of response particles—a conceptual measure of how likely a real particle is to contribute to a tally, i.e., the importance. In essence, the adjoint flux is a measure of the expected score a unit weight particle at $\mathbf{P}$ will contribute to a tally. When the weight window generator estimates the importance in a region, it is estimating an average adjoint flux over some phase-space region in a forward calculation where the weighting function is the forward particle density determined by the Monte Carlo transport processes. In MCNP, the weight-window generator is restricted to space-energy (averaging performed over spacial volumes, energy bins, all directions, and all time) or space-time weight windows (averaging performed over spacial volumes, time bins, all directions, and all energies), and thus the examples in this work are similarly restricted.

Establishing a definition of the physical source in a transport problem is generally intuitive. This is the distribution of particles, be them neutrons, photons, etc., emitted from a certain point or region, and the transport calculation determines the flux ϕ resulting from that physical source. The adjoint flux describes the behavior of response particles, so the adjoint source describes the origin of *response particles*, which is dependent on the specific physical detector/tally response function used in the forward calculation. The response function is independent of the forward flux, just as the physical source is independent of the adjoint flux. One defines the total detector/tally response R as

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

where S is some spatial region and σ_d is the detector/tally response function, which in general could depend on position, direction, and energy of the particles. Fundamentally, σ_d does two things: 1. determines what particles are “accepted” as part of the response and 2. scales the response for incoming particles.

As an example, consider an energy dependent response of

$$\sigma_d(E) = \begin{cases} e^{-E}, & 0 \leq E < E_o \\ 0, & \text{otherwise} \end{cases} \quad (5)$$

Such a response makes the detector insensitive (0 contribution) to particles with energy greater than E_o . The response to particles with energies less than E_o is scaled in proportion to e^{-E} .

As another example, consider a tally of surface current (an MCNP F1 tally) where the response R_C is given by

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

where S is now the area of the surface, and $\hat{\mathbf{n}}$ is the unit normal vector to the surface. Because there is no energy dependence, it may be integrated out to give

$$R_C = \int_S \int_{4\pi} \phi(\mathbf{r}, \hat{\Omega}) \hat{\Omega} \cdot \hat{\mathbf{n}} d\Omega dS. \quad (7)$$

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

$$R_C = \int_S \int_{4\pi} \mu \phi(\mathbf{r}, \hat{\Omega}) d\Omega dS, \quad (8)$$

and one concludes from $\sigma_d = \mu$.

When constructing adjoint transport problems, adjoint particles are emitted from the detector or tally region in proportion to σ_d . Thus, the adjoint source of the first example should not emit particles with energies greater than or equal to E_o . Additionally, as the energy of the particle goes down, the response of the first example goes up exponentially, implying that the adjoint source should emit more particles at low energies and asymptotically negligible particles at very high energies. In the second example, the adjoint source should emit in all energies but not equally at all directions. The adjoint source should, in this case, emit particles in proportion to the cosine of the surface-normal vector.

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

$$R_F = \int_S \int_{4\pi} \int_0^\infty \phi(\mathbf{r}, \hat{\Omega}, E) dE d\Omega dS, \quad (9)$$

meaning that $\sigma_d = 1$, a uniform distribution of all variables.

For the verification discussed below, it is necessary to create models to compute the adjoint flux. The adjoint sources for these models are constructed by considering what the response σ_d is in the forward calculation. Once it is clear what σ_d is, the correct adjoint source distribution is then a normalized form of σ_d over the source emission variables.

3. METHOD

A linear tally combination was recently added to a research version of MCNP to test the generation of weight window parameters for the combination [1, 2]. The resulting combined tally T_{LC} is of the form

$$T_{LC} = m_1 T_1 + m_2 T_2 + \dots + m_k T_k, \quad (10)$$

where m_i represents the multiplier for tally T_i with $1 \leq i \leq k$. All tallies, except the pulse height tallies, may be used in the linear tally combination. The resulting scores from each of the tallies can then be passed to the generator as the numerator of Eq. (3).

NEED MORE ON ACTUAL WORKINGS HERE!!!

3.1. Multiplier Selection

The selection of multipliers is crucial to the generated weight window lower bounds. As a thought experiment, 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. Now, imagine a particle in between the two tallies moving away from the near tally, toward the far tally, but in a region where the near tally's importance function dominates. From the "rules" of the importance splitting game, this particle will be rouletted, because the importance along its current direction is dropping, as it continues along its trajectory, even though it is headed toward the far tally and may contribute there. This rouletting is less than ideal if one is interested in scores to the far detector as well.

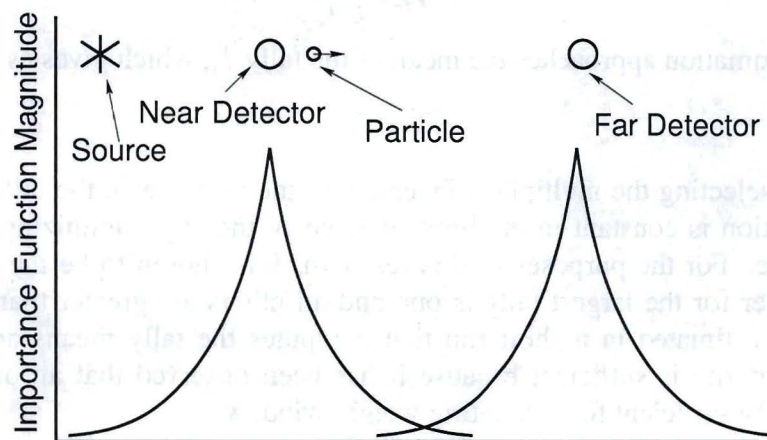


Figure 1. Importance splitting example .

If the importance function were not to drop so dramatically after the first detector then more of the particles would survive to the second detector. The large drop is a result of the lower scores resulting from lower weight particles contributing to the far detector than the near detector. If larger scores are contributed to the far detector from the same, statistically lower weight, particles then the importance will be higher, as exhibited by Eq. (3). The linear tally combination's multipliers provide a method of inflating the contribution of individual tallies to obtain the desired higher importance. The thought experiment included multiple detectors, and, if each detector is included in the linear tally combination, they become a single tally with its own importance function. If both of the tallies in the thought experiment 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 then the resulting importance produced by the generator will be higher toward the far detector. Essentially, selecting multipliers in the manner above minimizes variation in the the

linear tally combination scores.

Another way to look at this minimization of variation to the linear tally combination is that all the tallies in the linear combination should, on average, contribute equally to combination. One way to obtain this equal contribution is to make all the tally multipliers inverse to the tally mean, namely

$$m_i \propto \frac{1}{\overline{T_i}}. \quad (11)$$

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 i th tally on the j th history is

$$C_i^j = m_i T_i^j = \frac{k}{\overline{T_i}} T_i^j, \quad (12)$$

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

$$\overline{C_i} = \frac{k}{\overline{T_i} N} \sum_{j=1}^N T_i^j. \quad (13)$$

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

$$\overline{C_i} = k. \quad (14)$$

One finds that, by selecting the multipliers inversely to the tally mean, the tally's contribution to the linear combination is constant in the limit of large N thereby minimizing fluctuation to the combination's score. For the purposes of this research, k is chosen to be the largest tally value so that the multiplier for the largest tally is one and all others are greater than one. Practically, the multipliers are estimated in a short run that computes the tally means and from those the multipliers. A short run is sufficient because it has been observed that an order of magnitude multiplier is typically sufficient for generating weight windows.

3.2. Multiplier Effect on Generated Windows

The weight-window generator, by means of Eq. (3), is estimating 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. Provided that the weight-window generator is estimating the adjoint flux in conjunction with the linear properties of the adjoint flux, the adjoint flux resulting from the linear tally combination given in Eq. (10) is

$$\phi_{TLC}^\dagger = m_1 \phi_{T_1}^\dagger + m_2 \phi_{T_2}^\dagger + \dots + m_k \phi_{T_k}^\dagger, \quad (15)$$

where $\phi_{TLC}^\dagger$ represents the adjoint flux for the linear combination and $\phi_{T_i}^\dagger$ is the adjoint flux for tally T_i .

The multiplier in front of the individual tally adjoint fluxes in Eq. (15) effectively scales the adjoint source because the adjoint Boltzmann transport equation being solved is linear. 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

The method above was implemented as a patch to MCNP5 (RSICC version 1.40). Many different test problems were run to investigate the capabilities of the linear tally combination method. One of the more important problems investigated is that of a one-group purely-absorbing infinite medium with infinite plane sources because it has a closed form analytical solution for comparison to the implemented method. Also, the method was compared to a one-group scattering and absorbing media problem.

4.1. Geometry

The geometry of all the problems is the same and is illustrated in Fig. 2. The idea is to construct a geometry that resembles an infinite slab and be able to source particles all along that slab. Because MCNP requires that the source specified be finite, a specularly reflecting cylinder was created such that particles could never leave the cylinder, just as with the infinite slab, except by the end surfaces that were positioned at $x = -10$ cm and $x = 24$ cm. The end surfaces were placed sufficiently many mean free paths away to account for any backscattering into the regions of interest (in and around the source and tallies).

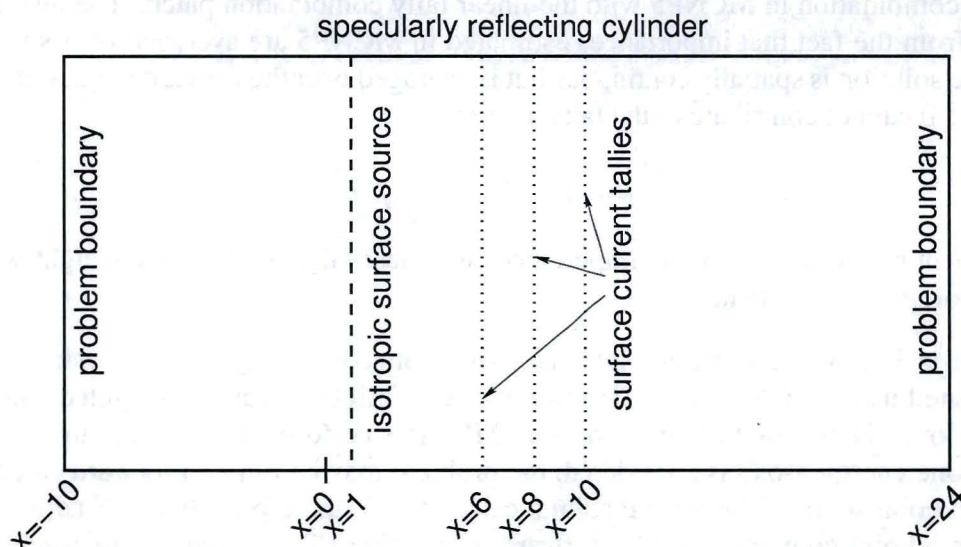


Figure 2. One dimensional geometry used in all verification problems .

The source for the forward calculation is a plane located at $x = 1$ cm sampled uniformly over area. The source emits isotropically. The energy of source particle emission is dependent on the

problem. In the one group problems, the source emits into that single group, but in the two group problem the source emits into the high energy group.

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 response is for the current tallies. The response to an MCNP current tally is

$$R = \int_S \int_{-1}^1 |\mu| \phi(x, \mu) d\mu dS \quad x \in S, \quad (16)$$

where $|\mu|$ is used because particles contribute the same regardless of the direction they are crossing the surface¹. From this response one finds that the adjoint source must be angularly distributed as $|\mu|$. More specifically, it must be distributed as μ out both sides of the physical detector location.

4.2. One-Group Pure Absorber

A one-group infinite-medium model was created for MCNP5 that has an isotropic plane source located at $x = 1$ cm and three surface current tallies located at 6 cm, 8 cm, and 10 cm. MCNP5 was used to generate spatial weight-windows for the linear combination of the three tallies as well as compute the adjoint flux density. The multipliers for the linear combination are selected inversely to the tally means so as to minimize the variation to the linear combination. The analytic solution, continuous in space and direction, was numerically integrated over direction to find the importance and adjoint flux density as a function of position.

Figure 3(a) compares the results of the new method to the known analytic solution for the 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 analytic solution is spatially continuous but is averaged over the forward angular flux for $\mu > 0$ because $\mu < 0$ cannot contribute to the tally, namely

$$I_{analytic} = \int_0^1 \phi(x, \mu) \phi^\dagger(x, \mu) d\mu \bigg/ \int_0^1 \phi(x, \mu) d\mu \quad (17)$$

The agreement between the analytic importance and linear tally combination weight-window generation importance is excellent.

Also shown in Fig. 3(b) are the adjoint fluxes (normalized to unity at the physical source location) calculated using MCNP5, analytic solutions, and PARTISN for the weighted adjoint sources discussed above. The adjoint calculation using MCNP is performed in multigroup mode, and, because only one energy group is considered, the problem may be run as a forward calculation with the correct adjoint source. 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 good, thus supplying evidence that, because the calculated importance is dependent on the adjoint flux, the importance being calculated is indeed the importance for the weighted adjoint source.

¹MCNP’s “current tally” is really more of a particle density tally and not a *net current* tally as the name might imply.

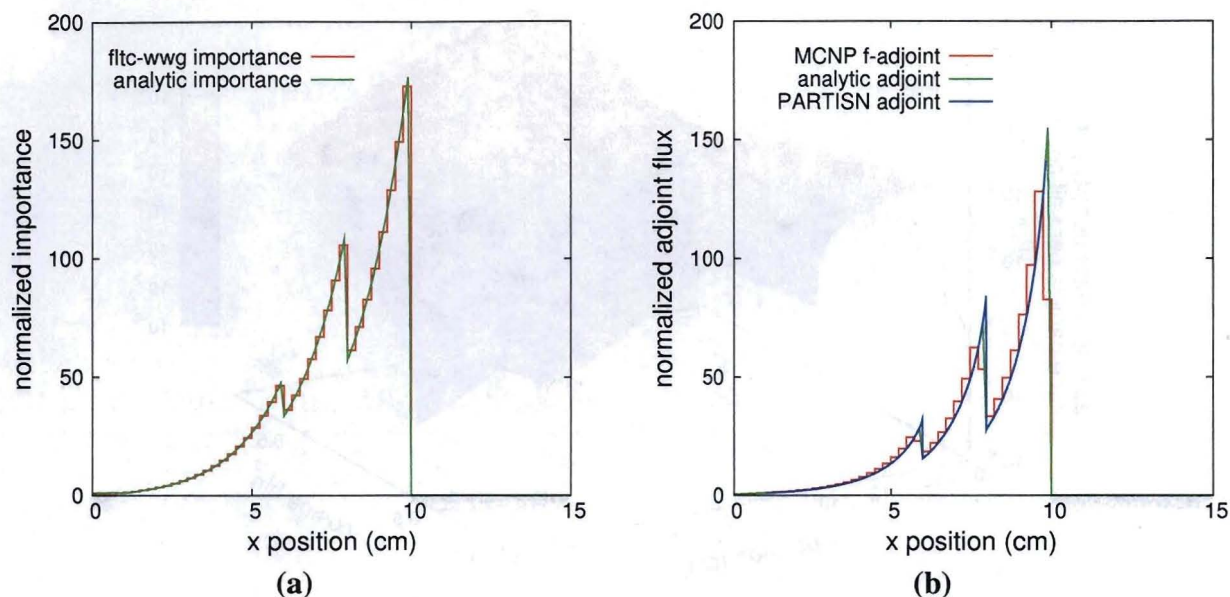


Figure 3. (a) Comparison of the spatial analytic importance function to the importance function generated using MCNP's weight-window generator and the linear tally combination, and (b) a similar comparison of the adjoint fluxes. All results are normalized to unity in the cell containing the physical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

4.3. One-Group Absorbing and Scattering Medium

While the pure absorption problem has a nice analytic solution with which to compare, the particle interactions in such a medium are obviously non-realistic. A more realistic, yet still simplified by the one-group approximation, calculation was performed with MCNP to compare the weight windows generated using the linear tally combination as the tally to those obtained by weighting the adjoint by the forward particle density.

To perform this comparison the one dimensional geometry is 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 is performed such that the multipliers are determined. Then, each of the dividing planes is used for a surface current tally and binned by the cosine of the direction the particle crosses the surface for both an adjoint calculation and a forward calculation. The adjoint calculation is performed using the multigroup adjoint capabilities of MCNP [5] with sources appropriately weighted by the multiplier values, and the adjoint response (or expected score) at each of the dividing surfaces, as a finely histogrammed function of particle direction, is calculated. The angular adjoint particle density is shown in Fig. 4.

A similar calculation is performed in the forward direction to obtain the forward particle density with the same cosine binning; however, because the adjoint is already accounting for the total expected score from a particle crossing a surface in a specific direction, it is imperative that the tallies for the forward calculation only count each history's first contribution to the tally. If the

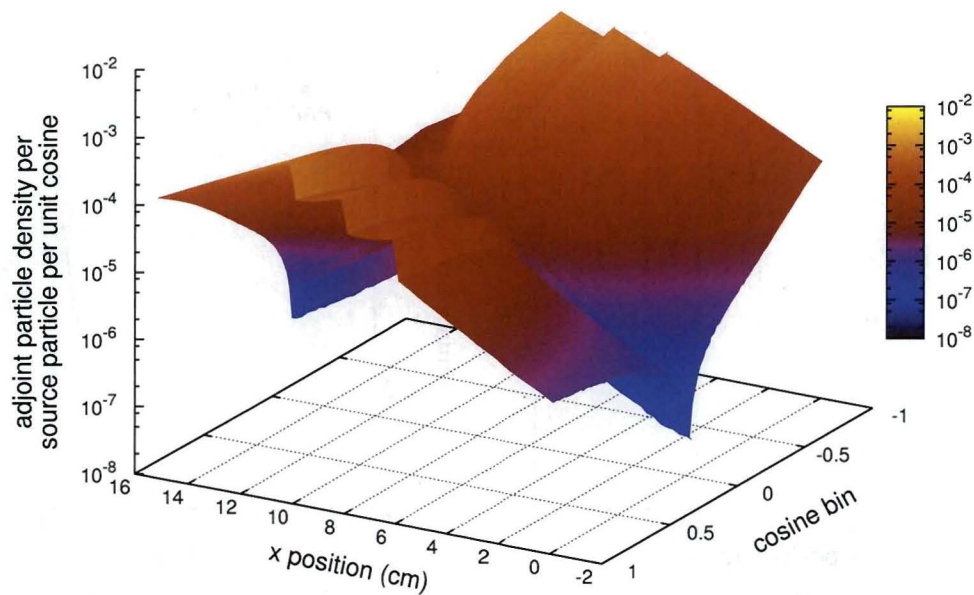


Figure 4. Adjoint particle density as a function of surface position and particle direction crossing the surface.

tallies were allowed to count multiple contributions from the same history then, when used to weight the adjoint flux, more weight than appropriate would be given to adjoint particles crossing a surface in a specific direction. Put another way, allowing a history to contribute multiple times over accounts for that history's weight.

To obtain the desired first crossing score to each surface, a single 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 resulting angular particle densities are shown in Fig. 5. One will note that in directions where particles are moving back toward the physical source (located at $s = 1$ cm) the forward densities are zero because a particle must contribute to the tally the first time in a direction away from the source, and, because only the first crossings are sought, all contributions moving back toward the source are zero. Some statistical fluctuations for direction bins containing particles crossing the surfaces at nearly perpendicular to the surface normal are observed. However, the adjoint response for similar particle directions tends to be about an order of magnitude less than particles crossing more parallel to the surface normal and therefore the fluctuations are of only minor concern.

The adjoint particle density is weighted by the forward particle density to obtain an average importance using Eq. (2). The importance obtained using this averaging is compared to that produced using the weight-window generator and the linear tally combination. A comparison of the importance calculated from the adjoint and that from the weight-window generator are presented in Fig. 6, and excellent correlation exists between the two sets of data.

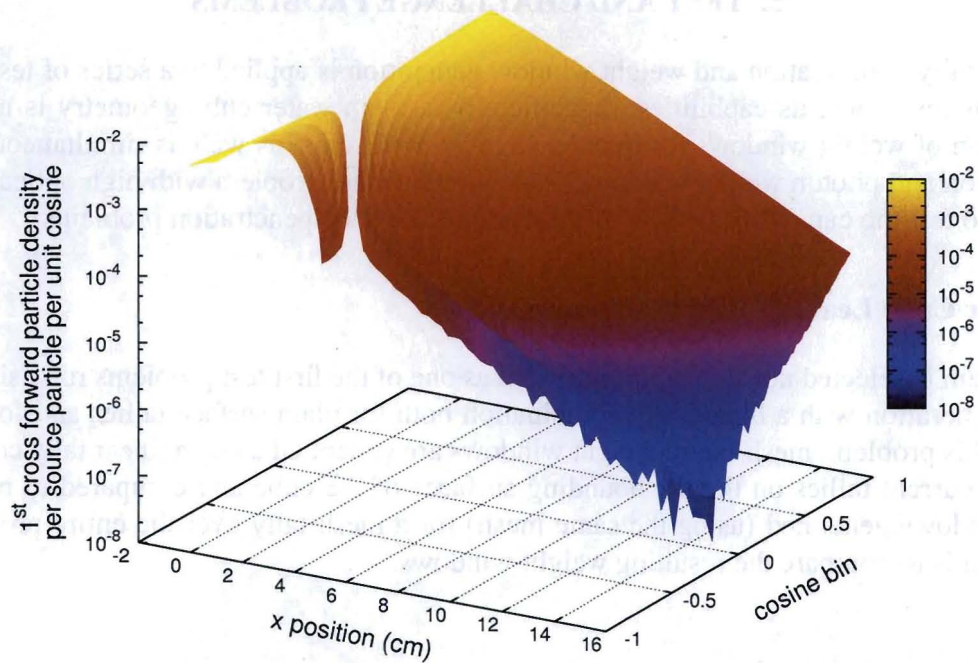


Figure 5. Forward particle density as a function of surface position and particle direction crossing the surface.

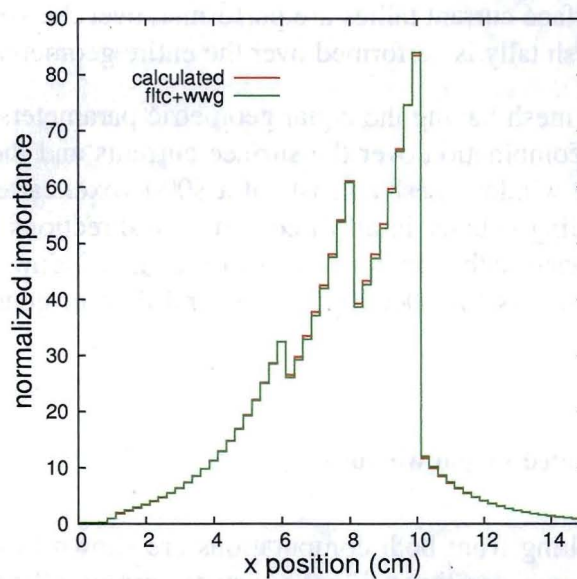


Figure 6. Comparison of the spacial importance function generated by the MCNP weight window generator and linear tally combination ant the spacial importance obtained by computing the forward particle density and adjoint response and combining them via Eq. (2) .

5. TEST AND CHALLENGE PROBLEMS

The linear tally combination and weight window generation is applied to a series of test and challenge problems to test its capabilities. Specifically, a plain water cube geometry is used to test optimization of weight windows for total leakage from the cube as well as simultaneously generating neutron and photon weight windows. A concrete sphere problem with high optical thickness is chosen to test the capabilities of the method applied to deep penetration problems.

5.1. Water Cube Leakage Weight Windows

This problem is selected not for its difficulty, but as one of the first test problems run using weight-window generation with a linear tally combination both for plain surface tallies and for the mesh tally. For this problem, mesh-based weight windows are generated using a linear tally combination of surface current tallies on the six bounding surfaces of the cube and compared to mesh-based weight windows generated (using the same mesh) for a mesh tally over the entire problem. The overall goal is to compare the resulting weight windows.

5.1.1. Problem geometry

The problem geometry is intentionally simplistic. As shown in Fig. 7 the geometry is indeed just a cube of water with density 1.00 g cm^{-3} . A 1-MeV point isotropic neutron source is located at the center of the cube. Surface current tallies are performed over the six bounding surfaces of the cube in one case, and a mesh tally is performed over the entire geometry in another.

The same weight window mesh having the equal geometric parameters as the mesh tally is used with both the linear tally combination over the surface currents and the linear combination over the mesh tally. The weight window mesh consists of a 8000-voxel cartesian mesh centered at the problem origin and extending equally in all three cartesian directions to form a large cube that encompasses the physical water cube. In both cases of weight window generation the problem is run once to generate multipliers for 500000 histories and then to generate weight windows for another 500000 histories.

5.1.2. Comparison of generated weight windows

The weight windows resulting from both computations are shown in Fig. 8. Figure 8(a) shows the results of weight window generation using the surface current tallies in the linear combination for a cross-section of the geometry through the x - y plane at $z = 0 \text{ cm}$. Figure 8(c) presents the weight window for the same cross sectional cut through the geometry but for the weight window generation using the mesh tally. The weight windows for a cross sectional cut along the x - y plane at $z = 22.5 \text{ cm}$ is presented in Fig. 8(b) and Fig. 8(d) for weight window generation using the surface current tallies in the linear combination and the mesh tally in the linear combination, respectively.

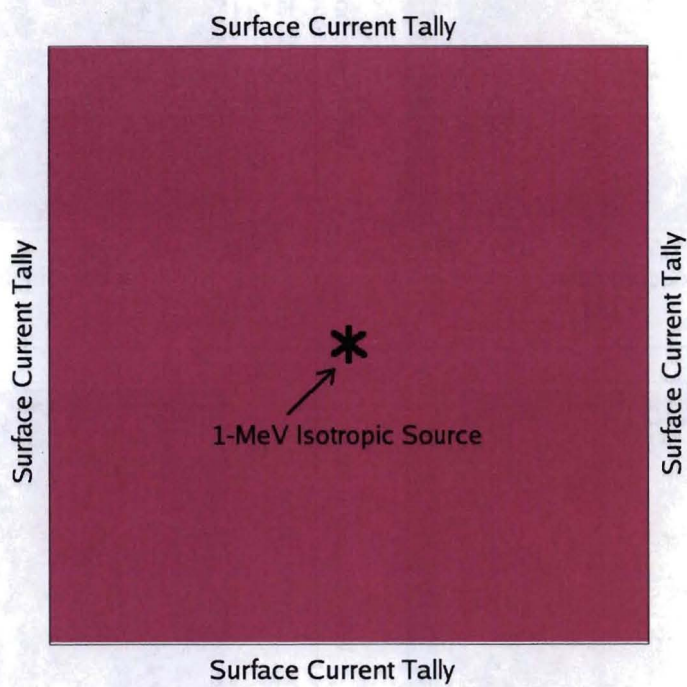


Figure 7. Water cube problem geometry .

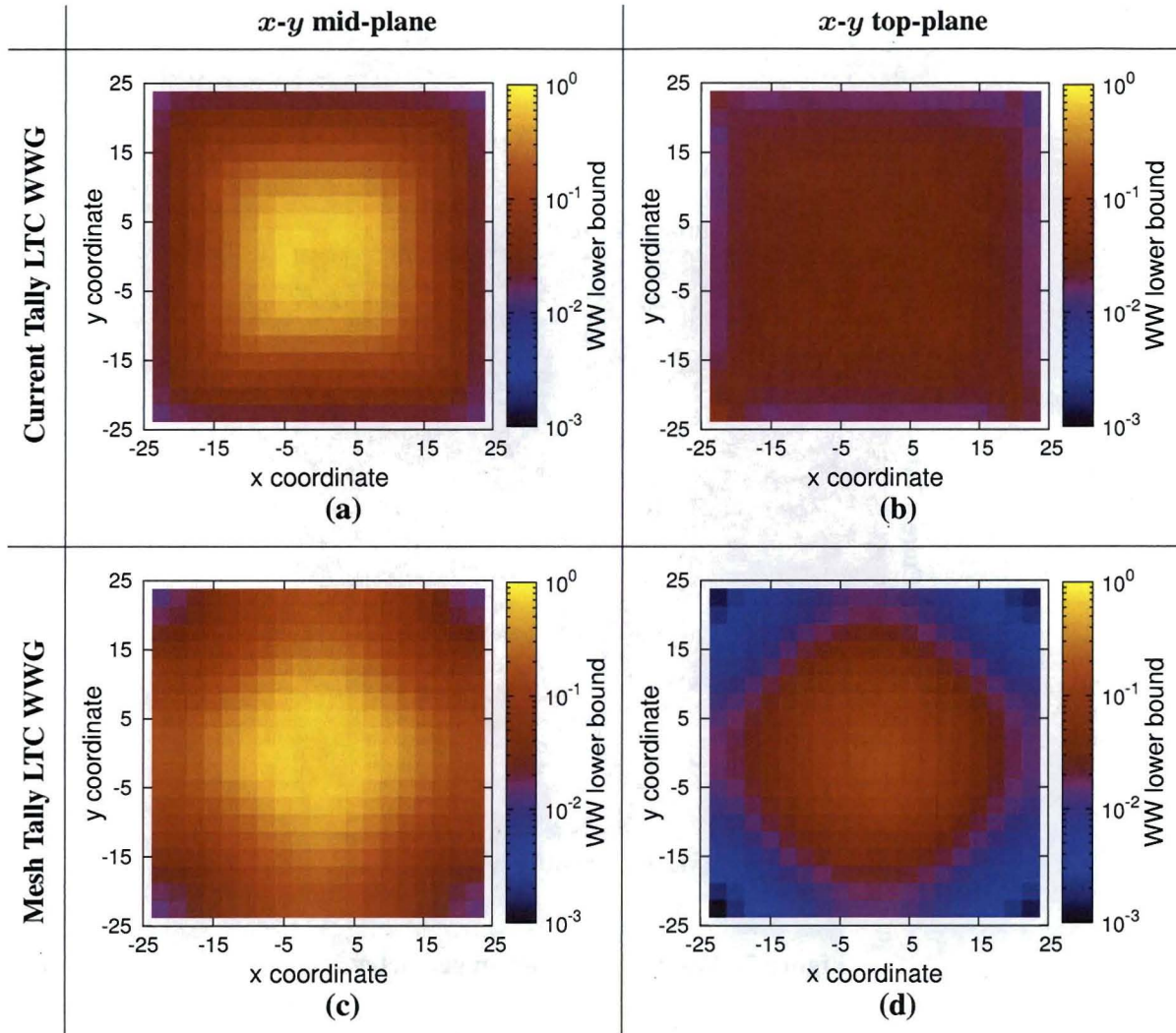


Figure 8. Lower weight window bound results at the mid-plane $z = 0$ cm and top-plane $z = 22.5$ cm for the water cube problem generated using both the current tallies and the mesh tally .

When weight windows are generated using the surface current tallies in the linear combination the resulting windows are shaped like the cube. When the mesh tally is used in the linear combination the windows appear more spherically shaped indicating that the window will more uniformly populate the entire geometry and not just “push” particles to the boundaries.

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 by (n,γ) reaction, which will in 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 window that favors both tallies.

5.2.1. Problem geometry

A very similar geometry to the previous problem is used although with a $30\text{ cm} \times 30\text{ cm} \times 30\text{ cm}$ cube. However, rather than using a linear tally combination over the six bounding surfaces, 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. Figure 9 illustrates the problem geometry and tally positions.

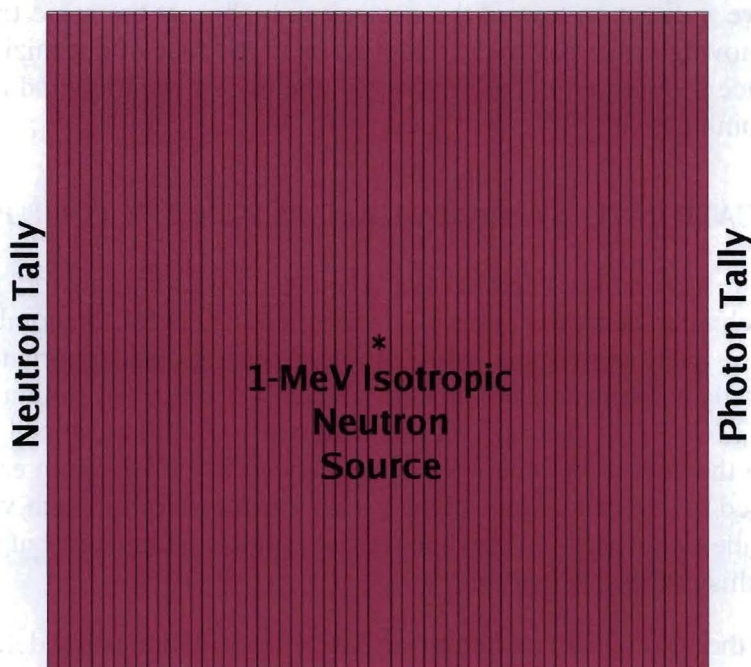


Figure 9. Neutron-photon cube problem geometry .

The problem is subdivided into a series of 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 window results

Figure 10 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 windows favor neutrons moving in the negative y direction, and, even after multiple iterations of weight window generation, a neutron window for the cells near the photon tally is not acquired.

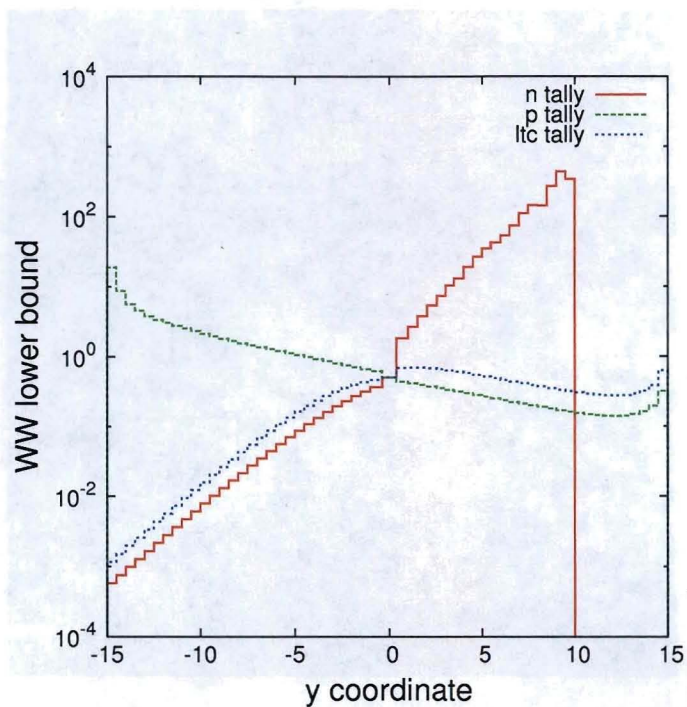
For the photon tally, it is evident from Fig. 10(b) that the photon weight window favors photons moving in the positive y direction. Also of note is that the neutron weight window for optimizing only the photon tally also favors neutrons moving in the positive y direction except in the cells at the problem boundaries. This behavior in the neutron weight window arises from the fact that (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 used to generate windows a very different neutron window is obtained. Figure 10(a) shows that, for the linear tally combination, the neutrons are favored to move in the negative y direction toward the neutron tally, but, at the same time, they are not as 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.

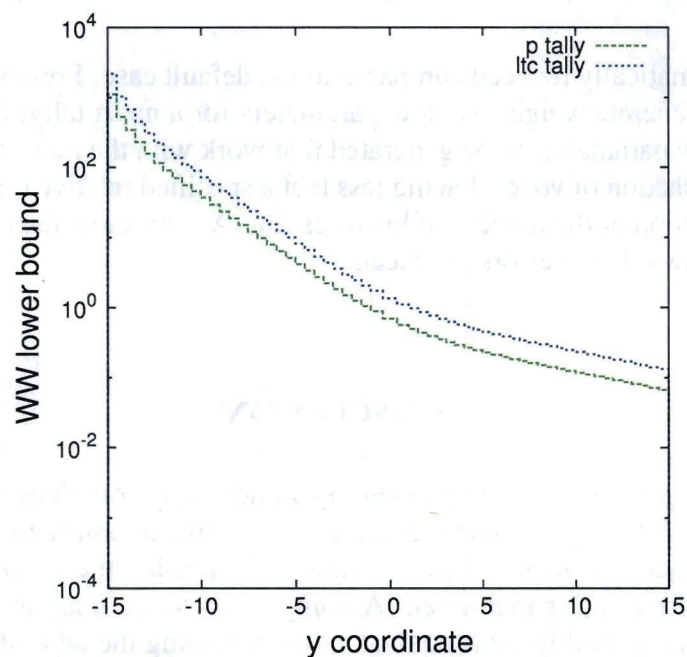
6. APPLICATION TO A GAMMA-GAMMA DENSITY TOOL PROBLEM

The present technique has also been applied to a lithodensity well-logging tool model [6] (Fig. 11). In this study, the technique generates weight-window parameters for the combination of both the near and far tallies as well as over the entire problem for a global importance map. The latter employs the linear tally combination and weight-window generation in conjunction with the mesh tally capabilities of MCNP5. 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 was used to determine the weight-window parameters for each voxel; each iteration consists of refining the estimate of not only the weight-window parameters but also the multipliers. Three iterations of this process were used.

Figure 12(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. 12(b)) that it is possible to obtain values throughout the problem and that the



(a)



(b)

Figure 10. (a) neutron and (b) photon weight windows as a function of the tally being optimized .

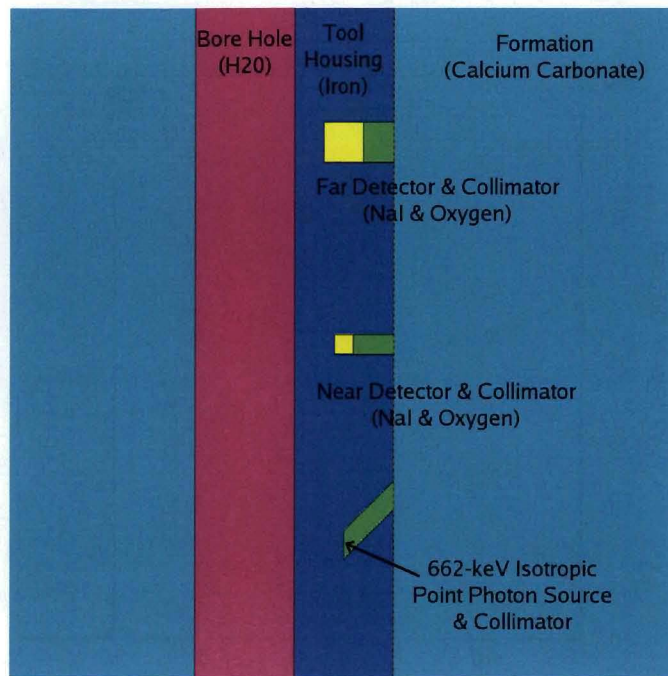


Figure 11. Lithodensity oil-well logging tool model geometry.

relative errors are dramatically reduced compared to the default case. Previously in MCNP5 it was not even 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 13 shows the fraction of voxels having less than a specified relative error for the lithodensity 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.

7. 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 an analytic solution was 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 solution and the computed importances and adjoint fluxes.

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.

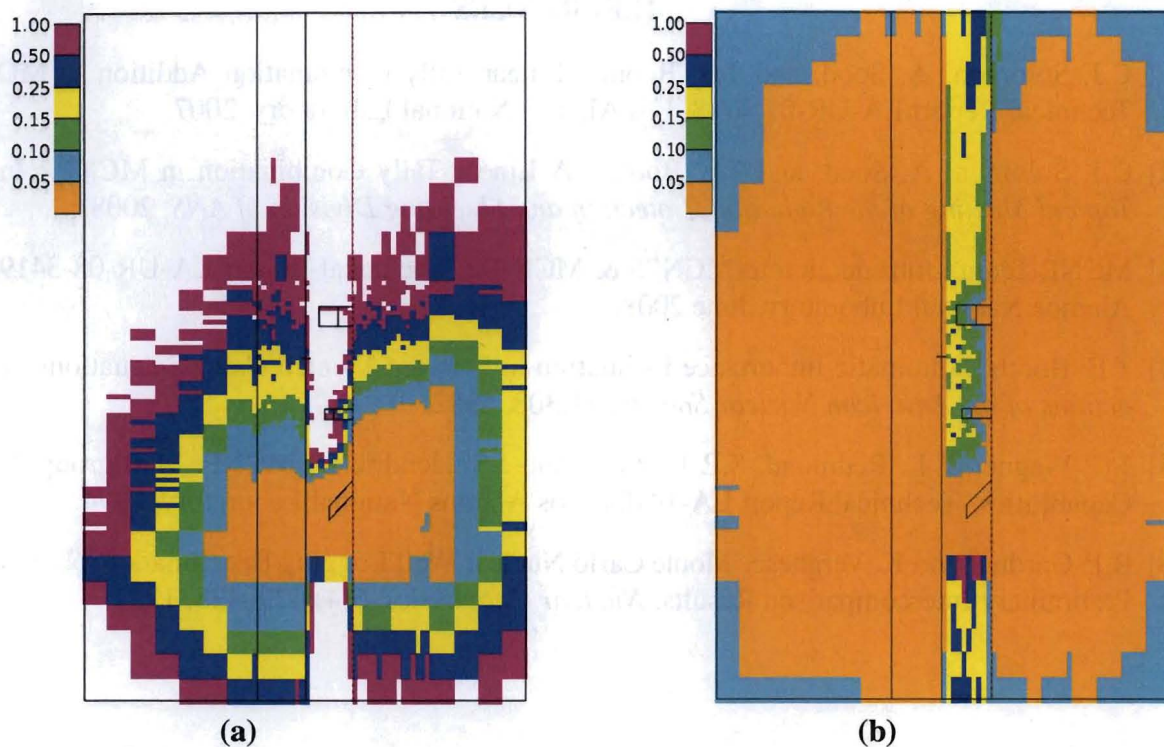


Figure 12. (a) Voxel relative error after default mesh tally production run of 1×10^8 histories, and (b) voxel relative error after mesh tally weight-window generation using linear tally combination and production run of 5×10^7 histories.

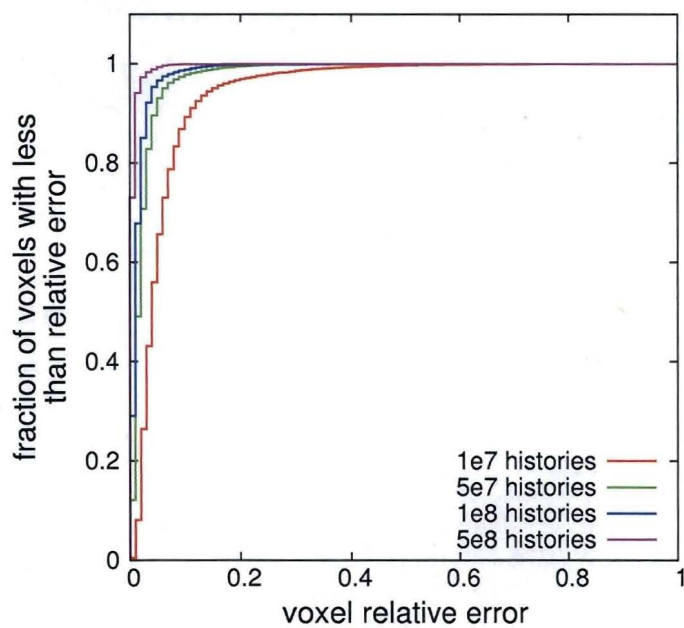


Figure 13. Fraction of voxels having less than given relative error as a function of number of histories.

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