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6. Gamma-Ray and Electron Transport by Monte Carlo, *William L. Thompson (U of Va)*

A Monte Carlo computer code, MONTELEC, which simulates gamma-ray and electron transport, including an explicit treatment of bremsstrahlung effects for energies up to 10 MeV, has been developed at the University of Virginia. Results of sample calculations made with the code are in good agreement with similar calculations by other models and with experimental results (for electrons incident on thin and thick targets) found in the literature.

The gamma-ray portion of the code treats the transport of gamma rays by standard Monte Carlo techniques. The three primary gamma-ray events (photoelectric absorption, Compton scattering, and pair production) are considered explicitly in order to generate the appropriate secondary electrons that contribute to the total effect of the incident radiation.

Histories of electrons (whether the electrons are the primary radiation or the result of gamma-ray interactions) are followed using ETRAN, an electron Monte Carlo program developed by Berger, as a model.[1] Rather than explicitly following the electrons collision by collision as is done with gamma rays (an electron may have many thousands of collisions while losing a few MeV versus 20 or 30 for gamma rays), groups of collisions are considered using multiple scattering theories of electron interactions as reviewed by Zerby and Keller.[2] The production of bremsstrahlung, including energy and angular distributions, is described by the Bethe-Heitler cross section with analytical and empirical corrections as outlined in the classic paper by Koch and Motz.[3]

Heretofore, the contribution of bremsstrahlung to the shielding problem of high-energy gamma rays has not been taken into account. This contribution has been calculated by the MONTELEC code to be a significant portion of the total transmitted dose for 8-MeV gamma rays normally incident on lead (see Table I). Furthermore, albedo calculations for 8-MeV photons incident on lead also indicate a large contribution (50% of dose albedo) from bremsstrahlung to the total reflected dose. The bremsstrahlung contribution is in the form of photons having energies above 0.51 MeV, which would not have been predicted by calculations that only consider primary gamma-ray interactions. These calculations represent about 1 h of CDC-6400 computer time for 3200 initial histories. The results are in good agreement with experimental measurements obtained at the University of Virginia, some of which appear in Table I.[4-6]

Although this present work is preliminary with a further study of bremsstrahlung planned, the corroboration of the MONTELEC and experimental results strongly suggests that high-energy photon and/or electron transport studies should account for bremsstrahlung.

TABLE I

Dose Attenuation Factors for 8-MeV Gamma Rays Normally Incident on Lead

Lead Thickness (g/cm²)	Monte Carlo[a] without Brems	Monte Carlo[b] with Brems	Experiment[c]
29.2	0.31 (1.1)[d]	0.37 (2.7)[d]	0.38 (2.5)[d]
58.3	0.099 (2.0)	0.12 (4.6)	0.13 (3.4)
87.5	0.029 (3.5)	0.037 (7.9)	0.040 (4.9)
116.5	0.0090 (6.0)	0.012 (14)	0.013 (7.3)
145.8	0.0026 (10)	0.0031 (25)	0.0040 (11.2)

[a]Results from MONTELEC without including bremsstrahlung production.

[b]Results from MONTELEC including electron transport and bremsstrahlung.

[c]Experimental measurements from the University of Virginia (for 8.2-MeV average gamma-ray energy)

[d]Numbers in parentheses are percent fractional standard deviations.

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7. A Directional-Biasing Solution for Radiation Transport, *A. A. Harms, W. J. Garland (McMaster Univ)*

The transport of radiation in cases of deep penetration and streaming requires particular emphasis on the directional ranges that contain the dominant radiations. The practical importance of these directional considerations has motivated the development of specialized calculational innovations.[1,2]

It is possible to introduce a directional flexibility into the framework of polynomial approximation which can readily be used to emphasize a desired directional detail and lead to more accurate results even in a low-order approximation. Such a formalism is described herein.

We consider, as one application, the asymptotic spatial moment in plane geometry

$$\phi_{as}(x) = \phi_0 \exp(-\kappa_0 x), \qquad (1)$$

and propose to evaluate the asymptotic decay constant κ_0 in accordance with a chosen directional bias which will lead to most accurate results. To accomplish this, we define an N'th-order segmentation of the cosine of the scattering angle, μ, by the following ordered partition of the range $\{-1, +1\}$:

$$\{-1, \mu_1, \mu_2, \ldots, \mu_n, \ldots, \mu_{N-1}, +1\}. \qquad (2)$$

Since these partitions are arbitrary, they may accordingly be optimally chosen to emphasize the directional detail as necessary.

The appropriately biased asymptotic decay constant κ_0 is found by expanding the directional moments over each of the N angular intervals using a modified Legendre polynomial representation which we define as

$$P_{n,l}(u) = P_l \frac{2\mu-\mu_n-\mu_{n-1}}{\mu_n-\mu_{n-1}} \quad , \mu_{n-1} < \mu < \mu_n . \tag{3}$$

The appropriate properties of orthogonality, integrability, and recurrence of these functions for the one-speed case have recently been demonstrated[3]; hence, the substitution of these polynomials into the transport equation and the subsequent algebraic operations lead to an eigenvalue condition for the determination of κ_0.

With the asymptotic decay constant κ_0 thus specified, we have analytically and computationally studied the effect of angular segmentation on various radiation transport parameters. One such result is shown in Table I. Here we have evaluated the asymptotic decay constant, κ_0, in Eq. (1) and compared it[4] to κ_{exact}. Both a systematic and random search was undertaken to find an optimum angular segmentation with respect to the calculation of κ_0.

TABLE I

Evaluation of Asymptotic Decay Constant κ_0 Using Modified Legendre Polynomials for L = 1; N = 2,3,4,5; c = 0.3; κ_{exact} = 0.99741

N	$\{-1, \mu_1, \ldots, \mu_n, \ldots, \mu_{\mu 1}, +1\}$	κ_0	% Error
2	{-1, 0, +1}	1.1493	15.2
	{-1, ±0.86, +1} †	1.0106	1.32
3	{-1, 0, ±0.99, +1}*	1.0000	0.27
	{-1, -0.36, +0.55, +1} †	0.99993	0.26
4	{-1, 0, +0.70, +0.99, +1}*	1.0000	0.27
	{-1, -0.01, +0.48, +0.98, +1} †	0.99993	0.26
5	{-1, μ_a, 0, +0.70, +0.99, +1}*	1.0000	0.27
	{-1, -0.97, -0.72, -0.39, +0.52, +1} †	0.99987	0.25

†: Optimum angular segmentation based on a random search of 100 sets.

*: Optimum angular segmentation based on knowledge of N-1 order of approximation.

μ_a: Calculation of κ_0 is insensitive to variations in μ_a.

Several conclusions have emerged from the use of the modified Legendre polynomials, Eq. (3): (a) some radiation transport parameters can be evaluated with very high accuracy even in a low-order approximation; (b) optimum angular segmentations are generally nonsymmetric about $\mu = 0$; (c) numerical accuracy for some transport parameters increases significantly with increasing radiation absorption and, in this domain, may yield more accurate results than are attainable using P_L and S_N theory of comparable algebraic complexity.

Calculations have been undertaken for various transport parameters and comparisons with other solution formalism made where possible.

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8. Experimental Study of Basement Ceiling Attenuation Factors, *R. S. Reynolds (Miss State Univ)*

Eisenhauer developed the Standard Method[1] from Spencer's data.[2] Several evaluations[3-8] have shown that the Standard Method predicts structure fallout protection quite well for above-grade locations. The principal weakness occurs in the prediction of basement protection. Several studies have been undertaken to determine the origin of the weakness,[9-14] the consensus being that the ceiling barrier factor, $B_0'(X_0')$, was improperly formulated.

This work was undertaken to measure the ceiling attenuation factor as a function of ceiling mass thickness and solid angle fraction, ω, and compare the results with experimental and empirical formulations previously developed.[9,10,12] The test structure and fallout simulation technique has been previously described.[7]

The experiments were to yield data to determine the ceiling attenuation factor, $B_c(X_c,\omega)$, for a mass thickness of 12 psf as a function of ω, and as a function of X_c for ω near unity. In the first series, ω varied between 0.72 and 0.96; in the second series, X_c varied between 0 and 81 psf.

Equations (1) and (2) represent the expressions used in the Standard Method to calculate the ground contribution reduction factor in a basement. Equation (2) is for a 0-psf basement ceiling.

$$R_f = B_c(X_c,\omega)B_e(X_e,3')G_g(\omega,\omega',X_e) + A_a(\omega')B_c(X_c+X_r,\omega) \tag{1}$$

$$R_f' = B_e(X_e,3')G_g(\omega,\omega',X_e) + A_a(\omega')B_c(X_r,\omega) . \tag{2}$$

The notation is that of the Standard Method, where X_e and X_r are the exterior wall and first-story mass thicknesses, respectively. The last term in both equations represents the skyshine contribution. If skyshine is removed, the ratio of R_f to R_f' yields $B_c(X_c,\omega)$. Experimentally, the superposition technique is used to measure the reduction factors and $B_c(X_c,\omega)$ may be represented as

$$B_c(X_c,\omega) = \frac{\sum_{i=1}^{n} R_i(X_c,\omega) + R_F(X_c,\omega)}{\sum_{i=1}^{n} R_i(0,\omega) + R_F(0,\omega)} \quad , \tag{3}$$

which assumes skyshine is not present. $R_F(X_c,\omega)$ is the far-field contribution for a given X_c and ω.

The far-field contribution may be determined experimentally[15] or mathematically using the finite field data.[16] A useful model is

$$R_F(X_c,\omega) = \alpha_D(X_c,\omega)D_F + \alpha_S(X_c,\omega)S_f \quad , \tag{4}$$

where α_D and α_S are direct and skyshine structure attenuation coefficients estimated from the finite field data. D_F and S_F are the corresponding free-field exposures for the