Monte Carlo Based Formula for Radiation Shielding Assessment in the Forward Direction

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Abstract

Monte Carlo simulations of 800-MeV proton beam spills in common shielding materials show that neutron dose equivalent rates in the forward direction can be characterized by a Moyer Model-like formula[1,2]. Particle transport codes were used to determine the neutron flux at depths up to 6 meters and for production angles from 0° to 30° for primary proton beam spills on cylindrical beam stops. The flux was then converted to dose equivalent rate as a function of depth and angle. The results for three common shielding materials were combined and the resulting fitted formula provides a quick method for estimating the dose equivalent rates and shielding effectiveness outside thick shielding at forward angles.

I. INTRODUCTION

The assessment of radiation shielding for the beam lines and experimental areas at the Los Alamos Meson Physics Facility (LAMPF) required a quick and simple method of estimating neutron dose equivalent rates for 800-MeV proton beam spills in the forward direction. Although some work has been done on simple formulas for forward production at energies above a few GeV[3], no useful formula exists at the intermediate energies found at LAMPF. Since the Moyer Model formula worked well for us for calculations in the transverse direction, it was our hope that we could fit a similar, simple formula to Monte Carlo results for dose equivalent rates in the forward direction.

II. MONTE CARLO SIMULATION

A. Particle Transport Codes and Computer

The particle transport codes LAHET[4] and MCNP[5] were used to simulate particle histories resulting from the interaction of a monochromatic 800-MeV proton beam in three common shielding materials: concrete, natural iron, and magnetite concrete. LAHET was used to create and track histories for protons above 1 MeV and neutrons above 20 MeV, while MCNP was used to track neutrons below 20 MeV and photons. No variance reduction techniques were used in the simulations. The simulations were run on an HP-730 workstation, which has been shown to be approximately equivalent in speed to a CRAY Y-MP in benchmark tests for these codes.

B. Simulation Geometry and Data Records

The Monte Carlo geometry simulated proton beam spills on three cylindrical beam stops made of the individual shielding materials. The beam-spill point was taken to be the center of the end face of each beam stop, with the incident beam parallel to the axis of the cylinder. See Figure 1. For each of the shielding materials, the particle fluxes $\phi(E, \theta, r)$ as a function of energy E, production angle θ, and material depth r were recorded on several surfaces bisecting the cylinder normal to the incident beam direction. Each surface was divided into seven concentric annuli subtending production angles $\theta \pm 2.5°$, where $\theta = 0°, 5°, 10°, 15°, 20°, 25°$, or $30°$. The distance r was measured from the spill point to the midpoint of each annular ring, and θ was the production angle as measured from the incident beam direction. Dose equivalent rates DER(θ, r) were obtained by multiplying the flux by the energy-dependent ICRP[6] conversion factors and summing over energy for each θ and r.

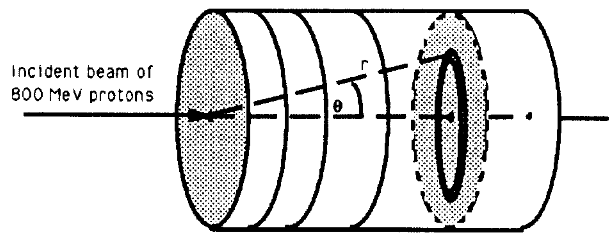

Figure 1. Cylindrical beam stop geometry used for Monte Carlo simulations. The spill point is the center of the incident face. Particle flux as a function of energy, production angle θ, and distance r from the spill point was recorded over annular areas on surfaces at several depths.

C. Removal of Backscatter and Minimal Contributions

Contributions to the total dose equivalent rate DER(θ, r) from photons were on the order of a few percent or less and were therefore ignored. Protons, however, contributed a substantial fraction to the calculated dose equivalent rate up to depths of several meters. By the time the DER had reached acceptable biological occupation levels, however, contributions by protons were a few percent and were ignored for the purposes of this study. Only neutron fluxes were used in the fit.

We were interested in the neutron dose equivalent rate outside the shielding. The neutron flux inside the cylinders, however, included contributions from internally back-scattered neutrons. This internal backscattering component must first be removed before using the results from inside the cylinder. To do this, several additional Monte Carlo runs were performed with truncated cylinders whose end faces corresponded to the positions of some of the internal faces. A comparison of internal- and end-surface DER's allowed an estimate of the backscattered contributions to be made. For the three materials discussed here, the fraction of backscattered contributions for each material was essentially constant for all angles and all surfaces tested. Correction factors of 0.70 for concrete, 0.68 for magnetite concrete, and

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0.40 for iron were applied to the dose equivalent rates for internal surfaces so that the fitted values would be accurate for calculations outside shielding.

III. SELECTION OF DATA SAMPLE

It was our intent to obtain adequate statistical samples in each material to depths of at least 7 radiation attenuation lengths, approximately the shielding thickness needed for our worst-case spills. A sufficient number of source protons, several million in the cases of both concrete and magnetite concrete, were started such that the final average statistical errors for the flux bins $\phi(E, \theta, r)$ up to depths of $r \cong 9\lambda$ were ~11%. If the data at $\theta=0^o$ (the annulus with the smallest sampling area) were excluded, the average statistical errors on the fluxes were ~6%. The iron data presented a slightly different picture: the average statistical error on the flux bins for depths up to 6λ was 19%. This number was influenced by a few bins at wide angles and large depths, as indicated by the fact that 90% of the flux was contained in bins with statistical errors of 5% or less. Slightly more than a million source protons were required to obtain this accuracy in iron. For the purposes of developing a simple formula for dose equivalent rates outside the shielding, we excluded data within two attenuation lengths of the spill point to get past the build-up of particles and into an equilibrium region that could be fitted simply. The data included in the fit are given in Table 1.

Table 1.
Input data for the weighted MINUIT fit of Monte Carlo dose equivalent rates and the parameters of the fit. Data for all angles between 0^o and 30^o were included. Numbers in parentheses give the depth in terms of attenuation lengths, λ.

Input Data to the Monte Carlo		
Material	**Density** gm/cm^3	**Depth** meters
Concrete	2.42	1.5 - 5.0 (2.6 -8.6)λ
Iron	7.87	0.70 - 2.0 (2.0 - 5.7)λ
Magnetite Concrete	3.64	1.0 - 4.0 (2.3 - 9.3)λ

IV. RESULTS OF A WEIGHTED FIT TO MOYER MODEL FORMULA

The dose equivalent rates DER(θ, r) and statistical errors for the three materials, at all angles and at the depths listed in Table 1, were used to perform a global, weighted fit to a Moyer-type formula of the form

$$D = \frac{H_o}{r^2}\exp(-\beta\theta)\exp(-\frac{r}{\lambda}).$$

Here D(rem/hr-nA) is the neutron dose equivalent rate, H_o(rem-m^2/hr-nA) is the source term, r(m) is the distance from spill to observation point, β(rad^{-1}) is the angular relaxation parameter, θ(rad) is the production angle between the incident beam direction and the ray from spill to observation point, and λ(m) is the attenuation length for a material. The fitted parameters H_o, β, and the individual λ's for concrete, iron, and magnetite concrete are given in Table 2.

Table 2.
Fitted parameters from a MINUIT fit to a Moyer-type formula. Units are rem-m^2/hr-nA for the source term H_o. Numbers in parentheses give the radiation attenuation lengths in gm/cm^2.

H_o	β	λ_{conc}	λ_{iron}	λ_{magn}
856	2.14 rad-1	0.58 m (140.4)	0.35 m (275.5)	0.43 m (156.5)

The fitted values were insensitive to the inclusion of Monte Carlo data at greater depths than those listed in Table 1. When the fit was expanded to include additional data for depths up to 6 m in concrete, 3 m in iron, and 5 m in magnetite concrete, there was no significant change in the fit parameters, although the relative errors for the parameters increased several percent. The plots in Figures 2-4 show the Monte Carlo results at all depths, but the line representing the fit only includes the data listed in Table 1. It can be seen that the calculated values using the formula are still a good fit to the data at the greatest depths, but not for data in the build-up region at depths less than 2λ.

It should be noted that the fitted attenuation length λ=0.35 m for iron for forward-production angles is significantly longer than the value of 0.21 m normally quoted for use in the transverse Moyer Model. This is because the forward formula is fit to data that explicitly includes low energy neutrons. When neutrons with energy below 20 MeV are excluded from the forward fit to iron, an attenuation length of 0.21 m is obtained. This inclusion of the low energy data in the forward parameters and formula removes the need for the addition of hydrogenous material to obtain the calculated iron dose equivalent rate normally advised in the transverse case .

V. SUMMARY

A Moyer Model-like function provides a very good fit to the Monte Carlo results for neutron dose equivalent rates in the forward direction for beam spills by a monochromatic 800-MeV proton beam. This function can be used to estimate neutron dose equivalent rates outside radiation shielding in simple geometries where the contributions from indirect sources such as skyshine and backscattering from nearby structures are not significant. A comparison of estimated dose equivalent rates from the formula and measured values for beams spills at LAMPF[7] shows that the formula gives a useful estimate of the neutron dose equivalent rate in cases with minimal indirect contributions.

VI. REFERENCES

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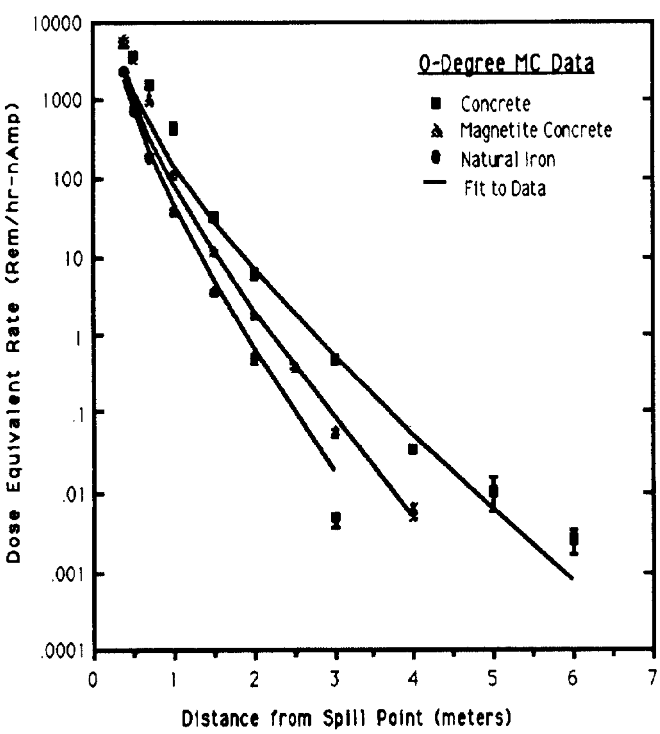

Figure 2. Comparison of Monte Carlo data and the fit to a Moyer-like formula for neutron dose equivalent rates at a production angle of 0 degrees.

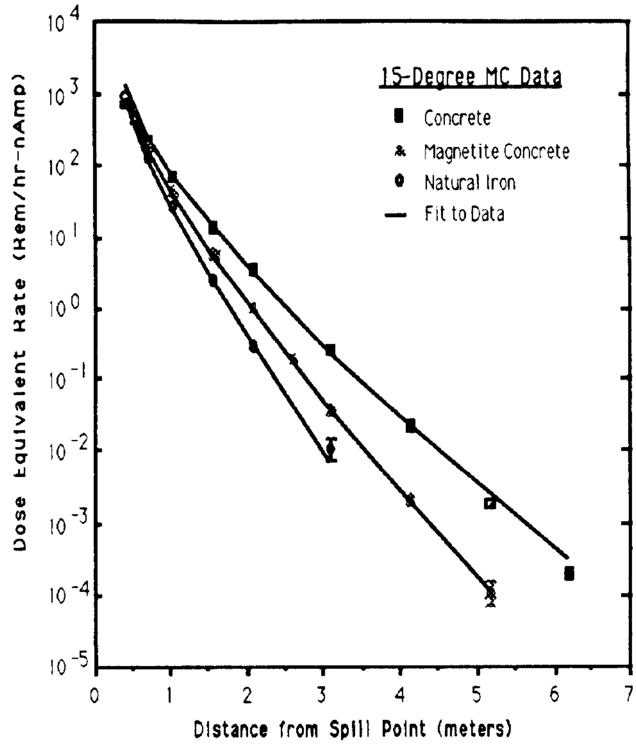

Figure 3. Comparison of Monte Carlo data and the fit to a Moyer-like formula for neutron dose equivalent rates at a production angle of 15 degrees.

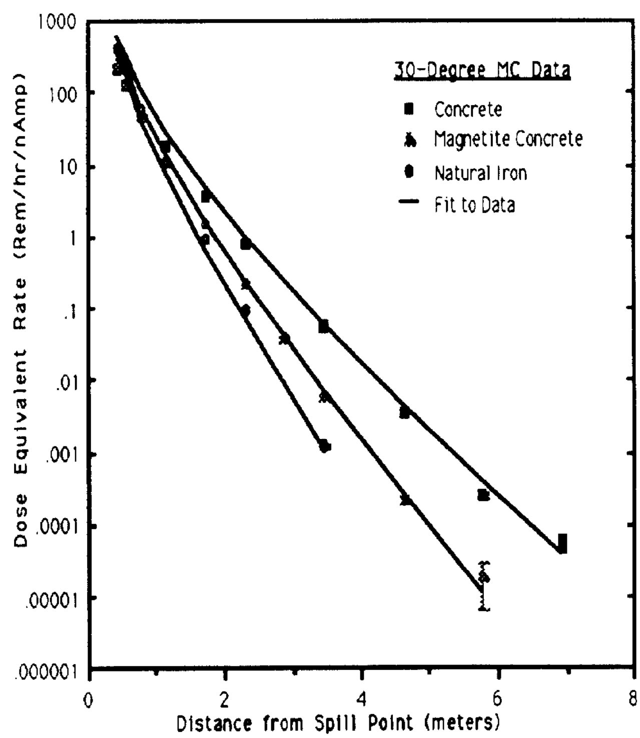

Figure 4. Comparison of Monte Carlo data and fit to Moyer-like formula for neutron dose equivalent rates at a production angle of 30 degrees.