Parameterizations for Shielding Electron Accelerators Based on the Results of Monte Carlo Studies*

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Introduction

Numerous recipes for designing lateral slab neutron shielding for electron accelerators are available and each generally produces rather similar results for shield thicknesses of about 2 m of concrete and for electron beams with energy in the 1 to 10 GeV region (Tesch 1988 reviews many such recipes). For thinner or much thicker shielding the results tend to diverge and the standard recipes require modification. Likewise for geometries other than lateral to the beam direction further corrections are required so that calculated results are less reliable and hence additional and costly conservatism is needed. With the adoption of Monte Carlo (MC) methods of transporting particles a much more powerful way of calculating radiation dose rates outside shielding becomes available. This method is not constrained by geometry, although deep penetration problems need special statistical treatment, and is an excellent approach to solving any radiation transport problem providing the method has been properly checked against measurements and is free from the well known errors common to such computer methods. However, for electron beams MC methods have presented problems in the provision of an event generator for source neutron angular energy spectra. Such codes as PICA at the lower energies and the VMD models at very high electron energies have been very useful but there has not been an event generator for all electron beam energies from a few tens of MeV up to ten's of GeV (Gabriel et al. 1969, Ranft et al. 1987). Recent work by Degtyarenko shows considerable promise in remedying this deficiency (Degtyarenko 1995). Degtyarenko and colleagues have produced an event generator based on a nuclear fragmentation model DINREG, which correlates

* Work supported by the U.S. Department of Energy under contract number DE-AC05-84ER40150.
† The Thomas Jefferson National Accelerator Facility (previously the Continuous Electron Beam Accelerator Facility - CEBAF) is informally called the Jefferson Laboratory (JLab). The existing accelerator facility at JLab is still referred to as CEBAF.

well with the sparse experimental data - a review of the development of DINREG and its use in radiation protection studies can also be found in (Degtyarenko 1995). However, the authors wish to caution that until the model has been thoroughly verified with experimental data, the results of this exercise must remain tentative. An appropriate experimental proposal for verifying the model is discussed by Degtyarenko (Degtyarenko 1997). This present paper utilizes the results of MC calculations based on DINREG using the Monte Carlo transport code GEANT (GEANT 1994) and models them with the normal two parameter shielding expressions. Because the parameters can change with electron beam energy, angle to the electron beam direction and target material, the parameters are expressed as functions of some of these variables to provide a universal equation for shielding electron beams which can be used rather simply for deep penetration problems in simple geometry without the time consuming computations needed in the original MC programs. A particular problem with using simple parameterizations based on the uncollided flux is that approximations based on spherical geometry might not apply to the more common cylindrical cases used for accelerator shielding. This source of error has been discussed at length by Stevenson and others (Stevenson et al 1982 and Stevenson 1995). To study this source of error, a run in both spherical and cylindrical geometry were compared.

Analytical Shielding Expressions

The most commonly used expression for shield calculation assumes an exponential removal process resulting in a constant "relaxation length" (Chilton et al 1984).

To accommodate the change in properties of the neutron cascade from the thin shielding situation to the thick shield, the exponential shielding equation is generally decomposed into two or three parts. For this study we have found that for most purposes a two part expression is adequate and which takes the form:

$$H_p = \frac{H_l exp(-t/\lambda_l) + H_h exp(-t/\lambda_h)}{(d+t)^2}$$

where	H_p	is the dose equivalent at point P outside
	t	thickness of shielding at distance

d	from a point source
H_l and H_h	are the low and high energy source terms and
λ_l and λ_h	are the low and high energy relaxation lengths

If we assume that (d+t) = 1 then the equation simplifies to just the numerator:

$$H_p = H_l exp(-t / \lambda_l) + H_h exp(-t / \lambda_h) \quad (1)$$

Because we would only use equation (1) to solve a shielding problem for a given electron beam energy, the variation of the shielding constants with beam energy do not need to be included in the equation as a continuous function, neither do we need to include target or shield material in such a way. However, there are many ways in which the angular production is needed such as for the line source calculation. Expressions of angular dependency have already been published, notably those of Moyer (the utility of Moyer's method is discussed by Routti et al 1969 and McCaslin et al 1987), Jenkins and DeStaebler (Jenkins 1979, DeStaebler et al 1962). Both formulations apply the angular dependence to the source terms. Moyer's expression is applied to the neutron radiation produced by proton accelerators. Jenkins and DeStaebler's expressions apply to electron machines and their full shielding expressions have been coded for computer running by Nelson 1994.

Monte Carlo Techniques

The MC transport code utilized is GEANT (GEANT 1994, Zeitnitz et al. 1995) coupled to the event generator DINREG (Degtyarenko 1995). For the deep penetration aspects a process was adopted whereby particles with favorable direction cosines would be amplified to give some factor of 100 increase in sensitivity and also the production cross section was also increased (without perturbing the e,γ shower) to improve the probability of events per incident electron. The results were presented as a matrix with 5 energies, 7 concrete thicknesses plus zero, at 9 production angle intervals. The dose equivalent was determined from the neutrons per unit area crossing the shield surface boundary divided by their direction cosine to the normal to the surface. The resultant fluence was converted to dose equivalent by using the conversion coefficients given in US DOE 1993. Simple spherical and a cylindrical shell geometries were

modeled. The set of runs used a long (l = 25 cm, ϕ = 5 cm) cylindrical copper target and shielding made of standard concrete with density ρ = 2.35 g cm^{-3}; this was considered representative of many practical design requirements.

Fitting Equations

We found that a reasonable approximation to the MC data can be obtained with an expression of the form given in equation (1), assuming that the low energy term is isotropic and the angular dependence enters only into the high energy term:

$$H_l(\theta) = a_l;\ \lambda_l(\theta) = \lambda_l;\ H_h(\theta) = a_2 \exp(c_1 \cos\theta);\ \lambda_h(\theta) = \lambda_2 / (1 - c_2 \cos\theta - c_3 \cos^2\theta). \qquad (2)$$

Thus, we used 7 parameters to fit the dose dependence on t and θ: $a_{1,2}$ and $\lambda_{1,2}$ parameters determine the low and high energy source terms and relaxation lengths at 90 degrees, and $c_{1,2,3}$ control the angular dependence. The fitting parameters were obtained using the minimization routine MINUIT (MINUIT 1993), within the CERN data analysis and presentation package PAW (PAW 1995). An example of the data and the 7-parameter fit is shown in figure 1 for $E_0 = 0.5$ GeV. The results of dose calculations at different wall thicknesses are shown using different symbols, with the lines representing the fitting function. The statistical errors (one standard deviation) on the MC calculation larger than the size of the marker symbol are shown as error bars. The points calculated at zero wall thickness, and also at the very forward direction interval ($0.9 < \cos\theta < 1$) were not used in the fitting procedure because of the influence of neutron absorption and rescattering in the model target. The results are set out in table 1.

Table 1. Fitting Constants for Parameterization (2)

E_0	0.2	0.5	1.0	4.0	8.0	GeV
a_1	18.92(58)[a]	19.96(74)	19.5(1.2)	23.1(1.1)	20.7(1.2)	Sv [kWh]$^{-1}$ m^2
λ_1	32.09(39)	32.61(62)	33.2(1.2)	31.71(81)	33.2(1.1)	g cm^{-2}
a_2	0.31(2)	0.80(5)	1.24(13)	1.32(7)	1.35(10)	Sv [kWh]$^{-1}$ m^2
λ_2	86.5(1.0)	96.0(1.2)	96.9(2.2)	104.8(1.4)	105.1(1.9)	g cm^{-2}
c_1	0.43(13)	0.48(5)	0.37(9)	0.50(6)	0.50(7)	-
c_2	0.095(22)	0.094(10)	0.129(16)	0.133(11)	0.142(14)	-
c_3	0.004(9)	0.031(6)	0.051(9)	0.026(7)	0.026(9)	-

(a) The figures in parentheses give 1-standard-deviation uncertainties in the last digits of the main numbers

The extrapolation of the fitting function into these regions is shown by the dashed parts of the

curves. The statistical quality of the fits at 5 different energies was good: χ^2 from 2.2 to 2.9 per number of degrees of freedom. The energy dependence of the parameters is shown in figure 2. It is worth noticing that the parameters of the isotropic low energy term a_1 and λ_1 show no dependence on the beam energy. Qualitatively this observation indicates that the low energy term in the neutron dose is determined by the abundant low energy photon yield in the thick target electromagnetic cascade, which scales with the beam power. The c_1 parameter also shows no significant E_0-dependence. Another feature is that the parameters a_2, λ_2, c_2, c_3 show the effect of a slow trend to a constant value with increasing beam energy. This means that at beam energies of the order of 10 GeV and above, the dose is likely to scale with the beam power. We found that the behavior of the high energy term may be approximated by using the variable:
$z = 1 - \exp[-\ln(E_0 / E_m) / C]$, where E_m is a parameter determining the energy at which the high energy contribution begins to become significant, and C is a parameter. In terms of this variable, the energy dependence of the parameters a_2, λ_2, c_2, c_3 can be expressed as:

$$a_2(E_0) = A_{a2}z;\ \lambda_2(E_0) = B_{\lambda 2} + (A_{\lambda 2} - B_{\lambda 2})z;\ c_2(E_0) = B_{c2} + (A_{c2} - B_{c2})z;\ c_3(E_0) = A_{c3}z \quad (3)$$

The 11-parameter fit of the whole data set was performed and the results are shown in table 2. The agreement between the data points and the fitting function is still good: $\chi^2 / NDF = 2.55$.

Table 2 Fitting Constants for Parameterization (3)

parameter	value	units
a_1	21.43 ±0.35	Sv [kWh]$^{-1}$ m^2
λ_1	31.73 ±0.22	g cm^{-2}
A_{a2}	1.64 ±0.03	Sv [kWh]$^{-1}$ m^2
$A_{\lambda 2}$	105.33 ±0.50	g cm^{-2}
$B_{\lambda 2}$	83.28 ±1.10	g cm^{-2}
E_m	0.144 ±0.002	GeV
C	1.674 ±0.042	
c_1	0.470 ±0.023	
A_{c2}	0.146 ±0.006	
B_{c2}	0.059 ±0.006	
A_{c3}	0.047 ±0.004	

The comparison is illustrated in figures 3, 4, and 5. In figure 3 the neutron dose equivalent is

shown as a function of the wall thickness in g cm^{-2} for 5 different beam energies at 90 degrees. Points shown are calculations and lines represent the fitting function. Figures 4 and 5 show the angular dose dependence.

Application to Cylindrical Shielding

Figure 6 shows the parameterizations applied to a cylindrical shielding configuration together with the results from MC calculations. Differences between the results for the spherical and cylindrical cases using the same thickness of shielding (the shield thickness along the radius vector are the same for the cylinder and sphere) do not seem to be significant for thin shielding at any production angle. However, when the shield thickness increase to 2 - 3 m then the differences become quite marked as suggested by Stevenson.

Comparisons With Other Shielding Recipes

Energy and angular corrections were derived for H_p in other recipes - notably Jenkins (1979) (SHIELD-11). Below a few GeV, energy correction were provided by Sullivan (1981) who used the measurements of von Eyss et al (1973). Angular corrections have already been discussed above. It is observed that for beam energies greater than 0.5 GeV and forward production angles the SHIELD-11 results compare very well with the parameterization but for lateral and backward angles and at low electron beam energies, the SHIELD-11 results are a factor 2 to 3 lower. Examples of calculations using SHIELD-11 and the present parameterization are presented in figure 7.

Conclusions

It must be clearly understood that this exercise can only be regarded as preliminary until the event generator DINREG has been properly validated by comparison with experimental measurements. Comparisons with earlier published measurements indicates that the event generator shows considerable promise in reproducing angular energy hadron production cross sections (von Eyss et al 1973, Bathow et al. 1967, Alanakyan 1981). However, the form of the parameterizations should be valid and, with to minor corrections, should make the basis of a useful and simple general shielding expression for electron accelerators.

Acknowledgments

The authors wish to acknowledge the help and support of Bob May and also Scott Schwahn who kindly provided help with generating the current SHIELD-11 data presented in this paper.

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Figure 1 Examples of Results Using the 7 Parameter Fit

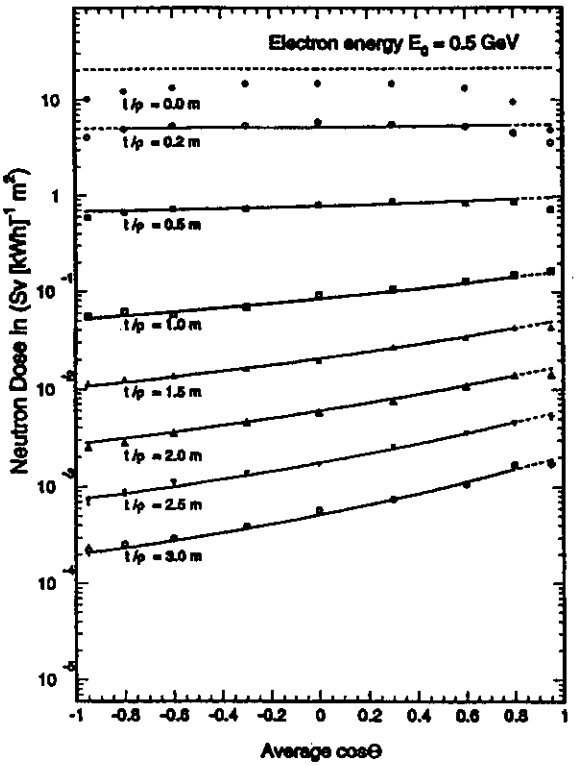

Figure 2 Energy Dependence of Fitting Parameters

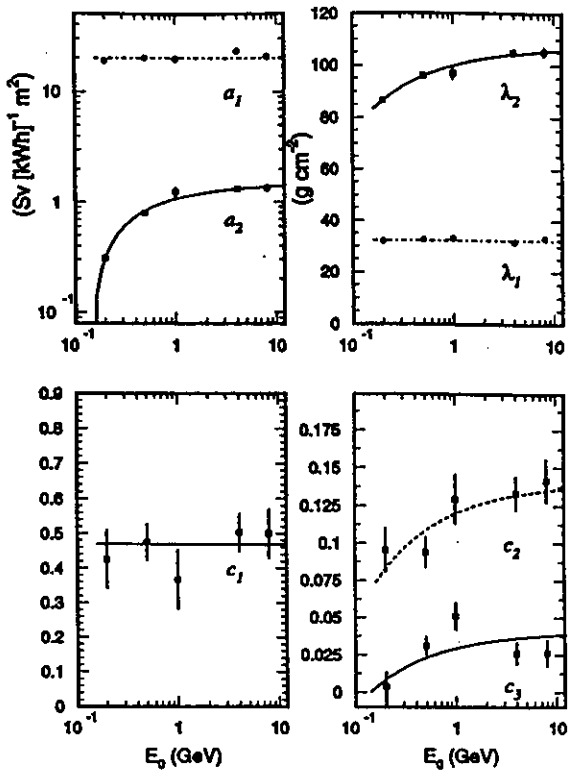

Figure 3 Shielding Curves Generated Using the 11 Parameter Fit with MC Data Points

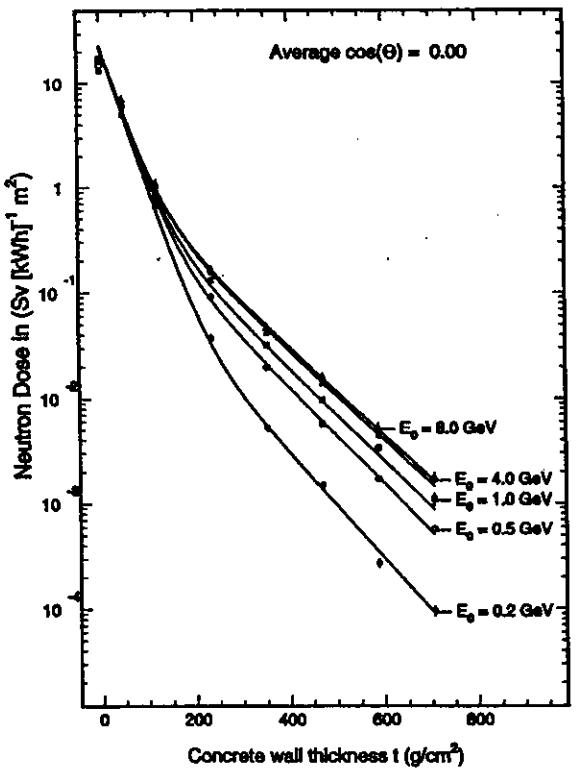

Figure 4 Angular Dose Dependence Using 11 Parameter Fit at 0.2 GeV

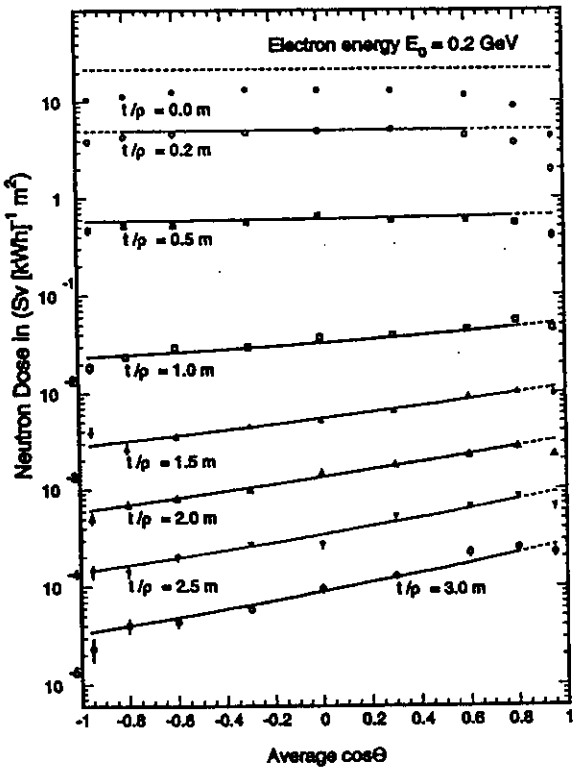

Figure 5 Angular Dose Dependence Using 11 Parameter Fit at 4.0 GeV

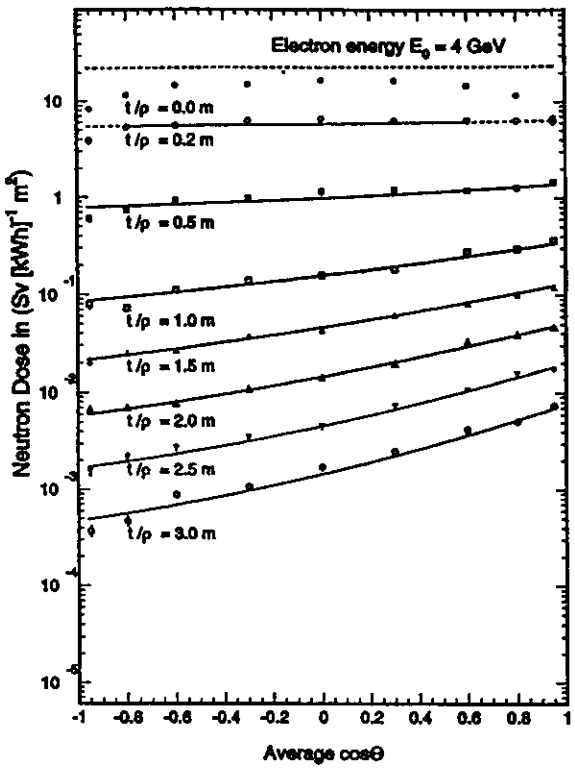

Figure 6 Angular Dependence for the Cylindrical Case

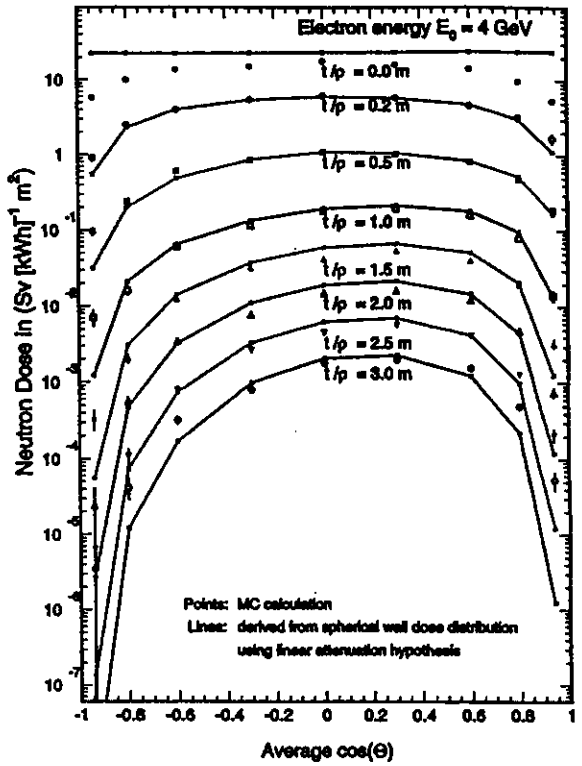
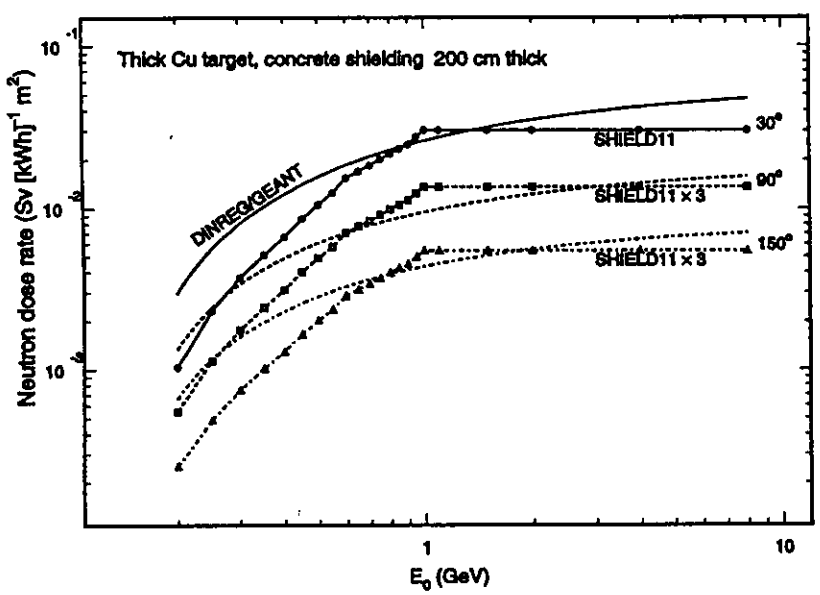
Figure 7 Comparison with SHIELD-11 Code Calculations