Particle Accelerators, 1994, Vol. 44(1), pp. 1–15
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ACCELERATOR SKYSHINE: TYGER, TYGER, BURNING BRIGHT

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(Received 5 July 1993; in final form 30 July 1993)

"Tyger! Tyger! burning bright
In the forests of the night,
What immortal hand or eye
Could frame thy fearful symmetry?"

From "The Tyger," *Songs of Experience*
William Blake, 1757–1827

Neutron skyshine is, in most cases, the dominant source of radiation exposure to the general public from operation of well-shielded high-energy accelerators. To estimate this exposure, tabulated solutions of the transport of neutrons through the air are frequently used. In previous works on skyshine, these tabular data have been parameterized into simple empirical equations that are easy and fast to use but are limited to distances greater than a few hundred meters from the accelerator. Our current report refines this earlier work by including more-realistic assumptions of neutron differential energy spectrum and angular distribution. These improved calculations essentially endorse the earlier parameterizations but make possible reasonably accurate dose estimates much closer to the skyshine source than before.

KEY WORDS: Radiation, Shielding

1 INTRODUCTION

Some fifteen years ago, Rindi and Thomas[1] ended their review of particle accelerator skyshine by saying:

> When unexpectedly high radiation levels were observed around the early synchrocyclotrons and proton synchrotrons, it seemed that a "tiger" had been loosed on the world. Early theoretical studies identified the tiger as skyshine, but the experimental data obtained in the fifties were not sufficiently accurate to confirm this

> suggestion. The addition of roof shielding to accelerators was sufficient to substantially reduce radiation levels and seemed to make the tiger disappear into the jungle. It was not clear whether the tiger had teeth or whether he was a paper tiger. However, the "beaters" of the USAEC and EPA have been at work, and the tiger has reemerged. Let us hope he may soon be safely placed in his cage.

Experience has shown us that indeed the "tiger" has reemerged; increasing public concern over ionizing radiation exposure has led to increasing control over radiation levels at the boundaries of nuclear facilities. In the wake of this trend, and following the general reduction of equivalent doses for permissible radiological protection standards, the U.S. Department of Energy (DOE) has recently revised its action level to 100 μSv per year, and new accelerators now being planned or constructed with design goals for site boundary levels at 100 μSv per year are now reconsidering their criteria.[2]

2 PREVIOUS WORK

In their earlier review, Rindi and Thomas summarized experimental and theoretical studies of neutron transport through the air at distances up to about 1000 m from high-energy particle accelerators.[1] They were able to qualitatively explain experimental observations in terms of the neutron spectrum emerging into the air from the roof of the accelerator and suggested an expression of the form

$$\phi(r) = \frac{aQ}{4\pi r^2} \exp\left(\frac{-r}{\lambda}\right) , \tag{1}$$

where $\phi(r)$ is the neutron fluence at distance r, Q is the neutron source strength, and a and λ are constants to be determined empirically.

In practice, Rindi and Thomas found that λ varied between 250 and 850 m. The lower value of λ corresponds to those conditions where low-energy (evaporation or giant-resonance) neutrons dominate the shield leakage spectra, and the higher value is more appropriate when the high-energy cascade is in equilibrium in the air.

Stevenson and Thomas[3] extended this work by combining the experimental work described by Rindi and Thomas with "Importance Functions" calculated by Alsmiller *et al.*[4]

2.1 *Importance Functions*

Solutions or Importance Functions for neutron and photon skyshine have been calculated by Alsmiller *et al.*[4] and are available in tabular form. All of the calculations were carried out with the two-dimensional, discrete-ordinates code DOT[5] and the first-collision source code GRTUNCL.[6] The differential particle-production cross sections used in the calculations were taken from Alsmiller *et al.*[4] The restriction of consideration to neutron energies of less than or equal to 400 MeV arises because,

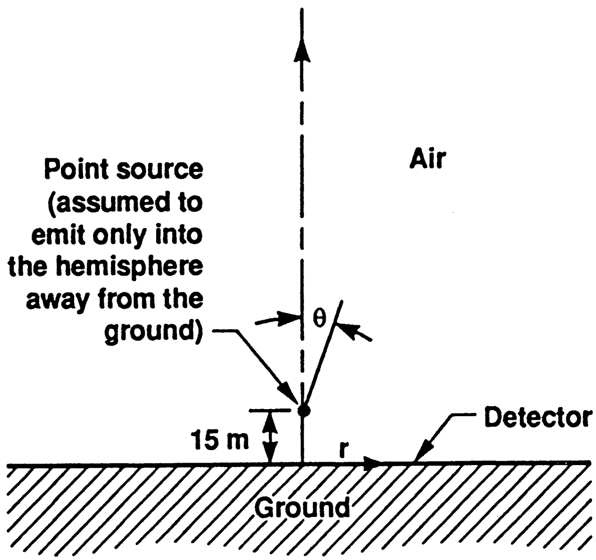

FIGURE 1: Geometry for which Importance Functions are calculated (after Alsmiller *et al.*[4]).

at higher energies, pion production becomes significant. This limit on energy range is sufficient, however, for most applications, even around very-high-energy accelerators.[4,7,8] The neutron and photon flux densities were converted to equivalent dose rates using the data given by the National Council on Radiation Protection and Measurements (NCRP)[9] and Claiborne and Trubey.[10]

"Importance" in the context of skyshine is defined to be the equivalent dose per unit source particle and is calculated as a function of the particle energy, distance from the source, and semivertical angle of the cone into which source particles are emitted. Importance Functions as calculated by Alsmiller *et al.*[4] are defined by the following equation:

$$H(\bar{r}) = \int S(E,\, \cos\theta)\, I(E,\, \cos\theta,\, \bar{r})\, dE\, d\theta\ , \tag{2}$$

where $H(\bar{r})$ is the equivalent dose at average radial distance $\bar{r}$; $S(E,\, \cos\theta)$ is the number of source particles per unit solid angle at energy E and polar angle θ (source is assumed to be independent of azimuthal angle); and $I(E,\, \cos\theta,\, \bar{r})$ is the importance of particles at energy E and polar angle θ at average radial distance $\bar{r}$. Figure 1 shows the geometry for Equation (2). Equation (2) gives the equivalent dose at the air-ground interface; in the case of neutrons, the equivalent dose includes the contribution from photons produced by neutron interactions.

The use of these Importance Functions is extremely convenient, reducing the problems of determining skyshine equivalent dose to trivial proportions provided the source term, composed of energy, angular, and spatial distribution of particle fluence over the accelerator roof, is known.

Importance Functions have been calculated for only a limited range of parameters because their calculation requires a great deal of computer time. For neutrons, Importance Functions have been tabulated for 4 average radial distances, 5 angular ranges (as equal cosine intervals, which are directly proportional to solid angles of emission), and 63 neutron energy groups lying within the range of 10^{-10} to 4×10^2 MeV. In the case of photons, Importance Functions have been calculated for the same distances and angular ranges but for 21 energy groups lying in the energy between 0.1 and 14 MeV.

In this paper, we are concerned only with the neutron Importance Functions because at most high-energy accelerators, neutrons dominate radiation fields outside thick shielding. While the Importance Functions are convenient, their use is limited because they have been calculated only for a limited range of parameters. It is necessary to calculate equivalent dose for accelerator shield spectra from many roof geometries and for a wide range of energies and distances, and it is therefore helpful to have a simple analytical technique for interpolation between the tabulated importance function data and even for extrapolation to higher neutron energies and greater distances. For this purpose it is useful to express Equation (2) in the following form:

$$H_i(\bar{r}) = \sum_{g=1}^{n} \sum_{\mu=1}^{m} S_{ig\mu} \, I_{ig\mu}\,(\bar{r}) \,, \tag{3}$$

where i is the particle type; μ is $\cos\theta$ (θ is the polar angle); n is the number of energy groups g; m is the number of polar angle intervals expressed in terms of the cosine of the polar angle; $S_{ig\mu}$ is the number of source particles of type i and energy group g in polar angular interval μ; and $I_{ig\mu}\,(\bar{r})$ is the importance of particles of type i for group g and angular interval μ at an average radial distance $\bar{r}$.

Tables of Importance Functions are available as computer-readable data files from Oak Ridge National Laboratory.[11]

2.2 *Approximation by Stevenson and Thomas*

To interpolate between the values in the tabulated Importance Functions of Alsmiller *et al.*,[4] Thomas and Stevenson[3] used experimental data and made three simplifying assumptions:

- The neutron differential energy spectrum emerging from the accelerator roof was $\frac{1}{E}$ in form.
- Neutrons were isotropically emitted from the roof surface.
- Neutrons were emitted upwards into a cone with a semivertical angle of 78°.

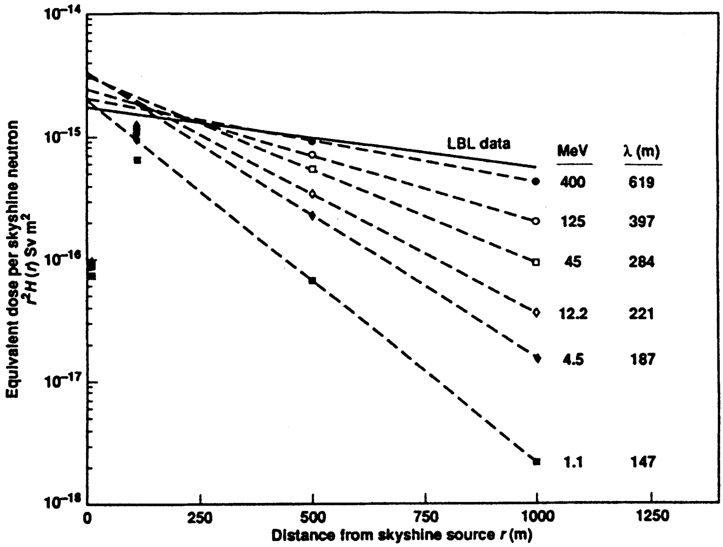

FIGURE 2: Equivalent dose at distance r calculated from neutron Importance Functions multiplied by r^2 for $\frac{1}{E}$ spectrum accelerator neutron leakage radiation and stated upper cut-off energies (after Stevenson and Thomas[3]).

Figure 2 shows the values of $r^2\,H(r)$ versus distance calculated in this manner. Stevenson and Thomas[3] assumed that at the larger distances (495–1005 m), the residual component was attenuated exponentially. Extrapolation to $r = 0$ gave the value of the empirical constant, a, to be substituted in Equation (1); values between 1.5×10^{-15} to 3.0×10^{-15} Sv per source neutron were obtained where the source strength was obtained by integration over the entire neutron energy spectrum.

These authors concluded that at distances greater than about 300 m from the accelerator, the neutron equivalent dose, $H(r)$, could be conservatively expressed in Sv per neutron as a function of distance by the equation

$$H(r) = \frac{(1.5 \text{ to } 3) \times 10^{-15}}{r^2} \exp\left[\frac{-r}{\lambda(E_c)}\right], \tag{4}$$

where $\lambda(E_c)$ corresponds to an effective absorption length at cut-off energy E_c. Values of $\lambda(E_c)$ were obtained from the curve given in Figure 3 by assuming that the upper energy of the particle accelerator could be set equal to E_c.

Because there are no calculated Importance Functions for energies above 400 MeV, Stevenson and Thomas used an experimentally determined high-energy limit of

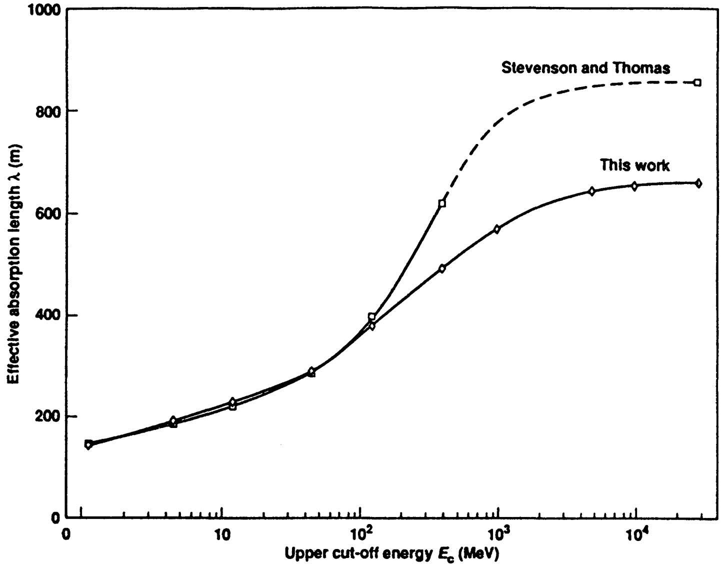

FIGURE 3: The effective neutron absorption length in air as a function of the upper neutron energy cut-off assuming an $\frac{1}{E}$ and a typical accelerator leakage differential energy spectrum.

850 m for λ (based on the analysis of Rindi and Thomas[1]). This choice was conservative because there was some evidence for a smaller value. For example, Distenfeld and Colvett[8] reported experimental data, giving a value of 600 m for this limit.

3 NEW WORK

This note reports improvement in the calculations of Stevenson and Thomas[1] in several respects by:

- Using a neutron spectrum that more realistically matches an accelerator shield-leakage spectrum.
- Assuming that neutrons are emitted from an accelerator shield with a cosine distribution.
- Assuming that neutrons of energy greater than 400 MeV can be included in the highest energy group of the Importance Functions, weighted in direct proportion to their energy.
- Modifying the geometry on the assumption that the skyshine source behaves as a virtual source in the sky and, therefore, correcting Stevenson and Thomas' expression at small values of $r(< 100 \text{ m})$.

3.1 *Accelerator Spectrum*

The choice of a $\frac{1}{E}$ differential energy neutron spectrum by Stevenson and Thomas was made for simplicity and because it gave a conservative result. However, the choice had its difficulties, since it is not mathematically well-behaved as $E \rightarrow 0$ and also overemphasizes the number of neutrons at high energies.

As early as 1965, Thomas[12] had proposed a composite spectrum approximating that to be found outside high-energy proton accelerator shields. This work was itself based upon estimates of the cosmic-ray neutron spectrum in the Earth's atmosphere due to Hess *et al.*[14] and calculations of the intranuclear cascade initiated by protons up to 200 GeV in energy (Riddell[15]). At energies above a few GeV, a differential energy spectrum close to $\frac{1}{E^2}$ was proposed.

Since that time, measurements of neutron spectra outside the shielding of several high-energy proton accelerators have been reported (for a summary, see Thomas and Stevenson[15]) and improved measurements of the cosmic-ray neutron spectrum have been made (Hewitt *et al.*[16]; Stephens *et al.*[17]).

Calculations of the neutron spectra emerging from the side shield of a large accelerator using the method of spherical harmonics[18] suggest that the differential energy spectrum falls off as $E^{-3.4}$. Measurements of accelerator spectra both outside the shielding[19] and inside the accelerator tunnel[20] at Fermi National Accelerator Laboratory also show a steep fall at the higher energies.

Combining these calculations and measurements, we propose a composite spectrum to represent the differential neutron spectrum transmitted through thickness of concrete (>100 g/cm^2) above a high-energy accelerator of maximum energy E_{MAX}. This is comprised of four energy regions:

1. Low-energy region:

$$\frac{d\phi}{dE} = \frac{AE}{T^2} \exp\left(\frac{-E}{T}\right) \qquad E \leq 10^{-7}\ \mathrm{MeV}\ . \tag{5.1}$$

2. Intermediate-energy region:

$$\frac{d\phi}{dE} = \frac{B}{E} \qquad 10^{-7}\ \mathrm{MeV} < E \leq 200\ \mathrm{MeV}\ . \tag{5.2}$$

3. High-energy region:

$$\frac{d\phi}{dE} = \frac{C}{E^2} \qquad 200\ \mathrm{MeV} < E \leq 1000\ \mathrm{MeV} \tag{5.3}$$

4. Ultra-high-energy region:

$$\frac{d\phi}{dE} = \frac{D}{E^3} \qquad 1000\ \mathrm{MeV} < E \leq E_{\mathrm{MAX}} \tag{5.4}$$

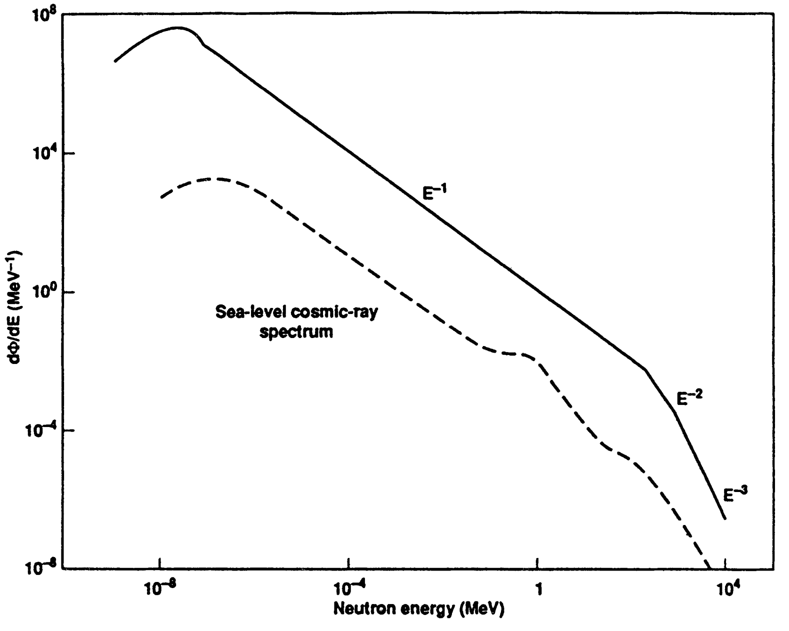

FIGURE 4: Composite neutron differential spectrum from parameterization to represent lateral shield spectrum. The proposed spectrum is compared with the cosmic ray neutron spectrum at sea level measured by Hess *et al.*[13]

Table 1 summarizes the values of the constants of Equations (5.1–5.4), which normalize the composite spectrum to the $\frac{1}{E}$ part of the spectrum.

TABLE 1: Values of constants for neutron spectra equations.

Parameter	Value
A	3.126
T	2.618×10^{-8} MeV
B	1
C	200 MeV
D	2×10^5 MeV^2

The entire composite spectrum is shown in Figure 4.

3.2 *Angular Distribution*

Stevenson and Thomas[3] assumed that neutrons were emitted isotropically upwards to the sky. However, for a thick shield it is more realistic to assume that neutrons are emitted with a cosine distribution:

$$\frac{dM}{d(\cos\theta)} = \cos\theta \tag{6}$$

Table 2 summarizes the contribution of neutrons to each angular range.

TABLE 2: Fraction of neutrons emitted into given angular range.

Angular (degrees)	Range in $\cos\theta$	Fraction of neutrons within angular range	
		This work	Stevenson and Thomas[31]
0–37	1.0–0.8	0.36	0.25
37–53	0.8–0.6	0.28	0.25
53–66	0.6–0.4	0.20	0.25
66–78	0.4–0.2	0.12	0.25
78–90	0.2–0.0	0.04	0

3.3 *Equivalent Dose as a Function of Distance*

Table 3 shows calculated values of equivalent dose per neutron as a function of distance from the source (accelerator) using the improved estimates of neutron differential energy spectra and angular distribution described in the two previous sections. Table 3 also includes values of H for $\bar{r} = 11$ m, not included by Stevenson and Thomas.[3]

Values of equivalent dose are included for maximum neutron energies above 400 MeV. In Table 3, the values of equivalent dose for neutrons greater than 400 MeV in energy were obtained by assigning them to the importance function calculated for the highest energy group of Equation (3) (375–400 MeV). The number of neutrons above 400 MeV added to the highest energy group were enhanced, conservatively, in proportion to their energy greater than 400 MeV; thus,

$$\frac{d\phi}{dE} = \frac{C}{E^2}\frac{E}{400} \qquad 400\ \text{MeV} < E < 1000\ \text{MeV}\,, \tag{7.1}$$

$$\frac{d\phi}{dE} = \frac{D}{E^3}\frac{E}{400} \qquad 1000\ \text{MeV} < E_{\text{MAX}}\,. \tag{7.2}$$

TABLE 3: Equivalent dose per neutron (in Sv).

Maximum energy (MeV)		$\bar{r}$ (m)			
$\frac{1}{E}$ spectrum	This work	11	108	495	1005
	30,000	6.5×10^{-19}	8.1×10^{-20}	3.2×10^{-21}	4.0×10^{-22}
	10,000	6.5×10^{-19}	8.1×10^{-20}	3.2×10^{-21}	3.9×10^{-22}
	5,000	6.5×10^{-19}	8.0×10^{-20}	3.2×10^{-21}	3.8×10^{-22}
	1,000	6.4×10^{-19}	7.8×10^{-20}	2.9×10^{-21}	3.1×10^{-22}
400		7.4×10^{-19}	1.0×10^{-19}	3.8×10^{-21}	4.0×10^{-22}
	400	6.4×10^{-19}	7.7×10^{-20}	2.5×10^{-21}	2.4×10^{-22}
125		7.6×10^{-19}	1.0×10^{-19}	2.8×10^{-21}	1.9×10^{-22}
	125	6.5×10^{-19}	7.4×10^{-20}	2.0×10^{-21}	1.3×10^{-22}
45		7.8×10^{-19}	9.7×10^{-20}	2.1×10^{-21}	8.6×10^{-23}
	45	6.6×10^{-19}	7.1×10^{-20}	1.5×10^{-21}	5.8×10^{-23}
12.2		7.9×10^{-19}	9.0×10^{-20}	1.4×10^{-21}	3.4×10^{-23}
	12.2	6.6×10^{-19}	6.6×10^{-20}	9.7×10^{-22}	2.3×10^{-23}
4.5		7.7×10^{-19}	8.1×10^{-20}	9.2×10^{-22}	1.5×10^{-23}
	4.5	6.4×10^{-19}	5.8×10^{-20}	6.3×10^{-22}	1.0×10^{-23}
1.1		6.1×10^{-19}	5.5×10^{-20}	2.7×10^{-22}	2.0×10^{-24}
	1.1	5.3×10^{-19}	4.0×10^{-20}	1.9×10^{-22}	1.5×10^{-24}

Inspection of Table 3 shows that

- The agreement between the results using a $\frac{1}{E}$ spectrum with an upper energy cut-off up to 400 MeV and this work is quite good.
- (2) Very little benefit is gained by the addition of the low-energy term; see Equation (5.1). Stevenson and Thomas[3], in their analysis, do not provide a prescription for calculating similar data points at cut-off energies greater than 400 MeV. The data points for the $\frac{1}{E}$ spectrum are those given in Figure 2 divided by the square of the distance.

3.4 *Analytic Expression for the New Data*

Alsmiller *et al.* calculated Importance Functions up to 400 MeV.[4] This limit on energy range is sufficient, however, for most applications even around high-energy accelerators, because the number of neutrons at higher energy in the lateral cascade is small.[21] Although the fluence of neutrons above 400 MeV is small, an arbitrary cut-off of 400 MeV for $\lambda(E_c)$ did not seem reasonable for particle accelerators in the GeV range. Stevenson and Thomas[3] dealt with this problem by extrapolating to an upper energy

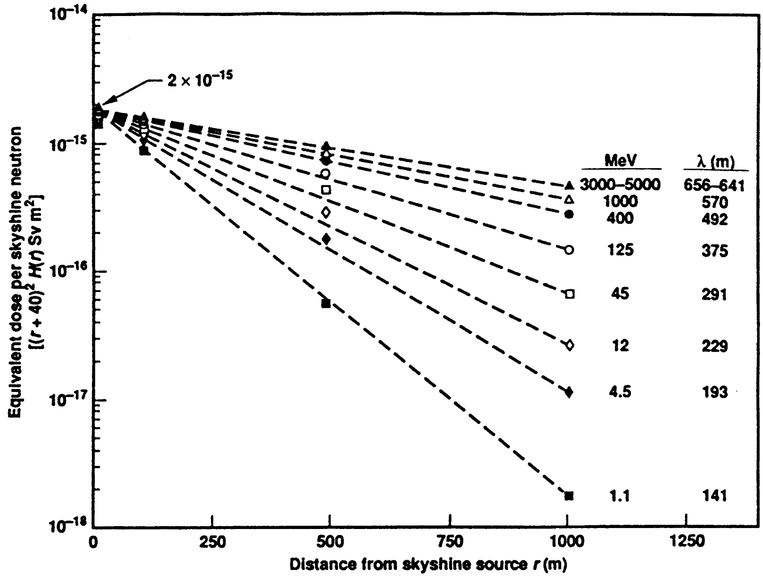

FIGURE 5: Equivalent dose at distance r calculated from neutron Importance Functions multiplied by $(r{+}40)^2$ for typical accelerator neutron leakage radiation and stated upper cut-off energies.

limit defined by the Lawrence Berkeley Laboratory experimental data, which they translated into an upper value of $\lambda(E_c)$ to be used in Equation (4). Figure 3 shows the values of $\lambda(E_c)$ as a function of energy. The values of $\lambda(E_c)$ between 400 MeV and the high-energy limit of 850 m are indicated by the dashed line.

To improve the calculation of equivalent dose given by Equation (4) at distances less than 100 m, we postulate that skyshine will produce a virtual neutron source in the air at some height above the ground; therefore, the equivalent dose at some distance r, measured horizontally from the accelerator, is given by a function such as:

$$H(r) = \frac{a \, \exp\left[\frac{-r}{\lambda(E_c)}\right]}{(b + r)^2} \, . \tag{8}$$

Figure 5 shows the data from this work (Table 3), presented as $(b + r)^2 H(r)$ versus distance (r). The data are reasonably fitted by an equation of the form of Equation (8) with $b = 40$ m. Figure 3 also summarizes the values of λ as a function of E_c.

Substituting values of $a = 2 \times 10^{-15}$ m^{2}Sv and $b = 40$ m into Equation (8) and appropriate values of λ taken from Figure 3 provides a reasonable representation of skyshine equivalent dose at distances from 11 to 1005 m per source neutron.

Given the double differential source spectrum, Equation (2) can be used directly, using quadrature, and the result can be fitted to Equation (8), yielding all three parameters.

The reader is reminded that in data given by Distenfeld and Colvett,[8] $\lambda = 600$ m is rather close to the value given in this paper, $\lambda = 650$ m. Furthermore, Distenfeld and Colvett also offer a parameterization, which includes a correction for the data at short distances from the skyshine source, using an exponential build-up argument; an expression of this kind had been originally proposed by Thomas:[22]

$$H(r) = \frac{a\ \exp\left(\frac{-r}{600}\right)\ \left[1 - \exp\left(\frac{-r}{47}\right)\right]}{r^2} \tag{9}$$

where r is expressed in meters.

3.5 *Calculations of the Source Term*

Having found an expression for the variation of equivalent dose with distance from the accelerator, it merely remains to determine a source term $\frac{dQ}{d\Omega}$.

Equivalent dose at the accelerator shield surface may be determined by experimental or theoretical methods. The source term $\frac{dQ}{d\Omega}$ is given by:

$$\frac{dQ}{d\Omega} = \frac{d^2}{g}\,H(d,t)sr^{-1} \tag{8}$$

where $H(d,t)$ is the equivalent dose rate on the roof; d is the source to rooftop distance (m); t is the thickness of the roof shield (m); and g is the equivalent dose to fluence conversion coefficient (fSvm^2).

For a cylindrical building with a vertical half angle θ (polar angle), the solid angle subtended by the source at the roof is given by:

$$\Omega = 2\pi(1 - \cos\theta) \tag{9}$$

The neutron yield from the roof, Q, is given by:

$$Q = 2\pi\frac{d^2}{g}\,H(d,t)\,\Omega \tag{10}$$

where $H(d,t)$ is taken to be constant over the roof.

For a flat roof, which varies in thickness with polar angle, a better result is obtained by use of the expression:

$$Q = 2\pi\frac{d^2}{g}\int_0^\theta \exp\left(-\frac{t}{\Lambda\cos\theta}\right)\ \sin\,d\theta\ , \tag{11}$$

where Λ is the appropriate removal mean free path for the roof.

To complete the calculation we need a value for g, which is the equivalent dose per source neutron.

The neutron fluence to dose conversion coefficients used by Alsmiller *et al.*[4] are taken from NCRP,[9] and it should be remarked that the equivalent doses so calculated are overestimates, as pointed out by Thomas and Stevenson,[12] because of the random orientation of the body in the neutron field; this overestimate can amount to as much as a factor of two. This could nicely compensate for the proposed effective increase in quality factor for neutrons (weighting factor) of 2.[22]

The conversion factors given in Table 4 are for the $\frac{1}{E}$ spectrum and for the composite spectrum used in this work based on a parameterization of the ICRP coefficients.[23] The data in Table 4 show clearly the overestimate that results in equivalent dose produced by neutrons above 400 MeV using a $\frac{1}{E}$ spectrum. It should be noted that using the composite spectrum data at the higher energies results in a greater neutron yield for any given equivalent dose, but this only serves to bring the two results — i.e., Stevenson and Thomas and the work reported here — closer together at the higher energies.

TABLE 4: Equivalent dose per unit fluence for composite and $1/E$ neutron spectra of various upper energies.[a]

Upper energy (MeV)	Composite spectrum averaged equivalent dose (fSvm^2)	$\frac{1}{E}$ spectrum averaged equivalent dose (fSvm^2)
1.6	4.0	3.9
2.5	4.8	4.8
4.0	5.5	5.6
6.3	6.3	6.4
10.0	7.1	7.2
16.0	7.8	7.9
25.0	8.6	8.6
40.0	9.4	9.4
63.0	10.1	10.1
100.0	10.9	10.9
160.0	11.7	11.7
250.0	12.5	12.5
400.0	13.2	13.4
630.0	13.7	14.6
1000.0	14.1	16.2
1600.0	14.4	18.4
2500.0	14.5	21.2
4000.0	14.6	25.0
6300.0	14.6	30.0
10000.0	14.7	36.5

[a] Based on conversion coefficients given in ICRP (1971).

4 CONCLUSIONS

The allusion by Rindi and Thomas,[1] to the notion that skyshine is a tiger seems appropriate, since it still has savage teeth! Skyshine is generally the most significant source of leakage radiation but is often neglected or ignored; it is also very costly to combat, especially after the fact. The cost of extra side shielding can often amount to no more than just bulldozing a few extra feet on the side of an earthen berm, but for a roof with a span of any significance, such as an experimental hall, the addition of extra roof shielding can be prohibitively expensive in the additional support structure needed for the extra weight. Design concepts that incorporate thin (and less costly) roofs can result in serious skyshine problems.

The complexity of calculating equivalent dose due to skyshine has been reduced by the use of the solutions provided by Alsmiller *et al.*[4]; these are probably still the best starting point for skyshine determinations.[19] With these solutions as the basis, simplifying analytic expressions have been derived for determining skyshine equivalent dose at any distance from the skyshine source. Approximations of source conditions can be made with relatively simple measurements or calculations of equivalent dose on the roof. This simplicity provides a means of quickly obtaining a measure of the tiger's ferocity rather more accurately than is expected of estimates of beam loss conditions.

ACKNOWLEDGMENTS

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48 and supported by the U.S. Department of Energy under Contracts DE-AC05-84ER40150 and DE-AC03-76SF00098.

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