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Dosimetric Quantities and Neutron Spectra Outside the Shielding of Electron Accelerators

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Typical neutron spectra as found at high energy electron accelerators outside concrete shielding of various thicknesses (at 90 degrees) have been calculated at three electron energies (100 MeV, 1 and 10 GeV) with the FLUKA Monte Carlo transport code. The results have provided useful information about neutron attenuation lengths and about the fraction of neutrons with energy larger than 20 MeV, not detectable by the usual radiation protection instruments.

Keywords: High-Energy Electron Accelerators; Monte Carlo; Shielding; Neutron Spectra; Dosimetric Quantities; Attenuation Length; Andersson-Braun; FLUKA; Ambient Dose Equivalent; Effective Dose

1. Introduction

Typical neutron spectra as found at high energy electron accelerators outside concrete shielding of various thicknesses (at 90 degrees) have been calculated at three electron energies (100 MeV, 1 and 10 GeV) with the FLUKA Monte Carlo transport code.

The results have provided useful information about neutron attenuation lengths and about the fraction of neutrons with energy larger than 20 MeV, not detectable by the usual radiation protection instruments.

The response of an Andersson-Braun neutron detector outside different shield thicknesses has been evaluated.

The results have also been compared to those obtained with SHIELD11, an analytical point-kernel code widely used at electron accelerators.

2. The calculations

2.1 Details of the calculations

The calculations were made with the Monte Carlo code FLUKA [1], version 2008.3.5.

An electron beam was assumed to be incident on an "optimum" copper target (i.e., where an electromagnetic cascade would be fully developed) 30.48 cm long and 5.08 cm in radius, surrounded at a distance of 2 m by a cylindrical shield of ANSI ordinary concrete NBS04 [2] 30.5 to 244 cm thick. To save time, photons and electrons were not transported in the shield: this approximation was checked not to change the results by more than 1%.

Scored quantities were neutron spectral fluence, fluence folded with conversion coefficients of $H^*(10)$ and Effective Dose from ICRP 74 [3], extended to higher energies by Pelliccioni [4], and folded with the response curve of the Andersson-Braun detector. [5]. The scoring was done in three angular intervals: 65º–75º, 75º–85º and 85º–95º, since experience has shown that the maximum dose is found generally at angles slightly smaller than 90º.

All scoring was done at 5 m from the target, independent of shielding thickness, to allow comparisons of attenuation lengths without corrections for $1/r^2$ attenuation. Separate calculations were done for each thickness to avoid correcting for backscattering inside the shielding**.**

2.3. Dose fraction due to high energy neutrons

The usual properties of protection and operational dosimetric quantities are not applicable to neutrons. Both kinds of quantities can neither be measured nor be calculated directly, but both can be derived from calculated fluences by means of conversion coefficients, and both can be measured using a calibrated instrument with a suitable energy response. In addition, for neutrons with energies larger than a few tens of MeV, which constitute an important fraction of the radiation fields at high energy accelerators, operational quantities such as $H^*(10)$ are not conservative with respect to protection quantities [6].

2.1. Neutron spectra

Typical neutron spectra as found at high energy electron accelerators outside concrete shielding of various thicknesses (at 90 degrees) have been calculated at three electron energies (100 MeV, 1 and 10 GeV).

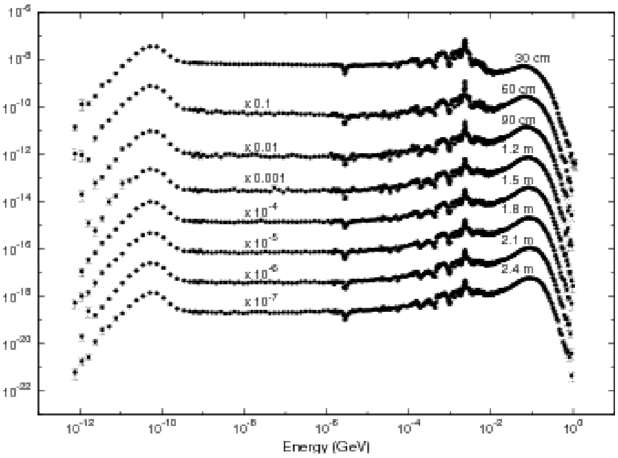

Figure 1. Neutron energy spectra at various shielding thicknesses. Electron energy: 10 GeV

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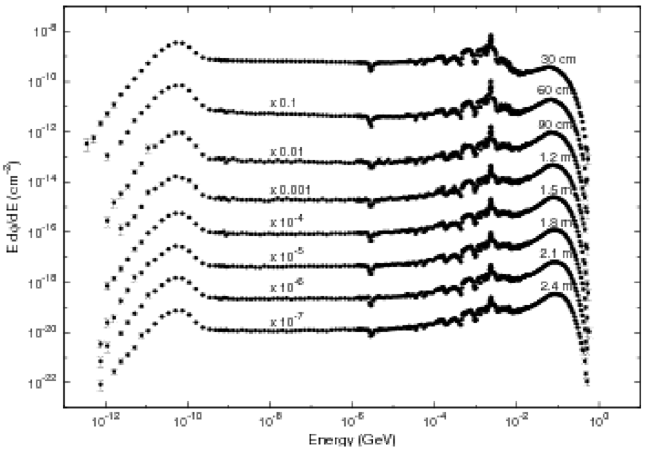

Figure 2. Electron energy: 1 GeV

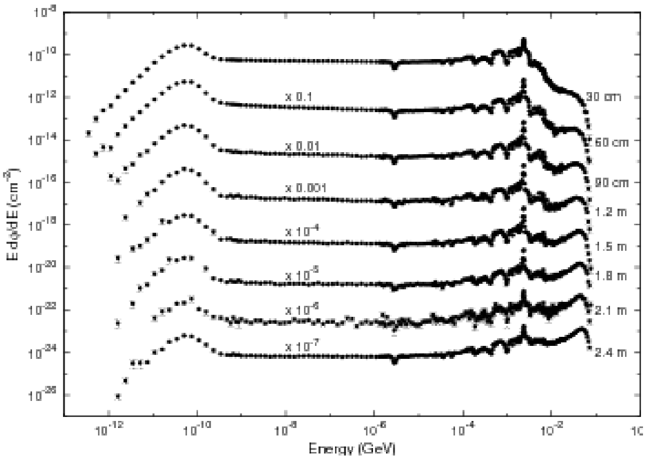

Figure 3. Electron energy: 100 MeV

The spectral shape becomes about constant only for concrete thicknesses larger than 2 m, confirming the existence of an equilibrium spectrum beyond such thickness.

2.2.Radiation quantities

For Effective Dose, two conversion coefficients have been considered: AP (Antero-Posterior) and “worst” (at any neutron energy, the highest value among the different possible irradiation geometries)

At low energies, the largest values of Effective Dose occur for the Anterior-Posterior (AP) irradiation geometry: and indeed, as shown in Fig. 4, E(AP) appears to coincide with E(worst), or to be smaller by less than 1%, at all thicknesses in the 100 MeV case. In the other cases, E(AP) is always slightly lower (maximum by 6%).

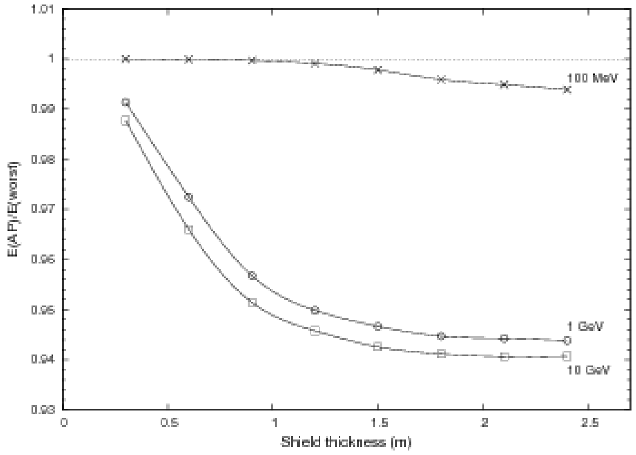

Figure 4. Ratio of calculated E(AP) and E(worst) as a function of electron energy and shielding thickness

2.3. Dose fraction due to high energy neutron

For 1 and 10 GeV electrons, the dose fraction due to neutrons with energy > 20 MeV is gradually increasing with shielding thickness from about 15% to about 65%. For 100 MeV electrons, that fraction increases from about 5% to 50% (Fig. 5 and 6).

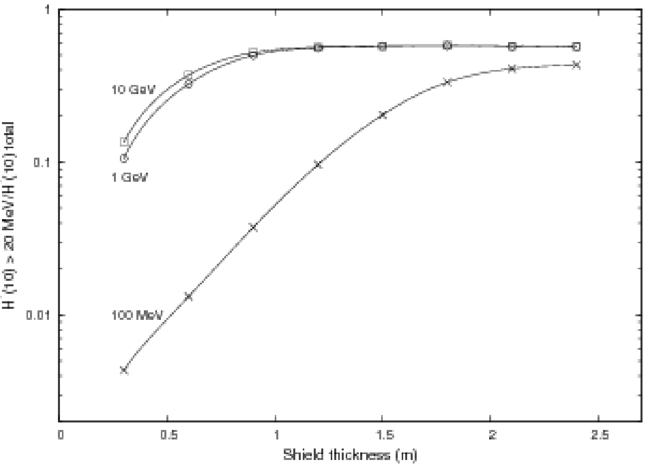

Figure 5. Fraction of Ambient Dose Equivalent due to neutrons with energy > 20 MeV

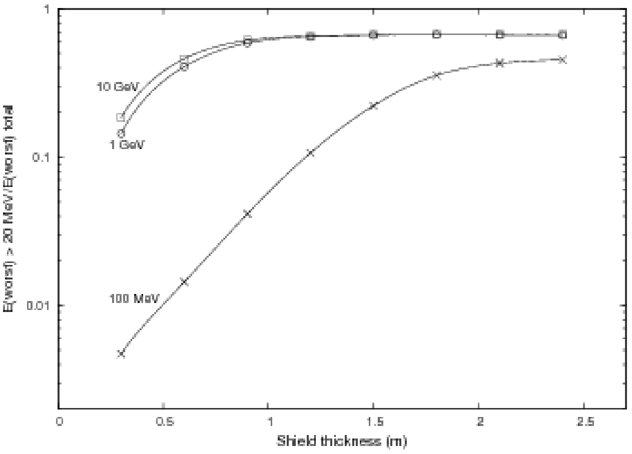

Figure 6. Fraction of Effective Dose (worst irradiation geometry) due to neutrons with energy > 20 MeV

2.4. Ambient Dose Equivalent or Effective Dose?

Effective Dose is the legally limiting quantity. Operational quantities are allowed in practice, if they provide an overestimation of the protection quantity.

However, above about 40 MeV Ambient Dose Equivalent is not conservative with respect to the maximum (“worst”) value of Effective Dose (Fig. 7)

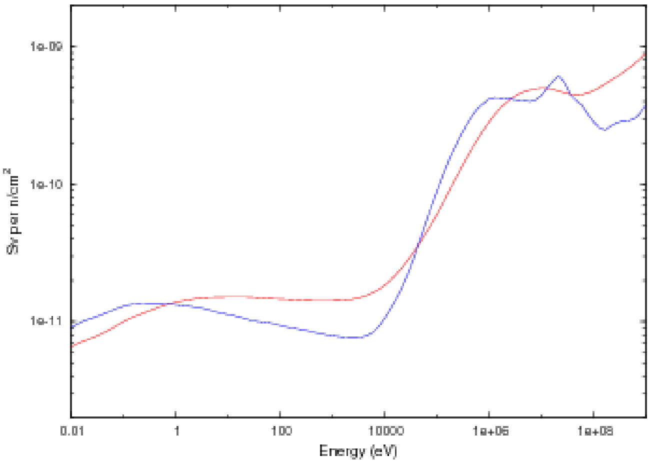

Figure 7. Comparison of H*(10) (blue curve) and E(worst) (red)

The calculated ratio between $H^*(10)$ and Effective Dose E is shown in Fig. 8. Ambient Dose Equivalent is found to underestimate Effective Dose by more than 10% in most cases (1 and 10 GeV electron beam, concrete shielding thicker than 1 m).

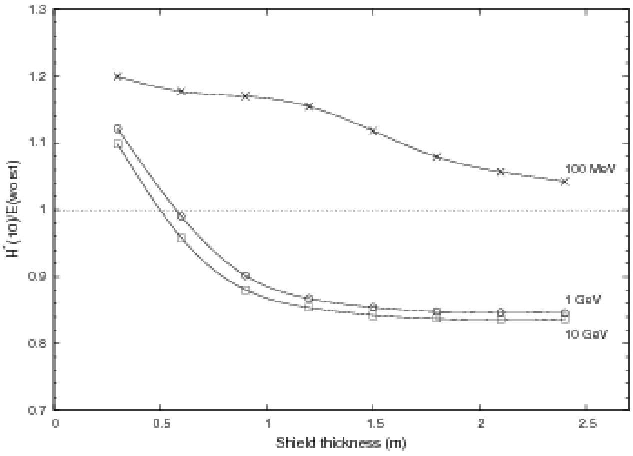

Figure 8. Ratio of calculated H*(10) and E(worst) as a function of electron energy and shielding thickness

It can be seen that $H^*(10)$ is always conservative in the case of a 100 MeV electron beam, it underestimates E for shielding thicknesses larger than 60 cm in the case of 1 and 10 GeV, and the maximum underestimation is about 15%. On the other hand, the usual properties of protection and operational dosimetric quantities are not applicable to neutrons: both kinds of quantities can neither be measured nor be calculated directly, both can be derived from calculated fluences by means of conversion coefficients, and both can be measured with some approximation using a calibrated instrument with a suitable energy response (the Andersson-Braun response can be adjusted to fit either H*(10) or E).

In addition, for neutrons with energies larger than a few tens of MeV, which constitute an important fraction of the radiation fields at high energy accelerators, the operational quantity $H^*(10)$ is not conservative with respect to the protection quantity E. Therefore: why use H*(10), an approximation which is not even conservative, when with the same techniques one can obtain directly E? E(worst) is a much better choice, since it is always conservative by definition.

2.5. Attenuation length

In the literature, different values have been reported for the attenuation length at equilibrium of neutron dose at about 90° in electron accelerator shielding. Table 1 shows some of the reported values as a function of electron energy.

Table 1. Values of attenuation lengths reported in the literature .

Ref.	Electron energy (GeV)	λ (g/cm²)
7	0.027	28
8	0.4	35
9	0.75	96
10	3.0	110
11	6.3	91
12	10	105
13	15	104
14	20	120
15	20	120
16	28.7	116
17	30	94
18	100	115

Because the attenuation at equilibrium is governed by neutrons of similar energies, it is generally believed that the equilibrium attenuation length should be equal to that found at proton accelerators, which has been evaluated to be 117 ± 2 g/cm^2 [19].

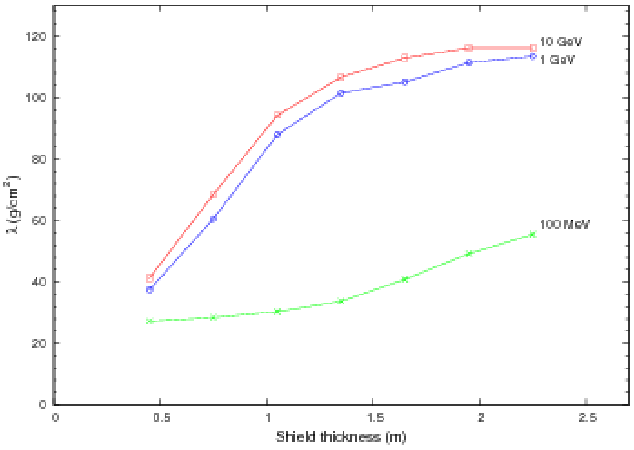

Figure 9. Neutron dose attenuation length as a function of electron energy and shielding thickness

However, early calculations seemed to indicate that the equilibrium attenuation length at electron accelerators would be much shorter, and a “conservative” value of 100 g/cm^2 was recommended by Tesch in 1988 [20], based on

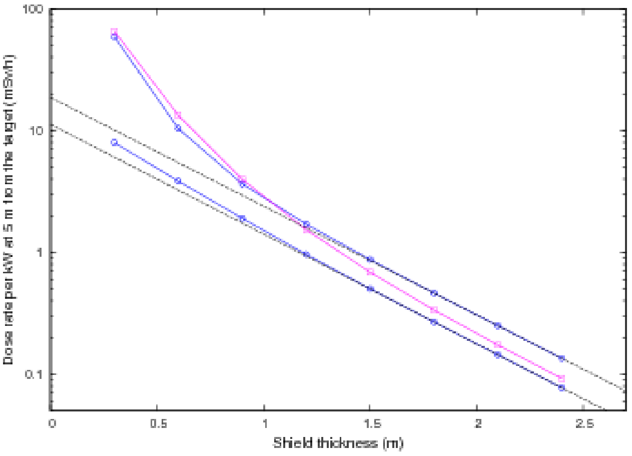

Figure 10. Neutron dose attenuation as a function of shielding thickness for a 10 GeV electron beam. Upper blue curve: total Effective Dose, lower: the same for neutrons with energy > 20 MeV. Dotted lines: corresponding asymptotic slopes. Magenta curve: total dose calculated by SHIELD11.

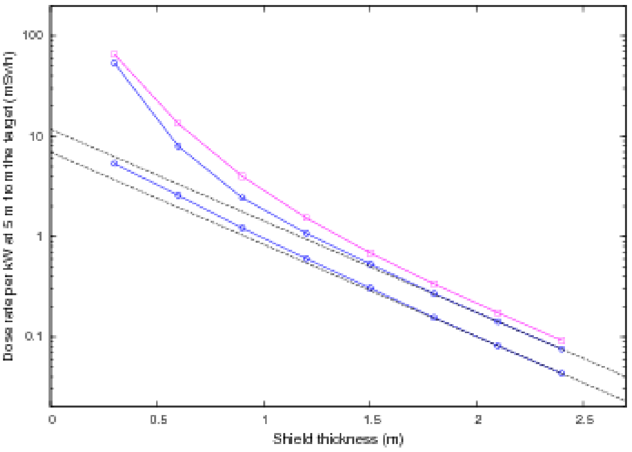

Figure 11. Neutron dose attenuation as a function of shielding thickness for a 1 GeV electron beam. Curves: as for Fig. 10

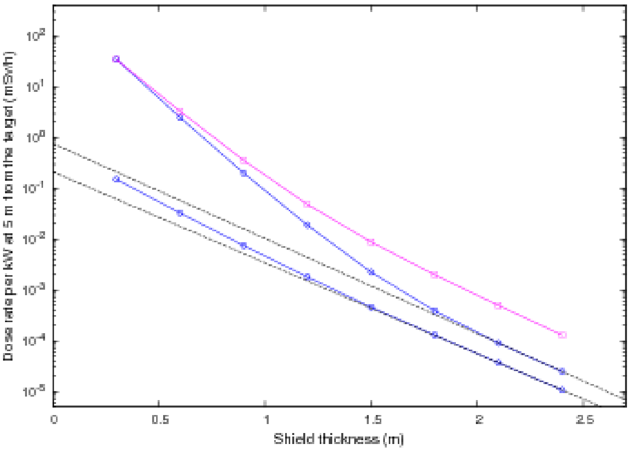

Figure 12. Neutron dose attenuation as a function of shielding thickness for a 100 MeV electron beam. Curves: as for Fig. 10

an examination of the available experimental data at that time. The maximum values of λ calculated in this work are:

10 GeV: 116.1 g/cm^2, 1 GeV: 113.5 g/cm^2, 100 MeV: 56.0 g/cm^2. The 10 GeV value is consistent with that evaluated for proton accelerators, and that at 1 GeV is only slightly lower. Notice, however, that true complete equilibrium is established only at 7 feet (2.1 m), and no equilibrium is found at 100 MeV at any shielding thickness (Fig. 9). In Fig 10-12 are shown the calculated attenuation curves together with those obtained with SHIELD11 [21], an analytical point-kernel code widely used for electron accelerator shielding.

2.6. Andersson-Braun calculated response

Despite its response falls down to nearly zero above 20 MeV, the response of the Andersson-Braun remmeter overestimates E and H*(10) in some cases (for 100 MeV electrons and small shielding thicknesses). In all the other cases, the instrument underestimates total neutron dose by up to 70%, as shown in Fig. 13 and 14.

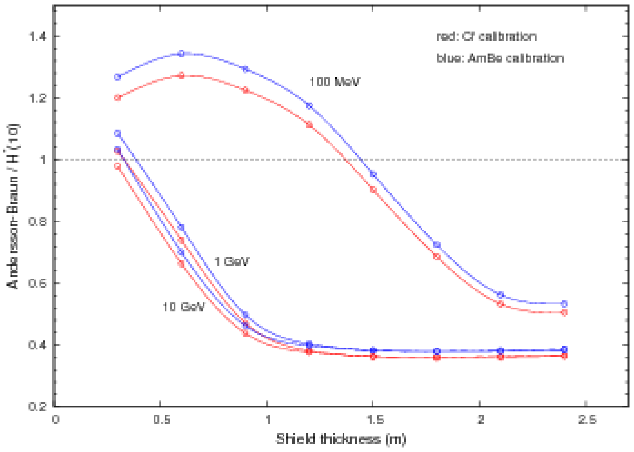

Figure 13. Ratio of Andersson-Braun response to H*(10) as a function of shielding thickness. Red curve: ^{252}Cf calibration, blue: AmBe calibration.

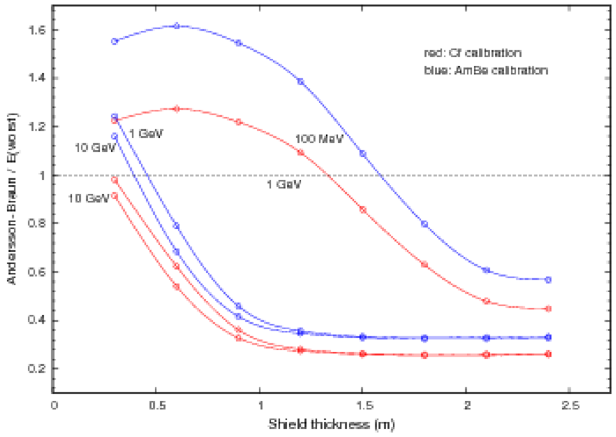

Figure 14. Ratio of Andersson-Braun response to E(worst) as a function of shielding thickness. Calibration: as in Fig. 13

The actual ratios vary, as expected, with the quantity (H*(10) or E) and with the calibration source chosen (AmBe or ^{252}Cf), but not much. The A-B instrument is known to measure only a fraction of the total neutron dose, and it has been customary at SLAC to double its readings.

It can be seen that the A-B response does indeed underestimate the total neutron dose in the 1 GeV and 10 GeV cases, the underestimation reaching a constant value for shielding thicknesses larger than 4 feet (1.2 m). The underestimation is worse for ^{252}Cf than for AmBe calibration, and worse for Effective Dose (–74%) than for H*(10) (–64%). The SLAC practice to double the A-B readings in accelerator fields is thus shown to be justified.

In the 100 MeV case, however, the Andersson-Braun overestimates the total neutron dose for shielding thicknesses < 5 ft (150 cm).

3. Conclusions

The FLUKA calculations have provided some interesting information not available before.

For 1 and 10 GeV electrons, the dose fraction due to neutrons with energy > 20 MeV is gradually increasing with shielding thickness from about 15% to about 65%.

For 100 MeV electrons, that fraction increases from about 5% to 50%. The spectral shape becomes about constant only for concrete thicknesses larger than 7 feet (2.1 m), confirming the existence of an equilibrium spectrum beyond a 2 m thickness.

The SHIELD11 analytic shielding code is conservative in most cases. Except for 10 GeV electrons at large thicknesses, where it underestimates doses by about 40%, SHIELD11 provides overestimations from 50% to a factor 16 (at 100 MeV). The attenuation lengths used by that code are consistent with those found by Monte Carlo.

The value of the dose attenuation length λ at equilibrium coincides within errors with the one evaluated for proton accelerators. In the cases of 1 and 10 GeV electron beam, λ increases steadily with shielding thickness up to 2 m, consistent with the setting up of an equilibrium spectrum.

Despite its response falls down to nearly zero above 20 MeV, the response of the Andersson-Braun rem-meter overestimates E and $H^*(10)$ neutron doses in some cases (for 100 MeV electrons and small shielding thicknesses). In all the other cases, the Andersson-Braun underestimates total neutron dose by up to 70%. The SLAC practice to double the rem-meter readings in accelerator fields is thus shown to be justified.

Acknowledgments

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References

[1] A. Ferrari, P.R. Sala, A. Fassò and J. Ranft, *FLUKA: a multi-particle transport code*, CERN-2005-10 (2005), INFN/TC_05/11, SLAC-R-773;
G. Battistoni, S. Muraro, P.R. Sala, F. Cerutti, A. Ferrari, S. Roesler, A. Fassò and J. Ranft, *"The FLUKA code: Description and benchmarking"*, Proc. Hadronic Shower Simulation Workshop, Fermilab 6--8 Sept. 2006, M. Albrow, R. Raja eds., AIP Conference Proceeding 896, 31-49 (2007)

[2] J.K. Shultis and R.E. Faw, *Radiation Shielding*, Prentice Hall PTR, Upper Saddle River, NJ (1996)

[3] ICRP Publication 74, Annals of the ICRP 26, 3-4 (1997)

[4] M. Pelliccioni, *Overview of Fluence-to-Effective Dose and Fluence-to-Ambient Dose Equivalent Conversion Coefficients for High Energy Radiation Calculated Using the FLUKA Code,* Rad. Prot. Dosim. 88, 279 (2000)

[5] *Compendium of Neutron Spectra and Detector Responses for Radiation Protection Purposes*, Tech. Rep. 403, IAEA, Vienna (2001)

[6] A. Ferrari and M. Pelliccioni, *Fluence to Dose Equivalent Conversion Data and Effective Quality Factors for High Energy Neutrons,* Radiat Prot Dosim. 76, 215-224 (1998)

[7] Yu.G. Teterev, *Radiation environment of an MT-22 microtron*, Atomic Energy 62, 396-400 (1987)

[8] R.G. Alsmiller, Jr. and J. Barish, *Shielding against the neutrons produced when 400-MeV electrons are incident on a thick copper target*, Part. Accel. 5, 155-159 (1973)

[9] T.A. Gabriel, R.A. Lillie and B.L. Bishop, *Shielding considerations for the 750 MeV electron accelerator at University of Illinois*, ORNL/TM-10036 (1986)

[10] J.C. Liu, H. Khater, S. Mao, S.H. Rokni and H. Vincke, *FLUKA calculations of source terms and attenuation profiles for generic shielding design of SPEAR3 ring*, SLAC RP-Note 02-20 (2002)

[11] G. Bathow, E. Freitag and K. Tesch, *Measurements on 6.3 GeV electromagnetic cascades and cascade produced neutrons*, Nucl. Phys. B2, 669-689 (1967)

[12] K. O'Brien, *Tables for the determination of the lateral shielding requirements of high-energy accelerators*, HASL-203 (1968)

[13] T.M. Jenkins, *Neutron and photon measurements through concrete from a 15 GeV electron beam on a target – Comparison with models and calculations*, Nucl. Instrum. Meth. 159, 265-288 (1979)

[14] H. DeStaebler, *Transverse radiation shielding for the Stanford Two-Mile Accelerator*, Internal SLAC Report No. 9 (1962)

[15] W.P. Swanson, *Radiological Safety Aspects of the Operation of Electron Linear Accelerators*, Tech. Rep. Series No. 188, IAEA, Vienna (1979)

[16] S. Roesler, J.C. Liu, S.H. Rokni and S. Taniguchi, *Neutron energy and time-of-flight spectra behind the lateral shield of a high energy electron accelerator beam dump*. Part II: Monte Carlo simulations, Nucl. Instrum. Meth. A503, 606-616 (2003)

[17] H. Dinter, A. Leuschner, K. Tesch, D. Dworak and J. Łoskiewicz, *Calculation of hadron yields around thick targets and doses behind concrete shielding of high-energy electron accelerators*, Nucl. Instrum. Meth. A455, 460-469 (2000)

[18] K. Goebel, M. Höfert and T.M. Jenkins, *LEP interaction regions shielding criteria – An update*, CERN LEP Note 538 (1985)

[19] R.H. Thomas and G.R. Stevenson, *Radiological Safety Aspects of the Operation of Proton Accelerators*, Tech. Rep. Series No. 283, IAEA, Vienna (1987)

[20] K. Tesch, *Shielding against high energy neutrons from electron accelerators – A review,* Rad. Prot. Dosim. 22, 27-32 (1988)

[21] W.R. Nelson and T.M. Jenkins, *The SHIELD11 Computer Code*, SLAC-Report-737 (2005)