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Protection Quantities and Conversion Coefficients for Use in Radiation Shielding

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Two types of quantities are specifically defined for use in radiological protection: protection quantities and operational quantities. In order to determine these quantities, conversion coefficients from physical quantities are needed. The International bodies provided such coefficients for photons and electrons of energy up to 10 MeV and for neutrons of energy up to 180 MeV. For purposes of shielding calculation around high-energy accelerators, conversion coefficients for other types of radiation and higher energies need to be calculated. Coefficients appropriate for radiation shielding estimates, calculated by the Monte Carlo transport code FLUKA, are summarised and discussed in this paper. Some significant examples of applications of the calculated conversion coefficients for accelerator shielding purposes are presented. On the basis of preliminary results, the effective dose for AP incidence seems to be the most appropriate quantity for a conservative estimate of the shields.

KEYWORDS: Conversion coefficients, effective dose, ambient dose equivalent, shielding, accelerators, FLUKA.

I. Introduction

There are two types of quantities specifically defined for use in radiological protection: protection quantities, defined by the ICRP, and operational quantities, defined by ICRU.

The most recent set of protection quantities was recommended in ICRP Publication 60[1]. It includes the effective dose, E, and the tissue or organ equivalent doses, H_T.

The equivalent dose, H_T, in a tissue or organ, T, is given by:

$$H_T = \Sigma_R \, w_R \, D_{T,R}$$

where $D_{T,R}$ is the average absorbed dose from radiation R, in tissue T, and w_R the radiation weighting factor of radiation R.

The effective dose, E, is the sum of the weighted equivalent doses in all the tissues and organs of the body. It is given by the expression:

$$E = \Sigma_T \, w_T \, H_T$$

where H_T is the equivalent dose in tissue or organ T and w_T is the weighting factor for tissue T.

These quantities are not directly measurable but may be related by calculation to the radiation field if the conditions of irradiation are known.

The ICRU has defined a set of operational quantities for area and individual monitoring. The operational quantities were first defined in ICRU Report 39[2], and subsequent changes to the definitions were made in ICRU Report 51[3]. A complete compilation of all operational quantities currently recommended by the ICRU is available in ICRU Report 51. For strongly penetrating radiation, the appropriate operational quantity for area monitoring is the ambient dose equivalent. The ambient dose equivalent, H*(d), at a point in a radiation field is the dose equivalent that would be produced by the corresponding expanded and aligned field in the ICRU sphere at a depth, *d*, on the radius opposing the direction of the aligned field. The currently recommended value of *d* for penetrating radiation is 10 mm.

The operational quantities were designed to provide a reasonable estimate of the appropriate protection quantities. According to paragraph 319 of ICRP Publication 74[4], this may be simply expressed by the goal that the value of the appropriate protection quantity is less than that of the operational quantity. For some types of radiation and their energies or directions of incidence, the dose equivalent at a single depth may provide an unacceptable underestimate of the effective dose. In such instances, the dose equivalent at other depths may be considered[2].

Both protection and operational quantities can be related to the basic physical quantities, mainly the particle fluence, Φ.

Shielding calculations are usually performed by Monte Carlo method and the results are expressed in terms of spectral fluences. Therefore, fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients are needed. ICRP Publication 74 provides such coefficients for photons and electrons of energy up to 10 MeV and for neutrons of energy up to 180 MeV.

In order to design shielding for high-energy accelerators, the energy range of the available conversion coefficients needs to be extended to greater energies and conversion coefficients for other kinds of radiation need to be calculated. A few groups of authors have provided useful data in this field.

II. Conversion Coefficients Calculated by FLUKA

Sets of conversion coefficients in terms of the most important radiological quantities (effective dose and ambient dose equivalent) have been calculated by the Monte Carlo transport code FLUKA for all kinds of radiation (photons, electrons, protons, neutrons, muons, pions, kaons) and energies (up to 10 TeV) of practical interest. The calculated results are scattered

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Table 1 Energy ranges in which conversion coefficients have been calculated by the FLUKA code

Primary particles	Energy range for effective dose calculations (GeV)	Energy range for ambient dose equiv. calculations (GeV)
Electrons	0.005-100[7,8]	0.001-10[7,15,16]
Kaons	0.001-10000[19]	0.001-10000[19]
Muons	0.001-10000[10]	0.001-10000[18]
Neutrons	2.5E-11-10000[5]	2.5E-11-10000[13]
Photons	0.00005-100[6,7]	0.00001-10[7,14,15]
Pions	0.001-10000[12,19]	0.001-10000[18,19]
Positrons	0.005-100[9]	0.001-10[17]
Protons	0.05-10000[11]	0.05-10000[18]

through several papers[5-19].

FLUKA is a general purpose transport code which has been substantially improved in recent years[20,21]. The particle interactions and the transport models used, as well as the performances of the code in simulating electromagnetic and hadron transport can be found in literature[21-24]. The anthropomorphic phantom used for the calculations of effective dose was an hermaphrodite mathematical model, derived from the male phantom developed for MCNP by GSF[25]. The MCNP phantom was translated for the combinatorial geometry of FLUKA. Then the female organs (breast, ovaries, uterus) were added.

Table 1 summarises the quantities, the radiation and the energy ranges investigated as well as the relevant references. **Figures 1-3** give a graphical presentation of the calculated results in terms of effective dose and ambient dose equivalent. Only the irradiation geometry AP and ISO have been considered because they seem to be the most appropriate under normal working conditions. Parallel radiation incident on the human body in the AP direction gives the maximum effective dose per unit fluence at low energies. Conversely ISO irradiation gives the largest values at higher energies. The values of conversion coefficients calculated by FLUKA are tabulated at the Internet address: http://www.lnf.infn.it/lnfadmin/radiation/.

The values of effective dose shown in figures 1-3 have been obtained on the basis of the radiation weighting factors recommended in ICRP Publication 60. For radiation types and energy that are not included in Publication 60, an approximation to w_R values have been obtained by calculation of the effective quality factor at a depth of 10 mm in the ICRU sphere, as stated in Paragraph (A14) of Publication 60. However, it may be shown that the recommended w_R values for high-energy neutrons and protons are inconsistent with the recommended Q-L relationship and that the approximation obtained by the rule recommended in Paragraph (A14) is generally inadequate for high-energy radiation. Therefore, modifications of the recommended values have been proposed in ref. 26.

For AP incidence (figure 1), all conversion coefficients increase steeply with rising energy at low energies. On the contrary, at high energies, the rise is more slight and for many primary particles the coefficients tend to be approximately constant. This is not true for hadrons, especially for neutrons, whose coefficients also keep increasing at high energies.

For ISO irradiation (figure 2), the behaviour of the curves is approximately the same as for AP irradiation. However, the rise at high energies is more evident than for AP irradiation, and not only for hadrons.

It is to be noted the relatively low values of conversion coefficients for photons (under equal fluence) for both the considered irradiation geometries.

For ambient dose equivalent H*(10) (figure 3), the conversion coefficients appear to be approximately independent of the energy for several kinds of primary radiation. Only those for photons and neutrons rise as function of energy, and only at low energies.

The ambient dose equivalent, H*(d), has been introduced for purposes of monitoring. Using the currently recommended value of 10 mm for the depth *d*, ambient dose equivalent does not always give a prudent estimate of effective dose, especially

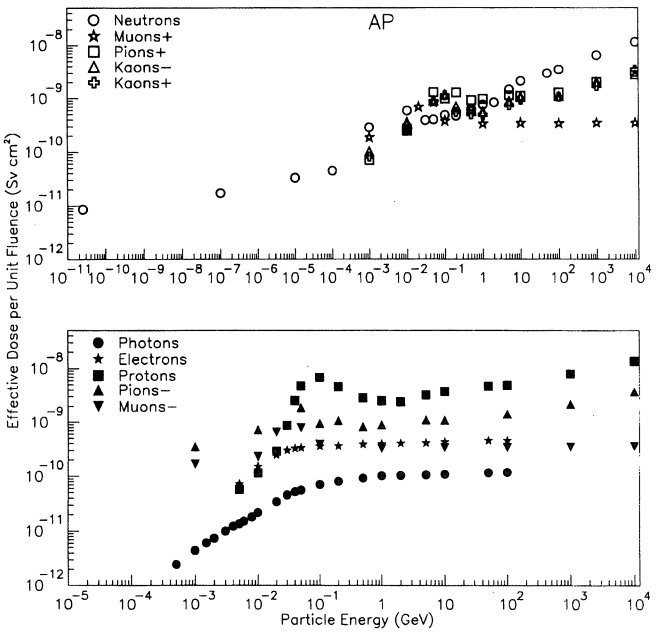

Fig. 1 Effective dose (AP) per unit fluence for various kinds of radiation.

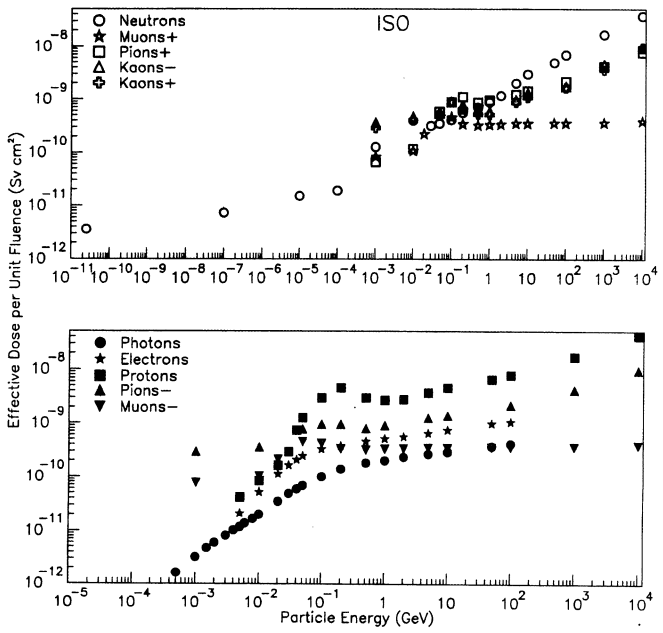

Fig. 2 Effective dose (ISO) per unit fluence for various kinds of radiation.

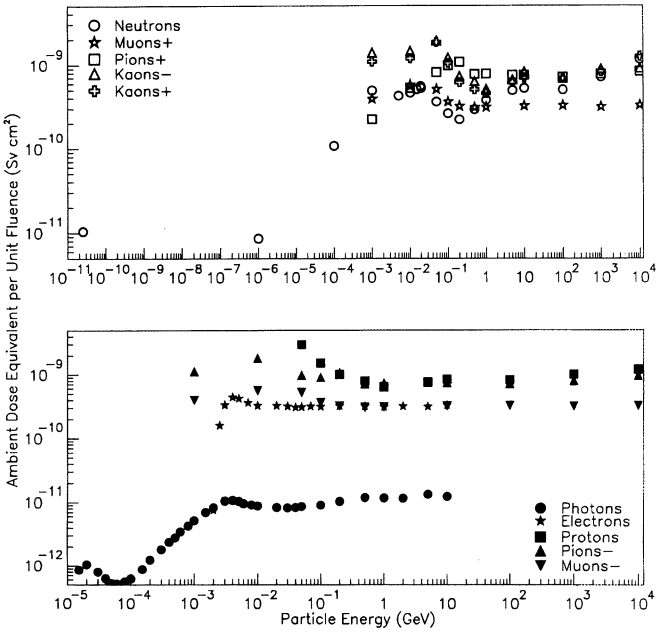

Fig. 3 Ambient dose equivalent per unit fluence for various kinds of radiation.

at higher energies. On the other hand, a single value of depth, *d*, which would make H*(d) an appropriate operational quantity irrespective of incident radiation energy cannot be specified[13,18]. However the radiation field through the shields is progressively constituted of low-energy radiation, when the concept of ambient dose equivalent could be applied.

Conversion coefficients for H*(10) are the same in all irradiation geometries. In the case of effective dose, on the contrary, there are significant differences depending on the irradiation geometries.

It should be noted that all the coefficients shown in figures 1, 2 and 3, have been calculated by the same group of authors under the same conditions (same code, same geometry, same rules, etc.). Hence, they are more directly comparable to each other than those calculated by different authors.

The agreement with the calculation of other authors is generally satisfactory, with a few exceptions.

III. Shielding Calculations

In order to use protection or operational quantities for shielding calculation, a few basic questions need to be answered first. It is necessary to specify what kind of quantity needs to be used, as well as the relative set of conversion coefficients and the w_R values.

This problem has been studied on the basis of a few practical examples. However, it is to be noted that both protection and operational quantities have been defined in order to estimate the stochastic risks related to the irradiation of the human body at low doses. Hence, no meaning has to be associated to their values when they are exceeding the recommended limits, as it occurs in the early layers of the shields.

A 800 MeV proton beam was made to impinge on a copper cylindrical target 40 cm thick, radius in the range from 1 to 30 cm, followed by a concrete shield 5 m thick. The yield of secondary particles produced in the target and the attenuation on the concrete have been studied by Monte Carlo simulations performed using the transport code FLUKA. The results of the simulations were expressed in terms of spectral fluences at various angles and depths. Then the calculated fluences of protons, neutrons, charged pions and photons, were converted in protection and operational quantities by means of the conversion coefficients of Figures 1, 2 and 3.

Figure 4 shows the calculated yield in terms of ambient

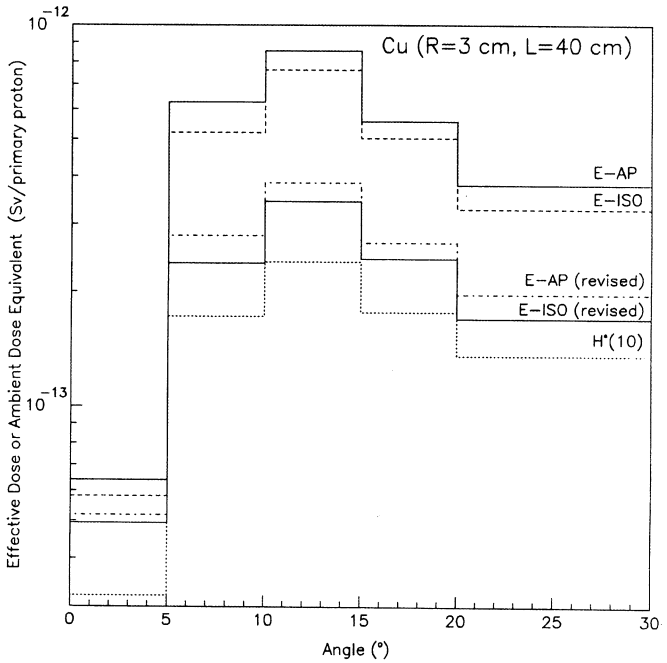

Fig. 4 Calculated doses as a function of the angle with the primary beam direction at 20 cm from a thick copper target hit by a 800 MeV proton beam.

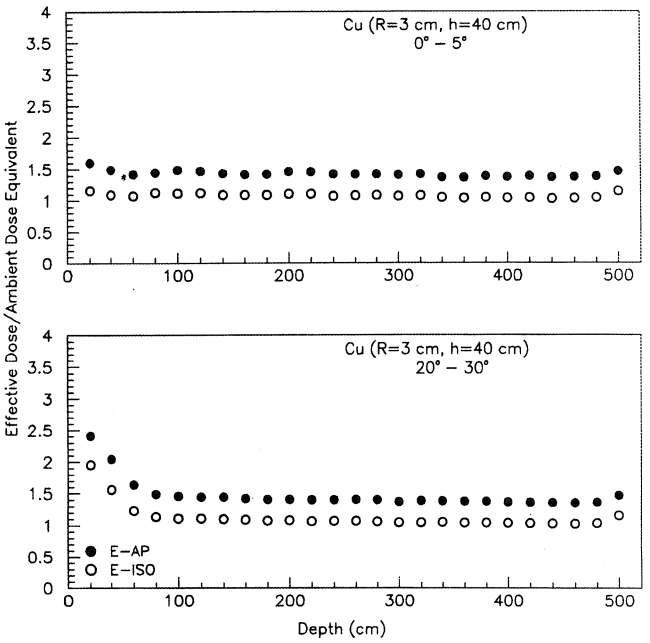

Fig. 5 Ratio effective dose to ambient dose equivalent as a function of the concrete depth for a 800 MeV proton beam impinging on a thick copper target.

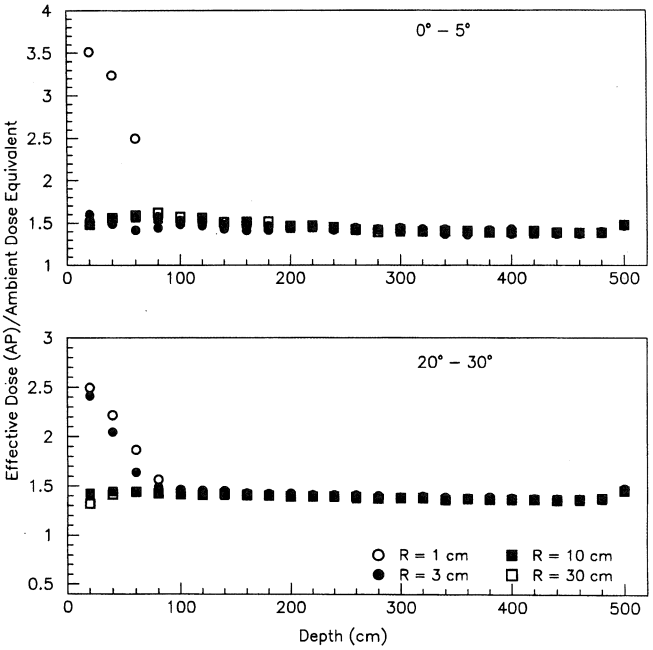

Fig. 6 Ratio effective dose for AP incidence to ambient dose equivalent as a function of the concrete depth for a 800 MeV proton beam impinging on thick copper targets of various radius.

dose equivalent and effective dose for AP and ISO irradiation geometries, as a function of the angle of scoring, when the proton beam was incident on a target having a radius of 3 cm. The vertex of the angle was located at the "effective" centre of the target. The scoring surfaces were lying in a plane perpendicular to the beam direction, at 20 cm of distance from the target. It is evident that the operational quantity cannot provide a good measure of the protection quantities. Using the more appropriate values of the radiation weighting factors proposed in ref. 26, the discrepancy between operational and protection quantities is alleviated, but not eliminated (see Figure 4).

Figure 5 shows the ratio effective dose to ambient dose equivalent in the forward direction (angle of scoring between 0° and 5°) and in the direction between 20° and 30° as a function of concrete depth, for the same target and irradiation geometries as those of Figure 4. No significant differences have been observed using the set of radiation weighting factors suggested in ref. 26, since the doses are mainly due to the neutron component.

Figure 6 shows the ratio effective dose for AP incidence to ambient dose equivalent in the forward direction as well as between 20° and 30° as a function of concrete depth and of the target radius.

The operational quantity does not seem to give a conservative measure of the protection quantities, though it does not significantly under-estimate them, especially for ISO irradiation. The discrepancy for front incidence is a factor 2.5 which increases to 3-4 at the early layers of the shield. However, the discrepancy is expected to increase in the case of primary beam of higher energy. For purposes of shielding design, it seems prudent to use the sets of conversion coefficients from fluence to effective dose calculated for AP irradiation, at least for the radiation and the energies here investigated. On the other hand, the operational quantities have been defined for purposes of monitoring in the workplaces. However, looking at figures 5 and 6, it is likely that, in the case of high-energy accelerators, the ambient dose equivalent does not provide a good measure in the workplaces either.

IV. Conclusions

On the basis of the preliminary results above presented, the effective dose calculated for AP incidence seems to be the most appropriate quantity for a conservative estimate of the accelerator shields.

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