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OVERVIEW OF FLUENCE-TO-EFFECTIVE DOSE AND FLUENCE-TO-AMBIENT DOSE EQUIVALENT CONVERSION COEFFICIENTS FOR HIGH ENERGY RADIATION CALCULATED USING THE FLUKA CODE

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Abstract — ICRP 74 and ICRU 57 recommended conversion coefficients for use in radiological protection for electrons and photons of energies up to 10 MeV and for neutrons up to 180 MeV. For various purposes (radiation protection around high energy accelerators, shielding calculations, air crew dose assessment, space activity) conversion coefficients for higher energies and other kinds of radiation are needed. Sets of fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients for all kinds of radiation (photons, electrons, positrons, protons, neutrons, muons, charged pions, kaons) and incident energies (up to 10 TeV) of practical interest have been calculated in recent years by the Monte Carlo transport code FLUKA. Since the calculated results are scattered through several papers (journals and proceedings of conferences), it has been considered useful to summarise them in the present paper.

INTRODUCTION

There are two types of quantities specifically defined for use in radiological protection: protection quantities, defined by the ICRP and used for assessing the limits, and operational quantities, defined by the ICRU and intended to provide a reasonable estimate of the protection quantities. Compliance with the limits is demonstrated by a determination of the appropriate operational quantities[1,2].

Protection quantities

The most recent set of protection quantities was recommended in ICRP Publication 60[3]. It includes the tissue or organ equivalent doses, H_T, and the effective dose, E.

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

$$H_T = \Sigma_R\, w_R D_{T,R} \qquad (1)$$

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.

Table 1 gives the values of radiation weighting factor as recommended by ICRP. It is noticeable that, in the case of neutrons, as an approximation, a continuous function was also recommended in Paragraph (A12) of ICRP Publication 60.

For radiation types and energy that are not included in Table 1, the ICRP stated in Paragraph (A14) of ICRP Publication 60 that an approximation to w_R can be obtained by calculation of $\overline{Q}$ at a depth of 10 mm in the ICRU sphere:

$$\overline{Q} = \frac{1}{D}\int_L Q(L)D(L)dL \qquad (2)$$

where D(L)dL is the absorbed dose at 10 mm between linear energy transfer values of L and L+dL and Q(L) the corresponding quality factor.

It is interesting to note that, for some kinds of high energy radiation, the recommended w_R values have been found inconsistent with those obtained by Equation 2 and with the Q–L relationship. Therefore, based on the values of several effective quality fac-

Table 1. Values for radiation weighting factors recommended in ICRP Publication 60.

Radiation	w_R
Photons	1
Electrons and muons	1
Neutrons, energy	
<10 keV	5
10 keV–100 keV	10
>100 keV–2 MeV	20
>2 MeV–20 MeV	10
>20 MeV	5
Protons, other than recoil protons, energy >2 MeV	5
Alpha particles, fission fragments, heavy nuclei	20

tors, a new methodology of calculation has been recently proposed[4]. Table 2 shows the set of coherent w_R values for high energy radiation, evaluated according to this methodology.

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:

$$E = \Sigma_T \, w_T H_T \quad (3)$$

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

Table 3 gives the values of tissue weighting factor as recommended by ICRP.

However, the ICRP has frequently revised its specification of the organs to be included and the rules to be applied for the calculation of effective dose[5–7]. In particular, as far as the rules are concerned, while in ICRP Publication 67[5], the Commission stated that the higher value of doses to the ovaries and testes had to be applied to the gonad weighting factor, in ICRP Publication 74, the average of the doses to these organs was considered in the analysis of the published data. Although the values of effective dose are only slightly affected by these changes, care is needed to avoid ambiguity. In practice, it is always desirable to specify the way of evaluating the effective dose.

Table 2. Radiation weighting factors for high energy radiation proposed in Reference 4.

Radiation	Energy (GeV)	Radiation weighting factor
Neutrons	0.05–0.1	5
	0.1–0.5	4
	0.5–10	3
	>10	2
Protons	>0.01	2
Negative pions	<0.05	5
	⩾0.05	2
Positive pions	<0.1	1
	⩾0.1	2
Negative and positive muons	10^{-3}–10^4	1
Negative and positive kaons	10^{-3}–10^4	2

Table 3. Tissue weighting factors recommended in ICRP Publication 60.

Tissue or organ	w_T
Gonads	0.20
Red bone marrow, Colon, Lung, Stomach	0.12
Bladder, Breast, Liver, Oesophagus, Thyroid, Remainder	0.05
Bone surface, Skin	0.01

The limiting quantities (H_T and E) are not directly measurable but may be related by calculation to the radiation field if the conditions of irradiation are known. The only way to estimate H_T and E is to measure the radiation field outside the body and convert it to H_T and E using previously calculated conversion coefficients.

Operational quantities

The mean absorbed dose $D_{T,R}$ was soon recognised as a quantity that cannot be evaluated experimentally[8,9]. Therefore, according to the ICRU[9], Equations 1 and 3 cannot be used as a basis for measurements. For these purposes, the operational quantities defined in terms of the quality factor (Q), namely ambient dose equivalent, directional dose equivalent and personal dose equivalent, should be used. These operational quantities were first defined in ICRU Report 39[10]. Changes to the definitions of the quantities recommended for individual monitoring were subsequently made. A complete compilation of all operational quantities currently recommended by the ICRU is available in ICRU Report 51[9]. 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.

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[10].

Really, it is quite questionable whether the operational quantities may be defined as ‘measurable quantities’. In fact, an instrument can be calibrated in terms of one of them provided that previously calculated conversion coefficients are known. Operational quantities are just more stable than protection quantities, because the tissue weighting factor does not appear in their definitions.

According to paragraph 70 of both ICRP Publication 74 and ICRU Report 57, the operational quantities are intended to provide a reasonable estimate of the protection quantities in assessing compliance with the limits. This may be simply expressed by the goal that the value of the appropriate protection quantity is less than that of the operational quantity (paragraph 319 of both ICRP Publication 74 and ICRU Report 57). It is to be noted that ICRP Publication 74 and ICRU Report 57 have identical contents. It was agreed that the final report of a Joint Group of the ICRP and the ICRU, aimed to determine whether the operational quantities represent adequately the protection quantities, would be published in the Annals of the ICRP and as an ICRU Report.

Conversion coefficients

The international bodies provided conversion coefficients for protection and operational quantities only in the case of photons and electrons of energy up to 10 MeV and neutrons of energy up to 180 MeV (ICRP Publication 74 and ICRU Report 57). Conversion coefficients for higher energies and other kinds of radiation can be found in the literature.

The fluence-to-dose conversion coefficients at high energies are the basic data for various purposes like shielding calculations, dose evaluations around targets, gas bremsstrahlung estimates, air crew dose assessment, dose evaluations in space activities, etc.

Sets of fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients have been homogeneously calculated in recent years by the Monte Carlo transport code FLUKA for all kinds of radiation (photons, electrons, positrons, protons, neutrons, muons, charged pions, kaons) and incident energies (up to 10 TeV) of practical interest[11–25]. The calculated results, however, are scattered through several papers. It has therefore been considered useful to summarise them in the present paper, referring for discussion and comments to the original texts.

Other sets of conversion coefficients (i.e. fluence-to-effective dose equivalent for electrons[16] and photons[15]; dose equivalent at 0.07 and 3 mm depths for electrons[12] and positrons[13]) calculated by FLUKA code are not considered here.

Sets of conversion coefficients for high energy electrons, photons, neutrons and protons, have also been calculated by a few other groups of authors[26–45] using various Monte Carlo codes (EGS4, HADRON, HERMES, LAHET, MCNP, MORSE). The present author knows of no other authors who have made calculations for muons, pions and kaons.

METHOD OF CALCULATION

FLUKA code

The Monte Carlo code FLUKA is a general purpose transport code which has been substantially improved in recent years[46,47]. The particle interactions and the transport models used, as well as details about the capability of FLUKA to simulate electromagnetic and hadron transport are discussed elsewhere[47–50].

Three models are currently used to describe hadronic

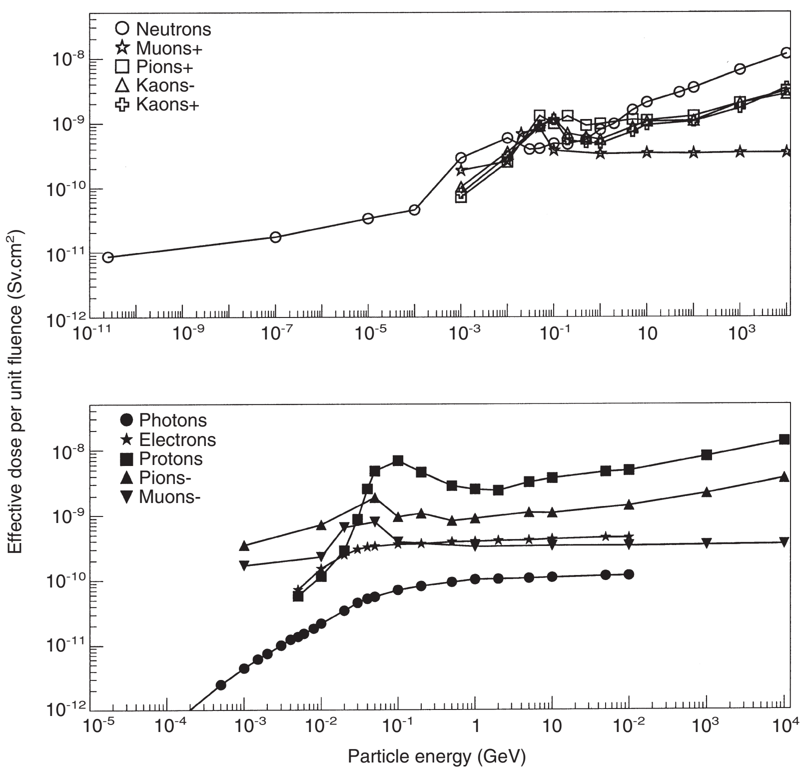

Figure 1. Effective dose (AP) per unit fluence as a function of particle energy for various kinds of radiation.

inelastic interactions in different projectile energy ranges. A specific model, the Pre-Equilibrium Approach to Nuclear Thermalization (PEANUT) model[51,52], is implemented for nucleons and pions of energy below 2 GeV. PEANUT consists of four stages: intranuclear cascade (INC), pre-equilibrium, evaporation and disexcitation. Since in the case of light nuclei (typically A≤16) other de-excitation mechanisms are more suitable, the Fermi break-up model was adopted. The PEANUT model is essential to describe properly the interactions of nucleons and pions at intermediate energies (from about 20 MeV to few GeV). Primary interactions between 2 and 5 GeV are described via a quasi-two particle resonance–decay model, and above 5 GeV by multichain fragmentation in the frame of the Dual Parton Model (DPM).

Low energy neutrons (below 19.6 MeV) are transported according to a multigroup approach (72 neutron groups and 22 gamma rays groups), based either on the ENDF/B-VI[53] or JEF-2.2[54] neutron cross sections, depending on the material. Capture gamma rays are generated according to the appropriate group probabilities and are transported using continuous energy-dependent cross-sections until they are either leaked out or their histories are terminated. Energy deposited by low energy neutrons is computed using kerma factors, tabulated in the multigroup cross section data file. However protons generated from reactions in hydrogen and nitrogen are transported explicitly as any other proton.

Charged particles are transported by applying an improved multiple scattering algorithm[46] based on Molière's theory of Coulomb scattering. To evaluate the unrestricted energy loss of heavy charged particles in elemental substances, FLUKA makes use of the Bethe–Bloch formula with mean excitation energy and density effect parameters taken from the compilations of References 55 and 56. In the case of compounds and mixtures, the Bragg additivity rule is used only when the relevant parameters of the compound or mixture under investigation are not known. In order to improve the mean excitation energies of liquid and solid compounds over the simple Bragg addition rule, the suggestions given in ICRU Report 49[57] are applied whenever the material is not included in the available compilations.

The mathematical anthropomorphic model used for effective dose calculations

In computing effective dose an hermaphrodite mathematical model has been used. It was derived from the male phantom developed for MCNP by GSF-Forschungszentrum für Umwelt und Gesundheit

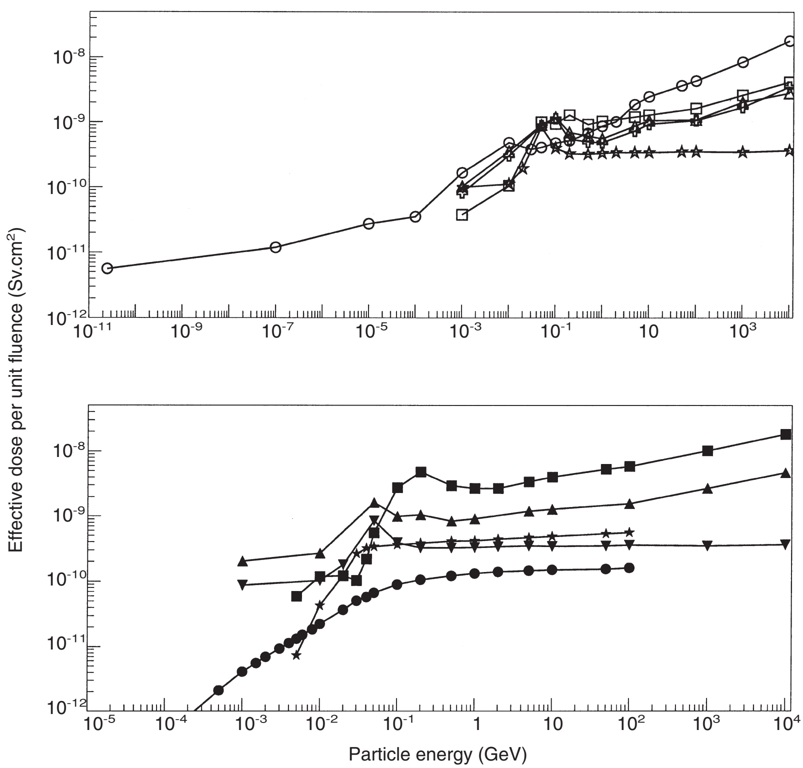

Figure 2. Effective dose (PA) per unit fluence as a function of particle energy for various kinds of radiation. Key as Figure 1.

(Germany)[58]. The MCNP phantom was translated in terms of bodies and regions appropriate for the combinatorial geometry of FLUKA. Then the female organs (breast, ovaries, uterus) were added. Additional changes with respect to the original model concern the representation of bone surfaces and red bone marrow.

Some difficulties have been encountered in the translation, due to the minor number of surfaces which FLUKA can handle. As a consequence, the geometry of some organs had to be changed. The guideline was a reasonable compromise between a simplified geometry and an accurate description of the original phantom. The encountered surfaces which can not be handled by FLUKA were: the generic ellipsoid with the three axes of arbitrary length, used in the MCNP phantom to represent brain, cranium, urinary bladder, stomach, testes, etc.; the torus, used in the MCNP phantom to model the clavicles and the sigmoid colon; the frustum of an elliptical cone, used for the bones of the arms and for the legs. The generic ellipsoid has been replaced by an ellipsoid of revolution. The major and minor axis of this ellipsoid were assumed to be equal to the generic ellipsoid major axis, and to the square root of the product of the other two axes, respectively. The torus has been substituted by two concentric cylinders cut by appropriate planes. The frustum of the elliptical cone was replaced by two pieces of an elliptical cylinder of different circumference.

The various organs and tissues of the human body have been represented by 68 regions.

Internal organs have been considered to be homogeneous in composition and density. Different densities and compositions have been used for the lungs, bone, red bone marrow, soft tissues and skin. The composition of these five tissues were limited to the 14 elements H, C, N, O, Na, Mg, P, S, Cl, K, Ca, Fe, Zr, Pb. The density was assumed 0.296 g.cm^{-3} for the lungs, 1.486 g.cm^{-3} for the bone, 1.028 g.cm^{-3} for red bone marrow, 0.987 g.cm^{-3} for soft tissues, 1.105 g.cm^{-3} for skin. Since the fluence can be interpreted as the track length density of the particles at a point in space, the volumes of the organs were estimated using an empty phantom and track length estimators.

CALCULATED CONVERSION COEFFICIENTS

Fluence-to-effective dose conversion coefficients

Calculations of effective dose have been carried out on the basis of Equation 3 using the official values of

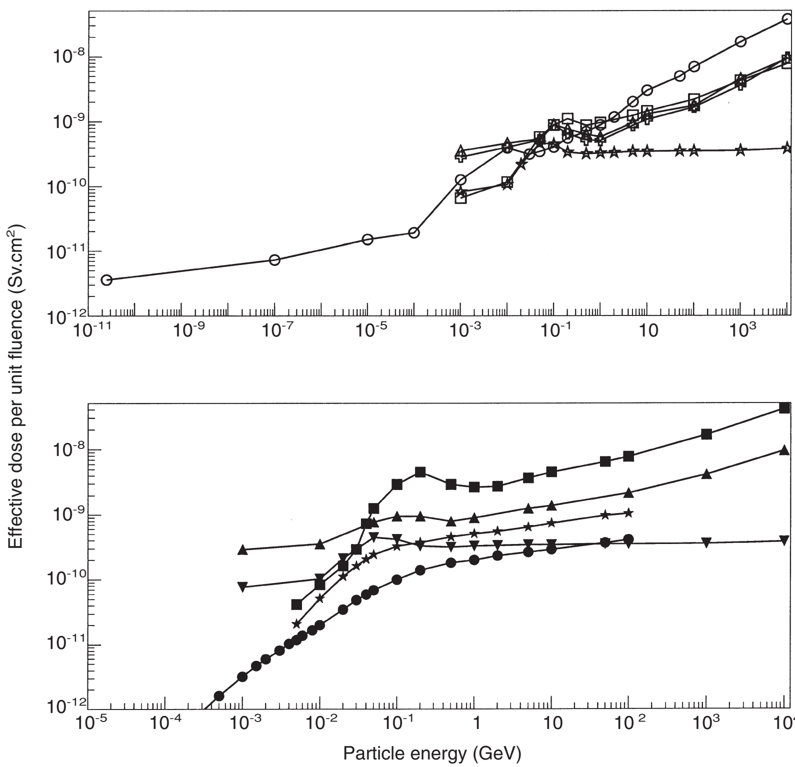

Figure 3. Effective dose (ISO) per unit fluence as a function of particle energy for various kinds of radiation. Key as Figure 1.

the radiation weighting factor shown in Table 1. For charged pions and kaons the approximation given by Equation 2 has been applied[22,25]. A few changes have been introduced with respect to the definition of effective dose given in ICRP Publication 60. Concerning the so-called remainder, according to ICRP Publication 67, the upper large intestine has not been included and the rules suggested in Reference 59 have been adopted. Thus the remainder dose has been evaluated from the doses to nine additional individual organs and tissues as arithmetic mean. The recommendations given in footnote 3 of Table 2 in ICRP Publication 60 have been ignored. It should, however, be noted that this rule is of poor concern in the case of a uniform whole-body irradiation. Nevertheless some guidance on this matter would be desirable.

Guidance would also be desirable about the way of evaluating the dose received by organs or tissues spread throughout the whole body and represented in the mathematical model by several regions, as for instance, skin, bone, red bone marrow, muscle, etc. In principle two methods can be proposed, the maximum of the doses to the single constituent regions or their mean (arithmetic or mass weighted). In the present calculations, the dose to a given organ or tissue has been determined as arithmetic mean of the doses received in the single constituent regions.

According to ICRP Publication 67, the higher value of doses to the ovaries and to testes was applied to the gonad weighting factor.

The dose to the muscles has been assumed as the arithmetic mean of the doses received by that part of the body volume which is not attributed to any other organ or tissue of the anthropomorphic model.

Calculations were usually performed for whole-body irradiation of the phantom with broad parallel beams and fully isotropic radiation incidence. The directions of incidence of the parallel beams were anterior-posterior (AP), posterior-anterior (PA) and right lateral (LAT). The isotropic irradiation (ISO) has been obtained by the use of an inward-directed, biased cosine source on a spherical surface. The medium between the source and the phantom was assumed to be a vacuum.

By Monte Carlo simulations, the energy per primary incident particle deposited in the regions representing the various organs and tissues of the human body has been determined.

The statistical uncertainties were estimated by doing calculations in several batches and computing the standard deviation of the mean. The total number of histories was large enough to keep the standard deviation of conversion coefficients below a few per cent. A greater accuracy seemed to be superfluous, in consideration that differences of 5% can be expected among the results of well proven codes[60].

Tables A1.1--A1.11 of Appendix 1 summarise the calculated results in terms of effective dose per unit of fluence (Sv.cm^2). Statistical uncertainties (standard deviation) are presented following each value. Figures 1, 2 and 3 give a graphical presentation of the calculated results in the case of AP, PA and ISO irradiation, respectively. The solid lines in the graphs were drawn to guide the eye.

The data of Tables A1.1–A1.11 constitute a coherent system of conversion coefficients because they have all been calculated under the same conditions (same code, same geometry, same rules, etc.). If one is willing to adopt the w_R values given in Table 2, the calculated data should be simply scaled with respect to the w_R values used.

Usually AP or PA irradiation gives the maximum effective dose per unit of fluence for low incident energies (up to 50–100 MeV). Conversely, LAT or ISO irradiation gives the highest values at high incident energies (in excess of 100 MeV), due to the greater paths of the particles through the phantom. Inspection of Figures 1, 2 and 3 shows that the shape of the curves is very complicated. Therefore, it has not been possible to formulate a simple mathematical approximation for these curves. The effective dose per unit of fluence increases over the entire energy range practically for all types of radiation investigated, with a few exceptions in the energy range 0.1–1 GeV. For ISO irradiation, the rise of conversion coefficients as a function of energy is more evident at high incident energies than for the other geometrical conditions of irradiation, especially for hadrons.

It is interesting to note the relatively high values of conversion coefficients for protons, due to the value of 5 assigned to their radiation weighting factor, when different from recoil protons.

Fluence-to-ambient dose equivalent conversion coefficients

According to the definition of ambient dose equivalent, the geometry considered in the calculations was very simple. A 30 cm diameter sphere of unit density tissue and composition as specified by ICRU (H, 10.1% by weight; C, 11.1%; N, 2.6%; O 76.2%), was exposed to a parallel particle beam uniformly expanded over its front surface. The medium between the source and the phantom was assumed to be a vacuum. It should be recalled that the international bodies (ICRP and ICRU) considered this medium to be a vacuum for electrons and neutrons, but not for photons. As a result, the recommended conversion coefficients for primary electrons are implicitly different from those for secondary electrons. Unfortunately, an instrument being irradiated cannot identify the forebear of the electron with which it is interacting and modify its response accordingly.

In order to obtain the depth–dose distributions along the principal axis of the sphere, the energy deposited has been scored as a function of the depth and radius in an R-Z binning cylindrical structure. Different grids have been selected according to the depth: 0.2 cm longitudinal bins have been considered up to 2 cm, 1 cm ones for larger depths. The radial bin was taken usually to be 1 cm.

The determination of the dose equivalents has been carried out taking the quality factor to be a function of the linear energy transfer according to the relationship recommended in ICRP Publication 60. Therefore the energies deposited per unit mass have been directly multiplied by the quality factor appropriate to the linear energy transfer of the charged particle imparting energy to the matter. In the case of neutron interactions at energies below 19.6 MeV, however, the quality factors applied to the energy depositions computed by using kerma factors have been properly determined by the methodology described in Reference 23. The values of the ambient dose equivalent have been averaged over the depth 0.95–1.05 or 0.9–1.1 cm according to the incident energy.

In order to improve statistics, a special algorithm has been used to concentrate artificially the incident particles on the sphere axis[11]. The statistical uncertainties were estimated by doing all calculations in several batches and computing the standard error of the average. The total number of histories was large enough to keep the standard error on the computed dose equivalents usually below few %.

Tables A2.1–A.2.11 of Appendix 2 summarise the calculated results in terms of ambient dose equivalent per unit of fluence (Sv.cm^2). Statistical uncertainties (standard deviation) are presented following each value. Figure 4 gives a graphical presentation of the calculated results. The solid lines in the graph were drawn to guide the eye. The maximum of the dose equivalent along the principal diameter of an ICRU sphere is also reported in Tables A2.1–A2.11.

The ambient dose equivalent per unit fluence tends to be approximately independent of energy for a lot of radiation in the high energy region. On the contrary, at low incident energies, it strongly rises as function of energy, at least in the case of photons and neutrons.

It is noticeable that, in contrast to the case of effective dose, the coefficients for protons are now of the same order of magnitude as those for negative pions, since the ambient dose equivalent is defined by means of quality factors instead of radiation weighting factors.

As far as fluence-to-ambient dose equivalent conversion coefficients for photons are concerned, it should be noted that there are significant discrepancies between the set recommended by ICRP–ICRU[1,2] and the results of Table A2.1, in the energy range 3 to 10 MeV (for example, at 10 MeV, 25.6 pSv.cm^2[1,2] against 8.76 pSv.cm^2[11]). These discrepancies have been analysed and discussed in previous papers[4,11,19,61,62]. The conclusion was that the influence of the air is dramatically overestimated by the conversion coefficients adopted by the international bodies.

The use of the ICRP–ICRU conversion coefficients up to 10 MeV (maximum energy considered) jointly with those of Table A2.1 above 10 MeV is not advisable, because it would be the cause of an unphysical discontinuity for incident photons of energy in excess of 10 MeV. In order to evaluate the ambient dose equivalent, especially for high-energy radiation, it is appropriate to fold separately electron and photon spectra with the relative set of conversion coefficients calculated in a vacuum.

It is evident from the data collected in Tables A2.1–A2.11 that, for high energy radiation, the ambient dose equivalent, H*(10), is usually smaller than the maximum dose equivalent value and differs appreciably from it over certain sections of the energy range. The ambient dose equivalent, H*(10), is expected to give a conservative approximation of the effective dose only at relatively low incident energies and with a few exceptions.

According to ICRU, for high energy radiation, a depth value higher than 10 mm might be more appropriate. Unfortunately, a depth value common to all kinds of high energy radiation cannot be defined. The maximum of the dose equivalent along the principal axis of the ICRU sphere is in fact an overestimator of the effective dose for electrons, photons, muons and pions, but not for neutrons of energy in excess of 100 MeV and for protons. Hence, no single depth value can be usefully specified in the ICRU sphere which makes ambient dose equivalent appropriate for purposes of high energy neutron and proton dosimetry. As a consequence, it could be stated that the ICRU sphere is an unsuitably simplified phantom, at least for purposes of high energy proton and neutron dosimetry.

The lack of conservatism of the ambient dose equivalent with respect to the effective dose might be mitigated using the set of w_R values of Table 2, consistent with the Q–L relationship. Incidentally, as far as protons are concerned, the inadequacy of the recommended w_R value can be seen very clearly when comparing the curves for protons and negative pions of Figures 1, 2 and 3 with those of Figure 4.

CONCLUSIONS

Sets of fluence-to-effective dose and fluence-to-ambient dose equivalent conversion coefficients have been calculated by the Monte Carlo code FLUKA for all kinds of high energy radiation of practical interest[11–25]. The calculated results have been summarised in the Appendices of this paper. All conversion coefficients have been calculated using the same methodology (same code, same geometry, same rules, etc.). Therefore they constitute a coherent system of dosimetric data. The calculated sets of conversion coefficients can be found on the web site http://www.lnf.infn.it/lnfadmin/radiation/.

Only few other groups of authors[28,29,31–45] have made calculations of effective dose and ambient dose equivalent for radiation of energies in excess of those considered in ICRP Publication 74 and in ICRU Report

57. As far as the present author is aware, no other author has made calculations for muons, pions and kaons. Comparisons between FLUKA and other computer code calculations can be found in literature(34,39,40,42). The agreement is generally satisfactory. Nevertheless, significant discrepancies have been found for neutrons in the energy range 1–5 GeV, probably due to the different physical models adopted by the different codes at intermediate energies. In order to make clear the reasons of these discrepancies, benchmarks between the various codes and experimental results would be highly desirable. However, it is interesting to recall that the predictive power of FLUKA has been proved to be very reliable in numerous applications at high energy accelerators, where detailed comparisons with experimental data are possible(47–52).

Finally, it would be desirable that the international bodies (ICRP and ICRU) consider revising the recommended w_R values and give additional guidance regarding the various problems encountered in the calculations of the presented conversion coefficients.

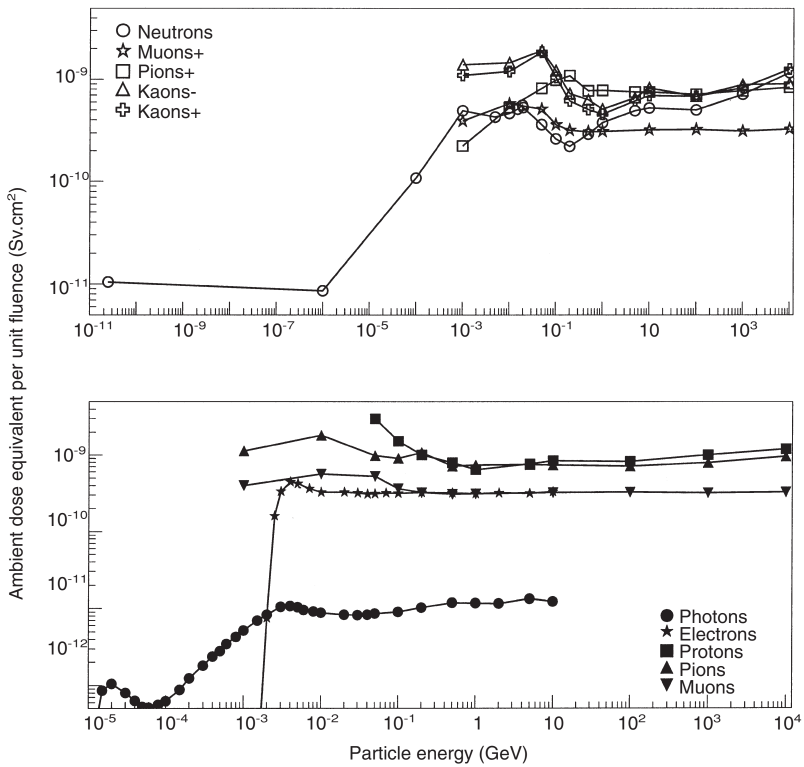

Figure 4. Ambient dose equivalent per unit fluence as a function of particle energy for various kinds of radiation.

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APPENDIX 1

Fluence-to-Effective Dose Conversion Coefficients

Table A1.1. Fluence-to-effective dose conversion coefficients (Sv.cm^2) as a function of photon incident energy for different geometrical conditions of irradiation of an anthropomorphic mathematical model[15,19].

Photon energy (GeV)	AP		PA		LAT		ISO	
0.00005	3.68E−13	2.2%	2.35E−13	3.7%	1.23E−13	2.7%	1.69E−13	4.2%
0.0001	5.13E−13	1.3%	4.00E−13	2.5%	2.28E−13	2.1%	2.75E−13	3.4%
0.0005	2.48E−12	1.4%	2.11E−12	2.1%	1.44E−12	1.2%	1.61E−12	3.2%
0.001	4.47E−12	2.4%	4.09E−12	2.7%	2.95E−12	3.1%	3.19E−12	4.5%
0.0015	6.13E−12	2.0%	5.54E−12	2.3%	4.34E−12	1.7%	4.69E−12	4.5%
0.002	7.47E−12	1.7%	6.92E−12	2.9%	5.62E−12	1.8%	5.97E−12	3.8%
0.003	9.94E−12	2.1%	9.28E−12	4.5%	7.77E−12	1.7%	8.11E−12	3.7%
0.004	1.22E−11	3.2%	1.13E−11	2.9%	9.66E−12	2.1%	1.03E−11	3.6%
0.005	1.36E−11	2.0%	1.32E−11	2.6%	1.14E−11	2.7%	1.18E−11	4.1%
0.006	1.52E−11	2.8%	1.50E−11	2.8%	1.33E−11	2.0%	1.37E−11	3.6%
0.008	1.82E−11	3.0%	1.83E−11	2.8%	1.66E−11	2.7%	1.66E−11	3.7%
0.01	2.16E−11	2.8%	2.23E−11	3.0%	1.96E−11	2.7%	2.00E−11	2.5%
0.02	3.44E−11	3.5%	3.66E−11	2.4%	3.47E−11	2.9%	3.48E−11	4.3%
0.03	4.54E−11	3.5%	5.06E−11	3.2%	4.80E−11	2.1%	4.88E−11	4.0%
0.04	5.22E−11	3.3%	5.75E−11	2.4%	6.21E−11	2.3%	5.92E−11	3.9%
0.05	5.55E−11	2.4%	6.72E−11	2.3%	7.37E−11	3.5%	6.89E−11	3.8%
0.1	7.06E−11	3.7%	8.91E−11	3.1%	1.19E−10	2.6%	1.00E−10	4.3%
0.2	8.16E−11	3.0%	1.06E−10	4.1%	1.51E−10	2.6%	1.40E−10	3.2%
0.5	9.37E−11	3.6%	1.21E−10	3.3%	1.90E−10	4.2%	1.81E−10	4.1%
1.0	1.03E−10	3.4%	1.32E−10	2.8%	2.14E−10	4.3%	2.01E−10	3.5%
2.0	1.05E−10	3.3%	1.40E−10	3.4%	2.43E−10	4.1%	2.35E−10	3.2%
5.0	1.07E−10	3.8%	1.46E−10	2.8%	2.69E−10	3.8%	2.64E−10	3.7%
10.0	1.10E−10	3.0%	1.49E−10	2.9%	2.81E−10	3.7%	2.93E−10	3.9%
50.0	1.17E−10	3.1%	1.54E−10	1.7%	3.18E−10	3.2%	3.68E−10	2.5%
100.0	1.19E−10	2.4%	1.60E−10	2.0%	3.31E−10	3.9%	4.14E−10	3.5%

E−13 = $\times 10^{-13}$.

Table A1.2. Fluence-to-effective dose conversion coefficients (Sv.cm^2) as a function of electron incident energy for different geometrical conditions of irradiation of an anthropomorphic mathematical model[16,19].

Photon energy (GeV)	AP		PA		LAT		ISO	
0.005	7.19E−11	3.0%	7.37E−12	1.9%	8.95E−12	3.1%	2.07E−11	4.3%
0.01	1.52E−10	1.7%	4.27E−11	1.1%	2.05E−11	2.3%	5.12E−11	4.3%
0.02	2.48E−10	1.8%	1.24E−10	2.4%	8.11E−11	1.8%	1.12E−10	4.7%
0.03	2.99E−10	1.9%	2.64E−10	3.2%	1.36E−10	2.0%	1.63E−10	4.6%
0.04	3.26E−10	2.6%	3.22E−10	3.0%	1.90E−10	3.3%	2.06E−10	4.5%
0.05	3.37E−10	2.6%	3.41E−10	2.8%	2.30E−10	1.9%	2.45E−10	3.2%
0.1	3.58E−10	3.3%	3.64E−10	1.9%	3.29E−10	2.5%	3.28E−10	3.4%
0.2	3.66E−10	3.2%	3.84E−10	2.8%	4.07E−10	4.0%	3.77E−10	3.8%
0.5	3.89E−10	2.8%	4.15E−10	2.3%	4.68E−10	2.9%	4.53E−10	4.0%
1.0	3.99E−10	3.6%	4.18E−10	2.3%	5.09E−10	3.7%	5.06E−10	3.5%
2.0	4.07E−10	3.5%	4.46E−10	3.4%	5.82E−10	3.8%	5.51E−10	4.2%
5.0	4.16E−10	3.5%	4.68E−10	2.4%	6.34E−10	4.0%	6.48E−10	3.7%
10.0	4.30E−10	2.7%	4.91E−10	3.0%	7.21E−10	3.5%	7.39E−10	3.5%
50.0	4.57E−10	2.1%	5.37E−10	1.0%	8.74E−10	3.4%	9.76E−10	3.2%
100.0	4.57E−10	1.7%	5.58E−10	1.0%	8.66E−10	2.6%	1.05E−09	2.2%

Table A1.3. Fluence-to-effective dose conversion coefficients (Sv.cm^2) as a function of positron incident energy for isotropic irradiation of an anthropomorphic mathematical model[20].

Positron energy (GeV)	ISO	
1.0E−02	5.17E−11	2.4%
5.0E−02	2.30E−10	1.6%
1.0E−01	3.24E−10	2.1%
5.0E−01	4.47E−10	1.5%
1.0E+00	4.90E−10	2.9%
5.0E+00	6.43E−10	2.2%
1.0E+01	7.51E−10	3.7%
5.0E+01	9.39E−10	2.5%
1.0E+02	1.02E−09	3.2%

Table A1.4. Fluence-to-effective dose conversion coefficients (Sv.cm^2) as a function of negative muon incident energy for different geometrical conditions of irradiation of an anthropomorphic mathematical model[21].

Negative muon energy (GeV)	AP		PA		LAT		ISO	
1.0E−03	1.69E−10	1.1%	8.72E−11	2.1%	5.14E−11	1.9%	7.67E−11	2.6%
1.0E−02	2.31E−10	1.2%	1.03E−10	1.6%	6.96E−11	1.5%	1.03E−10	2.2%
2.0E−02	6.55E−10	2.0%	1.80E−10	1.3%	1.19E−10	1.3%	2.13E−10	1.9%
5.0E−02	7.95E−10	2.3%	8.47E−10	1.6%	3.89E−10	0.6%	4.47E−10	3.1%
1.0E−01	3.93E−10	1.0%	3.91E−10	0.9%	5.26E−10	1.9%	4.21E−10	0.9%
2.0E−01			3.27E−10	0.7%			3.33E−10	1.1%
5.0E−01			3.27E−10	1.7%	3.19E−10	0.8%	3.18E−10	1.2%
1.0E+00	3.33E−10	0.8%	3.32E−10	0.9%	3.32E−10	2.4%	3.29E−10	1.2%
2.0E+00			3.41E−10	2.0%			3.34E−10	1.5%
5.0E+00			3.49E−10	1.6%			3.47E−10	1.3%
1.0E+01	3.40E−10	1.6%	3.46E−10	0.8%	3.50E−10	2.7%	3.46E−10	1.1%
5.0E+01			3.50E−10	1.2%			3.55E−10	2.1%
1.0E+02	3.41E−10	1.9%	3.58E−10	1.9%	3.50E−10	0.8%	3.53E−10	1.1%
1.0E+03	3.50E−10	1.2%	3.51E−10	1.7%	3.54E−10	1.6%	3.58E−10	1.9%
1.0E+04	3.61E−10	1.0%	3.65E−10	1.2%	3.71E−10	0.6%	3.86E−10	1.6%

Table A1.5. Fluence-to-effective dose conversion coefficients (Sv.cm^2) as a function of positive muon incident energy for different geometrical conditions of irradiation of an anthropomorphic mathematical model[21].

Positive muon energy (GeV)	AP		PA		LAT		ISO	
1.0E−03	1.85E−10	1.7%	9.96E−11	2.1%	5.36E−11	1.5%	8.19E−11	1.7%
1.0E−02	2.55E−10	0.9%	1.12E−10	2.2%	7.68E−11	2.0%	1.07E−10	2.1%
2.0E−02	6.90E−10	1.3%	1.93E−10	1.6%	1.24E−10	1.7%	2.20E−10	3.3%
5.0E−02	8.48E−10	2.3%	8.45E−10	1.7%	4.00E−10	0.9%	4.64E−10	1.8%
1.0E−01	3.77E−10	0.7%	3.99E−10	1.6%	5.49E−10	1.2%	4.52E−10	2.4%
2.0E−01			3.29E−10	1.0%			3.38E−10	2.3%
5.0E−01			3.26E−10	0.9%	3.27E−10	3.0%	3.18E−10	1.2%
1.0E+00	3.32E−10	2.2%	3.36E−10	2.0%	3.33E−10	2.8%	3.28E−10	1.3%
2.0E+00			3.41E−10	0.9%			3.33E−10	3.1%
5.0E+00			3.41E−10	0.8%			3.47E−10	1.4%
1.0E+01	3.41E−10	1.7%	3.42E−10	1.2%	3.51E−10	2.4%	3.47E−10	1.1%
5.0E+01			3.54E−10	1.8%			3.55E−10	2.1%
1.0E+02	3.40E−10	1.1%	3.51E−10	3.1%	3.52E−10	0.8%	3.53E−10	1.1%
1.0E+03	3.48E−10	1.2%	3.50E−10	0.9%	3.55E−10	1.2%	3.58E−10	1.9%
1.0E+04	3.49E−10	1.2%	3.67E−10	2.5%	3.73E−10	0.7%	3.86E−10	1.6%

Table A1.6. Fluence-to-effective dose conversion coefficients (Sv.cm^2) as a function of neutron incident energy for different goemetrical conditions of irradiation of an anthropomorphic mathematical model[18].

Neutron energy (GeV)	AP		PA		LAT		ISO	
2.5E−11	8.65E−12	2.0%	5.56E−12	4.4%	2.31E−12	3.2%	3.61E−12	3.0%
1.0E−07	1.73E−11	3.0%	1.18E−11	2.8%	4.98E−12	2.1%	7.28E−12	3.4%
1.0E−05	3.31E−11	3.7%	2.72E−11	4.7%	1.09E−11	4.8%	1.50E−11	4.5%
1.0E−04	4.50E−11	1.7%	3.53E−11	3.6%	1.34E−11	3.6%	1.91E−11	1.8%
1.0E−03	2.91E−10	2.3%	1.67E−10	2.3%	8.48E−11	1.8%	1.26E−10	2.8%
1.0E−02	5.89E−10	2.8%	4.83E−10	3.7%	3.40E−10	0.9%	3.93E−10	3.1%
3.0E−02	3.93E−10	3.3%	3.82E−10	2.3%	3.07E−10	2.8%	3.15E−10	3.4%
5.0E−02	4.06E−10	2.6%	4.12E−10	2.1%	3.45E−10	4.8%	3.48E−10	3.4%
1.0E−01	4.85E−10	3.8%	4.79E−10	3.0%	4.04E−10	3.8%	4.06E−10	2.4%
2.0E−01	4.71E−10	4.0%	5.24E−10	2.3%	5.61E−10	3.3%	5.58E−10	3.8%
5.0E−01	5.58E−10	1.2%	6.79E−10	3.9%	6.63E−10	4.6%	6.95E−10	3.0%
1.0E+00	7.92E−10	2.7%	8.74E−10	2.1%	8.92E−10	3.8%	8.86E−10	2.6%
2.0E+00	9.80E−10	3.5%	1.02E−09	1.6%	1.15E−09	3.5%	1.16E−09	3.1%
5.0E+00	1.59E−09	0.8%	1.88E−09	1.6%	2.16E−09	4.8%	2.01E−09	3.5%
1.0E+01	2.08E−09	1.1%	2.47E−09	2.0%	3.05E−09	4.4%	3.01E−09	4.8%
5.0E+01	2.97E−09	4.0%	3.65E−09	1.9%	4.85E−09	2.7%	4.98E−09	2.7%
1.0E+02	3.48E−09	4.0%	4.33E−09	1.6%	6.45E−09	3.3%	6.92E−09	3.7%
1.0E+03	6.55E−09	2.0%	8.45E−09	2.0%	1.43E−08	4.3%	1.67E−08	3.7%
1.0E+04	1.15E−08	3.6%	1.78E−08	2.3%	3.31E−08	4.3%	3.67E−08	4.7%

The data in the energy range 0.5–10 GeV for AP irradiation have been recently recalculated improving the statistical accuracy.

Table A1.7. Fluence-to-effective dose conversion coefficients (Sv.cm^2) as a function of proton incident energy for different goemetrical conditions of irradiation of an anthropomorphic mathematical model[17].

Proton energy (GeV)	AP		PA		LAT		ISO	
5.0E−03	5.75E−11	0.2%	5.92E−11	0.1%	3.81E−11	0.2%	4.18E−11	0.6%
1.0E−02	1.15E−10	0.2%	1.18E−10	0.1%	7.62E−11	0.1%	8.39E−11	0.7%
2.0E−02	2.89E−10	0.8%	1.22E−10	0.7%	1.34E−10	2.2%	1.63E−10	1.5%
3.0E−02	8.77E−10	1.8%	1.03E−10	2.3%	1.86E−10	2.4%	2.91E−10	1.8%
4.0E−02	2.54E−09	1.3%	2.19E−10	2.7%	3.72E−10	2.5%	7.27E−10	4.2%
5.0E−02	4.81E−09	0.9%	5.56E−10	1.9%	4.81E−10	3.1%	1.25E−09	2.8%
1.0E−01	6.82E−09	0.4%	2.75E−09	0.6%	2.50E−09	1.2%	2.95E−09	1.3%
2.0E−01	4.57E−09	1.4%	4.79E−09	1.2%	5.64E−09	2.4%	4.54E−09	1.5%
5.0E−01	2.84E−09	1.8%	2.95E−09	2.1%	2.77E−09	1.9%	2.95E−09	3.6%
1.0E+00	2.53E−09	2.1%	2.65E−09	1.2%	2.49E−09	1.7%	2.68E−09	1.4%
2.0E+00	2.42E−09	2.6%	2.67E−09	1.9%	2.51E−09	2.6%	2.73E−09	3.4%
5.0E+00	3.24E−09	3.2%	3.38E−09	1.0%	3.35E−09	3.4%	3.65E−09	2.4%
1.0E+01	3.73E−09	1.6%	3.97E−09	1.1%	4.55E−09	2.6%	4.49E−09	3.5%
5.0E+01	4.64E−09	4.4%	5.24E−09	1.5%	6.39E−09	3.2%	6.47E−09	3.8%
1.0E+02	4.87E−09	2.5%	5.82E−09	1.5%	7.65E−09	3.2%	7.74E−09	2.5%
1.0E+03	7.97E−09	2.5%	1.01E−08	2.3%	1.57E−08	4.2%	1.68E−08	2.6%
1.0E+04	1.35E−08	3.4%	1.82E−08	2.1%	3.42E−08	4.2%	4.11E−08	4.3%

Table A1.8. Fluence-to-effective dose conversion coefficients (Sv.cm^2) as a function of negative pion incident energy for different geometrical conditions of irradiation of an anthropomorphic mathematical model[22].

Negative pion energy (GeV)	AP		PA		LAT		ISO	
1.0E−03	3.49E−10	2.2%	2.04E−10	4.0%	1.13E−10	3.8%	2.93E−10	3.2%
1.0E−02	7.21E−10	2.0%	2.70E−10	3.4%	2.25E−10	3.7%	3.56E−10	2.5%
5.0E−02	1.88E−09	3.7%	1.61E−09	3.1%	7.28E−10	1.8%	7.71E−10	1.5%
1.0E−01	9.53E−10	1.0%	9.98E−10	4.0%	1.14E−09	3.4%	9.51E−10	3.4%
2.0E−01	1.08E−09	0.6%	1.05E−09	1.9%	9.44E−10	0.6%	9.49E−10	0.7%
5.0E−01	8.29E−10	0.9%	8.35E−10	5.9%	7.79E−10	1.0%	7.98E−10	2.3%
1.0E+00	8.95E−10	3.0%	9.18E−10	1.6%	8.95E−10	3.2%	9.00E−10	2.5%
5.0E+00	1.11E−09	3.5%	1.19E−09	2.9%	1.19E−09	1.2%	1.25E−09	2.7%
1.0E+01	1.10E−09	2.3%	1.27E−09	1.7%	1.41E−09	2.9%	1.38E−09	3.0%
1.0E+02	1.43E−09	2.8%	1.54E−09	2.6%	2.15E−09	3.7%	2.15E−09	1.6%
1.0E+03	2.19E−09	3.6%	2.68E−09	2.3%	4.22E−09	3.8%	4.18E−09	4.2%
1.0E+04	3.70E−09	3.9%	4.63E−09	2.9%	7.93E−09	4.3%	9.63E−09	5.3%

Table A1.9. Fluence-to-effective dose conversion coefficients (Sv.cm^2) as a function of positive pion incident energy for different geometrical conditions of irradiation of an anthropomorphic mathematical model[22].

Positive pion energy (GeV)	AP		PA		LAT		ISO	
1.0E−03	7.13E−11	1.3%	3.75E−11	3.9%	1.97E−11	1.8%	6.58E−11	1.7%
1.0E−02	2.48E−10	2.0%	1.05E−10	1.9%	7.05E−11	1.7%	1.16E−10	2.6%
5.0E−02	1.30E−09	1.4%	1.00E−09	3.5%	5.34E−10	1.0%	5.79E−10	1.4%
1.0E−01	9.83E−10	1.7%	9.42E−10	1.3%	1.05E−09	2.4%	8.85E−10	2.1%
2.0E−01	1.29E−09	0.8%	1.28E−09	2.0%	1.07E−09	2.3%	1.11E−09	2.6%
5.0E−01	9.18E−10	1.4%	9.24E−10	1.0%	8.86E−10	0.7%	8.75E−10	0.5%
1.0E+00	9.80E−10	2.2%	1.03E−09	3.7%	9.17E−10	2.4%	9.65E−10	2.4%
5.0E+00	1.14E−09	2.7%	1.20E−09	1.2%	1.24E−09	3.6%	1.24E−09	2.7%
1.0E+01	1.11E−09	2.2%	1.28E−09	1.0%	1.58E−09	4.0%	1.43E−09	2.4%
1.0E+02	1.29E−09	1.7%	1.63E−09	2.3%	2.06E−09	2.1%	2.17E−09	2.9%
1.0E+03	2.04E−09	4.2%	2.60E−09	2.2%	3.92E−09	4.0%	4.23E−09	4.5%
1.0E+04	3.15E−09	3.8%	4.12E−09	4.6%	7.10E−09	3.2%	7.72E−09	4.3%

Table A1.10. Fluence-to-effective dose conversion coefficients (Sv.cm^2) as a function of negative kaon incident energy for different geometrical conditions of irradiation of an anthropomorphic mathematical model[25].

Negative kaon energy (GeV)	E (AP) (Sv.cm^2)		E (ISO) (Sv.cm^2)	
1.0E−03	1.02E−10	0.7%	3.58E−10	0.7%
1.0E−02	3.58E−10	0.7%	4.66E−10	0.8%
5.0E−02	9.12E−10	0.6%	5.44E−10	0.9%
1.0E−01	1.18E−09	0.8%	9.02E−10	0.7%
2.0E−01	6.94E−10	2.5%	7.65E−10	1.7%
5.0E−01	6.18E−10	1.1%	6.41E−10	5.6%
1.0E+00	5.60E−10	1.6%	5.82E−10	2.3%
5.0E+00	8.71E−10	3.8%	9.66E−10	1.0%
1.0E+01	1.06E−09	2.4%	1.31E−09	2.2%
1.0E+02	1.09E−09	0.8%	1.75E−09	2.9%
1.0E+03	2.04E−09	1.2%	4.58E−09	3.2%
1.0E+04	2.82E−09	2.4%	9.30E−09	4.6%

Table A1.11. Fluence-to-effective dose conversion coefficients (Sv.cm^2) as a function of positive kaon incident energy for different geometrical conditions of irradiation of an anthropomorphic mathematical model[25].

Positive kaon energy (GeV)	E (AP) (Sv.cm^2)		E (ISO) (Sv.cm^2)	
1.0E−03	8.23E−11	0.4%	2.87E−10	0.6%
1.0E−02	3.06E−10	1.2%	4.03E−10	0.6%
5.0E−02	8.85E−10	1.4%	5.22E−10	0.8%
1.0E−01	1.13E−09	0.9%	8.78E−10	0.8%
2.0E−01	5.48E−10	0.5%	6.47E−10	1.8%
5.0E−01	4.97E−10	0.7%	5.19E−10	0.6%
1.0E+00	4.89E−10	0.9%	5.12E−10	0.6%
5.0E+00	7.36E−10	0.6%	8.77E−10	2.2%
1.0E+01	9.33E−10	1.1%	1.08E−09	1.1%
1.0E+02	1.06E−09	4.2%	1.66E−09	1.7%
1.0E+03	1.71E−09	3.4%	3.60E−09	3.3%
1.0E+04	3.51E−09	2.9%	9.52E−09	4.5%

APPENDIX 2

Fluence-to-Ambient Dose Equivalent Conversion Coefficients

Table A2.1. Conversion coefficients from fluence to ambient dose equivalent and from fluence to maximum dose equivalent along the principal diameter of the ICRU sphere as a function of photon incident energy. Relative statistical uncertainties (standard deviation in %) are also reported[11,14].

Photon energy (GeV)	Ambient dose equivalent (Sv.cm^2)		Max. dose equivalent along the diameter of the ICRU sphere (Sv.cm^2)	
1.0E−05	8.33E−14	⩽1.0%	1.26E−11*	⩽1.0%
1.5E−05	8.52E−13	⩽1.0%	5.54E−12*	⩽1.0%
2.0E−05	1.05E−12	⩽1.0%	3.26E−12*	2.5%
3.0E−05	0.80E−12	⩽1.0%	0.84E−12	⩽1.0%
4.0E−05	0.62E−12	1.2%	0.62E−12	1.2%
5.0E−05	0.52E−12	1.1%	0.55E−12	3.0%
6.0E−05	0.51E−12	2.4%	0.54E−12	2.8%
8.0E−05	0.56E−12	1.4%	0.56E−12	4.5%
1.0E−04	0.62E−12	3.0%	0.65E−12	3.8%
1.5E−04	0.87E−12	1.6%	0.91E−12	2.7%
2.0E−04	1.23E−12	1.2%	1.23E−12	1.0%
3.0E−04	1.81E−12	1.4%	1.81E−12	⩽1.0%
4.0E−04	2.36E−12	2.1%	2.41E−12	1.2%
5.0E−04	2.78E−12	⩽1.0%	2.91E−12	1.1%
6.0E−04	3.46E−12	2.0%	3.51E−12	2.2%
8.0E−04	4.29E−12	1.4%	4.43E−12	1.1%
1.0E−03	5.18E−12	1.5%	5.23E−12	1.3%
1.5E−03	6.92E−12	1.5%	7.03E−12	1.0%
2.0E−03	8.25E−12	1.3%	8.57E−12	⩽1.0%
3.0E−03	1.04E−11	2.0%	1.11E−11	1.7%
4.0E−03	1.07E−11	2.4%	1.36E−11	⩽1.0%
5.0E−03	1.04E−11	1.6%	1.50E−11	1.1%
6.0E−03	9.58E−12	⩽1.0%	1.69E−11	⩽1.0%
8.0E−03	9.10E−12	1.7%	2.08E−11	1.6%
1.0E−02	8.76E−12	⩽1.0%	2.40E−11	1.2%
2.0E−02	8.29E−12	1.9%	4.07E−11	1.3%
3.0E−02	8.23E−12	2.0%	5.73E−11	1.4%
4.0E−02	8.26E−12	1.8%	7.20E−11	1.3%
5.0E−02	8.64E−12	2.0%	8.72E−11	1.8%
1.0E−01	9.00E−12	5.9%	1.55E−10	2.1%
2.0E−01	1.02E−11	5.6%	2.21E−10	1.8%
5.0E−01	1.18E−11	4.0%	3.16E−10	1.3%
1.0E−00	1.17E−11	3.9%	3.61E−10	⩽1.0%
2.0E−00	1.15E−11	3.5%	4.17E−10	1.0%
5.0E−00	1.33E−11	5.0%	5.00E−10	⩽1.0%
1.0E+01	1.22E−11	4.1%	5.46E−10	1.2%

*Mean value in the superficial shell 0.02 cm depth

Table A2.2. Conversion coefficients from fluence to ambient dose equivalent and from fluence to maximum dose equivalent along the principal diameter of the ICRU sphere as a function of electron incident energy. Relative statistical uncertainties (standard deviation in %) are also reported[12,14].

Electron energy (GeV)	Ambient dose equivalent (Sv.cm^2)		Max. dose equivalent along the diameter of the ICRU sphere (Sv.cm^2)	
2.5E−03	1.60E−10	⩽1.0%	4.75E−10	⩽1.0%
3.0E−03	3.33E−10	⩽1.0%	4.62E−10	⩽1.0%
4.0E−03	4.44E−10	⩽1.0%	4.53E−10	⩽1.0%
5.0E−03	4.21E−10	⩽1.0%	4.33E−10	⩽1.0%
7.0E−03	3.60E−10	⩽1.0%		
8.0E−03			4.01E−10	⩽1.0%
1.0E−02	3.25E−10	1.3%	3.85E−10	⩽1.0%
1.5E−02			3.73E−10	⩽1.0%
2.0E−02	3.27E−10	⩽1.0%	3.54E−10	1.2%
3.0E−02	3.18E−10	1.1%	3.43E−10	1.9%
4.0E−02	3.06E−10	1.2%	3.43E−10	⩽1.0%
5.0E−02	3.10E−10	1.0%	3.37E−10	1.8%
7.0E−02	3.19E−10	1.3%	3.50E−10	1.1%
1.0E−01	3.15E−10	1.3%	3.62E−10	1.5%
2.0E−01	3.23E−10	1.4%	4.22E−10	1.8%
5.0E−01	3.18E−10	1.5%	5.75E−10	2.2%
1.0E−00	3.08E−10	3.5%	6.75E−10	1.1%
2.0E−00	3.17E−10	2.2%	8.21E−10	1.6%
5.0E−00	3.14E−10	1.3%	1.01E−09	1.5%
1.0E+01	3.28E−10	2.0%	1.16E−09	1.1%

Table A2.3. Conversion coefficients from fluence to ambient dose equivalent and from fluence to maximum dose equivalent along the principal diameter of the ICRU sphere as a function of positron incident energy. Relative statistical uncertainties (standard deviation in %) are also reported[13].

Positron energy (GeV)	Ambient dose equivalent (Sv.cm^2)		Max. dose equivalent along the diameter of the ICRU sphere (Sv.cm^2)	
7.0E−05	6.31E−12	6.1%		
8.0E−05	5.63E−12	7.3%		
9.0E−05	5.55E−12	7.3%		
0.1E−03	5.94E−12	7.3%		
0.2E−03	5.65E−12	5.9%		
0.3E−03	6.06E−12	7.7%		
0.4E−03	5.18E−12	7.1%		
0.5E−03	6.11E−12	8.4%		
0.6E−03	6.29E−12	9.5%		
0.7E−03	7.39E−12	8.1%		
0.8E−03	5.95E−12	6.1%		
0.9E−03	7.23E−12	9.4%		
1.0E−03	5.91E−12	6.1%		
1.5E−03	7.81E−12	9.3%		
2.0E−03	1.79E−11	3.6%		
2.5E−03	1.72E−10	1.1%	4.67E−10	0.6%
3.0E−03	3.38E−10	0.8%	4.52E−10	0.8%
4.0E−03	4.24E−10	1.3%	4.22E−10	1.3%
5.0E−03	4.07E−10	1.0%	4.18E−10	1.0%
7.0E−03	3.45E−10	0.9%	3.99E−10	1.0%
1.0E−02	3.23E−10	0.7%	3.70E−10	1.3%
2.0E−02	3.06E−10	1.0%	3.28E−10	1.2%
3.0E−02	3.11E−10	0.2%	3.30E−10	0.8%
4.0E−02	3.08E−10	1.7%	3.27E−10	1.0%
5.0E−02	3.06E−10	2.1%	3.25E−10	1.9%
7.0E−02	3.20E−10	2.1%	3.39E−10	2.6%
1.0E−01	3.19E−10	0.8%	3.56E−10	0.8%
2.0E−01	3.11E−10	1.3%	3.97E−10	2.6%
5.0E−01	3.17E−10	1.2%	5.35E−10	2.0%
1.0E−00	3.19E−10	1.4%	6.73E−10	2.6%
2.0E−00	3.14E−10	2.2%	7.63E−10	1.3%
5.0E−00	3.16E−10	1.8%	1.00E−09	1.9%
1.0E+01	3.13E−10	1.4%	1.18E−09	1.3%

Table A2.4. Conversion coefficients from fluence to ambient dose equivalent and from fluence to maximum dose equivalent along the principal diameter of the ICRU sphere as a function of negative muon incident energy. Relative statistical uncertainties (standard deviation in %) are also reported[24].

Negative muon energy (GeV)	Ambient dose equivalent (Sv.cm^2)		Max. dose equivalent along the diameter of the ICRU sphere (Sv.cm^2)	
1.0E−03	3.99E−10	4.7%	(6.37E−09)*	1.7%
1.0E−02	5.60E−10	2.0%	(8.22E−09)*	0.7%
5.0E−02	5.23E−10	4.9%	2.44E−09	1.9%
1.0E−01	3.63E−10	0.8%	9.47E−10	2.0%
2.0E−01	3.22E−10	0.4%	3.32E−10	1.1%
5.0E−01	3.08E−10	1.2%	3.26E−10	0.4%
1.0E+00	3.12E−10	0.7%	3.38E−10	2.5%
1.0E+01	3.20E−10	1.5%	3.71E−10	2.3%
1.0E+02	3.25E−10	1.0%	3.76E−10	1.0%
1.0E+03	3.17E−10	1.2%	3.89E−10	1.3%
1.0E+04	3.26E−10	0.5%	4.18E−10	1.1%

*Averaged over 0.2 cm instead of 1 cm.

Table A2.5. Conversion coefficients from fluence to ambient dose equivalent and from fluence to maximum dose equivalent along the principal diameter of the ICRU sphere as a function of positive muon incident energy. Relative statistical uncertainties (standard deviation in %) are also reported[24].

Positive muon energy (GeV)	Ambient dose equivalent (Sv.cm^2)		Max. dose equivalent along the diameter of the ICRU sphere (Sv.cm^2)	
1.0E−03	3.89E−10	2.8%	(3.14E−09)*	0.6%
1.0E−02	5.79E−10	2.7%	(5.28E−09)*	0.6%
5.0E−02	5.08E−10	1.1%	2.12E−09	0.7%
1.0E−01	3.61E−10	0.8%	9.52E−10	1.7%
2.0E−01	3.18E−10	0.9%	3.30E−10	1.4%
5.0E−01	3.08E−10	1.6%	3.25E−10	0.9%
1.0E+00	3.11E−10	0.8%	3.40E−10	1.8%
1.0E+01	3.20E−10	1.5%	3.69E−10	2.7%
1.0E+02	3.25E−10	1.0%	3.76E−10	1.0%
1.0E+03	3.13E−10	1.1%	3.85E−10	1.5%
1.0E+04	3.27E−10	0.4%	4.24E−10	0.7%

*Averaged over 0.2 cm instead of 1 cm.

Table A2.6. Conversion coefficients from fluence to ambient dose equivalent and from fluence to maximum dose equivalent along the principal diameter of the ICRU sphere as a function of neutron incident energy. Relative statistical uncertainties (standard deviation in %) are also reported[23].

Neutron energy (GeV)	Ambient dose equivalent (Sv.cm^2)		Max. dose equivalent along the diameter of the ICRU sphere (Sv.cm^2)	
2.5E−11	1.04E−11	4.3%	1.19E−11	2.1%
1.0E−06	8.62E−12	4.3%	1.30E−11	2.1%
1.0E−04	1.08E−10	1.2%	1.45E−10	0.3%
1.0E−03	4.92E−10	1.6%	5.30E−10	0.9%
5.0E−03	4.26E−10	2.5%	4.44E−10	0.6%
1.0E−02	4.63E−10	3.4%	4.85E−10	2.6%
1.5E−02	5.08E−10	2.7%	5.25E−10	2.1%
1.9E−02	5.56E−10	1.4%	5.75E−10	2.6%
2.0E−02	5.26E−10	1.7%	5.35E−10	1.6%
5.0E−02	3.59E−10	2.8%	4.08E−10	3.6%
1.0E−01	2.62E−10	2.3%	3.52E−10	1.4%
2.0E−01	2.21E−10	2.2%	3.73E−10	2.2%
5.0E−01	2.90E−10	3.4%	4.53E−10	2.3%
1.0E+00	3.77E−10	4.6%	5.73E−10	2.5%
5.0E+00	4.92E−10	3.3%	1.13E−09	3.3%
1.0E+01	5.23E−10	7.6%	1.62E−09	5.8%
1.0E+02	4.99E−10	6.1%	3.40E−09	4.3%
1.0E+03	7.17E−10	8.6%	8.22E−09	3.3%
1.0E+04	1.16E−09	8.3%	1.97E−08	2.7%

Table A2.7. Conversion coefficients from fluence to ambient dose equivalent and from fluence to maximum dose equivalent along the principal diameter of the ICRU sphere as a function of proton incident energy. Relative statistical uncertainties (standard deviation in %) are also reported[24].

Proton energy (GeV)	Ambient dose equivalent (Sv.cm^2)		Max. dose equivalent along the diameter of the ICRU sphere (Sv.cm^2)	
5.0E−02	2.97E−09	1.4%	4.86E−09	0.4%
1.0E−01	1.52E−09	1.7%	6.50E−09	0.8%
2.0E−01	9.99E−10	1.8%	3.37E−09	0.9%
5.0E−01	7.86E−10	9.5%	8.62E−10	3.2%
1.0E+00	6.41E−10	4.6%	9.77E−10	2.6%
5.0E+00	7.65E−10	3.3%	1.44E−09	5.5%
1.0E+01	8.39E−10	5.1%	1.90E−09	7.4%
1.0E+02	8.22E−10	4.8%	3.52E−09	2.8%
1.0E+03	9.96E−10	9.9%	8.63E−09	5.0%
1.0E+04	1.20E−09	9.2%	1.94E−08	3.0%

Table A2.8. Conversion coefficients from fluence to ambient dose equivalent and from fluence to maximum dose equivalent along the principal diameter of the ICRU sphere as a function of negative pion incident energy. Relative statistical uncertainties (standard deviation in %) are also reported[24].

Negative pion energy (GeV)	Ambient dose equivalent ($Sv.cm^2$)		Max. dose equivalent along the diameter of the ICRU sphere ($Sv.cm^2$)	
1.0E−03	1.13E−09	4.5%	(1.40E−07)*	0.3%
1.0E−02	1.81E−09	1.8%	(1.14E−07)*	0.4%
5.0E−02	9.75E−10	4.6%	2.48E−08	0.7%
1.0E−01	8.97E−10	1.9%	1.10E−08	2.1%
2.0E−01	1.08E−09	6.8%	1.11E−09	6.8%
5.0E−01	7.12E−10	4.0%	8.35E−10	6.9%
1.0E+00	7.34E−10	5.3%	1.01E−09	4.8%
5.0E+00	7.43E−10	4.9%	1.34E−09	5.1%
1.0E+01	7.40E−10	5.2%	1.58E−09	6.8%
1.0E+02	7.13E−10	5.0%	2.96E−09	5.3%
1.0E+03	7.88E−10	6.8%	6.19E−09	3.2%
1.0E+04	9.53E−10	9.3%	1.33E−08	2.2%

*Averaged over 0.2 cm instead of 1 cm.

Table A2.9. Conversion coefficients from fluence to ambient dose equivalent and from fluence to maximum dose equivalent along the principal diameter of the ICRU sphere as a function of positive pion incident energy. Relative statistical uncertainties (standard deviation in %) are also reported[24].

Positive pion energy (GeV)	Ambient dose equivalent ($Sv.cm^2$)		Max. dose equivalent along the diameter of the ICRU sphere ($Sv.cm^2$)	
1.0E−03	2.24E−10	3.4%	(6.28E−09)*	0.2%
1.0E−02	5.28E−10	2.6%	(9.24E−09)*	0.3%
5.0E−02	8.19E−10	2.2%	2.65E−09	0.2%
1.0E−01	9.79E−10	4.2%	1.61E−09	1.3%
2.0E−01	1.08E−09	4.0%	1.25E−09	2.8%
5.0E−01	7.74E−10	3.9%	9.70E−10	6.0%
1.0E+00	7.80E−10	4.1%	1.00E−09	3.7%
5.0E+00	7.50E−10	3.4%	1.41E−09	5.6%
1.0E+01	7.56E−10	3.8%	1.63E−09	3.4%
1.0E+02	7.12E−10	4.8%	2.91E−09	2.9%
1.0E+03	7.76E−10	4.5%	6.30E−09	4.9%
1.0E+04	8.38E−10	9.5%	1.39E−08	6.7%

*Averaged over 0.2 cm instead of 1 cm.

Table A2.10. Conversion coefficients from fluence to ambient dose equivalent and from fluence to maximum dose equivalent along the principal diameter of the ICRU sphere as a function of negative kaon incident energy. Relative statistical uncertainties (standard deviation in %) are also reported[25].

Energy (GeV)	Ambient dose equivalent ($Sv.cm^2$)		Max. dose equivalent along the diameter of the ICRU sphere ($Sv.cm^2$)	
1.0E-03	1.39E−09	3.7%	1.08E−08	0.5%
1.0E−02	1.45E−09	5.2%	1.26E−08	1.3%
5.0E−02	1.92E−09	3.8%	6.92E−09	<0.1%
1.0E−01	1.22E−09	2.8%	5.30E−09	5.3%
2.0E−01	7.26E−10	2.7%	1.37E−09	1.1%
5.0E−01	6.32E−10	6.4%	9.25E−10	4.5%
1.0E+00	5.11E−10	4.1%	8.15E−10	>10%
5.0E+00	6.59E−10	4.4%	1.30E−09	5.2%
1.0E+01	8.20E−10	3.6%	1.56E−09	3.1%
1.0E+02	6.82E−10	7.3%	2.95E−09	5.0%
1.0E+03	8.89E−10	>10%	6.05E−09	6.8%
1.0E+04	9.11E−10	>10%	1.38E−08	2.4%

Table A2.11. Conversion coefficients from fluence to ambient dose equivalent and from fluence to maximum dose equivalent along the principal diameter of the ICRU sphere as a function of positive kaon incident energy. Relative statistical uncertainties (standard deviation in %) are also reported[25].

Energy (GeV)	Ambient dose equivalent ($Sv.cm^2$)		Max. dose equivalent along the diameter of the ICRU sphere ($Sv.cm^2$)	
1.0E−03	1.09E−09	4.3%	9.62E−09	0.1%
1.0E−02	1.20E−09	7.0%	1.17E−08	0.6%
5.0E−02	1.84E−09	2.0%	6.34E−09	0.5%
1.0E−01	1.05E−09	4.7%	5.56E−09	1.5%
2.0E−01	6.14E−10	1.6%	8.78E−10	>10%
5.0E−01	5.05E−10	5.4%	6.84E−10	>10%
1.0E+00	4.56E−10	4.1%	7.46E−10	>10%
5.0E+00	6.13E−10	5.1%	1.14E−09	4.6%
1.0E+01	6.95E−10	6.8%	1.31E−09	4.7%
1.0E+02	6.82E−10	6.4%	2.59E−09	3.8%
1.0E+03	8.28E−10	7.2%	5.97E−09	2.4%
1.0E+04	1.26E−09	>10%	1.34E−08	3.2%