CONVERSION COEFFICIENTS FOR COSMIC RADIATION IN THE ATMOSPHERE

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INTRODUCTION

The main purpose of the present calculations was the evaluation of the fluence-to-effective dose conversion coefficients for cosmic radiation in the atmosphere. During their work air crew members are exposed to elevated ionising radiation from cosmic radiation which shall be determined. Cosmic radiation in the Earth's atmosphere exhibits a complex environment consisting of neutrons, protons, photons, electrons, positrons, pions, muons and heavy ions. Their energy range extends up to hundreds of GeV. To calculate the dose components from the particle fluences in the atmosphere, the effective dose conversion coefficients of all particle types produced by the galactic cosmic rays have to be determined.

In the high energy range (approximately above 10 MeV) there is only a limited number of data available in the literature [1-8]. Only INFN (Instituto Nazionale di Fisica Nucleare) in Italy has published [3] a consistent set of fluence-to-effective dose conversion coefficients for all kinds of radiation and incident energies up to 10 TeV, calculated by the FLUKA transport code. The aim of this work is to validate these earlier calculations performed by FLUKA using the high energy code MCNPX [9, 10] and fill in the gaps in the conversion coefficients as a function of particle energy.

PROTECTION QUANTITIES

The ICRP in its Publication 60 [11] introduced the effective dose, E, as the quantity which relates to the risk from a given radiation exposure and serves as the limiting measure in occupational radiation protection. E is defined as the sum of the weighted equivalent doses in all the tissues and organs of the body

$$E = \sum_T w_T \cdot H_T \qquad (1)$$

where H_T is the equivalent dose in tissue or organ T and w_T is the tissue-weighting factor for tissue T. The recommended values for tissue-weighting factors for 11 tissues and organs, and a remainder, are given in [11]. The equivalent dose in tissue is the absorbed dose in an organ or tissue multiplied by the appropriate radiation-weighting factor. It is given by the expression

$$H_T = \sum_R w_R \cdot D_{T,R} \tag{2}$$

where $D_{T,R}$ is the absorbed dose averaged over the tissue or organ T, due to radiation R, and w_R is radiation-weighting factor for the type and energy of radiation R incident on the body. The specified values of w_R and the smooth w_R function for neutrons is taken from ICRP-60 [11].

ANTHROPOMORPHIC MODELS

The male (ADAM) and female (EVA) mathematical anthropomorphic phantoms developed by Kramer et al. [12] were applied in this work. ADAM represents the reference adult man 70 kg of weight and 170 cm of height and EVA the woman 60 kg of weight and 160 cm of height, respectively. The body and internal organs of ADAM and EVA are defined by equations of surfaces of cylinders, cones, ellipsoids, hyperboloids and torus. The oesophagus was added to the phantoms using the model reported by Zankl et al. [13]. The skin is represented by 2 mm layer covering the whole phantom's body. Muscle, one of the remainder organs, was taken as the volume of the phantom, other than the specified organs, within the phantom boundary.

The phantoms, ADAM and EVA, contain all organs of interest according to the ICRP recommendations [11]. The internal organs are considered to be homogeneous in composition and density. Four different compositions and densities were used for lung tissue, skeleton, skin and the bulk of the body considered as the soft tissue. The composition description of these four tissues were limited to 14 elements: H, C, N, O, Na, Mg, P, S, Cl, K, Ca, Fe, Zr and Pb. Other elements accounting for less than 2.10^{-4} percentage by weight were neglected in this work. The elemental compositions and the densities can be found in [14]. The dose to the bone marrow was estimated using the method described by Kramer [15]. The energy absorbed in the bone marrow was calculated from the energy absorbed in each bone corrected by the actual bone marrow mass distribution established by M. Cristy [16]. Due to the complicated geometry of some organs, the volumes of the organs were calculated stochastically by the MCNP [17] code itself by the method of ray tracing. The resulting volumes and masses of ADAM and EVA can be found in [14], too.

In the present work, the recommendation of ICRP Publication 74 [18] was followed and the absorbed dose was calculated in each organ for both the male and female phantom, separately. The effective dose was then determined from the combination of male and female equivalent doses using the relation

$$E = w_{breast} \cdot H^{f}_{breast} + \sum_{T \neq breast} w_T \cdot \left(\frac{H^{m}_{T} + H^{f}_{T}}{2} \right) \tag{3}$$

where superscripts m and f denote male and female, respectively. To obtain the fluence-to-effective dose conversion coefficients the resulting effective dose was then divided by the total fluence of the radiation incident on body.

METHOD OF CALCULATION

The calculations have been performed using the MCNPX [9, 10] Monte Carlo code of the Los Alamos National Laboratory. MCNPX is the merged code combining the major capabilities of LAHET [19] and MCNP [17] Monte Carlo codes. We have used the beta-test version of MCNPX code, version 2.1.5, 2.2.3 and 2.2.6 with the options of the Bertini cascade model for nucleons and pions, and the pre-equilibrium model after intranuclear cascade. The cross sections of the main constituents, i.e. H, C, N, O, P, Ca, Fe and Pb, were available up to 150 MeV from the LA150N library [20]. The elements not included in LA150N, i.e. Na, Mg, S, Cl, K and Zr, were ommited. The sum of these 6 elements do only account for less than 0.9 percentage by weight.

The phantoms were irradiated with broad parallel beams in anterior-posterior (A-P) direction, or with fully isotropic (ISO) radiation modelled by the use of an inward-directed source on a spherical surface around the whole phantom. The space between source and phantoms was assumed to be vacuum. The energy deposited in the 60 regions of ADAM and 62 regions of EVA, representing the various organs and tissues of the human body has been determined for monoenergetic fields of neutrons, protons, electrons, photons, positive pions and negative muons. From the weighted organ doses the fluence-to-effective dose conversion coefficients were calculated according to the ICRP recommendations.

As recommended by ICRP 67 [21] the remainder dose has been evaluated as arithmetic mean of nine organs and tissues, the upper large intestine was not included in the remainder tissues. The higher value of doses to the ovaries and to testes was applied to estimate dose to gonads. The absorbed dose to organs and tissues consisting of two or more regions were calculated as the mass weighted average of the doses to each regions. The recommendations in footnote 3 of Table 2 in ICRP Publication 60 [11] could be ignored.

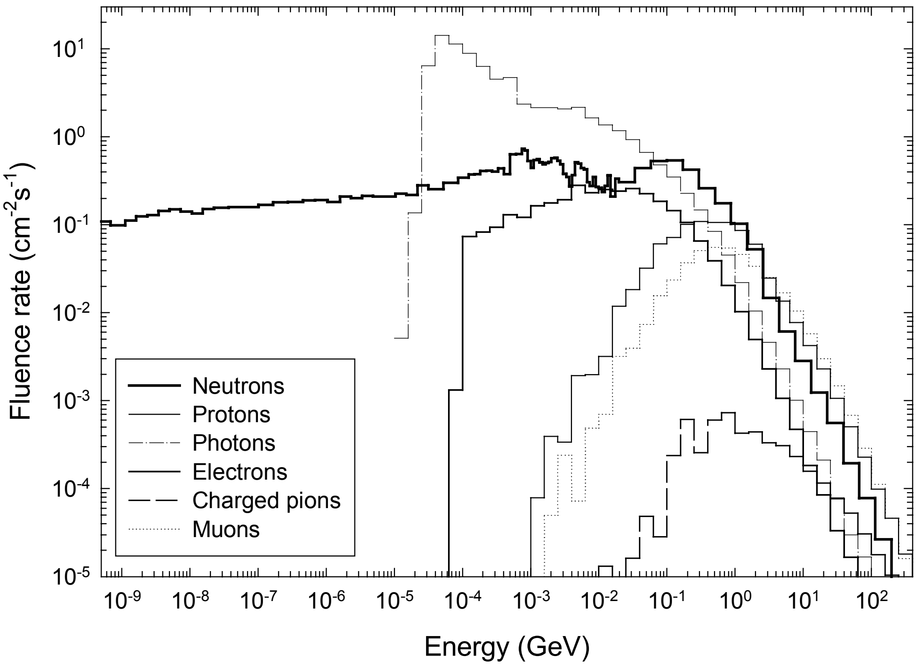

Figure 1. Particle fluence rates of cosmic radiation for flight altitude of 11.43 km, cut-off rigidity of 0 GV, and solar minimum (June, 1999)

The energy range of the calculations differs in the dependence of the spectral shape of particle fluence rates with the aim to cover the main energy interval from that the particles mostly contribute to the absorbed dose. The fluence rates for neutrons, protons, charged pions, photons, electrons and muons calculated by FLUKA Monte Carlo code for different civil flight conditions can be found in [22]. As example in Figure 1 the fluence rate of cosmic radiation is shown for the case of flight altitude equal to 11.43 km, cut-off rigidity of 0 GV (no geomagnetic shielding) and in time of solar minimum (June, 1999).

RESULT OF CALCULATIONS

The effective dose depends on the specific radiation incidence conditions, for instance, frontal (A-P) or isotropic (ISO) incidence. However, isotropic radiation incidence to the body appears to be the best estimate for the irradiation conditions expected in the airplanes.

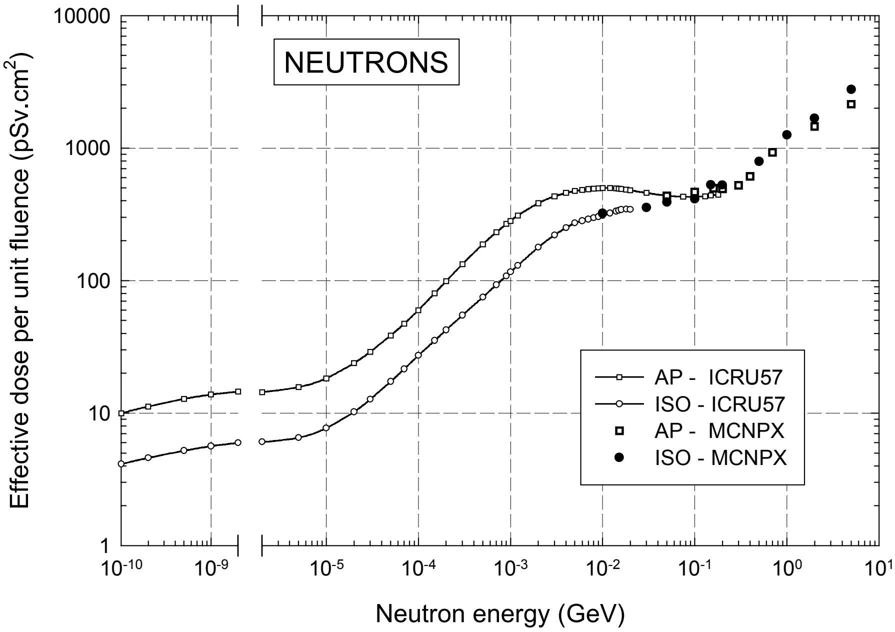

Figure 2. Effective dose per unit fluence of neutrons for AP and ISO irradiation.

Figure 2 shows the calculated effective dose per unit of fluence as a function of neutron energy for AP and ISO irradiation together with the data recommended by ICRU 57 [23] up to 180 MeV and 20 MeV, respectively. The solid line connects the ICRU data points as a guide to the eye. Into the averages of ICRU 57 our neutron conversion factors calculated with MCNP in the past [14] are also included, and therefore they are omitted for clearnes in Figure 2. The effective dose increases over the whole energy range with an exception in the energy range 0.01 – 0.1 GeV for AP irradiation. The detailed comparison with the data available in literature, especially with the FLUKA data [3], and discussion on the differences may be found in [24]. We can state that our MCNPX data for neutrons are systematically higher than those calculated with FLUKA in the energy range from 30 MeV to 100 MeV and then for energies higher than 200 MeV in ISO irradiation geometry, and for energies higher than 200 MeV in AP irradiation.

Figure 3 shows the proton conversion coefficients for AP and ISO irradiation. The agreement with FLUKA data is satisfactory, with the exception of the energy range from 10 to 50 MeV, where the MCNPX data are slightly higher [24]. It can be seen that AP irradiation gives the maximum effective dose per unit of fluence for lower incident energy of protons than in ISO irradiation. This is due to the shorter paths of the particles through the phantom to the organs as breast, gonads and thyroid, which contribute very significantly to the effective dose at energies below 100 MeV.

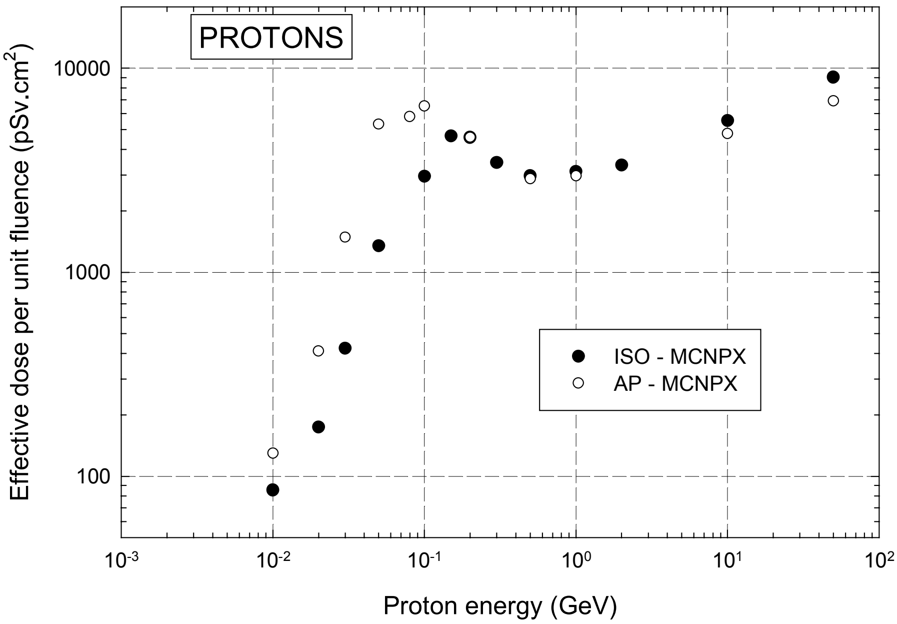

Figure 3. Effective dose per unit fluence of protons for AP and ISO irradiation.

Figure 4 shows the conversion coefficients for ISO irradiation geometry for electrons, negative muons, photons and positive pions. The effective dose per unit of fluence increases over the whole energy range practically for all particle types with an exception of pions and muons which build a local maximum at approximately 80 MeV. The agreement between FLUKA and MCNPX data is very good for negative muons, electrons and photons. In the case of positive pions the MCNPX data are systematically higher than those of FLUKA for energies higher than 500 MeV. However, it should be stressed, that the charged pions contribute less than 1% to the total effective dose at all altitudes up to 25 km.

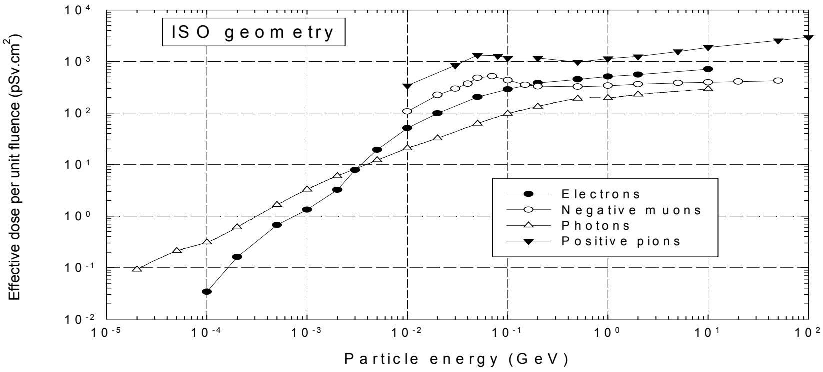

Figure 4. Effective dose per unit fluence as a function of particle energy for various kinds of radiation for ISO irradiation.

CONCLUSIONS AND OUTLOOK

The set of fluence-to-effective dose conversion coefficients for neutrons, protons, photons, pions, electrons and muons was derived using the same code, same phantoms and same geometry. The data were calculated using MCNPX Monte Carlo code, which is well experimentally proven high energy code, continuously improved and upgraded. Using this consistent set of conversion coefficients together with the particle spectra for specific position in the Earth's atmosphere the effective dose can be determined to which a person is exposed during the flight. The data set may be found in [24] or obtained from the authors on request.

The data are currently used to derive altitude dependent averaged conversion factors for inclusion into the computer program EPCARD [25]. However, the results obtained up to now indicate that the altitude dependence of the factors is small in view of the accuracy requirements of radiation protection dosimetry.

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