T-4-4, P-1a-45

Aviation Route Dose Calculation and its Numerical Basis

H.Schraube[1] , W.Heinrich[2] , G.Leuthold[1] , V.Mares[3] and S.Roesler[4]
[1] GSF - National Research Center for Environment and Health, D-85758 Neuherberg, Germany
[2] University of Siegen, Physics-Department, D-57078 Siegen, Germany
[3] Ludwig-Maximilian-University, D-80539 München, Germany
[4] Stanford Linear Accelerator Center, Stanford, CA 94309, USA

INTRODUCTION

The European Directive 96/12 adopted the recommendations of the ICRP (1) and claims in Article 42 that measures are taken to assess the individual doses of air crew and cabin personnel "who are liable to be subject to exposure to more than 1 mSv per year". Consequently, several European research institutes have undertaken an extensive programme of air borne and mountain based experiments to measure the radiation field in the Earth's atmosphere. Furthermore, Monte Carlo radiation transport calculations were done to follow the radiation cascades from the top of the atmosphere down to the Earth's surface.

We understand that the routine determination of radiation doses to air crew requires roughly the following scientific, numerical and administrative steps:

1. Calculation of particle fluence rates in the atmosphere at all solar and geomagnetic conditions as well as flight altitudes,
2. Final definition of quantities, quality factors and/or radiation weighting factors, and subsequent calculation of generally agreed fluence-to-dose conversion coefficients,
3. Consolidation of the calculated database and experimental validation,
4. General approval by national and international commissions,
5. Provision of a personal dose service which is subject to regular quality control. For this step the same requirements of precision of dose determination and record keeping apply as for any dosimetry service for occupationally radiation exposed individuals.

Though the basic physical processes and radiation components have been studied previously, the determination of dose quantities requires more physical information: Both operational (ambient dose equivalent) and risk related quantities (effective dose) contain non-physical information related to the radiation detriment to cells and organs. This is described by quality and radiation weighting factors, respectively. Therefore, the quantities can not be measured by direct dosimetric methods, though satisfying approaches are possible.

O’Brien (2) has developed a model (LUIN) which describes the propagation of cosmic rays in the atmosphere and determines the dose values for the different radiation components. The LUIN results are used as a data base for the route dose calculations with CARI (3).

The LUIN code treats the radiation transport based on some approximations which restrict the validity of the results to energies of secondary particles above some hundred MeV, but allows an analytic solution of the transport equations. This provides a fast computer code which has been used over almost thirty years. The cosmic ray input spectra and the particle production spectra at lower energies are taken from experimental and theoretical sources which are partly outdated by more recent data. Nevertheless the LUIN code predicts as final result dose values which are in general agreement with in-flight measurements.

A different strategy was followed by our calculations. Since computer time nowadays is no longer a limiting quantity, we handle the radiation transport and determine the secondary particle spectra by Monte Carlo (MC-) calculations (4). This allows to use detailed and state of the art models of particle interactions and of the primary galactic cosmic radiation (GCR) spectra and to update the model by including latest improvements of the codes available from NASA or from the high energy accelerator centres. For instance, early predictions of neutron spectra (5) could be verified by independent experimental means and MC-calculations, both using essentially the same environmental conditions (6). These observations suggest that approximately half of the neutron fluence and dose equivalent rate is expected in the high energy range.

The program EPCARD (European Computer Program Package for the Calculation of Aviation Route Doses) makes use of the results of these calculations and experimental data to determine the route doses.

Recent radiation transport calculations (4) of the authors and the more detailed investigations in this paper show that at commercial flight altitudes the spectral shapes of the particle fluences are essentially invariable. This permits to use calculated conversion coefficients to determine the dose quantities from the calculated and experimental spectral data. This appears necessary especially for those radiation components whose dose contribution can not be experimentally separated, but may considerably contribute to the effective dose considering the radiation weighting factors presently recommended by the ICRP, e.g. for protons.

CONCEPT

The concept of the computer programme EPCARD is based on the idea to collect and combine the large number of calculated and experimentally determined findings to an uniform data base.

Each major component of particle radiation in the atmosphere is treated separately, i.e. neutrons, protons and charged pions, electrons, photons and muons. The influence of geomagnetic shielding is considered based on calculations and experimental data, and the magnitude of solar modulation is inferred from neutron monitor data. This computer program is designed to calculate route doses along any specified aviation route and profile by integration along great circles. The whole effort is schematically depicted in Figure 1, including the effort of partner institutes and the information available from the literature:

The **hatched** areas depict experimental effort, the **light-grey** ones the radiation transport calculation work and the **dark-grey** ones the calculation of the integral route doses on the basis of a data matrix along specified aviation routes for specific time periods in the solar cycle.

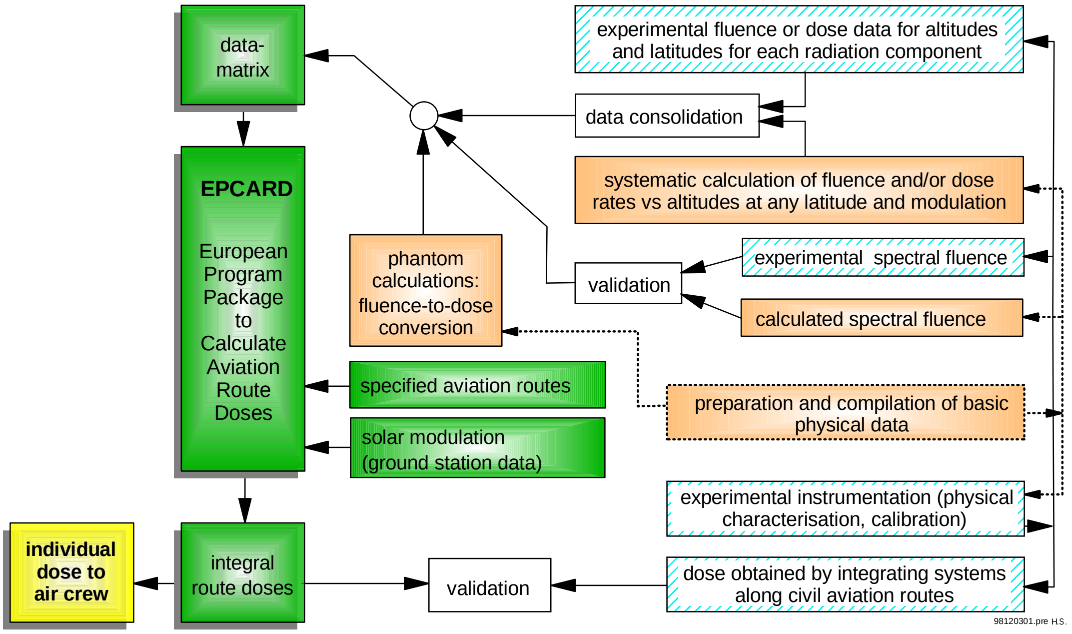

Figure 1. Schematic sketch of the physical background for the calculation of air crew doses

The radiation transport calculations are done employing Monte Carlo codes (MCNP, LAHET, FLUKA) to obtain the basic dosimetric quantities, spectral characteristics of the radiation fields, physical characteristics of experimental devices, and integral fluence data in the depth of the atmosphere. Important points to be noted here are the data base especially in the high energy range, and the appropriate models and cross section libraries for the respective nuclear processes.

Experimental data are obtained from air borne and mountain based measurements as appropriate for the respective quantity to be determined (e.g., particle fluence, spectra or dose). Data of active instruments, time differential devices, and radiation specific instruments are employed to verify the calculated data. The consolidated data are used to fill the data-matrix separately for each radiation component. On the other hand, integral data obtained at extensive long term exposures on specified routes of passive devices and integral measuring active devices are employed to validate the integral route dose obtained from the EPCARD calculations.

RADIATION TRANSPORT CALCULATIONS

The transport calculations of the primary GCR into the Earth's atmosphere were conducted by employing the transport code FLUKA (7). In contrast to the recent calculations (4), where we have used the model of Adams et al.(8), the spectral fluence rate of the primary GCR was used in a modified version of the Badhwar model (9), by adjusting its spectral shape for the proton component (full line in Figure 2 labelled here and in further Figures with "model Badhwar, reduced") to more recent experimental data (10, 11, 12). The energy spectra of the heavy primaries were used in the original version of the model (9). More details and references on the physical background and the modelling of the atmosphere are found in (4 and 13).

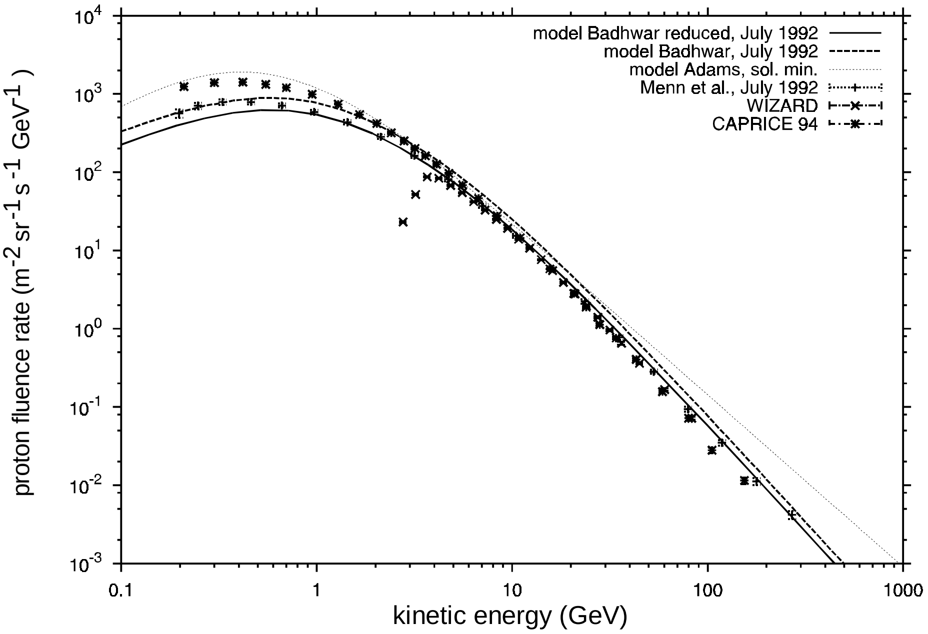

Figure 2. Energy spectra of primary cosmic ray protons for the reference time of July 1992. The full line is used for the present transport calculations. Experimental data are from the IMAX (Menn et al. (10), WIZARD (11) and CAPRICE (12) measurements.

The effect of solar modulation on the GCR spectrum is described in the model of Badhwar (see (9) and references therein) by a electric deceleration potential. The magnitude of the modulation effect for solar maximum and minimum is not a typical constant value, but varies for different cycles. For the data presented here we have used values of -465 MV for the solar minimum and -1700 MV for the solar maximum. It should be emphasised, that these are extreme values, which we have chosen as limits to cover the whole dynamic range of modulation effects. For a comparison to specific flight conditions it is necessary to use in the model a value for the modulation potential which represents the specific strength of solar modulation at the time of the flight.

The spectral fluence rates for neutrons, protons, charged pions, electrons, photons and muons have been calculated for the following conditions which span approximately the extreme conditions for civil flight routes including the flight level:

- solar minimum, no geomagnetic shielding (cut-off rigidity of 0 GV), flight altitude of 15.3 km,
- solar minimum, highest geomagnetic shielding (cut-off rigidity of 17 GV), flight altitude of 9.6 km,
- solar maximum, highest geomagnetic shielding (cut-off rigidity of 17 GV), flight altitude of 9.6 km,
- solar maximum, no geomagnetic shielding (cut-off rigidity of 0 GV), flight altitude of 15.3 km.

The results are depicted in Figures 3 through 8 in the following way: The spectral particle fluence rates $d^2\Phi/dt\cdot dE$ (cm^{-2} s^{-1} GeV^{-1}), i.e. particle fluence per time interval dt and energy interval dE, are multiplied with the energy E, and normalised to the energy integrated fluence rates (the normalisation factor is given in each Figure for the respective curves). It can be seen in Figure 3 and 7 that the independence of the spectral shape on the flight conditions is almost perfect for neutrons and photons. Some differences can be observed for the charged particles (Figures 4-6 and 8), however these differences are small. Based on this observation, constant conversion factors can be used to convert particle fluences into health physics dose quantities.

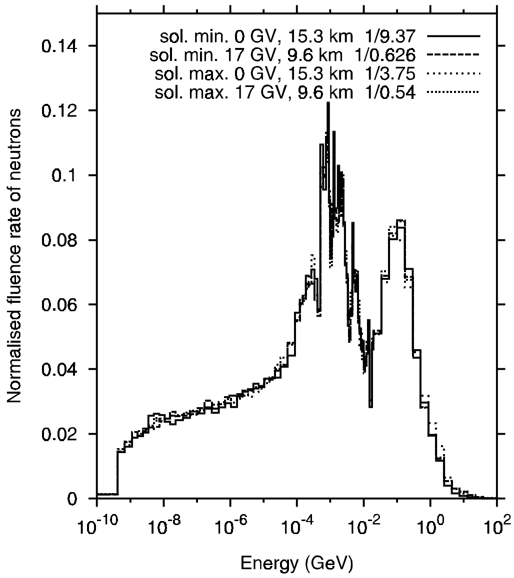

Figure 3. Normalised spectral neutron fluence rate.

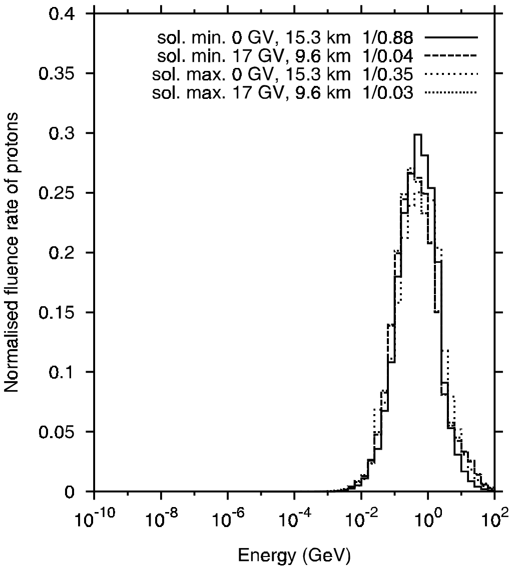

Figure 4. Normalised spectral proton fluence rate.

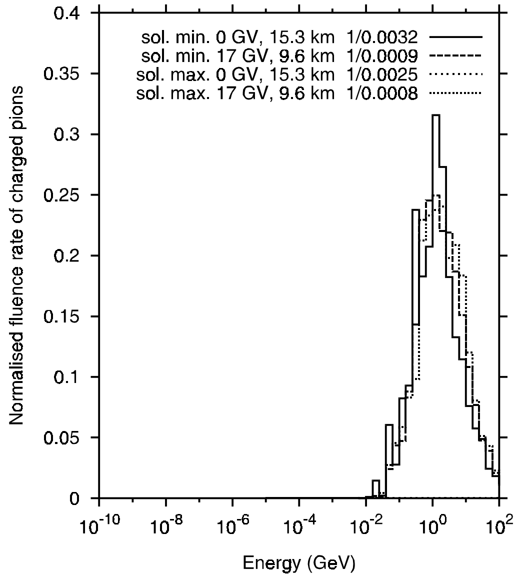

Figure 5. Normalised spectral fluence rate of charged pions.

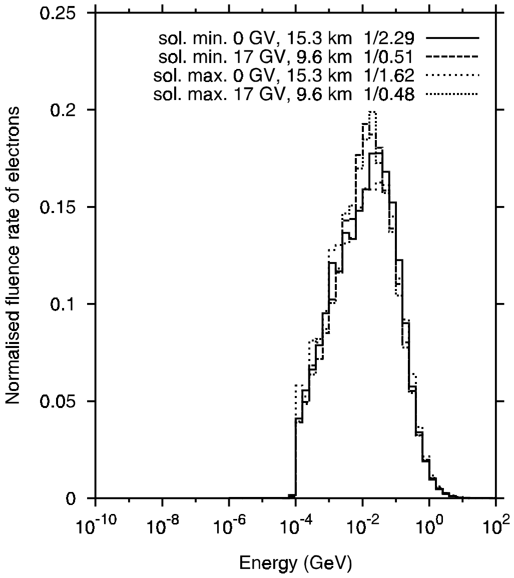

Figure 6. Normalised spectral fluence rate of electrons.

The calculated fluence rates, integrated over the particle spectra, for all particles with exception of charged pions are presented in Figures 10 to 15, after conversion of atmospheric depth into flight altitudes. It was observed that the shape of the primary CGR spectra does influence to some extent the particle fluence with depth in the atmosphere, and the relative contribution of each specific component to the total particle fluence at a specified point. The uncertainties can be overcome by a comparison of calculated fluences or doses to experimentally ones for those components which are accessible with experimental means. The Figures refer to solar minimum activity. Additionally, for neutrons the fluence rates at solar maximum activity are partly presented as well (Figure 11). It should be emphasised again that the conditions are extreme ones, also with respect to solar activity and geomagnetic shielding. The majority of flights are somewhere in between 3 and 10 GV geomagnetic shielding and for less extreme solar modulation conditions.

The FLUKA calculations are performed in air without the presence of an aircraft, i.e. at a point in the homogeneous medium air under particle equilibrium conditions, which may be assumed below the Pfotzer maximum (13). Air planes have a wall thickness of several g/cm^2. If it is assumed that the chemical composition is not too far from air, i.e. aluminium instead of oxygen and nitrogen, then the effect of the wall would be equivalent to a somewhat lower flight altitude, approximately by 100 m, and a dose rate reduced accordingly.

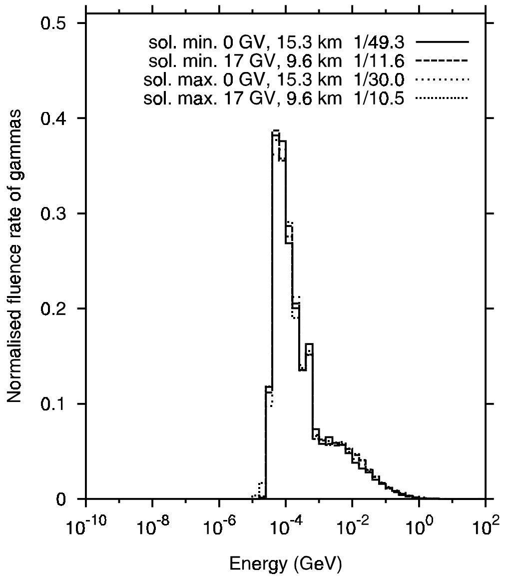

Figure 7. Normalised spectral photon fluence rate.

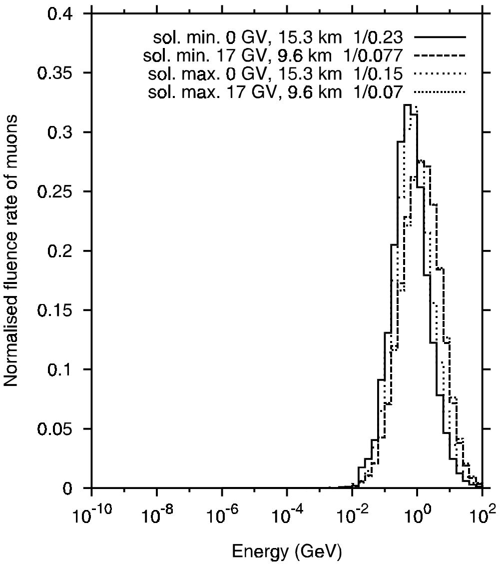

Figure 8. Normalised spectral muon fluence rate.

DOSE CALCULATION

Two health physics quantities are of interest in the context of the determination of the natural radiation exposure in the atmosphere:

i) The protection quantity effective dose which should give an estimate for the radiation risk. Its numerical values depend on radiation type and energy, and the irradiation geometry.

ii) The simplifying operational quantity ambient dose equivalent which is defined to be independent on the angle of radiation incidence, and additive with respect to any radiation component.

Both quantities are described by conversion coefficients which are to be determined by radiation transport calculations for the respective phantom, for each of the six essential radiation components, and irradiation geometry.

The ICRU (14, 15) and the ICRP(1) have defined quality factors for secondary charged particles for the calculation of the ambient dose equivalent as operational quantity. On the other hand, for the determination of the effective dose the ICRP has recommended radiation weighting factors for the radiation components incident on the body. For both concepts, coefficients to convert particle fluence into the dose quantities may be found in the literature. For radiation energies below approximately 20 MeV, the data are well established (15). In the high energy range, the INFN has published a series of data, and made them available on the WWW (16), but they require partly confirmation and amendments (see also (17) and (18), where the data for H*(10) are discussed).

Table 1. Averaged conversion coefficients for effective dose, E, and ambient dose equivalent, H*(10) (H is used as collective notation for E and H*(10)).

Particle, data source and quantity		H / Φ (pSv cm^2)	Particle, data source and quantity		H / Φ (pSv cm^2)
neutrons, exper. spectra	E (ISO)	207 ± 21	protons, calc. spectra	H*(10)	961
neutrons, exper. spectra	E (ROT)	226 ± 21	charged pions, calc. spectra	H*(10)	799
neutrons, exper. spectra	H*(10)	243 ± 21	electrons, calc. spectra	H*(10)	342
neutrons, calc. spectra	H*(10)	242	photons, calc. spectra	H*(10)	2.7
			muons, calc. spectra	H*(10)	328

As concluded above, the energy distribution of the relevant particles is essentially invariable for the flight altitudes considered here, i.e. in the range from 8000 m to 15000 m, and for all latitudes. Thus, one set of conversion factors for one quantity is sufficient for all altitudes and latitudes.

Using the energy dependent conversion coefficients, the conversion factors averaged over all spectra in Figure 3 through 8 were calculated. The results are listed in Table 1 (taken from (19)). The data show that for neutrons the mean conversion coefficients of a number of experimental spectra with considerable high energetic components are practically the same as those for the calculated spectra of Figure 3. It is also seen that the ambient dose equivalent, H*(10), exceeds somewhat the effective dose, E, for isotropic (ISO) and rotational (ROT) radiation incidence to the body, i.e. it appears to be a good and conservative estimate for the irradiation conditions expected in airplanes for the neutron component, which was also suggested earlier (18).

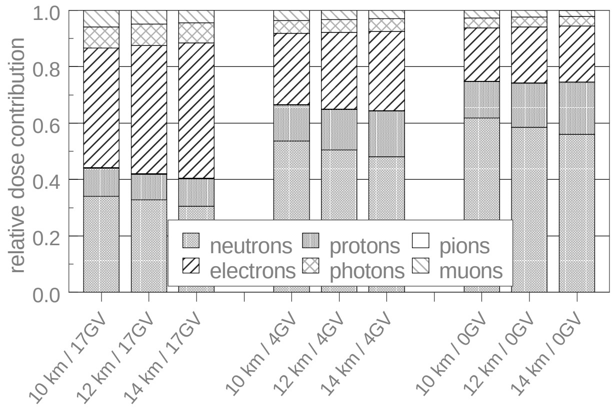

Figure 9. Relative contribution to ambient dose equivalent from the six particle types at flight altitudes of 10, 12 and 14 km at 0, 4 and 17 GV cut-off rigidity and minimum solar activity.

The data of Table 1 may be employed to convert the fluence rate data in Figures 10 through 15 into dose rate data. This was done for flight altitudes between 10 and 14 km, minimum solar activity and for 0, 4 and 17 GV cut-off rigidity. The results in Figure 9 exhibits the relative ambient dose equivalent of each of the radiation components. The contribution of charged pions is small (and disappears between the bars for protons and electrons in Figure 9). With increasing latitude (0 GV is in the magnetic polar region), the relative neutron and proton contribution increases.

The effective dose would be essentially determined by the neutron and proton components essentially because of the radiation weighting factor of 5 for protons other than recoil protons with energies in excess of 2 MeV, as proposed by the ICRP (1). This is currently re-considered by the ICRP and by a number of scientific institutions. The result of the international effort is expected in the near future. As the computer programme EPCARD makes use of particle fluence matrices with a set of conversion factors, any essential and serious change in quality factors and/or radiation weighting factors for defined radiation components may be incorporated into the conversion data set without changing the whole data base from the scratch.

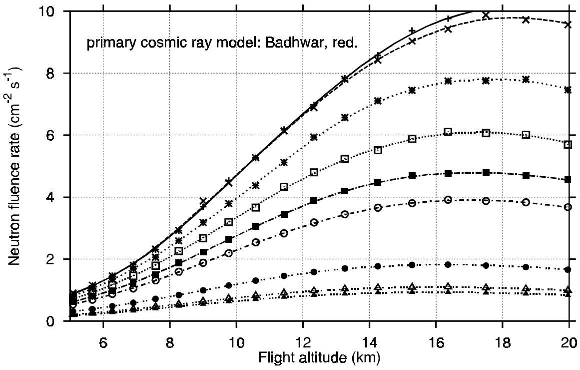

Figure 10. Fluence rate as a function of atmospheric depth for neutrons at solar minimum activity and cut-off rigidities of 0, 1, 2, 3, 4, 5, 10, 15 and 17 GV (from top to bottom).

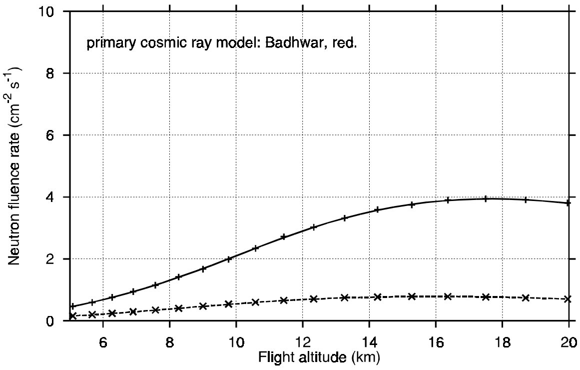

Figure 11. Fluence rate as a function of atmospheric depth for neutrons at solar maximum activity, and at minimum (top) and maximum (bottom) cut-off rigidities.

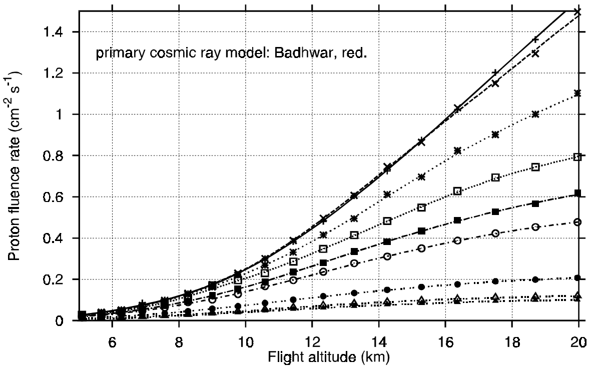

Figure 12. Fluence rate as a function of atmospheric depth for protons at solar minimum activity, and different cut-off rigidities as in Figure 10.

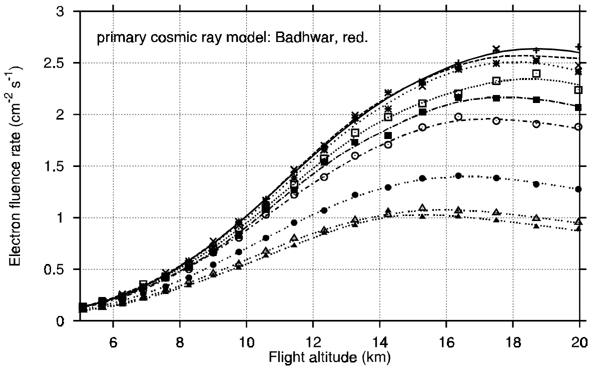

Figure 13. Fluence rate as a function of atmospheric depth for electrons at solar minimum activity, and different cut-off rigidities as in Figure 10.

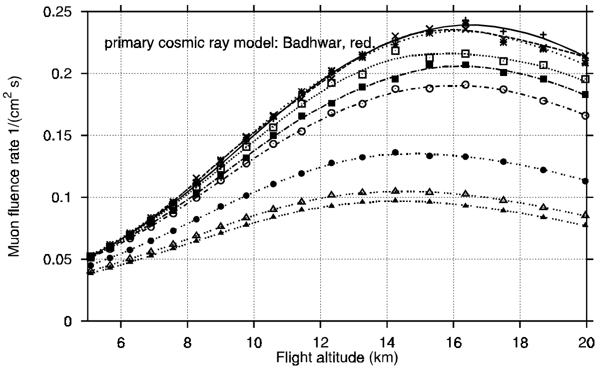

Figure 14. Fluence rate as a function of atmospheric depth for muons at solar minimum activity, and different cut-off rigidities as in Figure 10.

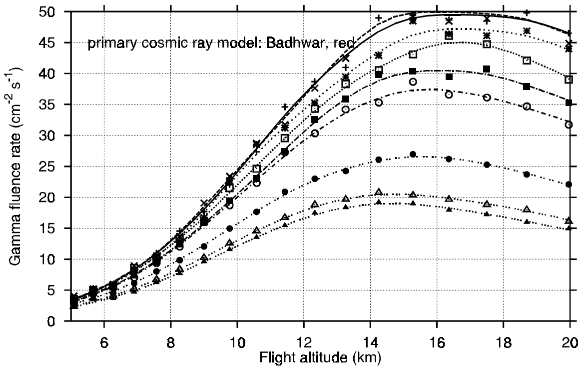

Figure 15. Fluence rate as a function of atmospheric depth for photons at solar minimum activity, and different cut-off rigidities as in Figure 10.

DISCUSSION ON THE REFERENCE DOSES

We would like to refer to a recent publication (20) and discuss to some extent the problem of the quantities to be used. There are two motivations to use ambient dose equivalent, H*(d), as the operational quantity also for air flight conditions.

The first one is that this quantity - together with the personal dose equivalent, $H_p(d)$ - is the operational quantity to be determined under ground level conditions, i.e. at places where survey and personal dosimetry is mandatory. The ICRU found the depth d=10 mm as a good approach for these conditions. H*(10) is well established in the system of radiation quantities of the ICRU, and has been introduced into most national regulations. It would be logical to keep this system for all occupationally radiation exposed individuals in an uniform way, if serious reasons do not contradict. One reason, of course, would be that the radiation exposure as a whole or for essential radiation components is not sufficiently assessed by the operational quantity.

The second motivation is more serious. As said above, all calculations (the analytical approaches as well as the MC-calculations) require experimental control and verification. Most devices are constructed to measure H*(10), or an approach to it with acceptable uncertainties, and are calibrated in terms of H*(10) under laboratory (reference) conditions. Therefore, most experimentalists do deliver their results in terms of H*(10). It is possible, of course, to transpose ambient dose equivalent, H*(10), into effective dose, E, and vice versa, by the relation

$$E = H^*(10)\cdot\frac{\int (E/\Phi)\cdot d\Phi_p/dE_p \cdot dE_p}{\int (H^*/\Phi)\cdot d\Phi_p/dE_p \cdot dE_p},$$

where $d\Phi_p/dE_p$ is the spectral fluence (rate) of the particle type, p, considered. H*(10) exhibits, for instance, the experimentally determined result for the specific particle or radiation type, if a discrimination against other radiation or appropriate corrections during the experiments were possible at all. (E/Φ) and (H^*/Φ) are the conversion coefficients as function of particle energy, E_p. These, and the spectral fluence (rates), $d\Phi_p/dE_p$, (see Figures 3 through 8) have to be known explicitly with sufficient precision before the equation is employed.

Part of the discussion on the conservativity of H*(10) suffers from the fact that data are available, but their uncertainties are not known.

In contrast to H*, the effective dose, E, is not a "receptor free quantity", but its numerical values depend on the orientation of the receptor (anthropomorphic phantom) in the field and on the direction distribution of the radiation field. Generally, it would be no problem to define one of the respective conversion functions for the effective dose, e.g. for isotropic incidence, as the "reference operational quantity" for flight conditions. The experimental devices have then to be calibrated in terms of this quantity, or the measurements have to be interpreted in the way described by the above equation. But this has to be agreed upon in the scientific and radiation administrative community.

PRACTICAL ASPECTS

As air crews are considered as occupationally radiation exposed persons by the European Directive, in principle the same requirements apply as for any other personnel to be surveyed by dosimetry services, e.g. in medical radiation diagnostic and therapy, and in nuclear industry: Precision of dose determination and quality assurance of the dose results, easy access to data listings for authorised people, easy recognition of excess of dose limits, evaluation of integrated personal doses during individual professional history, long term data maintenance, data protection (against unauthorised access) and data security (against loss). The only difference to the performance of standard routine service is that for air crews the doses are calculated for each flight segment, rather than measured during a time period. The responsibilities between dosimetry services and air companies could be divided by in the following way:

The air carrier(s) would be responsible for: i) delivering and up-date of the personal data, and delivering the personnel flight lists in time intervals as appropriate, ii) recalling the dose-lists, e.g. monthly, and taking care for the proper work plans and other measures required in Article 42.

The Personal Dose Service would be responsible for: i) maintenance of EPCARD, including up-dates of the physical data base, ii) taking care for a 24h world-wide access to the system, iii) providing all necessary measures for long term record keeping and data security.

The fluence or dose distribution of particles in the atmosphere which are produced by solar flare events have so far not been considered. Solar flares are extra-ordinary statistically observed radiation events which may occur during certain periods of the solar cycle. In some of these events particle fluxes and particle energies may be high enough to produce a radiation level at air flight altitudes which is significantly increased in comparison to that one caused by the continuos galactic cosmic radiation. However, these are rare and transient phenomena for which the respective dose data may additionally be evaluated and recorded, as soon as accepted approaches for the dose description are available. It is expected that proposals for the 5th EU frame program will be successful in this respect. Any information on solar flares could then automatically be attributed to the individual members of the dose records if they were on-flight during that period of time.

SUMMARY AND CONCLUSIONS

The routine determination of doses to which air crews are exposed due to natural penetrating radiation requires to be based on the same principles as for any other occupationally radiation exposed individual. The Monte Carlo code FLUKA delivers the basic information with respect to particle spectra, from which the averaged dose conversion factors are calculated, and with respect to particle fluence rate from which the numerical values of the dose quantities are derived for any depth in the atmosphere. The situation is somewhat facilitated as the spectral shapes do not change much at the flight levels considered, and a constant conversion factor may be used for every particle type which contributes to the total radiation dose. Also the introduction of a altitude dependent conversion factor would be no problem, if higher than present standard altitudes were considered.

Conversion factors for anthropomorphic phantoms to determine the effective dose, and the ICRU sphere phantom to determine ambient dose equivalent are not yet fully established. Especially, the radiation weighting factor for energetic protons requires further scientific consideration.

The precision of the dose calculation depends on the information of the primary galactic cosmic rays and the modelling of the atmosphere. Experimental data may be used to adjust the calculated ones. However, not all radiation components are accessible to direct measurements or are distinguishable against other particle types. EPCARD is the tool which permits to calculate the aviation route doses from the consolidated data matrix with calculated and experimental data which come from a number of internationally recognised institutes. It is designed in such a way that any interested air carrier may make use of it in the near future for dosimetry routine for his employees by the World Wide Web as a long term service.

ACKNOWLEDGEMENTS

The authors are grateful to Alfredo Ferrari, Milano, for providing the FLUKA-code and for valuable discussions and to Gautam Badhwar, Houston, for providing the code for primary cosmic ray and the solar modulation model. Furthermore, the authors wish to thank the EU-contractors group for their valuable discussions, especially Denis O'Sullivan, Dublin, David Bartlett, Chilton, Rudolf Grillmaier, Saarbrücken, Lennart Lindborg, Stockholm, Marco Silari, Geneva, and Luigi Tommasino, Rome; and the sponsor of the group, Hans Menzel, Brussels and Geneva. This work was supported by the European Commission under contracts FI4P-CT950011a and B4-3040/99/135999/MAR/C1. Part of the work of S.R. was supported by the US-Department of Energy under contract DE-AC03-76SF00515.

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