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Dosimetry for exposures to cosmic radiation in civilian aircraft —

Part 1:
Conceptual basis for measurements

Dosimétrie pour l'exposition au rayonnement cosmique à bord d'un avion civil —

Partie 1: Fondement théorique des mesurages

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Foreword

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ISO 20785-1 was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

This second edition cancels and replaces the first edition (ISO 20785-1:2006), which has been technically revised.

ISO 20785 consists of the following parts, under the general title *Dosimetry for exposures to cosmic radiation in civilian aircraft*:

— *Part 1: Conceptual basis for measurements*

— *Part 2: Characterization of instrument response*

Measurements at aviation altitudes is to form the subject of a future Part 3.

Introduction

Aircraft crews are exposed to elevated levels of cosmic radiation of galactic and solar origin and secondary radiation produced in the atmosphere, the aircraft structure and its contents. Following recommendations of the International Commission on Radiological Protection in Publication 60,[1] confirmed by Publication 103,[2] the European Union (EU) introduced a revised Basic Safety Standards Directive[3] which included exposure to natural sources of ionizing radiation, including cosmic radiation, as occupational exposure. The Directive requires account to be taken of the exposure of aircraft crews liable to receive more than 1 mSv per year. It then identifies the following four protection measures: (i) to assess the exposure of the crew concerned; (ii) to take into account the assessed exposure when organizing working schedules with a view to reducing the doses of highly exposed crews; (iii) to inform the workers concerned of the health risks their work involves; and (iv) to apply the same special protection during pregnancy to female crews in respect of the “child to be born” as to other female workers. The EU Council Directive has already been incorporated into laws and regulations of EU Member States and is being included in the aviation safety standards and procedures of the Joint Aviation Authorities and the European Air Safety Agency. Other countries such as Canada and Japan have issued advisories to their airline industries to manage aircraft crew exposure.

For regulatory and legislative purposes, the radiation protection quantities of interest are the equivalent dose (to the foetus) and the effective dose. The cosmic radiation exposure of the body is essentially uniform and the maternal abdomen provides no effective shielding to the foetus. As a result, the magnitude of equivalent dose to the foetus can be put equal to that of the effective dose received by the mother. Doses on board aircraft are generally predictable, and events comparable to unplanned exposure in other radiological workplaces cannot normally occur (with the rare exceptions of extremely intense and energetic solar particle events). Personal dosemeters for routine use are not considered necessary. The preferred approach for the assessment of doses of aircraft crews, where necessary, is to calculate directly the effective dose per unit time, as a function of geographic location, altitude and solar cycle phase, and to fold these values with flight and staff roster information to obtain estimates of effective doses for individuals. This approach is supported by guidance from the European Commission and the ICRP in Publication 75.[4]

The role of calculations in this procedure is unique in routine radiation protection and it is widely accepted that the calculated doses should be validated by measurement. The effective dose is not directly measurable. The operational quantity of interest is ambient dose equivalent, $H^*(10)$. In order to validate the assessed doses obtained in terms of effective dose, calculations can be made of ambient dose equivalent rates or route doses in terms of ambient dose equivalent, and values of this quantity determined by measurements traceable to national standards. The validation of calculations of ambient dose equivalent for a particular calculation method may be taken as a validation of the calculation of the effective dose by the same computer code, but this step in the process may need to be confirmed. The alternative is to establish *a priori* that the operational quantity ambient dose equivalent is a good estimator of effective dose and equivalent dose to the foetus for the radiation fields being considered, in the same way that the use of the operational quantity personal dose equivalent is justified for the estimation of effective dose for radiation workers. Ambient dose equivalent rate as a function of geographic location, altitude and solar cycle phase is then calculated and folded with flight and staff roster information.

The radiation field in aircraft at altitude is complex, with many types of ionizing radiation present, with energies ranging up to many GeV. The determination of ambient dose equivalent for such a complex radiation field is difficult. In many cases, the methods used for the determination of ambient dose equivalent in aircraft are similar to those used at high-energy accelerators in research laboratories. Therefore, it is possible to recommend dosimetric methods and methods for the calibration of dosimetric devices, as well as the techniques for maintaining the traceability of dosimetric measurements to national standards. Dosimetric measurements made to evaluate ambient dose equivalent must be performed using accurate and reliable methods that ensure the quality of readings provided to workers and regulatory authorities. This part of ISO 20785 gives a conceptual basis for the characterization of the response of instruments for the determination of ambient dose equivalent in aircraft.

Requirements for the determination and recording of the cosmic radiation exposure of aircraft crews have been introduced into the national legislation of EU Member States and other countries. Harmonization of methods used for determining ambient dose equivalent and for calibrating instruments is desirable to ensure the compatibility of measurements performed with such instruments.

This part of ISO 20785 is intended for the use of primary and secondary calibration laboratories for ionizing radiation, by radiation protection personnel employed by governmental agencies, and by industrial corporations concerned with the determination of ambient dose equivalent for aircraft crews.

Dosimetry for exposures to cosmic radiation in civilian aircraft —

Part 1:
Conceptual basis for measurements

1 Scope

This part of ISO 20785 gives the conceptual basis for the determination of ambient dose equivalent for the evaluation of exposure to cosmic radiation in civilian aircraft and for the calibration of instruments used for that purpose.

2 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

2.1 General

2.1.1
calibration
operation that, under specified conditions, establishes a relation between the conventional quantity, H_0, and the indication, G

Note 1 to entry: A calibration may be expressed by a statement, calibration function, calibration diagram, calibration curve, or calibration table. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty.

Note 2 to entry: Calibration should not be confused with adjustment of a measuring system, often mistakenly called “self-calibration”, or with verification of calibration.

Note 3 to entry: Often, the first step alone in the above definition is perceived as being calibration.

2.1.2
calibration coefficient
N_{coeff}
quotient of the conventional quantity value to be measured and the corrected indication of the instrument

Note 1 to entry: The calibration coefficient is equivalent to the calibration factor multiplied by the instrument constant.

Note 2 to entry: The reciprocal of the calibration coefficient, N_{coeff}, is the response.

Note 3 to entry: For the calibration of some instruments, e.g. ionization chambers, the instrument constant and the calibration factor are not identified separately but are applied together as the calibration coefficient.

Note 4 to entry: It is necessary, in order to avoid confusion, to state the quantity to be measured, for example: the calibration coefficient with respect to fluence, N_{Φ}, the calibration coefficient with respect to kerma, N_{K}, the calibration coefficient with respect to absorbed dose, N_{D}.

2.1.3
indication

G

quantity value provided by a measuring instrument or a measuring system

Note 1 to entry: An indication can be presented in visual or acoustic form or can be transferred to another device. An indication is often given by the position of a pointer on the display for analogue outputs, a displayed or printed number for digital outputs, a code pattern for code outputs, or an assigned quantity value for material measures.

Note 2 to entry: An indication and a corresponding value of the quantity being measured are not necessarily values of quantities of the same kind.

2.1.4
reference conditions

conditions of use prescribed for testing the performance of a detector assembly or for comparison of results of measurements

Note 1 to entry: The reference conditions represent the values of the set of influence quantities for which the calibration result is valid without any correction.

Note 2 to entry: The value of the measurand may be chosen freely in agreement with the properties of the detector assembly to be calibrated. The quantity to be measured is not an influence quantity but may influence the calibration result and the response.

2.1.5
response

R

quotient of the indication, G, or the corrected indication, G_{corr}, and the conventional quantity value to be measured

Note 1 to entry: To avoid confusion, it is necessary to specify which of the quotients, given in the definition of the response (to G or to G_{corr}) is applied. Furthermore, it is necessary, in order to avoid confusion, to state the quantity to be measured, for example: the response with respect to fluence, R_Φ, the response with respect to kerma, R_K, the response with respect to absorbed dose, R_D.

Note 2 to entry: The reciprocal of the response under the specified conditions is equal to the calibration coefficient $N_{\mathrm{coeff.}}$

Note 3 to entry: The value of the response may vary with the magnitude of the quantity to be measured. In such cases the detector assembly's response is said to be non-constant.

Note 4 to entry: The response usually varies with the energy and direction distribution of the incident radiation. It is, therefore, useful to consider the response as a function, $R(E,\Omega)$, of the radiation energy, E, and of the direction, $\vec{\Omega}$, of the incident monodirectional radiation. $R(E)$ describes the "energy dependence" and $R(\Omega)$ the "angle dependence" of response; for the latter, $\vec{\Omega}$ may be expressed by the angle, α, between the reference direction of the detector assembly and the direction of an external monodirectional field.

2.2 Quantities and units

2.2.1
particle fluence

fluence

Φ

number, dN, at a given point of space, of particles incident on a small spherical domain, divided by the cross-sectional area, da, of that domain:

$$\Phi = \frac{\mathrm{d}N}{\mathrm{d}a}$$

Note 1 to entry: The unit of the fluence is m^{-2}; a frequently used unit is cm^{-2}.

Note 2 to entry: The energy distribution of the particle fluence, Φ_E, is the quotient, dΦ, by dE, where dΦ is the fluence of particles of energy between E and E+dE. There is an analogous definition for the direction distribution, Φ_Ω, of the particle fluence. The complete representation of the double differential particle fluence can be written (with arguments) $\Phi_{\mathrm{E},\Omega}$ (E,Ω), where the subscripts characterize the variables (quantities) for differentiation and where the symbols in the brackets describe the values of the variables. The values in the brackets are needed for special function values, e.g. the energy distribution of the particle fluence at energy $E = E_0$ is written as $\Phi_\mathrm{E}(E_0)$. If no special values are indicated, the brackets may be omitted.

2.2.2
particle fluence rate
fluence rate
$\dot{\Phi}$

rate of the particle fluence expressed as

$$\dot{\Phi} = \frac{\mathrm{d}\Phi}{\mathrm{d}t} = \frac{\mathrm{d}^2 N}{\mathrm{d}a \cdot \mathrm{d}t}$$

where dΦ is the increment of the particle fluence during an infinitesimal time interval with duration dt

Note 1 to entry: The unit of the fluence rate is $\mathrm{m}^{-2}\ \mathrm{s}^{-1}$, a frequently used unit is $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$.

2.2.3
energy imparted
ε

for ionizing radiation in the matter within a given three-dimensional domain,

$$\varepsilon = \sum \varepsilon_\mathrm{i}$$

where

ε_i is the energy deposited in a single interaction, i, and given by $\varepsilon_\mathrm{i} = \varepsilon_\mathrm{in} - \varepsilon_\mathrm{out} + Q$, where

ε_in is the energy of the incident ionizing particle, excluding rest energy,

ε_out is the sum of the energies of all ionizing particles leaving the interaction, excluding rest energy, and

Q is the change in the rest energies of the nucleus and of all particles involved in the interaction

Note 1 to entry: Energy imparted is a stochastic quantity.

Note 2 to entry: The unit of the energy imparted is J.

2.2.4
mean energy imparted
$\bar{\varepsilon}$

mean energy imparted to the matter in a given domain, expressed as

$$\bar{\varepsilon} = R_\mathrm{in} - R_\mathrm{out} + \sum Q$$

where

R_{in} is the radiant energy of all those charged and uncharged ionizing particles that enter the domain,

R_{out} is the radiant energy of all those charged and uncharged ionizing particles that leave the domain, and

$\sum Q$ is the sum of all changes of the rest energy of nuclei and elementary particles that occur in that domain

Note 1 to entry: This quantity has the meaning of expected value of the energy imparted.

Note 2 to entry: The unit of the mean energy imparted is J.

2.2.5
specific energy imparted
specific energy
z
for any ionizing radiation,

$$z = \frac{\varepsilon}{m}$$

where

ε is the energy imparted to the irradiated matter,

m is the mass of the irradiated matter

Note 1 to entry: Specific energy imparted is a stochastic quantity.

Note 2 to entry: In the limit of a small domain, the mean specific energy imparted is equal to the absorbed dose.

Note 3 to entry: The specific energy imparted can be the result of one or more (energy-deposition) events.

Note 4 to entry: The unit of specific energy is $\text{J}\cdot\text{kg}^{-1}$, with the special name gray (Gy).

2.2.6
absorbed dose
D
for any ionizing radiation,

$$D = \frac{\mathrm{d}\bar{\varepsilon}}{\mathrm{d}m}$$

where

$\mathrm{d}\bar{\varepsilon}$ is the mean energy imparted by ionizing radiation to an element of irradiated matter of mass $\mathrm{d}m$, where

$$\bar{\varepsilon} = \int D \mathrm{d}m$$

Note 1 to entry: In the limit of a small domain, the mean specific energy is equal to the absorbed dose.

Note 2 to entry: The unit of absorbed dose is J kg^{-1}, with the special name gray (Gy).

2.2.7

kerma

K

for indirectly ionizing (uncharged) particles, the mean sum of the initial kinetic energies $\mathrm{d}E_{\mathrm{tr}}$ of all the charged ionizing particles liberated by uncharged ionizing particles in an element of matter, divided by the mass $\mathrm{d}m$ of that element:

$$K = \frac{\mathrm{d}E_{\mathrm{tr}}}{\mathrm{d}m}$$

Note 1 to entry: Quantity $\mathrm{d}E_{\mathrm{tr}}$ includes the kinetic energy of the charged particles emitted in the decay of excited atoms or molecules or nuclei.

Note 2 to entry: The unit of kerma is J kg^{-1}, with the special name gray (Gy).

2.2.8

unrestricted linear energy transfer

linear energy transfer

LET

L_{Δ}

for an ionizing charged particle, the mean energy, $\mathrm{d}E_{\Delta}$, imparted locally to matter along a small path through the matter minus the sum of the kinetic energies of all the electrons released with kinetic energies in excess of Δ, divided by the length, $\mathrm{d}l$:

$$L_{\Delta} = \frac{\mathrm{d}E_{\Delta}}{\mathrm{d}l}$$

Note 1 to entry: This quantity is not completely defined unless Δ is specified, i.e. the maximum kinetic energy of secondary electrons whose energy is considered to be “locally deposited”. Δ may be expressed in eV.

Note 2 to entry: Linear energy transfer is often abbreviated LET, but to which should be appended the subscript Δ or its numerical value.

Note 3 to entry: The unit of the linear energy transfer is J m^{-1}, a frequently used unit is keV µm^{-1}.

Note 4 to entry: If no energy cut-off is imposed, the unrestricted linear energy transfer L_{∞} is equal to the linear electronic stopping power S_{el} and may be denoted simply as L.

2.2.9

dose equivalent

H

at the point of interest in tissue,

$$H = DQ$$

where

D is the absorbed dose,

Q is the quality factor at that point, and

$$H = \int_{L-0}^{\infty} Q(L) D_{\mathrm{L}} \mathrm{d}L$$

Note 1 to entry: Q is determined by the unrestricted linear energy transfer, L_{∞} (often denoted as L or LET), of charged particles passing through a small volume element (domains) at this point (the value of L_{∞} is given for charged particles in water, not in tissue; the difference, however, is small). The dose equivalent at a point in tissue is then given by the above formula, where $D_{\mathrm{L}} = \mathrm{d}D/\mathrm{d}L$ is the distribution in terms of L of the absorbed dose at the point of interest.

Note 2 to entry: The relationship of Q and L is given in ICRP Publication 103 (ICRP, 2007).[2]

Note 3 to entry: The unit of dose equivalent is J kg^{-1}, with the special name sievert (Sv).

2.2.10
single-event dose-mean specific energy

dose-mean specific energy per event

$\bar{z}_D$

expectation

$$\bar{z}_D = \int_0^\infty z d_1(z) \mathrm{d}z$$

where $d_1(z)$is the dose probability density of z

Note 1 to entry: The dose probability density of z is given by $d_1(z)$, where $d_1(z)$ dz is the fraction of the absorbed dose delivered in single events with specific energies in the interval from z to z+dz.

2.2.11
lineal energy

y

quotient of the energy, ε_s, imparted to the matter in a given volume by a single energy deposition event, by the mean chord length, $\bar{l}$, in that volume:

$$y = \frac{\varepsilon_s}{\bar{l}}$$

Note 1 to entry: The unit of lineal energy is J m^{-1}, a frequently used unit is keV µm^{-1}.

2.2.12
dose-mean lineal energy

$\bar{y}_D$

expectation

$$\bar{y}_D = \int_0^\infty y\, d(y)\, \mathrm{d}y$$

where $d(y)$is the dose probability density of y

Note 1 to entry: The dose probability density of y is given by $d(y)$, where $d(y)$dz is the fraction of absorbed dose delivered in single events with lineal energy in the interval from y to y+dy.

Note 2 to entry: Both the dose-mean lineal energy and distribution $d(y)$ are independent of the absorbed dose or dose rate.

2.2.13
ambient dose equivalent

$H^*(10)$

dose equivalent at a point in a radiation field, that would be produced by the corresponding expanded and aligned field, in the ICRU sphere at 10 mm depth on the radius opposing the direction of the aligned field

Note 1 to entry: The unit of ambient dose equivalent is J kg^{-1} with the special name sievert (Sv).

2.2.14
particle-fluence-to-ambient-dose-equivalent conversion coefficient

h^*_{Φ}

quotient of the particle ambient dose equivalent, $H^*(10)$, and the particle fluence, Φ:

$$h^*_{\Phi} = \frac{H^*(10)}{\Phi}$$

Note 1 to entry: The unit of the particle-fluence-to-ambient-dose-equivalent conversion coefficient is J m^2 kg^{-1} with the special name Sv m^2, a frequently used unit is pSv cm^2.

2.2.15
atmosphere depth

X_v

mass of a unit-area column of air above a point in the atmosphere

Note 1 to entry: The unit of atmosphere depth is kg m^{-2}; a frequently used unit is g cm^{-2}.

2.2.16
standard barometric altitude

pressure altitude

altitude determined by a barometric altimeter calibrated with reference to the International Standard Atmosphere (ISA) (ISO 2533, *Standard Atmosphere*) when the altimeter's datum is set to 1 013,25 hPa

Note 1 to entry: The flight level is sometimes given as FL 350, where the number represents multiples of 100 ft of pressure altitude, based on the ISA and a datum setting of 1 013,25 hPa. However, in some countries flight levels are expressed in meters, in which case appropriate conversions should be made before applying the data given in this International Standard.

2.2.17
magnetic rigidity

P

momentum per charge (of a particle in a magnetic field), given by

$$P = \frac{p}{Ze}$$

where

p is the particle momentum,

Z is the number of charges on the particle, and

e is the charge on the proton

Note 1 to entry: The base unit of magnetic rigidity is the tesla metre (T·m) (= V·m^{-1}·s). A frequently used unit is V (or GV) in a system of units where the values of the speed of light, c, and the charge on the proton, e, are both 1, and the magnetic rigidity is given by pc/Ze.

Note 2 to entry: Magnetic rigidity characterizes charged-particle trajectories in magnetic fields. All particles having the same magnetic rigidity have identical trajectories in a magnetic field, independent of particle mass or charge.

2.2.18
geomagnetic cut-off rigidity
cut-off rigidity
r_c
minimum magnetic rigidity an incident particle can have and still penetrate the geomagnetic field to reach a given location above the Earth

Note 1 to entry: Geomagnetic cut-off rigidity depends on angle of incidence. Often, vertical incidence to the Earth's surface is assumed, in which case the vertical geomagnetic cut-off rigidity is the minimum magnetic rigidity a vertically incident particle can have and still reach a given location above the Earth.

2.2.19
vertical geomagnetic cut-off rigidity
vertical cut-off
cut-off
minimum magnetic rigidity a vertically incident particle can have and still reach a given location above the Earth

2.3 Atmospheric radiation field

2.3.1
cosmic radiation
cosmic rays
cosmic particles
ionizing radiation consisting of high-energy particles, primarily completely ionized atoms, of extra-terrestrial origin and the particles they generate by interaction with the atmosphere and other matter

2.3.2
primary cosmic radiation
primary cosmic rays
cosmic radiation incident from space at the Earth's orbit

2.3.3
secondary cosmic radiation
secondary cosmic rays
cosmogenic particles
particles which are created directly or in a cascade of reactions by primary cosmic rays interacting with the atmosphere or other matter

Note 1 to entry: Important particles with respect to radiation protection and radiation measurements in aircraft are: neutrons, protons, photons, electrons, positrons, muons and, to a lesser extent, pions and nuclear ions heavier than protons.

2.3.4
galactic cosmic radiation
galactic cosmic rays
GCR
cosmic radiation originating outside the solar system

2.3.5
solar particles
solar cosmic radiation
solar cosmic rays
cosmic radiation originating from the sun

2.3.6
solar particle event
SPE
large fluence rate of energetic solar particles ejected into space by a solar eruption

Note 1 to entry: Solar particle events are directional.

2.3.7
ground-level enhancement
GLE
sudden increase of cosmic radiation observed on the ground by at least two neutron monitor stations recording simultaneously a greater than 1 % increase in the five-minute-averaged count rate associated with solar energetic particles

Note 1 to entry: A GLE is associated with a solar-particle event having a high fluence rate of particles with high energy (greater than 500 MeV).

Note 2 to entry: GLEs are relatively rare, occurring on average about once per year. GLEs are numbered; the first number being given to that occurring in February 1942.

2.3.8
solar modulation
change of the GCR field (outside the Earth's magnetosphere) caused by change of solar activity and consequent change of the magnetic field of the heliosphere

2.3.9
solar cycle
period during which the solar activity varies with successive maxima separated by an average interval of about 11 years

Note 1 to entry: If the reversal of the Sun's magnetic field polarity in successive 11 year periods is taken into account, the complete solar cycle may be considered to average some 22 years, the Hale cycle.

Note 2 to entry: The sunspot cycle as measured by the relative sunspot number, known as the Wolf number, has an approximate length of 11 years, but this varies between about 7 and 17 years. An approximate 11 year cycle has been found or suggested in geomagnetism, frequency of aurora, and other ionospheric characteristics. The u index of geomagnetic intensity variation shows one of the strongest known correlations to solar activity.

2.3.10
relative sunspot number
Wolf number
measure of sunspot activity, computed from the expression $k(10g + f)$, where f is the number of individual spots, g the number of groups of spots and k a factor that varies with the observer's personal experience of recognition and with the observatory (location and instrumentation)

2.3.11
solar maximum
time period of maximum solar activity during a solar cycle, usually defined in terms of relative sunspot number

2.3.12
solar minimum
time period of minimum solar activity during a solar cycle, usually defined in terms of relative sunspot number

2.3.13
cosmic ray neutron monitor
ground level neutron monitor
cosmic radiation neutron monitor
GLNM
large detector used to measure the time-dependent relative fluence rate of high-energy cosmic radiation, in particular the secondary neutrons generated in the atmosphere (protons, other hadrons and muons may also be detected)

Note 1 to entry: Installed worldwide at different locations and altitudes on the ground (and occasionally placed on ships or aircraft), cosmic radiation neutron monitors are used for various cosmic radiation studies and to determine solar modulation.

3 General considerations

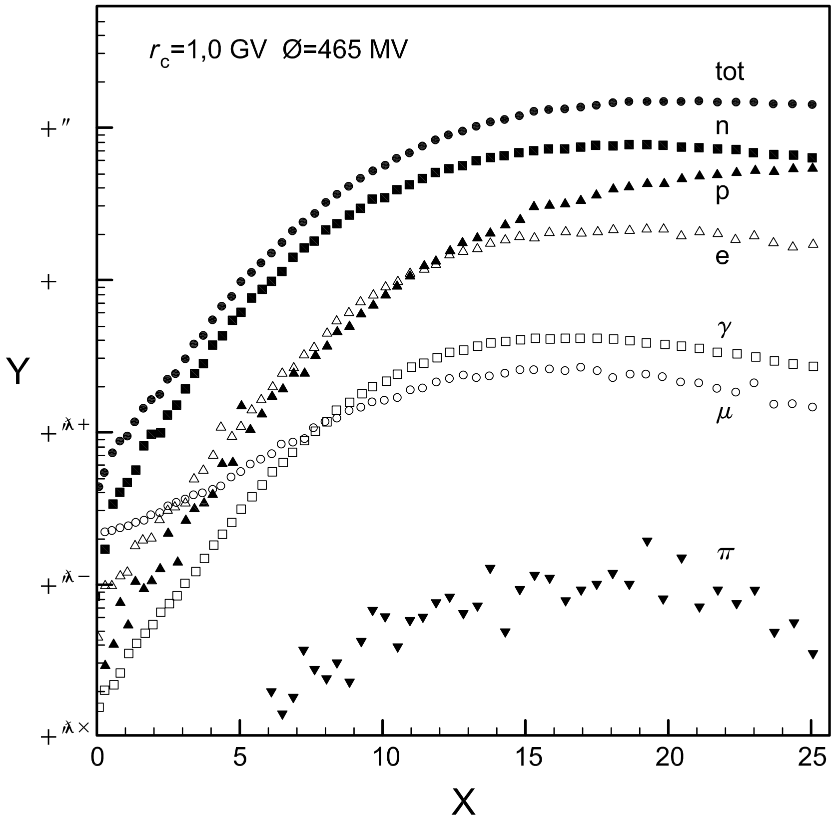
3.1 General description of the cosmic radiation field in the atmosphere

The primary galactic cosmic radiation (and energetic solar particles) interact with the atomic nuclei of atmospheric constituents, producing a cascade of interactions and secondary reaction products that contribute to cosmic radiation exposures that decrease in intensity with depth in the atmosphere from aviation altitudes to sea level.[5][6] Galactic cosmic radiation (GCR) can have energies up to 10^{20} eV, but lower energy particles are the most frequent. After the GCRs penetrate the magnetic field of the solar system, the peak of their energy distribution is at a few hundred MeV to 1 GeV per nucleon, depending on solar magnetic activity, and the spectrum follows a power function of the form $E^{-2,7}$ eV up to 10^{15} eV; above that energy, the spectrum steepens to E^{-3} eV. The fluence rate of GCR entering the solar system is fairly constant in time, and these energetic ions approach the Earth isotropically.

The magnetic fields of the Earth and sun alter the relative number of GCR protons and heavier ions reaching the atmosphere. The GCR ion composition for low geomagnetic cut-off and low solar activity is approximately 90 % protons, 9 % He ions, 1 % heavier nuclei; at a vertical cut-off of 15 GV, the composition is approximately 83 % protons, 15 % He ions, and nearly 2 % heavier ions.[7][8]

The changing components of ambient dose equivalent caused by the various secondary cosmic radiation constituents in the atmosphere as a function of altitude are illustrated in Figure 1. At sea level, the muon component is the most important contributor to ambient dose equivalent and effective dose; at aviation altitudes, neutrons, electrons, positrons, protons, photons, and muons are the most significant components. At higher altitudes, nuclear ions heavier than protons start to contribute. Figures showing representative normalized energy distributions of fluence rates of all the important particles at low and high cut-offs and altitudes at solar minimum and maximum are shown in Annex A.

The Earth is also exposed to bursts of energetic protons and heavier particles from magnetic disturbances near the surface of the sun and from ejection of large amounts of matter (coronal mass ejections – CMEs) with, in some cases, acceleration by the CMEs and associated solar wind shock waves. The particles of these solar particle events, or solar proton events (both abbreviated to SPEs), are much lower in energy than GCR: generally below 100 MeV and only rarely above 10 GeV. SPEs are of short duration, a few hours to a few days, and highly variable in intensity. Only a small fraction of SPEs, on average one per year, produce large numbers of high-energy particles which cause significant dose rates at high altitudes and low geomagnetic cut-offs and can be observed by neutron monitors on the ground. Such events are called ground-level events (GLEs). For aircraft crews, the cumulative dose from GCR is far greater than the dose from SPEs. Intense SPEs can affect GCR dose rates by disturbing the Earth's magnetic field in such a way as to change the galactic particle intensity reaching the atmosphere.



Key

X altitude (km)

Y ambient dose equivalent rate (μSv/h)

Conditions: 1 GV cut-off and solar minimum (deceleration potential, *ϕ*, of 465 MV) [9]

Figure 1 — Calculated ambient dose equivalent rates as function of standard barometric altitude for high latitudes at solar minimum for various atmospheric cosmic radiation component particles

3.2 General calibration considerations for the dosimetry of cosmic radiation fields in aircraft

3.2.1 Approach

The general approach necessary for measurement and calibration is given here. Details of calibration fields and procedures are given in ISO 20785-2.

3.2.2 Considerations concerning the measurement

Ambient dose equivalent cannot be measured directly by conventional dosimetric techniques.[10] The experimental determination of ambient dose equivalent for the complex radiation field considered here (see Figure 1) is particularly difficult. An approximate approach is to use a tissue equivalent proportional counter (TEPC) to measure dose equivalent to a small mass of tissue, by measuring the absorbed dose distribution in lineal energy (which is an approximation for LET), with corrections applied, and directly applying the LET-dependent quality factor. However, this measurement still does not realize the quantity.

Dosimetry of the radiation field in aircraft requires specialized techniques of measurement and calculation. The preferred approach would be to use devices that have an ambient dose equivalent response that is independent of the energy and the direction of the total field, or the field component to be determined. It is generally necessary to apply corrections using data on the energy and direction characteristics of the field and the energy and angle ambient dose equivalent response characteristics of the device.

3.2.3 Considerations concerning the radiation field

The field comprises mainly photons, electrons, positrons, muons, protons and neutrons. There is not a significant contribution to dose equivalent from energetic primary heavy charged particles (HZE) or fragments. The electrons, positrons and muons are directly ionizing radiation, and together with indirectly ionizing photons and secondary electrons, interact with matter via the electromagnetic force. Neutrons (and a small contribution from pions), interact via the strong interaction producing directly ionizing secondary particles. Protons are both directly ionizing via the electromagnetic force and indirectly via neutron-like strong interactions.

The directly ionizing component and the secondary electrons from indirectly ionizing photons, comprise the non-neutron component. The neutrons plus the neutron-like interactions of protons comprise the neutron component. Alternatively, for dosimetric purposes, the field can be divided into low-LET (<10 keV/µm) and high-LET (≥10 keV/µm) components. This definition is based on the dependence of quality factor on LET. Quality factor is unity below 10 keV/µm. This separation between low and high LET particles can be applied to TEPCs, and to other materials and detectors but the low-LET/high-LET threshold may vary between 5 keV/µm and 10 keV/µm. The low-LET component comprises the directly ionizing electrons, positrons and muons; secondary electrons from photon interactions, most of the energy deposition by directly ionizing interactions of protons; and part of the energy deposition by secondary particles from strong interactions of protons and neutrons. The high-LET component is from relatively short-range secondary particles from strong-interactions of protons and neutrons. The relative contributions to the total ambient dose equivalent of low-LET and non-neutron component, and high-LET and neutron and neutron-like component are not necessarily the same, but are generally similar in magnitude.

The operational dose quantity relevant for these determinations, ambient dose equivalent, is reasonably approximated, assuming suitable calibration and normalization, by the response of a tissue equivalent proportional counter (TEPC), recombination ionization chamber or semiconductor spectrometer. The low-LET or non-neutron energy deposition can be determined using an ionization chamber, silicon-based detector, or scintillation detector; or a passive luminescence or ion storage detector. The high-LET or neutron component can be measured using an extended range neutron survey meter or multi-sphere spectrometer; or a passive etched track detector, bubble detector or fission foil with damage track detector. The summed components, low LET plus high LET, or non-neutron plus neutron and neutron-like, with suitable calibration and normalization, give total ambient dose equivalent. It is essential for the measurement of the complex radiation fields that the instruments used be fully characterized at national standards laboratories where possible, and thus that full traceability is established.

Definitions of terms and details of normal procedures used in the calibration and use of measurement devices are given in various ISO and ICRU documents (for instance, ISO 4037-3[87], ISO 8529-3[88], ISO 20785-2 and ICRU Report 66:2001[10]). The determination of the uncertainties associated with any set of measurement is an important part of dosimetry. Uncertainties associated with specific methods of dosimetry are frequently not statistically independent. Even when they are independent, the total uncertainty is frequently not simply the root mean square of the individual uncertainties but depends upon the procedure for measurement and analysis. Details are given in ISO/IEC Guide 98-3[83].

3.2.4 Considerations concerning calibration

In terms of ambient dose equivalent, the main contributions to the radiation field at aviation altitudes are from neutrons from a few hundred keV up to a few GeV, protons from a few tens of MeV to a few GeV, electrons, positrons and photons from a few MeV to a few GeV. The determination of the response characteristics, both energy and angle dependence, of devices used for the determinations of ambient dose equivalent for the cosmic radiation fields in aircraft should be carried out where possible in ISO reference radiations. However, ISO reference radiations do not fully cover the energy range of photons, neutrons and electrons to account for the majority of the contributions to total ambient dose equivalent. Thus, additional calibration fields are required, including, for some devices, proton radiation fields.

To determine the response characteristics to high-energy low-LET radiation field components for which reference fields are not available, it can be demonstrated by measurement and calculation for particular devices, for example the tissue equivalent proportional counter (TEPC), that the details of the energy deposition distribution in the sensitive volume of the device are similar for these components to those for the ISO high-energy photon reference field R–F. This addresses the particular problems associated with the setting of the low-LET threshold of TEPCs and other devices.[11][12][13] Quasi-monoenergetic neutron fields are available for energies up to about 200 MeV.[14][15][16][17][18] For the determination of the neutron response characteristics of devices for higher energies, measurements may sometimes be made in mono-energetic proton beams in combination with calculation, or in broad energy distribution neutron fields, also in combination with calculation.

For non ISO fields, use can be made by using a traceable technique to measure the particle fluence and convert it to ambient dose equivalent by applying fluence to dose conversion factors.

3.2.5 Simulated aircraft fields

3.2.5.1 Accelerator-based fields

Instrument response measurements and inter-comparisons can be made in the simulated cosmic radiation neutron field which has been designed at, and provided by, CERN. The facility has been developed and characterized jointly with the European Commission and is known as CERF (CERN-EU high-energy Reference Field facility).[19][20][21] The fields are created by beams of high-energy protons and pions with momenta of either 120 GeV/c (positive or negative) or 205 GeV/c (positive) incident on a copper target. There is massive concrete shielding at the side of the beam at the target positions, and, depending on target position, either iron or concrete shields above. The areal mass of the 80 cm concrete shields are almost equal to the air layer above for flight altitudes of 10 km to 15 km. Well-characterized neutron fields are located both at the side of the target area and on the roof shields. The neutron component (plus other hadrons) of the radiation field in each calibration position has been calculated by using the Monte Carlo code FLUKA.[22] A number of multi-sphere spectrometry measurements have also been made. At present the metrology of the field is not traceable to national standards.

3.2.5.2 Cosmic radiation fields on mountains

The cosmic radiation fields on the ground at high elevations are the radiation fields closest to those in aircraft,[23][26] but, as with accelerator-produced simulated aircraft fields, differences between these fields and the aircraft fields may affect the intercomparisons and/or evaluations of some instruments and should be taken into account. The composition and spectral fluence of the cosmic radiation field on the ground, even at altitudes as high as 4 km, is not exactly the same as the cosmic radiation field at aviation altitudes. The fraction of dose from muons is higher at lower altitudes. The cosmic radiation neutron spectrum on the ground has relatively more neutrons with energies above 10 MeV, fewer with energies from 1 eV to about 2 MeV, and more at thermal energies.[27] Different materials of the “ground” – soil, water or snow, concrete, or other building materials – scatter neutrons differently and can affect the shape of the neutron spectrum.

3.3 Conversion coefficients

The fluence-to-ambient dose equivalent conversion coefficients depend on the particle type and their energy. The data up to 20 MeV are well established and part of international recommendations (ISO, IEC, ICRU[28]). A compilation of fluence-to-ambient dose equivalent conversion factor for all particles and energies of relevance may be found in reference.[29]

4 Dosimetric devices

4.1 Introduction

The types of detectors that can be used for measurements to determine ambient dose equivalent onboard aircraft are similar to those devices used at accelerator laboratories. They can be categorized as active or passive, or by the component of the field measured (see, for example, Reference[30]). This standard gives the basis for instruments' use in the determination of ambient dose equivalent.

4.2 Active devices

4.2.1 Devices to determine all field components

4.2.1.1 Energy deposition spectrometers

The two main types of energy deposition spectrometers are gas-filled devices, in particular tissue equivalent proportional counters (TEPCs), and solid state (normally silicon) devices.

4.2.1.1.1 Tissue equivalent proportional counters

A tissue equivalent proportional counter (TEPC) is sensitive to directly ionizing particles and to indirectly ionizing particles via the charged secondary particles created by them in the walls of the counter. The sensitive volume is filled with a gas of chemical composition similar to tissue, at a low pressure in order to simulate a biological site of a few microns. Although ideally of spherical symmetry, TEPCs are often cylindrical. Incident radiation produces electrons in the gas which are collected on the central anode, when an electric field is applied between the anode and the wall of the detector. Each event (or particle track through the gas) produces an output signal whose magnitude is proportional to the initial energy deposited. Each event detected is analysed using a pulse height analysis method and stored to produce the lineal energy distribution spectrum, $d(y)$; y is the energy deposited divided by the average chord length of the detector. For many practical purposes, y is used as an approximation to LET. The sum of the deposited energy for each event divided by the mass of gas provides the absorbed dose. The dose equivalent may be calculated by folding the absorbed dose distribution with the quality factor.

Ambient dose equivalent is determined by a calibration in reference fields but note that for use to determine ambient dose equivalent for cosmic radiation fields, a correction for the lower-LET threshold of the device is normally necessary. An internal source of alpha particles (^{244}Cm) can be used to calibrate in terms of y. See References [31] and [32] and references therein.

4.2.1.1.2 Solid-state energy deposition spectrometers

Solid-state energy deposition spectrometers measure the energy deposited in one or more silicon detectors. If a single detector is used, a pulse height distribution is recorded.[33] Alternatively, several detectors with differing LET thresholds may be used.[34] The total dose to silicon and its distribution in LET can be related to dose and dose equivalent to tissue. Suitable characterization and calibration allows ambient dose equivalent to be determined.

4.2.1.2 Devices based on the determination of absorbed dose and mean quality factor

Dose equivalent can be also determined when a device is able to determine simultaneously the absorbed dose and a mean quality factor in a radiation field. This approach includes the TEPC operated in the variance/co-variance mode and the recombination chamber.

4.2.1.2.1 The TEPC variance method

The variance method [35][36] is a way to use a TEPC or other microdosimetric detector to measure the dose-mean lineal energy, $\bar{y}_D$, of a radiation field, without measuring the y spectrum. In this method, the fluctuation in the value of specific energy is determined when energy is deposited by many independent particles (events) in equal time intervals. The single-event dose-mean specific energy is equal to the relative variance of the measurements times their mean. The mean is the absorbed dose in the detector. In pulsed or other strongly time- or spatially-varying radiation fields, a correction to the variance is obtained by using two detectors or by analysing the variance of consecutive measurements.[37] For general applications, a mean quality factor is determined from a linear function of $\bar{y}_D$. The slope and intercept coefficients are determined from instrument characterization in various photon and neutron radiation standard fields. In some applications, including cosmic radiation measurements, single high-LET events (>150 keV/µm) can be resolved in the multiple-event spectrum and a quality factor can be determined according to ICRP 60 for this fraction.[38]

4.2.1.2.2 Recombination chambers

The recombination chamber makes use of the fact that the initial recombination of ions in the gas cavity of the ionization chamber depends on local ionization density. The latter can be related to LET and provides information on radiation quality of the investigated radiation fields.[39] The saturation current of the recombination chamber is proportional to the total absorbed dose D. Measurements of ionization current at a specially chosen “recombination” voltage enables determination of a recombination index of radiation quality and thus the dose equivalent, and, after characterization and calibration, ambient dose equivalent.[40][41]

The combination of ionization chamber data with that obtained with a scintillation detector in current mode is based on the same principle as the recombination method. The ionization chamber measures the absorbed dose, and a mean quality factor is determined on the basis of the decrease of scintillation yield of organic scintillators with the increase in LET of particles transferring the energy.[42]

4.2.1.3 Scintillation counters

Organic and inorganic scintillators are commonly used to detect photons and charged particles with high detection efficiency. Owing to the high hydrogen and carbon content, large-volume organic scintillators are also used as neutron detectors with a neutron detection efficiency depending on the thickness of the scintillator material. Therefore, small-sized scintillation counters (scintillator thicknesses of the order of 1 cm) used as dosemeters usually do not have sufficient detection efficiency for neutron dosimetry, but organic scintillators of sufficient size (thicknesses of a few 10 cm) can be used for spectrometric purposes.[43][44]

The use of scintillation counters as dosemeters in low-energy photon fields requires a specific arrangement of absorber materials surrounding the scintillator itself, in order to match a flat energy-dependent response in terms of $H^*(10)$. Even though the scintillation counters are calibrated using reference photon fields, the reading of the instruments in the cosmic radiation field may differ significantly from the true value, or from the reading of an ionization chamber. This can be explained by the restricted range of energies measured by these devices. High-energy-charged particles may deposit energy above the upper energy limit of a few MeV leading to a reduced detection efficiency for these particles. The reading of the dosemeter has to be corrected to take account of this.

4.2.2 Devices for low LET/non-neutron

4.2.2.1 Ionization chambers

Ionization chambers are based on the collection of the electrons and ions created by radiation within a gas. The formation of each electron-ion pair requires about 30 eV of energy. An electric field is applied between electrodes. The electrons and ions are collected by the electrodes and the total charge or current measured by an electrometer. The signal is proportional to the total energy deposited in the gas by the ionizing radiation. Ionization chambers can be operated in current or pulse mode.[45] In most common applications, ionization chambers are used in current mode as dc devices. Although the detector is able to operate in free air, normally the chamber is used as an airtight container, usually spherical or cylindrical in shape. For low-dose-rate measurements, chambers are commonly filled with an inert gas at a higher pressure in order to increase the sensitivity. For measurements in mixed radiation a typical instrument has a sensitive volume of 8 l, filled with argon at a pressure of 2.5 MPa. The chamber is of a welded stainless steel construction for the shell and internal components.[46]

4.2.2.2 Geiger Müller counters

Geiger Müller (GM) counter equipment, mostly commercially available, is also often utilized to estimate low-LET radiation of onboard aircraft. Such equipment is very simple to operate, and provides measurements with high statistical accuracy from the levels corresponding to the natural radiation background up to high altitudes. GM counters register events from directly ionizing particles and photons, with almost no response to neutrons (less than 5 %). GM counters show almost the same response to cosmic radiation fields as ionization chambers, relative to a calibration in a ^{60}Co standard radiation field.[47][48]

4.2.2.3 Electronic personal dosemeters

There are a number of real-time electronic personal dosemeters available, mostly using silicon-based detectors, but also one type which couples a small gas-filled ion chamber with a semiconductor non-volatile memory cell.[49][50][51] Most of these have been designed to measure photon and beta radiations. Several have tissue-equivalent encapsulation, and might be considered for the measurement of the low-LET component of the field in aircraft. A few devices are designed to measure neutron fields up to about 10 MeV, either separately or as combined neutron–photon devices. Such dosemeters would require a full characterization of the proton and high-energy neutron response before use.

4.2.3 Devices for high-LET/neutron component

4.2.3.1 Moderated devices

Moderate-and-capture devices employing a thermal-neutron detector surrounded by a hydrogenous moderator are frequently used to determine $H^*(10)$ in neutron fields.[10] Such devices, often called rem meters, generally show a decreasing dose equivalent response with increasing energy in the MeV region. This is true both for homogeneous spheres (including multi-sphere spectrometer detectors) and for detectors with neutron absorbing layers to simulate the required dose equivalent response. In cosmic radiation neutron monitors, lead is used to “convert” high-energy particles, especially neutrons, into multiple lower-energy neutrons which are readily moderated and detected.[52] This converter principle has been implemented in survey instruments for routine use at high-energy accelerators in the LINUS (Long Interval Neutron Survey-meter),[53][54] which uses a lead converter, a similar device (NM500X),[55]] and the WENDI (Wide Energy Neutron Detection Instrument),[56] which uses tungsten as both a neutron generator material above 8 MeV and as an absorber below several keV.

Neutron measuring devices, such as extended range moderated devices described here, also respond to neutron-like (strong force) interactions of protons and, of lesser importance, pions. With suitable calibrations, these devices measure the contribution to ambient dose equivalent from the neutron component plus neutron-like components of the field.

4.2.3.2 Spectrometers

4.2.3.2.1 General considerations

Spectrometers are instrument systems used to measure the energy distribution of particle fluence, Φ_E, or fluence rate. If Φ_E is known for a given particle type, the ambient dose equivalent from that particle type is determined from $H^*(10) = \int \Phi_\mathrm{E} h^* dE$, where E is energy and h^* is the particle fluence-to-ambient dose equivalent conversion coefficient. Values of h^* have been calculated for neutrons, photons, electrons, and protons over the wide energy range found in the atmospheric cosmic radiation field.[29] Measurements with spectrometers can provide verification of the calculations of Φ_E that are the basis of numerical dosimetry. Spectrometers are also useful in measuring $H^*(10)$, particularly from high-LET radiations, such as neutrons and nuclear ions, where Q and h^* depend strongly on particle energy.

4.2.3.2.2 Neutron spectrometers

Of the many kinds of active neutron spectrometers,[57] two have high enough sensitivity to measure the cosmic radiation neutron energy distribution in aircraft: moderate-and-capture multi-detector (multi-sphere) spectrometers and recoil-proton spectrometers using organic liquid or solid scintillators. Only multi-sphere spectrometers have been used to make measurements in aircraft.

A multi-sphere neutron spectrometer [58][59] is a set of polyethylene moderator spheres, each with a detector at its centre having a large response to thermal neutrons. The larger the moderator, the higher the energy of incident neutrons for which the detector-sphere assembly has good detection efficiency. Once the neutron count rates and response functions of the detectors are known, a deconvolution (unfolding) computer code is applied to determine the neutron spectrum. ICRU Report 66,[10] includes an introduction to the principles and practice of multi-sphere neutron spectrometers for characterizing workplace neutron fields, with a comprehensive list of references and a discussion of the modifications necessary for use in high-energy fields. High atomic number converters (see 4.2.2.1) have been used to make high-energy detector assemblies and allow multi-sphere spectrometers to measure the entire cosmic radiation neutron energy distribution (thermal energy to > 10 GeV) on the ground [23][25][27] and in aircraft.[25][27] To measure just the neutron energy distribution, the raw count rates of the detector assemblies, especially those with heavy-metal converters, should be corrected for counts caused by high-energy cosmic radiation protons.[27] Multi-sphere neutron spectrometers are somewhat large and heavy for use in aircraft, and analysis of their data is complex, so they are better suited for determining reference values of $H^*(10)$ rates and verifying calculations of Φ_E for neutrons than for routine monitoring.

Passive multi-detector spectrometers have been developed for measurements in aircraft.[60][61] Such spectrometers are very compact and do not require power or in-flight technical intervention, but are relatively insensitive. The passive multi-detector spectrometer is based on different types of improved etched track detectors (see 4.3.2) and fission foil detectors (see 4.3.3). As an alternative to determining the neutron energy distribution, estimations of spectrum hardness can be made by evaluating the ratios of responses of detectors with different fissile radiators.[61][62] Fission detectors have also been used to supplement multi-sphere spectrometers in order to cover the high-energy part of the spectrum.[59]

4.3 Passive devices

4.3.1 General considerations

Passive detectors are suitable for measuring ambient dose equivalent integrated over flights or a number of flights. The sensitivity and intrinsic background need to be considered. The basic types of passive devices for high-LET/neutron components are track etch detectors and superheated emulsions (also known as bubble damage or superheated drop detectors). Both types of detectors respond to high-energy protons: the expected contribution of high-energy protons to the reading is unlikely to exceed 5 % to 10 %. Generally, the ambient dose equivalent response of these neutron passive detectors is lower for the neutron field in aircraft than for the ISO reference fields which extend up to 20 MeV. The large uncertainty associated with a measurement using a single-track etch detector can be reduced by using stacks. Track detectors can also be used with fission foils with sufficient sensitivity.

Basic types of passive detector for the low–LET/non-neutron component are thermoluminescent, optically stimulated luminescent and photoluminescent (TL, OSL and RPL) detectors. Several types can be used to determine onboard exposure level, for instance LiF:Mg,Ti; LiF:Mg, Cu, P and/or Al_2O_3:C; $CaSO_4$:Dy; Al-P glasses. Recently developed, more sensitive, TL materials allow the measurement of values of ambient dose equivalent down to about 1 µSv. The response to neutrons, particularly high-energy, should be considered.

4.3.2 Etched track detectors

Tracks of secondary particles created in the detector material by the passage of charged particles, either primary or produced during neutron nuclear interactions in the detector and/or its surroundings, are registered by chemical etching of damage “trails”. Details of etched track detector properties may be found in References[63] and.[64] The most frequently used material for these GCR measurements is poly allyl diglycol carbonate (PADC, also known by the trade name CR–39).[65] The same detectors can be also used to determine the spectra of particles with LET between about 5 keV/µm to 10 keV/µm and 500 keV/µm to 1 000 keV/µm in H_2O. The distribution of absorbed dose in LET can also be measured, and from this, dose equivalent can be determined. The dimensions of a large number of tracks of secondary particles, mostly protons, are measured and the LET of the particles is determined via the characterization of track parameters of samples of the track etch material in proton and heavy charged-particle beam.[66]

Among other types of material, polycarbonate is of interest because of its consistently low background and its reproducibility of response. Moreover, polycarbonate bottles or test tubes may be used as track detectors, including the bottles of bubble detectors.[67] These polycarbonate bottles can be useful as back-up detectors for bubble devices, the response of which may saturate in case of intense solar flares event. Problems of limited response and the low-signal-to-noise ratio of these detectors have been solved by counting coincident tracks on matched surfaces of paired detectors.

4.3.3 Fission foil detectors

The registration of sparked-through holes produced by etched tracks of fission fragments in thin plastic films (polyethylene terephthalate and polycarbonate) has been used for neutron detection and dosimetry since 1970.[68] Neutron-induced fission cross-sections for some heavy nuclei (^{235}U, ^{238}U, ^{232}Th, ^{209}Bi) are internationally recommended as secondary standards for neutron flux monitoring in the energy region above 20 MeV. Among these heavy elements, ^{209}Bi is the most useful standard for high-energy neutron studies for the following reasons: there are no reactions with low-energy neutrons; there is smooth variation of the cross-section with neutron energy; simplicity in the use and transport since it is not radioactive. The attractive characteristics of fission reactions for neutron detection and dosimetry can be exploited using different types of fission-fragment detectors, the most interesting of which are: fission chambers, thin film breakdown counters, and fission-fragment damage track detectors. Low sensitivity can be a serious disadvantage for the application of fission-type detectors to many high-energy situations but this can be overcome, even for such a low fission cross-section as that of bismuth, by using an advanced spark counter and special counting procedures.[69]

4.3.4 Superheated emulsion neutron detectors (bubble) detectors

Superheated emulsion neutron detectors (or neutron bubble detectors) have been used as passive detectors for neutron monitoring at aircraft altitudes because of their ability to be a direct reading detector completely insensitive to gamma radiation and because they can estimate neutron ambient dose equivalent down to 1 μSv.[70][71] The superheated emulsion neutron detector is a small polycarbonate bottle which contains small droplets of a superheated liquid that is dispersed throughout a visco-elastic medium. When neutrons enter the detector, they may produce recoil charged particles that can initiate bubble nucleation and gas-bubble growth.[72][73] The detection also depends on the temperature and pressure of the host medium. Normal variations in the aircraft pressure do not result in significant differences in sensitivity. In some cases, the detector can be reset (i.e. the bubbles compressed) by screwing down a cap which applies a pressure to the visco-elastic medium. By relieving this pressure, the detector is once again sensitized for measurement. Compensation for temperature changes can be achieved by introducing an expandable material on top of the gel. Detectors can be made with various sensitivities.

When using sets of detectors with differing energy dependences of response, an estimation of neutron fluence energy distribution spectra can be made.

4.3.5 Thermoluminescent detectors

Thermoluminescence, more correctly radiothermoluminescence is the phenomenon of light emission on heating of irradiated, generally crystalline, material. A fraction of the energy deposited by the radiation is stored in metastable “traps” [74]. Most commonly used thermoluminescent detectors (TLDs) provide good determinations of the low LET or non-neutron radiation field components from directly ionizing radiation and from secondary particles from photon interactions in the detector and its encapsulation. With some materials and/or special techniques the high-LET or neutron component may be estimated. Generally, however, TLDs are used to measure only the low-LET or non-neutron component and any response to neutrons introduces an uncertainty. However, whereas neutrons contribute about 50 % of the total ambient dose equivalent in the GCR field onboard aircraft, the contribution to the total absorbed dose in tissue is only about 10 %. In TLDs, the neutron kerma (for the energy distribution for the fields being considered) is lower than in tissue. For TLDs, in general, the relative light conversion efficiency for the secondary charged particles is also low overall. As a result, the unwanted neutron response is unlikely to exceed about 5 % in terms of total $H^*(10)$. The uncertainty of a TLD measurement can be reduced by the use of several detectors.

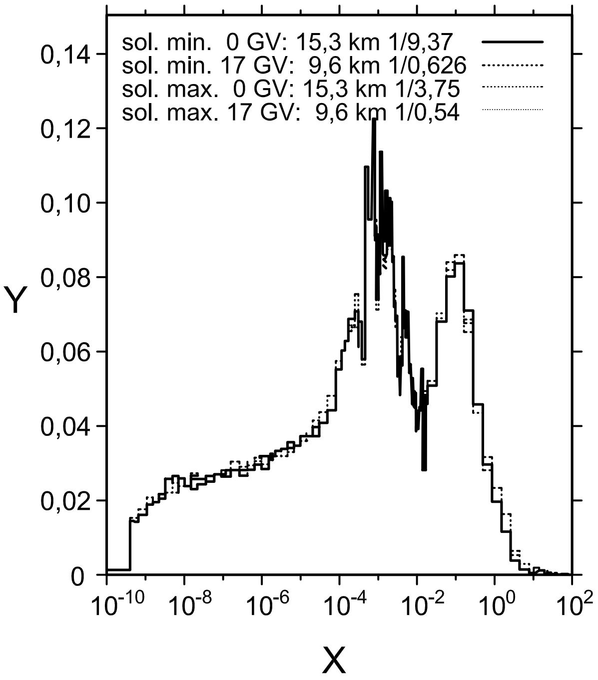
4.3.6 Photoluminescent detectors

A disadvantage of the use of some high-sensitivity materials for TL dosimetry is an observed heating rate dependence due to thermal quenching of the luminescence efficiency. This disadvantage can be overcome by using photoluminescent detectors (PLD) such as a radiophotoluminescent (RPL) glass or an optically stimulated luminescence (OSL) detector such as Al_2O_3:C. The radiation-induced luminescence signal is stimulated using light from a laser. Several photoluminescence readout modes have been successfully developed.[75][76][77] PLDs have low light conversion efficiencies for high-LET energy deposition.[78][79]

Annex A
(informative)

Representative particle fluence rate energy distributions for the cosmic radiation field at flight altitudes for solar minimum and maximum conditions and for minimum and maximum vertical cut-off rigidity [80]

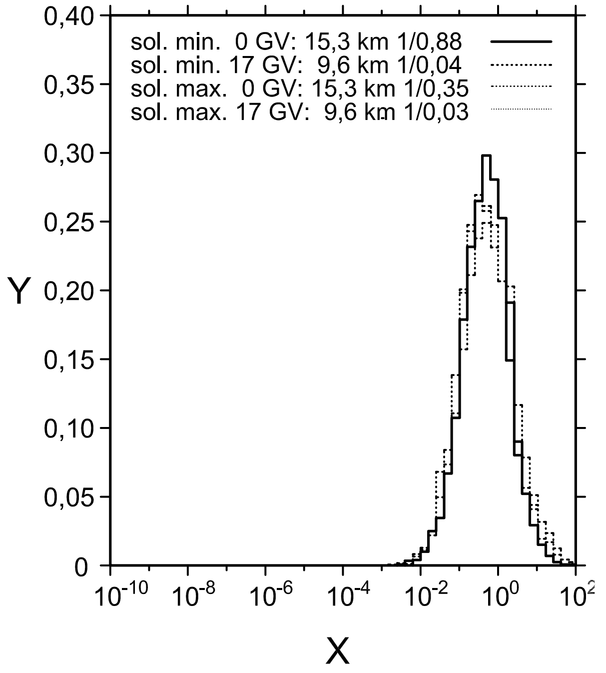
Figures A.1 to A.6 show the calculated particle fluence rate energy distributions for neutrons, protons, pions, electrons, photons and muons for the extreme values of solar activity, geomagnetic cut-off and altitude which could be expected for civilian aircraft. (In each figure, the energy distributions of particle fluence rates $d^2\Phi/dt{\cdot}dE$ (cm^{-2} s^{-1} GeV^{-1}), i.e. particle fluence per time interval d*t* and energy interval d*E*, are multiplied with the energy *E*, and normalized to the energy integrated fluence rates (the normalization factor is given in each figure for the respective curves).



Key

X energy (GeV)
Y normalized fluence rate of neutrons

Figure A.1 — Normalized energy distribution of neutron fluence rate

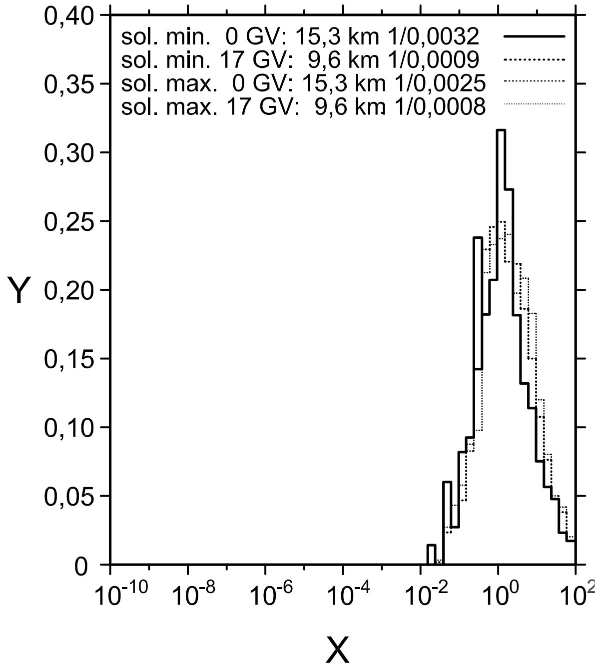


Key

X energy (GeV)

Y normalized fluence rate of protons

Figure A.2 — Normalized energy distribution of proton fluence rate

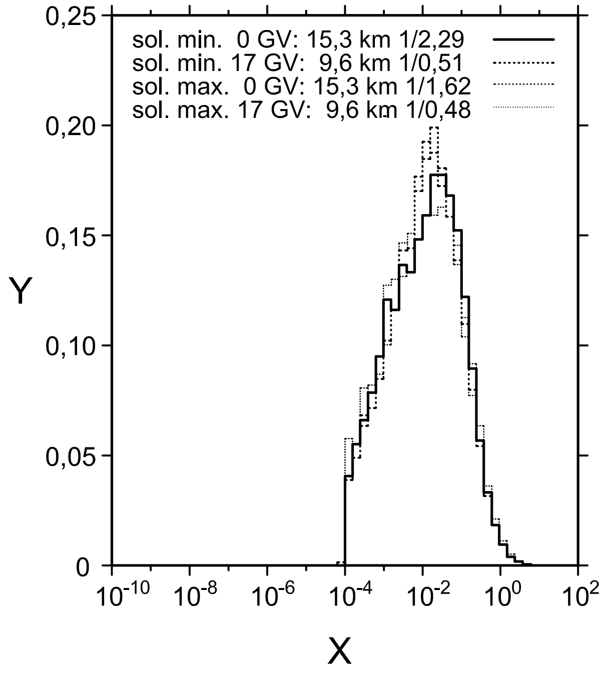


Key

X energy (GeV)

Y normalized fluence rate of pions

Figure A.3 — Normalized energy distribution of fluence rate of charged pions

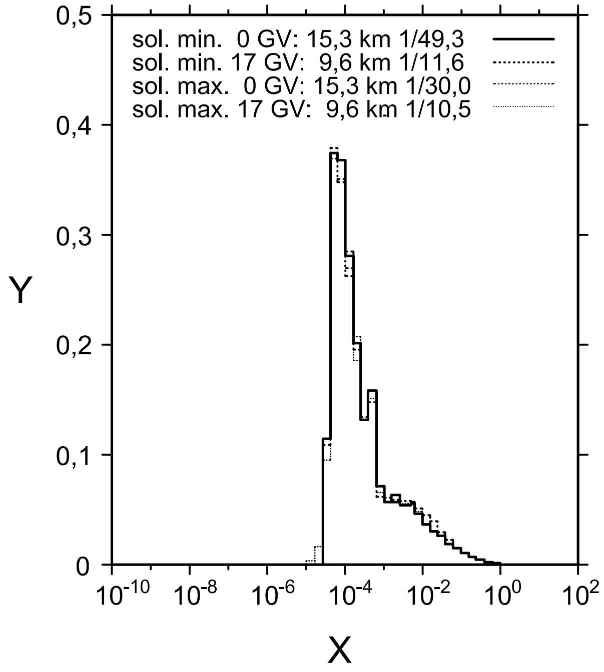


Key

X energy (GeV)

Y normalized fluence rate of electrons

Figure A.4 — Normalized energy distribution of electron fluence rate

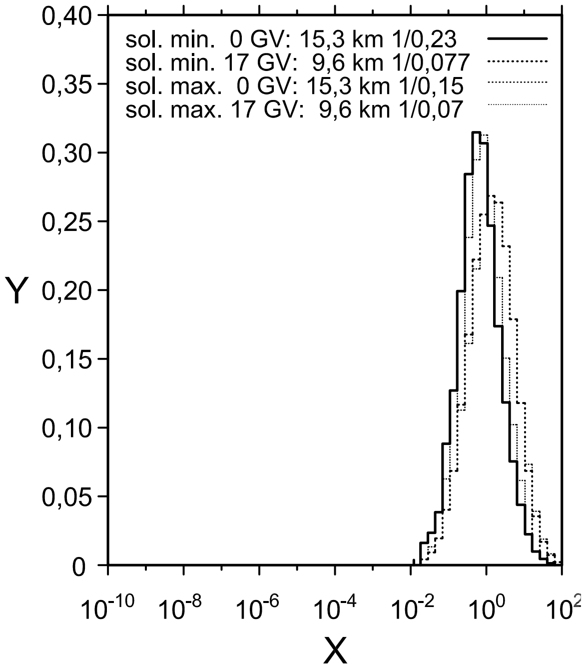


Key

X energy (GeV)

Y normalized fluence rate of photons

Figure A.5 — Normalized energy distribution of photon fluence rate



Key

X energy (GeV)

Y normalized fluence rate of muons

Figure A.6 — Normalized energy distribution of muon fluence rate

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