
**Dosemetry for exposures to cosmic
radiation in civilian aircraft —**

**Part 1:
Conceptual basis for measurements**

*Dosimétrie de l'exposition au rayonnement cosmique dans l'aviation
civile —*

Partie 1: Fondement théorique des mesurages



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Case postale 56 • CH-1211 Geneva 20
Tel. + 41 22 749 01 11
Fax + 41 22 749 09 47
E-mail copyright@iso.org
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Contents

Page

Foreword.....	iv
Introduction	v
1 Scope	1
2 Normative references	1
3 Terms, definitions and symbols	1
3.1 Quantities and units	1
3.2 Atmospheric radiation field	5
4 General considerations	7
4.1 General description of the cosmic radiation field in the atmosphere	7
4.2 General calibration considerations for the dosimetry of cosmic radiation fields in aircraft.....	9
4.3 Conversion coefficients	11
5 Dosimetric devices	11
5.1 Introduction	11
5.2 Active devices	11
5.3 Passive devices	14
Annex A (informative) Representative particle fluence 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.....	17
Bibliography	21

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

International Standards are drafted in accordance with the rules given in the ISO/IEC Directives, Part 2.

The main task of technical committees is to prepare International Standards. Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights.

ISO 20785-1 was prepared by Technical Committee ISO/TC 85, *Nuclear energy*, Subcommittee SC 2, *Radiation protection*.

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

— *Part 1: Conceptual basis for measurements*

A Part 2 dealing with the characterization of instrument response is in preparation.

Introduction

Aircraft crew 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], the European Union (EU) introduced a revised Basic Safety Standards Directive^[2], 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 crew 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 crew; (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 crew 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.

For regulatory and legislative purposes, the radiation protection quantities of interest are equivalent dose (to the foetus) and 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 dosimeters for routine use are not considered necessary^[2],^[3]. The preferred approach for the assessment of doses of aircraft crew, where necessary, is to calculate directly 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^[3].

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. 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 effective dose by the same computer code, but it can be necessary to confirm this step in the process. 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 integrated with flight and staff roster information. The calculations of ambient dose equivalent rates or route doses can then be validated by measurements traceable to national standards.

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, and the purpose of this International Standard is to give the conceptual basis for performing such measurements and for the calibration of instruments used for this purpose. 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 taken 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. The future Part 2 of ISO 20785 will give procedures for the characterization of the response of instruments for the determination of ambient dose equivalent in aircraft.

ISO 20785-1:2006(E)

Requirements for the determination and recording of the cosmic radiation exposure of aircraft crew 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 International Standard 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 crew.

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Dosemetry 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 this purpose.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

NOTE The documents published by the ICRP (International Commission on Radiological Protection) and the ICRU (International Commission on Radiation and Measurements) are recognised by the ISO committee as having a wide acceptance and authority status.

ICRU Report 60:1998, *Fundamental Quantities and Units for Ionizing Radiation*

3 Terms, definitions and symbols

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

3.1 Quantities and units

3.1.1 particle fluence fluence

Φ

quotient of dN by da , where dN is the number of particles incident on a sphere of cross-sectional area da

$$\Phi = \frac{dN}{da}$$

NOTE 1 The unit of the particle fluence is m^{-2} , a frequently used unit is cm^{-2} .

NOTE 2 The energy distribution of the particle fluence, Φ_E , is the quotient $d\Phi$ by dE , where $d\Phi$ 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) $\Phi_{E,\Omega}(E, \Omega)$, 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 the energy, $E = E_0$, is written as $\Phi_E(E_0)$. If no special values are indicated, the brackets can be omitted.

3.1.2
particle fluence rate
fluence rate

$\dot{\Phi}$

quotient of $d\Phi$ by dt , where $d\Phi$ is the increment of particle fluence in the time interval dt :

$$\dot{\Phi} = \frac{d\Phi}{dt} = \frac{d^2N}{da \cdot dt}$$

NOTE The unit of the particle fluence rate is m^{-2}/s , a frequently used unit is cm^{-2}/s .

3.1.3
energy imparted

ε
energy imparted by ionizing radiation to the matter in a given volume

NOTE The unit of the energy imparted is J.

3.1.4
mean energy imparted

$\bar{\varepsilon}$
expectation value of the energy imparted by ionizing radiation to the matter in a given volume

NOTE The unit of the mean energy imparted is J.

3.1.5
specific energy imparted

z
quotient of ε by dm , where ε is the energy imparted by ionizing radiation to matter of mass dm :

$$z = \frac{d\varepsilon}{dm}$$

NOTE The unit of specific energy is J/kg, with the special name gray (Gy).

3.1.6
absorbed dose

D
quotient of $d\bar{\varepsilon}$ by dm , where $d\bar{\varepsilon}$ is the mean energy imparted to matter of mass dm :

$$D = \frac{d\bar{\varepsilon}}{dm}$$

NOTE The unit of absorbed dose is J/kg, with the special name gray (Gy).

3.1.7
kerma

K
quotient of dE_{tr} by dm , where dE_{tr} is the sum of the initial kinetic energies of all the charged particles liberated by uncharged particles in the mass, dm , of material:

$$K = \frac{dE_{tr}}{dm}$$

NOTE The unit of kerma is J/kg, with the special name gray (Gy).

3.1.8 linear energy transfer LET

L

quotient of dE by dl , where dE is the energy lost in a material by a charged particle due to electronic collisions in traversing a distance dl :

$$L = \frac{dE}{dl}$$

NOTE The unit of the linear energy transfer is J/m, a frequently used unit is keV/ μ m.

3.1.9 dose equivalent

H

product of Q and D at the point of interest in tissue, where D is the absorbed dose, Q is the quality factor at that point, D_L is the distribution of the dose D in linear energy transfer L , and $Q(L)$ is the quality factor as a function of L in water:

$$H = Q \cdot D = \int Q(L) D_L dL$$

NOTE 1 The unit of dose equivalent is J/kg, with the special name sievert (Sv).

NOTE 2 Values for the relationship $Q(L)$ are given in ICRP Publication 60:1998.

3.1.10 dose-mean specific energy per event single-event dose-mean specific energy

\bar{z}_D

expectation value $\bar{z}_D = \int_0^{\infty} z d_1(z) dz$, where $d_1(z)$ is the dose probability density of z

NOTE The dose probability density of z is given by $d_1(z) = dD_1(z)/dz$, where $D_1(z)$ is the fraction of absorbed dose per event delivered with specific energy less than or equal to z .

3.1.11 lineal energy

y

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

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

NOTE The unit of the lineal energy is J/m, a frequently used unit is keV/ μ m.

3.1.12 dose-mean lineal energy

\bar{y}_D

expectation value $\bar{y}_D = \int_0^{\infty} y d(y) dy$, where $d(y)$ is the dose probability density of y .

NOTE 1 The dose probability density of y is given by $d(y) = dD(y)/dy$, where $D(y)$ is the fraction of absorbed dose delivered with lineal energy less than or equal to y .

NOTE 2 Both \bar{y}_D and the distribution $d(y)$ are independent of the absorbed dose or dose rate.

**3.1.13
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 The unit of the ambient dose equivalent is J/kg, with the special name sievert (Sv).

**3.1.14
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 The unit of the particle fluence-to-ambient dose equivalent conversion coefficient is J·m²/kg with the special name Sv·m², a frequently used unit is Sv·cm².

**3.1.15
indication
reading**

M

(of a measuring instrument) value of a quantity provided by a measuring instrument

NOTE 1 The value read from the displaying device can be called the direct indication; it is multiplied by the instrument constant to give the indication.

NOTE 2 The quantity can be the measurand, a measurement signal, or another quantity to be used in calculating the value of the measurand.

NOTE 3 It is necessary to document whether the indication (reading) is normalized to the reference conditions to account for influence quantities and is corrected for intrinsic background and other factors.

**3.1.16
response characteristic
response**

R

quotient of the indication (reading), M , of the instrument, by the value of the quantity, X , to be measured by the instrument, for a specified type, energy and direction distribution of radiation:

$$R = \frac{M}{X}$$

NOTE 1 VIM says, as a note in the definition of "measurement signal", that "the input signal to a measuring system may be called the stimulus, the output signal may be called the response." The term "response characteristic" is defined as the "relationship between a stimulus and the corresponding response, for defined conditions". In radiation metrology generally, the term "response" is an abbreviated form of "response characteristic".

NOTE 2 It is necessary, in order to avoid confusion, to state the type of response, e.g. fluence response (response with respect to ϕ):

$$R_\phi = \frac{M}{\phi}$$

or, dose equivalent response (response with respect to dose equivalent H)

$$R_H = \frac{M}{H}$$

3.1.17**atmospheric depth** X_v

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

NOTE The unit of atmospheric depth is kg/m²; a frequently used unit is g/cm².**3.1.18****magnetic rigidity****rigidity**

momentum per unit charge (of a particle in a magnetic field)

NOTE 1 The unit of rigidity is T·m. A frequently used unit is V (or GV) in a system of units where momentum, p , is given in eV/c (or GeV/c), and where rigidity is c times momentum per unit charge, $p \cdot c/Q$.

NOTE 2 Rigidity is especially useful in characterizing 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 atomic charge.

3.1.19**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 Cut-off rigidity depends on angle of incidence. Often vertical incidence is assumed.

3.1.20**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

3.2 Atmospheric radiation field**3.2.1****cosmic radiation****cosmic rays****cosmic particles**

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

3.2.2**primary cosmic radiation****primary cosmic rays**

cosmic radiation incident from space

3.2.3**secondary cosmic radiation****secondary cosmic rays****cosmogenic particles**

particles that are created, directly or in a cascade of reactions, by primary cosmic radiation interacting with the atmosphere or other matter

NOTE 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.

3.2.4

galactic cosmic radiation

galactic cosmic rays

GCR

cosmic radiation originating outside the solar system

3.2.5

solar cosmic radiation

solar cosmic rays

solar particles

cosmic radiation originating from the sun

3.2.6

solar particle event

SPE

large fluence rate of energetic solar particles ejected into space by a solar eruption, or the sudden increase of cosmic radiation observed when such particles arrive at Earth

3.2.7

ground level event

GLE

sudden increase of cosmic radiation, observed on the ground and at flight altitudes associated with a solar particle event, having a high flux of particles with high energy (greater than 500 MeV)

NOTE GLEs are rare, occurring on average about once per year.

3.2.8

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

3.2.9

solar cycle

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

NOTE 1 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.

NOTE 2 The sunspot cycle, as measured by the relative sunspot number, has an approximate length of 11 years, but this varies between about 7 years 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.

3.2.10

relative sunspot number

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

NOTE The relative sunspot number is also known as the "Wolf number".

3.2.11

solar maximum

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

3.2.12**solar minimum**

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

3.2.13**cosmic ray neutron monitor****ground level 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, but can also include protons, other hadrons, and muons

NOTE 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.

4 General considerations**4.1 General description of the cosmic radiation field in the atmosphere**

The earth is continually bombarded by high-energy particles that come from outside the solar system, called galactic cosmic radiation (GCR), and sporadically exposed to bursts of energetic particles from the sun. This primary cosmic radiation interacts 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 aircraft altitudes to sea level^{[4], [5], [6]}. Solar cosmic radiation is discussed at the end of this section; doses are far smaller than from GCR. About 98 % of the GCR are ionized atomic nuclei and about 2 % are electrons. Of the nuclei, about 90 % are protons (hydrogen nuclei), 9 % are helium ions, and 1 % are heavier ions^[7]. They can have energies up to about 10^{20} eV, but lower-energy particles are the most frequent. After the GCR penetrates the magnetic field of the solar system, the peak of its 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 the GCR entering the solar system is fairly constant in time, and these energetic ions approach the earth from all directions about equally.

Since cosmic radiation particles are electrically charged, their paths are bent when they cross a magnetic field. The lower the momentum per unit charge (magnetic rigidity) of an ion, the more its path is bent. The magnetic field that permeates the solar system and the stronger magnetic field of the earth act as shields that lower the number of low-momentum GCR striking the atmosphere and consequently lower atmospheric cosmic-ray dose rates.

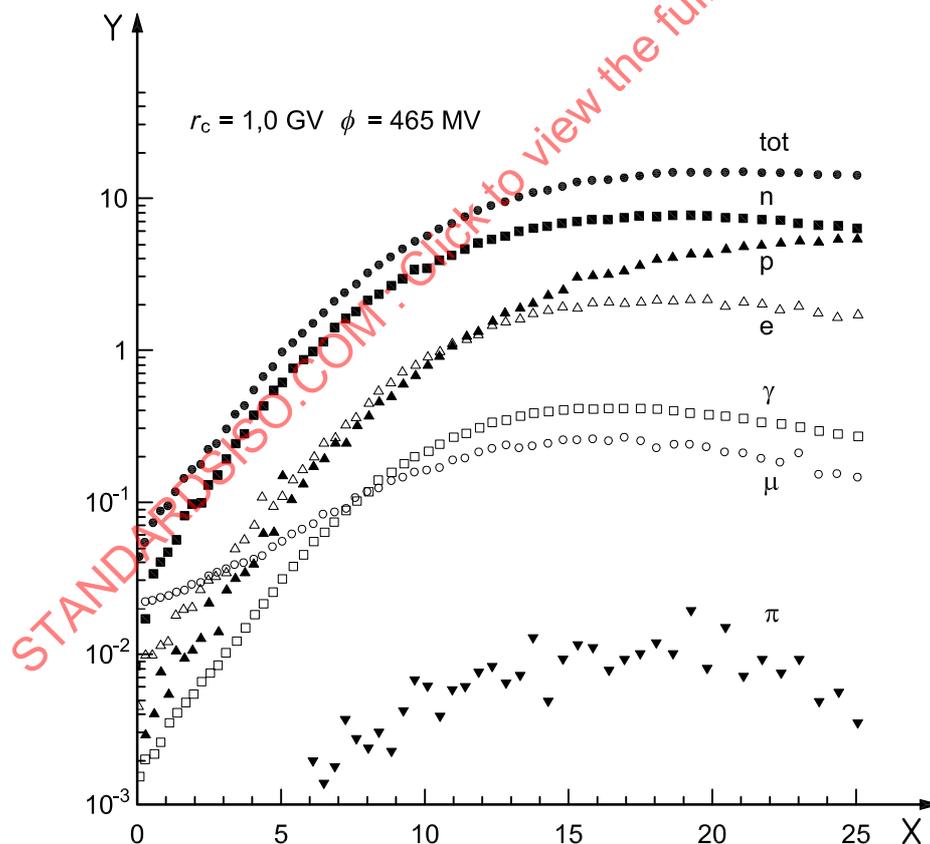
The Sun has a varying magnetic field with a basic dipole component that reverses direction approximately every 11 years. Near reversals, at "solar maximum", there are many sunspots and other manifestations of magnetic turbulence, and the plasma of protons and electrons ejected from the Sun (the solar wind) carries a relatively strong and convoluted magnetic field with it outward through the solar system. At a solar maximum, the GCR are maximally deflected as they enter the solar system, causing a radiation minimum at Earth. Between reversals, at a "solar minimum", there are few sunspots, and the heliosphere's magnetic field is relatively weak and smooth, so a solar minimum is the time of radiation maximum. The relative change in dose rates from this solar modulation depends on the other two main variables affecting cosmic radiation in the atmosphere: geomagnetic latitude and altitude.

The Earth's magnetic field has a larger effect than the Sun's on cosmic radiation particles approaching the atmosphere. Near the equator, where the geomagnetic field is nearly parallel to the ground, vertically incident particles with magnetic rigidity less than about 15 GV are bent back into space. The minimum rigidity that a vertically incident particle can have and still reach a given location is called the vertical geomagnetic cut-off rigidity (cut-off) for that point. Near the magnetic poles, where the geomagnetic field is nearly vertical, the vertical cut-off approaches zero, and the maximum number of primary cosmic radiation can reach the atmosphere. As a result, cosmic radiation exposure rates are highest in polar regions and decline toward the equator. The size of this effect depends on the altitude and the phase in the solar cycle.

The magnetic fields of the Earth and the Sun also alter the relative number of GCR protons and heavier ions reaching the atmosphere. The GCR ion composition entering the atmosphere, as given above (90 % protons, 9 % He ions, 1 % heavier nuclei), is true for low geomagnetic cut-off and low solar activity. At a vertical cut-off of 15 GV, the composition is approximately 83 % protons, 15 % He ions, and nearly 2 % heavier ions.

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 low altitudes, the muon component is the most important contributor to ambient dose equivalent and effective dose; at aircraft altitudes, neutrons, electrons, positrons, photons, and protons 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, or 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 of 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 particle fluence rate. Only a small fraction of SPEs, on average one per year, produce large numbers of high-energy particles that 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 crew, 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 GCR particle fluence rate reaching the atmosphere.



Key
 X altitude (km)
 Y ambient dose equivalent rate, ($\mu\text{Sv}\cdot\text{h}^{-1}$)

Conditions: 1 GV cut-off and solar minimum (deceleration potential, ϕ , of 465 MV)^[8]

Figure 1 — Calculated ambient dose equivalent rates as a function of standard barometric altitude for various atmospheric cosmic radiation component particles

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

4.2.1 Approach

The general approach necessary for measurement and calibration is given in 4.2. Details of calibration fields and procedures will be given in the future Part 2 of ISO 20785.

4.2.2 Considerations concerning the measurement

The ambient dose equivalent cannot be measured directly by conventional dosimetric techniques^[9]. 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 is 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.

4.2.3 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 force 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 ($< 10 \text{ keV}/\mu\text{m}$) and high-LET ($> 10 \text{ keV}/\mu\text{m}$) components. This definition is based on the dependence of the quality factor on LET. The quality factor is unity below $10 \text{ keV}/\mu\text{m}$. 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 can vary between $5 \text{ keV}/\mu\text{m}$ and $10 \text{ keV}/\mu\text{m}$. The low-LET component includes the directly ionizing electrons, positrons and muons; the secondary electrons from photon interactions, which contribute 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, the 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 the total ambient dose equivalent. It is essential for the measurement of the complex radiation fields that the instruments used are 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^[85], ISO 8529-3^[88], ICRU Report 66^[9]). 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 depend upon the procedure for measurement and analysis. Details are given in GUM.

4.2.4 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^{[10] to [12]}. Quasi-monoenergetic neutron fields are available for energies up to about 200 MeV^{[13] to [17]}. 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, a traceable technique can be used to measure the particle fluence and convert it to ambient dose equivalent by applying fluence to dose conversion factors.

4.2.5 Simulated aircraft fields

4.2.5.1 Accelerator based fields

Instrument response measurements and intercomparisons can be made in the simulated cosmic radiation neutron field, which has been designed and provided at 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)^{[18] to [20]}. 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 is 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^[21]. A number of multisphere spectrometry measurements has also been made. At present, the metrology of the field is not traceable to national standards.

4.2.5.2 Cosmic radiation fields on mountains

The cosmic radiation fields on the ground at high elevations are the radiation fields closest to those in aircraft^{[22] to [25]}, but, as with accelerator-produced simulated aircraft fields, differences between these fields and the aircraft fields can 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, are not exactly the same as the cosmic radiation field at aviation altitudes. The fraction of the 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^[26]. Different materials of the “ground”, e.g. soil, water or snow, concrete, or other building materials, scatter neutrons differently and can affect the shape of the neutron spectrum.

4.3 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 57^[27]). A compilation of fluence to ambient dose equivalent conversion factor for all particles and energies of relevance can be found in Reference [28].

Recommended conversion coefficients will be given in Part 2 of ISO 20785.

5 Dosimetric devices

5.1 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 [29]). This part of ISO 20785 gives the basis for instruments' use in the determination of ambient dose equivalent.

5.2 Active devices

5.2.1 Devices to determine all field components

5.2.1.1 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.

5.2.1.1.1 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 that 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, $d(y)$, where 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.

The ambient dose equivalent is determined by a calibration in reference fields, but note that for use, a correction for the lower LET threshold of the device is normally necessary to determine ambient dose equivalent for cosmic radiation fields. An internal source of alpha particles (²⁴⁴Cm) can be used to calibrate in terms of y . See References [30], [31] and references therein.

5.2.1.1.2 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^[32]. Alternatively, several detectors with differing LET thresholds may be used^[33]. 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.

5.2.1.2 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/covariance mode and the recombination chamber.

5.2.1.2.1 The TEPC variance method

The variance method^{[34], [35]} is a way to use a TEPC or other microdosemetric 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 the 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 multiplied by their mean. The mean is the absorbed dose in the detector. The use of the variance method is restricted to cases where the radiation is relatively constant and microdosemetric fluctuations are the only significant source of variation in the measured values. The variance-covariance method with two detectors is needed for measurements where the radiation field variation frequency is comparable to or shorter than an integration time of 100 ms. However, no significant covariance between the two detectors has been observed on-board aircraft^[36], indicating that the field intensity variations are small compared to the microdosemetric variance and that the variance method using one detector can be sufficient for aircraft dosimetry measurements. 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 ($> 150 \text{ keV}/\mu\text{m}$) can be resolved in the multiple event spectrum and a quality factor can be determined in accordance with ICRU 60 for this fraction.

5.2.1.2.2 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 the radiation quality of the investigated radiation fields^[37]. 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^{[38], [39]}.

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 of LET of particles transferring the energy^[40].

5.2.1.3 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 of the thickness of the scintillator material. Therefore, small-sized scintillation counters (scintillator thicknesses of the order of 1 cm), used as dosimeters, usually do not have sufficient detection efficiency for neutron dosimetry, but organic scintillators of sufficient size (with thicknesses of a few tens of centimetres) can be used for spectrometric purposes^{[41], [42]}.

The use of scintillation counters as dosimeters 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 can 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 can deposit energy above the upper energy limit of a few MeVs leading to a reduced detection efficiency for these particles. The reading of the dosimeter has to be corrected to take account of this.

5.2.2 Devices for low-LET/non-neutron

5.2.2.1 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^[43]. In most common applications, ionization chambers are used in current mode as direct-current 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 a 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^[44].

5.2.2.2 Geiger Müller counters

Geiger Müller (GM) counter based 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 precision 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 ⁶⁰Co standard radiation field^[45], ^[46].

5.2.2.3 Electronic personal dosimeters

There are a number of real-time electronic personal dosimeters 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^[47] to ^[49]. 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 dosimeters would require a full characterization of the proton and high-energy neutron response before use.

5.2.3 Devices for high LET/neutron component

5.2.3.1 Moderated devices

Moderate-and-capture devices employing a thermal-neutron detector surrounded by an hydrogenous moderator are frequently used to determine $H^*(10)$ in neutron fields^[9]. 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^[50]. This converter principle has been implemented in survey instruments for routine use at high-energy accelerators in the LINUS (Long Interval Neutron Survey-meter)^[51], ^[52], which uses a lead converter, a similar device (NM500X)^[53], and the WENDI (Wide Energy Neutron Detection Instrument)^[54], which uses tungsten as both a neutron generator material above 8 MeV and as an absorber below several keVs.

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 will measure the contribution to ambient dose equivalent from the neutron component plus neutron-like components of the field.

5.2.3.2 Spectrometers

5.2.3.2.1 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 $H^*(10) = \int \Phi_E h^* dE$, 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^[28]. 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.

5.2.3.2.2 Neutron spectrometers

Of the many kinds of active neutron spectrometers^[55], 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^{[56], [57]} 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 is, 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^[9] 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 5.2.2.1) 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^{[22], [24], [26]} and in aircraft^{[24], [26]}. 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^[26]. 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^{[58], [59]}. 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 (5.3.2) and fission foil detectors (5.3.3). 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^{[59], [60]}. Fission detectors have also been used to supplement multi-sphere spectrometers in order to cover the high-energy part of the spectrum^[57].

5.3 Passive devices

5.3.1 General considerations

Passive detectors are suitable to measure the ambient dose equivalent integrated over flights or a number of flights. The sensitivity and intrinsic background shall be considered. The basic types of passive devices for the high-LET/neutron component 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 Al₂O₃:C; CaSO₄: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 of to neutrons, particularly high energy, should be considered.

5.3.2 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 can be found in^[61], ^[62]. The most frequently used material for this GCR measurements is poly allyldiglycol carbonate (PADC, also known by the trade name CR-39)^[63]. 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 H₂O. 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 beams^[64].

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^[65]. These polycarbonate bottles can be useful as back-up detectors for bubble devices, the response of which can 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.

5.3.3 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^[66]. Neutron-induced fission cross-sections for some heavy nuclei (²³⁵U, ²³⁸U, ²³²Th, ²⁰⁹Pb) are internationally recommended as secondary standards for neutron flux monitoring in the energy region above 20 MeV. Among these heavy elements, ²⁰⁹Pb is the most useful standard for high energy neutron studies for the following reasons:

- a) no reactions with low energy neutrons;
- b) smooth variation of the cross section with neutron energy;
- c) simple use and transport are simple since it is not radioactive.

The attractive characteristics of fission reactions for neutron detection and dosimetry can be exploited using different types of fission fragments detectors, the most interesting of which are the following:

- fission chambers;
- thin film breakdown counters;
- fission-fragment damage track detectors.

Low sensitivity can be a serious disadvantage for application of fission-type of 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 ^[67].

5.3.4 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 that they can estimate neutron ambient dose equivalent down to $1 \mu\text{Sv}$ ^[68],^[69]. 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 can produce recoil charged particles that can initiate bubble nucleation and gas-bubble growth^[70],^[71]. 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 distributions can be made.

5.3.5 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"^[72]. 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 can 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.

5.3.6 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 $\text{Al}_2\text{O}_3:\text{C}$. The radiation-induced luminescence signal is stimulated using light from a laser. Several photoluminescence readout modes have been successfully developed^[73],^[74],^[75]. PLDs have low light conversion efficiencies for high-LET energy deposition^[76],^[77].

Annex A (informative)

Representative particle fluence 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

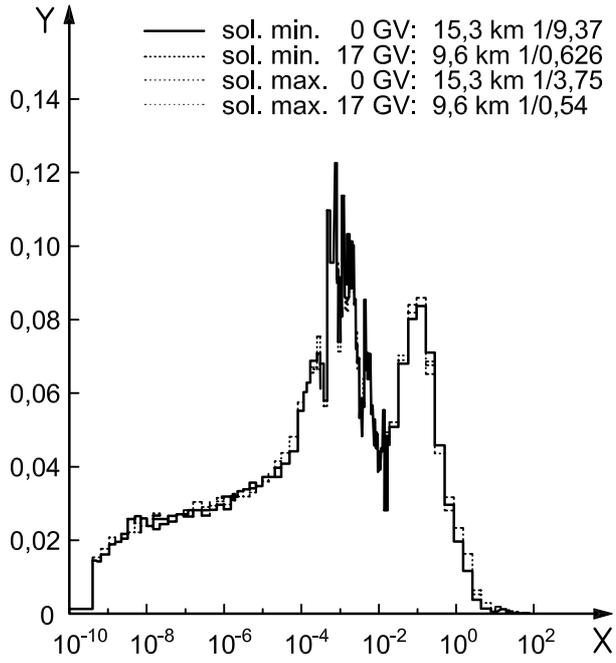
NOTE This annex is taken from Reference [78].

Figures A.1 through A.6 depict calculated spectral particle fluence rates free in air for neutrons, protons, pions, electrons, photons and muons. The values of solar activity, geomagnetic cut-off and altitude are assumed to approximate the extreme values which could be expected for civilian air crafts. These values are

- minimum and maximum solar activity, described by the solar deceleration potential $\phi = 465$ MV and 1 700 MV, respectively, which covers presumably the entire dynamic range of solar modulation;
- minimum and maximum geomagnetic cut-off rigidity $r_c = 0$ GV and 17 GV, respectively;
- minimum and maximum standard barometric flight altitude of 9,6 km and 15,3 km, respectively.

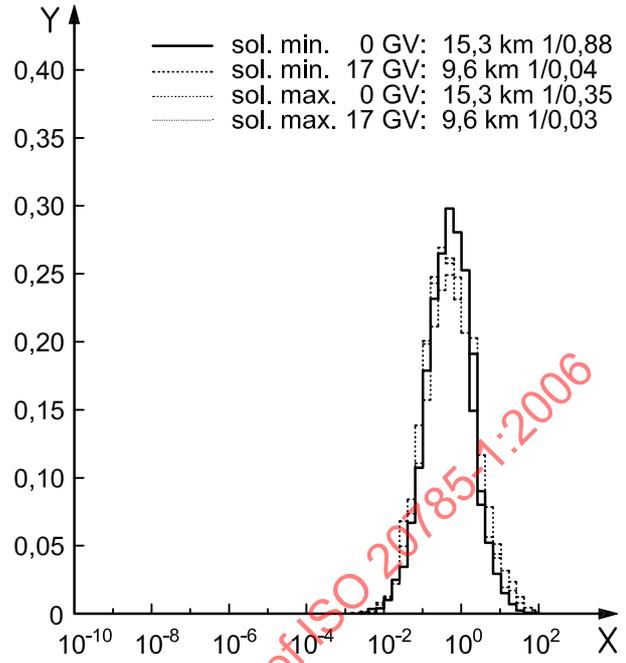
The minimum and maximum solar activity can vary from one solar cycle to the other. Therefore, the indicated values may be used to interpolate for the actual conditions.

In each figure, the spectral particle fluence rates $d^2\phi/dt \cdot dE$ ($\text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{GeV}^{-1}$), i.e. particle fluence per time interval, dt , and energy interval, dE , 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

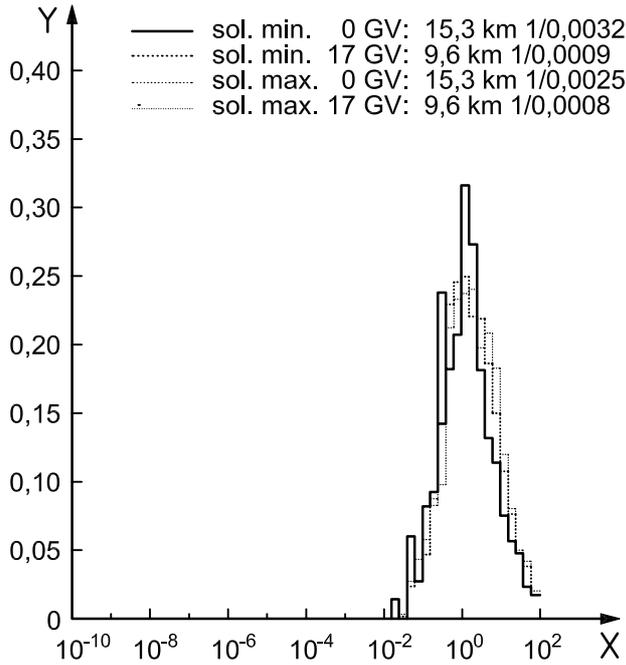
Figure A.1 — Normalized spectral neutron fluence rate



Key
 X energy (GeV)
 Y normalized fluence rate of protons

Figure A.2 — Normalized spectral proton fluence rate

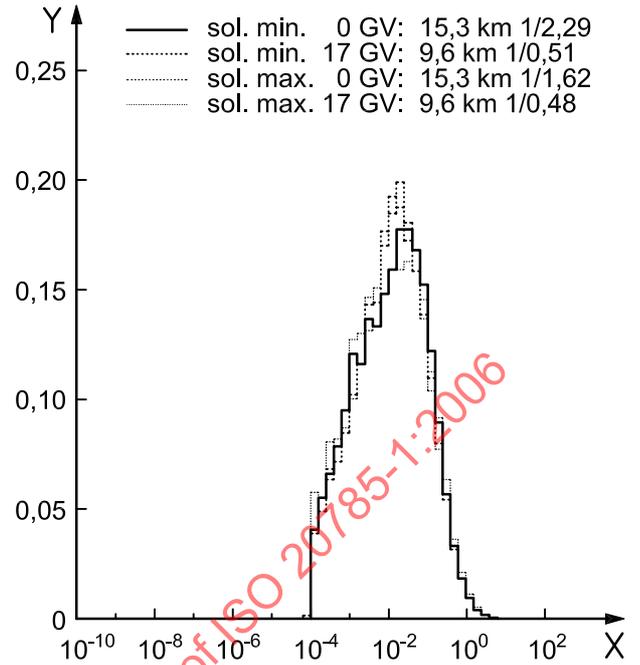
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Key

X energy (GeV)
 Y normalized fluence rate of charged pions

Figure A.3 — Normalized spectral fluence rate of charged pions

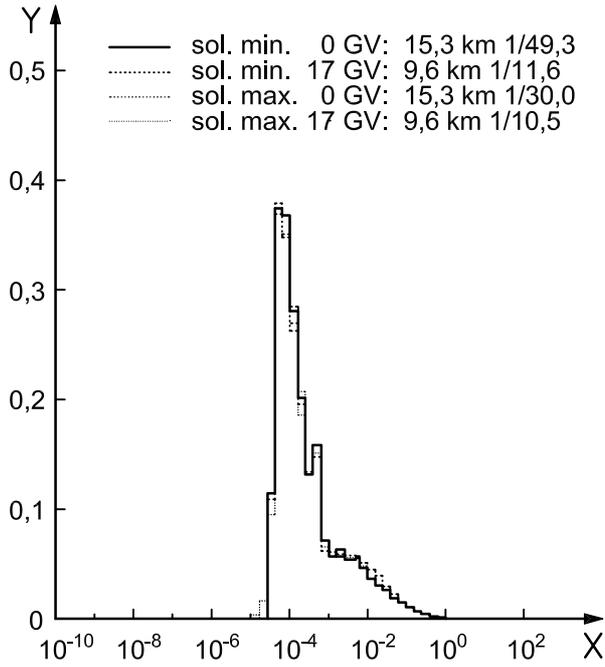


Key

X energy (GeV)
 Y normalized fluence rate of electrons

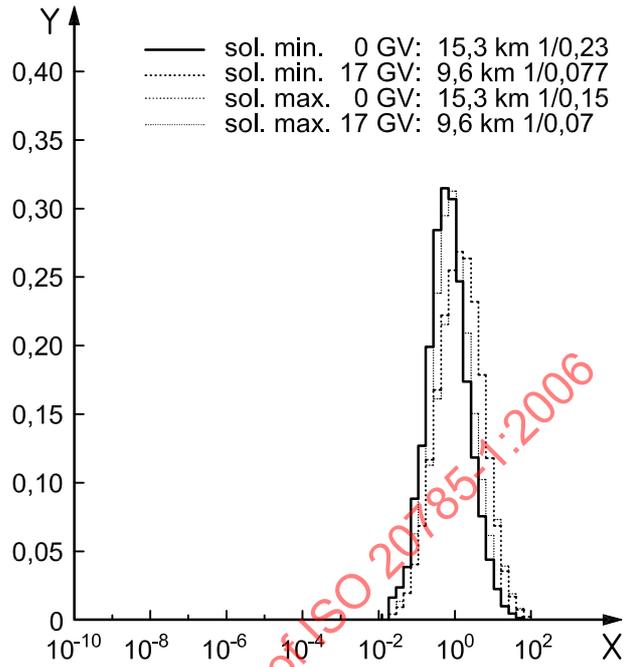
Figure A.4 — Normalized spectral fluence rate of electrons

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Key
 X energy (GeV)
 Y normalized fluence rate of photons

Figure A.5 — Normalized spectral photon fluence rate



Key
 X energy (GeV)
 Y normalized fluence rate of muons

Figure A.6 — Normalized spectral muon fluence rate

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