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BSI Standards Publication

# Dosimetry for exposures to cosmic radiation in civilian aircraft

## Part 2: Characterization of instrument response

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## National foreword

This British Standard is the UK implementation of ISO 20785-2:2011.

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A list of organizations represented on this committee can be obtained on request to its secretary.

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# Dosimetry for exposures to cosmic radiation in civilian aircraft —

## Part 2:
## Characterization of instrument response

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

*Partie 2: Caractérisation de la réponse des instruments*

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

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*

A Part 3 dealing with measurements at aviation altitudes is in preparation.

# 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 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. 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 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 dosemeters for routine use are not considered necessary. The preferred approach for the assessment of doses of aircraft crew, 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 combine 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[5]. Effective dose is not directly measurable. The operational quantity of interest is the 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 this step in the process might 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.

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 need to be performed using accurate and reliable methods that ensure the quality of readings provided to workers and regulatory authorities. The purpose of this part of ISO 20785 is to specify procedures for the determination of the responses of instruments in different reference radiation fields, as a basis for proper characterization of instruments used for the determination of ambient dose equivalent in aircraft at altitude.

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 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 crew.

# Dosimetry for exposures to cosmic radiation in civilian aircraft —

## Part 2:
## Characterization of instrument response

## 1 Scope

This part of ISO 20785 specifies methods and procedures for characterizing the responses of devices used for the determination of ambient dose equivalent for the evaluation of exposure to cosmic radiation in civilian aircraft. The methods and procedures are intended to be understood as minimum requirements.

## 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.

ISO/IEC Guide 98-1, *Uncertainty of measurement — Part 1: Introduction to the expression of uncertainty in measurement*

ISO/IEC Guide 98-3, *Uncertainty of measurement — Part 3: Guide to the expression of uncertainty in measurement (GUM:1995)*

ISO 4037-1, *X and gamma reference radiation for calibrating dosemeters and doserate meters and for determining their response as a function of photon energy — Part 1: Radiation characteristics and production methods*

ISO 6980-1, *Nuclear energy — Reference beta-particle radiation — Part 1: Methods of production*

ISO 8529-1:2001, *Reference neutron radiations — Part 1: Characteristics and methods of production*

ISO 12789-1, *Reference radiation fields — Simulated workplace neutron fields — Part 1: Characteristics and methods of production*

ISO 12789-2, *Reference radiation fields — Simulated workplace neutron fields — Part 2: Calibration fundamentals related to the basic quantities*

ISO 20785-1, *Dosimetry for exposures to cosmic radiation in civilian aircraft — Part 1: Conceptual basis for measurements*

ISO 29661, *Reference radiation fields for radiation protection — Definitions and fundamental concepts*

# 3 Terms and definitions

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

## 3.1 General terms

### 3.1.1
**angle of radiation incidence**

$\alpha$

angle between the direction of radiation incidence and the reference direction of the instrument

### 3.1.2
**calibration**

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

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

NOTE 2 It is important not to confuse calibration with adjustment of a measuring system, often mistakenly called “self-calibration”, or with verification of calibration.

### 3.1.3
**calibration coefficient**

$N_{\text{coeff}}$

quotient of the conventional quantity value to be measured and the corrected indication of the instrument

NOTE 1 The calibration coefficient is equivalent to the calibration factor multiplied by the instrument constant.

NOTE 2 The reciprocal of the calibration coefficient, $N_{\text{coeff}}$, is the response.

NOTE 3 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 It is necessary, in order to avoid confusion, to state the quantity to be measured, for example: the calibration coefficient with respect to fluence, $N_\Phi$, the calibration coefficient with respect to kerma, $N_K$, the calibration coefficient with respect to absorbed dose, $N_D$.

### 3.1.4
**calibration conditions**

conditions, within the range of standard test conditions, actually prevailing during the calibration

### 3.1.5
**calibration factor**

$N_{\text{fact}}$

factor by which the product of the corrected indication and the associated instrument constant of the instrument is multiplied to obtain the conventional quantity value to be measured under reference conditions

NOTE 1 The calibration factor is dimensionless.

NOTE 2 The corrected indication is the indication of the instrument corrected for the effect of influence quantities, where applicable.

NOTE 3 The value of the calibration factor can vary with the magnitude of the quantity to be measured. In such cases, a detector assembly is said to have a non-constant response.

### 3.1.6
### measured quantity value
### measured value of a quantity
### measured value

$M$

quantity value representing a measurement result

NOTE 1 For a measurement involving replicate indications, each indication can be used to provide a corresponding measured quantity value. This set of measured quantity values can be used to calculate a resulting measured quantity value, such as an average or a median value, usually with a decreased associated measurement uncertainty.

NOTE 2 When the range of the true quantity values believed to represent the measurand is small compared with the measurement uncertainty, a measured quantity value can be considered to be an estimate of an essentially unique true quantity value and is often an average or a median of individual measured quantity values obtained through replicate measurements.

NOTE 3 In the case where the range of the true quantity values believed to represent the measurand is not small compared with the measurement uncertainty, a measured value is often an estimate of an average or a median of the set of true quantity values.

NOTE 4 In ISO/IEC Guide 98-3:2008, the terms “result of measurement” and “estimate of the value of the measurand” or just “estimate of the measurand” are used for “measured quantity value”.

### 3.1.7
### conventional quantity value
### conventional value of a quantity
### conventional value

$H_0$

quantity value attributed by agreement to a quantity for a given purpose

NOTE 1 The term “conventional true quantity value” is sometimes used for this concept, but its use is discouraged.

NOTE 2 Sometimes, a conventional quantity value is an estimate of a true quantity value.

NOTE 3 A conventional quantity value is generally accepted as being associated with a suitably small measurement uncertainty, which might be zero.

NOTE 4 In ISO 20785, the conventional quantity value is the best estimate of the value of the quantity to be measured, determined by a primary or a secondary standard which is traceable to a primary standard.

### 3.1.8
### correction factor

$k$

factor applied to the indication to correct for deviation of measurement conditions from reference conditions

NOTE If the correction of the effect of the deviation of an influence quantity requires a factor, the influence quantity is of type F.

### 3.1.9
### correction summand

$G_\mathrm{S}$

summand applied to the indication to correct for the zero indication or the deviation of the measurement conditions from the reference conditions

NOTE If the correction of the effect of the deviation of an influence quantity requires a summand, the influence quantity is of type S.

### 3.1.10
### indication

$G$

quantity value provided by a measuring instrument or a measuring system

NOTE 1 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 An indication and a corresponding value of the quantity being measured are not necessarily values of quantities of the same kind.

### 3.1.11
### influence quantity

quantity that, in a direct measurement, does not affect the quantity that is actually measured, but affects the relation between the indication and the measurement result

NOTE 1 An indirect measurement involves a combination of direct measurements, each of which may be affected by influence quantities.

NOTE 2 In ISO/IEC Guide 98-3:2008, the concept “influence quantity” is defined as in ISO/IEC Guide 99:2007, covering not only the quantities affecting the measuring system, as in the definition above, but also those quantities that affect the quantities actually measured. Also, in ISO/IEC Guide 98-3, this concept is not restricted to direct measurements.

NOTE 3 The correction of the effect of the influence quantity can require a correction factor (for an influence quantity of type F) and/or a correction summand (for an influence quantity of type S) to be applied to the indication of the detector assembly, e.g. in the case of microphonic or electromagnetic disturbance.

EXAMPLE The indication given by an unsealed ionization chamber is influenced by the temperature and pressure of the surrounding atmosphere. Although needed for determining the value of the dose, the measurement of these two quantities is not the primary objective.

### 3.1.12
### instrument constant

$c_\mathrm{i}$

quantity value by which the indication of the instrument, $G$ (or, if corrections or normalization were carried out, $G_\mathrm{corr}$), is multiplied to give the value of the measurand or of a quantity to be used to calculate the value of the measurand

NOTE If the instrument's indication is already expressed in the same units as the measurand, as is the case with area dosemeters, for instance, the instrument constant, $c_\mathrm{i}$, is dimensionless. In such cases, the calibration factor and the calibration coefficient can be the same. Otherwise, if the indication of the instrument has to be converted to the same units as the measurand, the instrument constant has a dimension.

### 3.1.13
### measurand

quantity intended to be measured

### 3.1.14
### point of test

point in the radiation field at which the conventional quantity value is known

NOTE The reference point of a detector assembly is placed at the point of test for calibration purposes or for the determination of the response.

### 3.1.15
### primary measurement standard
### primary standard

measurement standard established using a primary reference measurement procedure or created as an artifact, chosen by convention

NOTE A primary standard has the highest metrological quality in a given field.

### 3.1.16
**quantity value**
number and reference together expressing the magnitude of a quantity

NOTE A quantity value is either a product of a number and a measurement unit (the unit "one" is generally not indicated for quantities of dimension "one") or a number and a reference to a measurement procedure.

### 3.1.17
**reference conditions**
conditions of use prescribed for testing the performance of a detector assembly or for comparing the results of measurements

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

NOTE 2 The value of the measurand can 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 can influence the calibration result and the response (see also Note 1).

### 3.1.18
**reference direction**
direction, in the coordinate system of the detector assembly, with respect to which the angle of the direction of radiation incidence is measured in reference fields

NOTE At the angle of incidence of 0°, the reference direction of the detector assembly is parallel to the direction of radiation incidence. At the angle of 180°, the reference direction of the detector assembly is anti-parallel to the direction of radiation incidence.

### 3.1.19
**reference orientation**
orientation of the detector assembly for which the direction of the incident radiation coincides with the reference direction of the detector assembly

### 3.1.20
**reference point**
point in the instrument that is placed at the point of test for calibration and test purposes

NOTE The distance of measurement is given by the distance between the radiation source and the reference point of the detector assembly.

### 3.1.21
**response**
$R$
quotient of the indication, $G$, or the corrected indication, $G_{\text{corr}}$, and the conventional quantity value to be measured

NOTE 1 To avoid confusion, it is necessary to specify which of the quotients given in the definition of the response (that for the indication, $G$, or that for the corrected indication, $G_{\text{corr}}$) has been used. Furthermore, it is necessary, in order to avoid confusion, to state the quantity to be measured, for example the response with respect to fluence, $R_{\Phi}$, the response with respect to kerma, $R_K$ or the response with respect to absorbed dose, $R_D$.

NOTE 2 The reciprocal of the response under the specified conditions is equal to the calibration coefficient, $N_{\text{coeff}}$.

NOTE 3 The value of the response can 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 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 the direction, $\vec{\Omega}$, of the incident monodirectional radiation. $R(E)$ describes the "energy dependence" and $R(\Omega)$ the "angle dependence" of the response; for the latter, $\vec{\Omega}$ may be expressed by the angle, $\alpha$, between the reference direction of the detector assembly and the direction of an external monodirectional field.

### 3.1.22
**secondary measurement standard**
**secondary standard**

measurement standard established through calibration with respect to a primary measurement standard for a quantity of the same kind

NOTE 1 Calibration can be carried out directly between a primary measurement standard and a secondary measurement standard or it can involve an intermediate measuring system calibrated by the primary measurement standard followed by assignment of a measurement result to the secondary measurement standard.

NOTE 2 A secondary standard can be variously represented, e.g. as a measuring device or a radionuclide source unit.

NOTE 3 The secondary standard can be used for calibrating a detector assembly and/or for determining its response. The calibration of the secondary standard needs to be valid for the irradiation conditions used, e.g. energy, dose and/or dose rate, and environmental conditions. The stability and reproducibility of the secondary standard has to be verified periodically.

NOTE 4 The quantity value of the secondary standard is equated to the best estimate of the quantity, i.e. the conventional quantity value.

### 3.1.23
**standard test conditions**

conditions represented by the range of values for the influence quantities under which a calibration or determination of the response is carried out

NOTE Ideally, calibrations are carried out under reference conditions. As this is not always possible (e.g. for ambient air pressure) or convenient (e.g. for ambient temperature), a (small) interval around the reference values can be acceptable. If a calibration factor or response determined under standard conditions deviates significantly from the value that would be obtained under reference conditions, a correction will normally be applied.

### 3.1.24
**true quantity value**
**true value of a quantity**
**true value**

quantity value consistent with the definition of a quantity

NOTE 1 In the error approach to describing a measurement, a true quantity value is considered unique and, in practice, unknowable. The uncertainty approach is to recognize that, owing to the inherently incomplete amount of detail in the definition of a quantity, there is not a single true quantity value but rather a set of true quantity values consistent with the definition. However, this set of values is, in principle and in practice, unknowable. Other approaches dispense altogether with the concept of a true quantity value and rely on the concept of metrological compatibility of measurement results for assessing their validity.

NOTE 2 In the special case of a fundamental constant, the quantity is considered to have a single true quantity value.

NOTE 3 When the definitional uncertainty associated with the measurand is considered to be negligible compared to the other components of the measurement uncertainty, the measurand can be considered to have an “essentially unique” true quantity value. This is the approach taken by ISO/IEC Guide 98-3 and associated documents, in which the word “true” is considered to be redundant.

## 3.2 Terms related to quantities and units

Most of the definitions in this subclause have been adapted from ISO 80000-10:2009[71] and ICRU Reports 36[6] and 51[7].

### 3.2.1

**particle fluence**

**fluence**

$\Phi$

at a given point in space, the mean number, d$N$, of particles incident on a small spherical domain, divided by the cross-sectional area, d$a$, of that domain:

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

NOTE 1 The base unit of particle fluence is $\mathrm{m}^{-2}$; a frequently used unit is $\mathrm{cm}^{-2}$.

NOTE 2 The energy distribution of the particle fluence, $\Phi_E$, is the quotient d$\Phi$ by d$E$, where d$\Phi$ is the fluence of particles of energy between $E$ and $E + \mathrm{d}E$. There is an analogous definition for the directional distribution, $\Phi_\Omega$, of the particle fluence.

### 3.2.2

**particle fluence rate**

**fluence rate**

$\dot{\Phi}$

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

where d$\Phi$ is the mean increment in the particle fluence, d$N$/d$a$, during an infinitesimal time interval of duration d$t$

NOTE The base unit of the particle fluence rate is $\mathrm{m}^{-2} \cdot \mathrm{s}^{-1}$; a frequently used unit is $\mathrm{cm}^{-2} \cdot \mathrm{s}^{-1}$.

### 3.2.3

**energy imparted**

$\varepsilon$

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

$$\varepsilon = \sum \varepsilon_i$$

where the energy deposit, $\varepsilon_i$, is the energy deposited in a single interaction, $i$, and is given by $\varepsilon_i = \varepsilon_{\mathrm{in}} - \varepsilon_{\mathrm{out}} + Q$, where $\varepsilon_{\mathrm{in}}$ is the energy of the incident ionizing particle, excluding rest energy, $\varepsilon_{\mathrm{out}}$ 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 Energy imparted is a stochastic quantity.

NOTE 2 The unit of energy imparted is J.

### 3.2.4

**mean energy imparted**

$\bar{\varepsilon}$

for the matter in a given domain,

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

where $R_{\mathrm{in}}$ is the radiant energy of all those charged and uncharged ionizing particles that enter the domain, $R_{\mathrm{out}}$ is the radiant energy of all those charged and uncharged ionizing particles that leave the domain and $\Sigma Q$ is the sum of all changes in the rest energies of nuclei and elementary particles that occur in that domain

NOTE 1 This quantity has the meaning of the expected value of the energy imparted.

NOTE 2 The unit of mean energy imparted is J.

### 3.2.5
### specific energy imparted
### specific energy

$z$

for any ionizing radiation,

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

where $\varepsilon$ is the energy imparted to the irradiated matter and $m$ is the mass of that matter.

NOTE 1 Specific energy imparted is a stochastic quantity.

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

NOTE 3 The specific energy imparted can be the result of one or more (energy-deposition) events.

NOTE 4 The unit of specific energy is $\mathrm{J \cdot kg^{-1}}$, with the special name gray (Gy).

### 3.2.6
### 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 the ionizing radiation to an element of irradiated matter of mass $\mathrm{d}m$

NOTE 1 $\bar{\varepsilon} = \int D \, \mathrm{d}m$ , where $\mathrm{d}m$ is the element of mass of the irradiated matter.

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

NOTE 3 The unit of absorbed dose is $\mathrm{J \cdot kg^{-1}}$, with the special name gray (Gy).

### 3.2.7
### kerma

$K$

for indirectly ionizing (uncharged) particles, the 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 The 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 The unit of kerma is $\mathrm{J \cdot kg^{-1}}$, with the special name gray (Gy).

### 3.2.8
### unrestricted linear energy transfer
### linear energy transfer
### LET

$L_\Delta$

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 $\Delta$, divided by the length $\mathrm{d}l$:

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

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

NOTE 2 Linear energy transfer is often abbreviated to LET, but the subscript $\Delta$ or its numerical value should be appended to it.

NOTE 3 The base unit of linear energy transfer is $\mathrm{J \cdot m^{-1}}$; a frequently used unit is $\mathrm{keV \cdot \mu m^{-1}}$.

NOTE 4 If no energy cut-off is imposed, the unrestricted linear energy transfer, $L_\infty$, is equal to the linear electronic stopping power, $S_{\mathrm{el}}$, and may be denoted simply as $L$.

### 3.2.9
### dose equivalent

$H$

at the point of interest in tissue,

$$H = D \cdot Q$$

where $D$ is the absorbed dose and $Q$ is the quality factor at that point

NOTE 1 $Q$ is determined by the unrestricted linear energy transfer, $L_\infty$ (often denoted by L or LET), of charged particles passing through a small volume element (domain) at this point (the value of $L_\infty$ 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:

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

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 The relationship between $Q$ and $L$ is given in ICRP Publication 103[2].

NOTE 3 The unit of dose equivalent is $\mathrm{J \cdot kg^{-1}}$, with the special name sievert (Sv).

### 3.2.10
### lineal energy

$y$

quotient of $\varepsilon_{\mathrm{s}}$ by $\bar{l}$, where $\varepsilon_{\mathrm{s}}$ 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:

$$y = \frac{\varepsilon_{\mathrm{s}}}{\bar{l}}$$

NOTE The base unit of lineal energy is $\mathrm{J \cdot m^{-1}}$; a frequently used unit is $\mathrm{keV \cdot \mu m^{-1}}$.

### 3.2.11
### dose-mean lineal energy

$\overline{y}_\mathrm{D}$

expectation value given by $\overline{y}_\mathrm{D} = \int_0^\infty y\, d(y)\, \mathrm{d}y$, where $d(y)$ is the dose probability density of $y$

NOTE 1 The dose probability density of $y$ is given by $d(y)$, where $d(y)\,\mathrm{d}z$ is the fraction of the absorbed dose delivered in single events with lineal energy in the interval from $y$ to $y+\mathrm{d}y$.

NOTE 2 Both $\overline{y}_\mathrm{D}$ and the distribution $d(y)$ are independent of the absorbed dose and the dose rate.

### 3.2.12
### 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 ambient dose equivalent is J·kg$^{-1}$, with the special name sievert (Sv).

### 3.2.13
### particle fluence to ambient dose equivalent conversion coefficient

$h_\Phi^*$

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

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

NOTE The base 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$^2$.

### 3.2.14
### magnetic rigidity

$r$

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

$$r = p/Ze$$

where $p$ is the particle momentum, $Z$ the number of charges on the particle and $e$ the charge on the proton

NOTE 1 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 Magnetic rigidity characterizes charged-particle trajectories in magnetic fields. All particles having the same magnetic rigidity will have identical trajectories in a magnetic field, independent of particle mass or charge.

### 3.2.15
### geomagnetic cut-off rigidity
### cut-off rigidity

$r_\mathrm{c}$

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

NOTE Geomagnetic cut-off rigidity depends on the angle of incidence. Often, vertical incidence is assumed.

**3.2.16**
**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

## 3.3 Terms related to the atmospheric radiation field

**3.3.1**
**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

**3.3.2**
**primary cosmic radiation**
**primary cosmic rays**
cosmic radiation incident from space

**3.3.3**
**secondary cosmic radiation**
**secondary cosmic rays**
**cosmogenic particles**
particles which 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.

**3.3.4**
**galactic cosmic radiation**
**galactic cosmic rays**
**GCR**
cosmic radiation originating outside the solar system

**3.3.5**
**solar cosmic radiation**
**solar cosmic rays**
**solar particles**
cosmic radiation originating from the sun

**3.3.6**
**solar particle event**
**SPE**
large fluence rate of energetic solar particles ejected into space by a solar eruption, or the sudden increase in cosmic radiation observed when such particles arrive at the Earth

**3.3.7**
**ground level enhancement**
**GLE**
sudden increase in 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 energetic solar particles

NOTE 1 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 GLEs are rare, occurring on average about once per year.

**3.3.8**
**solar modulation**
change in the GCR field (outside the Earth's magnetosphere) caused by change in solar activity and consequent change in the magnetic field of the heliosphere

**3.3.9**
**solar cycle**
period during which the solar activity varies, with successive maxima separated by an average interval of about 11 years

NOTE 1 If the reversal of the sun's magnetic-field polarity in successive 11-year periods is taken into account, the complete solar cycle can be considered to average some 22 years, the Hale cycle.

NOTE 2 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.

**3.3.10**
**relative sunspot 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 observatory (location and instrumentation)

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

**3.3.11**
**solar maximum**
period of maximum solar activity during a solar cycle, usually defined in terms of the relative sunspot number

**3.3.12**
**solar minimum**
period of minimum solar activity during a solar cycle, usually defined in terms of the relative sunspot number

**3.3.13**
**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

NOTE 1 Protons, other hadrons and muons might also be detected.

NOTE 2 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

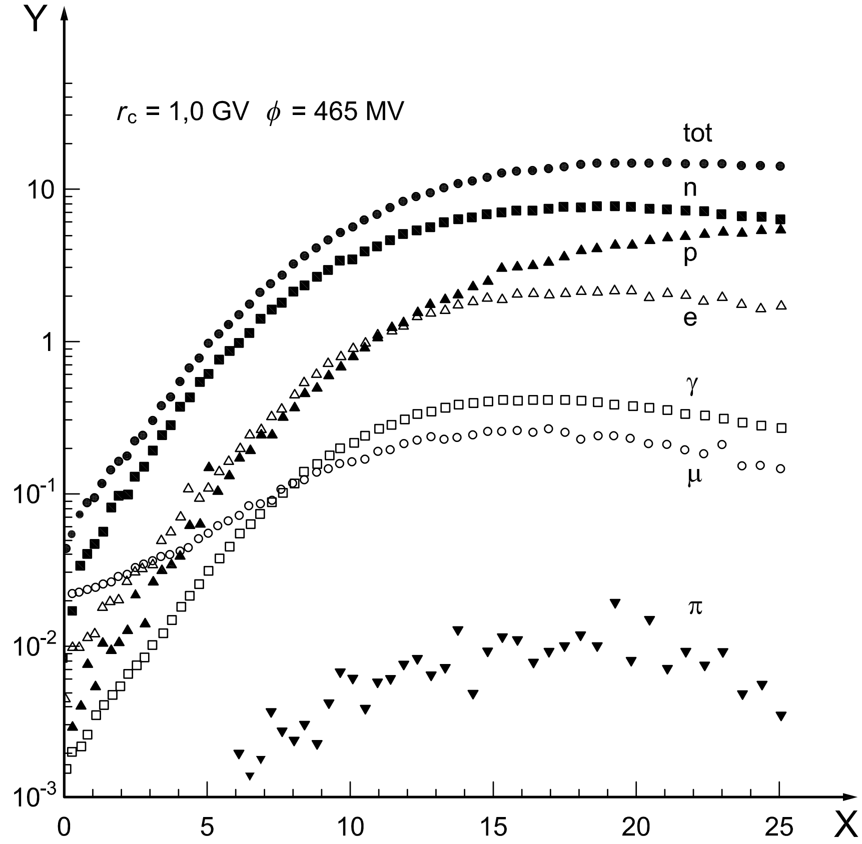
## 4.1 The cosmic radiation field in the atmosphere

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[8][9]. Galactic cosmic radiation (GCR) can have energies up to $10^{20}$ 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 $E^{-3}$. The fluence rate of GCR entering the solar system is fairly constant with 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 and 1 % heavier ions; at a vertical cut-off of 15 GV, the composition is approximately 83 % protons, 15 % He ions and nearly 2 % heavier ions[10][11].

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 SPE), 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 enhancements (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 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, $\phi$, of 465 MV).[12]

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

### 4.2 General considerations for the dosimetry of the cosmic radiation field in aircraft and requirements for the characterization of instrument response

Detailed consideration of the measurements to be made and the radiation field are given in ISO 20785-1.

The radiation field at aviation altitudes is complex. Thus, its dosimetry 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 to the results of measurements, using data on the energy and direction characteristics of the field and the energy and angle ambient dose equivalent response of the device.

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 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 (together with 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 strong force interactions.

The particle fluence energy distributions are shown in Annex A. The contributions of different particle types to ambient dose equivalent are shown in Figure 1 for a representative value of cut-off and solar modulation[12]. As a guide, at normal flight altitudes, the rounded percentage contributions to total ambient dose equivalent at temperate latitudes are: electrons and positrons 25 %, muons 5 %, photons 10 %, neutrons 50 % and protons 10 %[13].

For dosimetric purposes, it is convenient to divide the radiation field into low-LET ($< 10\ \text{keV}\cdot\mu\text{m}^{-1}$) and high-LET ($\geq 10\ \text{keV}\cdot\mu\text{m}^{-1}$) components, LET being the commonly used abbreviation for linear energy transfer. This definition is based on the dependence of the quality factor on LET, which is unity below $10\ \text{keV}\cdot\mu\text{m}^{-1}$. This separation between low- and high-LET particles can be applied to tissue-equivalent proportional counters and to other materials and detectors, but the low-LET/high-LET threshold can vary between $5\ \text{keV}\cdot\mu\text{m}^{-1}$ and $10\ \text{keV}\cdot\mu\text{m}^{-1}$. The low-LET component comprises the following components:

a) directly ionizing electrons, positrons and muons;

b) secondary electrons from photon interactions;

c) most of the energy deposition by directly ionizing interactions of protons;

d) 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 high LET are not necessarily the same, but are generally similar in magnitude.

Another common approach to classifying the components of a radiation field is to distinguish between neutron and non-neutron components. This approach is based on the detection technique applied, since many measurement systems are not sensitive to neutron radiation. There are similarities between the neutron and high-LET components and between the non-neutron and low-LET components. But at neutron energies above 20 MeV, the neutrons produce, in addition, an increasing low-LET contribution as well.

The low-LET and the non-neutron component can be measured using an ionization chamber, a silicon-based detector or scintillation detector, or a passive luminescence or ion storage detector. The neutron component can be measured using an extended-range neutron survey meter or a multi-sphere spectrometer, or a passive etched track detector, bubble detector or fission foil with damage track detector. A passive etched-track detector can be used to determine this component using one or both of two approaches: as a LET spectrometer and/or through the simple counting of the secondary particles mentioned above.

The summed components, low-LET plus high-LET, or non-neutron plus neutron, will, with suitable calibration and normalization, give the total ambient dose equivalent. Therefore, it is essential for the measurement of the complex radiation fields that the instruments used be fully characterized at national metrology institutes where possible, thus ensuring full traceability.

## 4.3 General considerations for measurements at aviation altitudes

The quantity to be measured, the measurand, is the ambient dose equivalent, $H^*(10)$, or its rate. Because of the number of different particles and the wide particle energy range of the radiation field at aviation altitudes, the characterization of instruments requires an extended set of measurements under well-defined conditions. Both the energy and angle dependence of response need to be measured and a calibration or response function (more usually matrix) established. Response measurements will need to be made in both reference fields and radiation fields representative of cosmic radiation. The influence of environmental parameters, such as air pressure and vibration, will also need to be tested.

A single calibration measurement can be determined under reference conditions, yielding a single calibration factor. A matrix of energy and angle of incidence correction factors then needs to be applied for each particle type, plus correction factors for influence quantities such as the environmental conditions. In a similar approach, a matrix of calibration coefficients, factors or responses is determined. In both approaches, knowledge of the energy distribution at aviation altitudes (see Annex A) is required for each particle type. These distributions are combined with the correction factors, or with the calibration coefficient/factor or response matrix. One then obtains a single field-specific correction factor, or a single field-specific calibration coefficient, factor or response matrix, for measurements at aviation altitudes, provided the dosemeter is additive, i.e. the accumulated dose is the sum of all the contributions from the different radiation types. Alternatively, a field-specific calibration factor or calibration coefficient can be established directly. All response measurements may be performed for conditions that are similar to those at aviation altitudes or the instrument indication corrected for all significant influence quantities.

The single field-specific correction factor, or calibration factor or coefficient, can be applied for the assumed energy and angle distributions of the given particle type or types. In some instances, this same factor or coefficient can be applied for the range of flight altitude, geomagnetic latitude and solar modulation over which measurements are being made.

In the case of photons and muons, for some instruments a calibration coefficient/factor for the radiation field in aircraft at altitude can be derived from calibration using the ISO high-energy photon reference field (R-F) or the $^{137}$Cs or $^{60}$Co reference field combined with response calculations for the instrument.

In general, a set of measurements establishes the relationship between the indication, $G$, and the measured quantity value, $M$, of an instrument:

$$M = N(A,E,\alpha)G_{\mathrm{corr}} \tag{1}$$

where

$M$ is the measured quantity value of the detector assembly for radiation of type $A$, energy $E$ and angle of incidence $\alpha$;

$N(A,E,\alpha)$ is the calibration coefficient function of the instrument.

The measured quantity value can also be expressed in terms of the response function (or matrix of responses), $r(A,E,\alpha)$:

$$M = G_{\mathrm{corr}}/r(A,E,\alpha) \tag{2}$$

$G_{\mathrm{corr}}$ is the indicated value of the detector assembly normalized to reference conditions and corrected for any other influence factors:

$$G_{\mathrm{corr}} = k_{\mathrm{n}}\prod_{f=1}^{q} k_f \times \left(G - \sum_{s=1}^{p} G_s\right) \tag{3}$$

where

$G$ is the indication of the instrument;

$k_\mathrm{n}$ is the correction factor for non-constant response;

$k_f$ is the correction factor for $f$, for a quantity whose deviation from its reference value induces a multiplicative change (influence quantity of type F) of the indication;

$G_s$ is the correction summand for $s$, for a quantity whose deviation from its reference value induces an additive change (influence quantity of type S) of the indication.

It should be noted that the correction factors, $k$, might not be independent of particle type, $A$, energy, $E$, or angle, $\alpha$.

## 5 Calibration fields and procedures

### 5.1 General considerations

The instrument energy dependence of response needs to be determined for the range of particle types and energies relevant to the radiation fields in aircraft at aviation altitudes plus the angle dependence of the response of the instrument, if any. The particle type, particle energy and angle dependence of response should be determined in ISO reference fields, where this is possible. For particle types and energies not covered, calibrations need to be carried out in radiation fields such as those recommended in Annex B. Traceable calibration coefficients or factors need to be determined. In addition, correction factors to reference conditions need to be determined to allow for the effects, if any, of influence quantities on the measurement conditions in aircraft.

The calibration factor, $N_\mathrm{fact}$, is a dimensionless factor by which the indication or reading, $G_{H\mathrm{corr}}$, of the instrument, expressed in terms of the quantity to be measured, is multiplied to obtain the value of the quantity to be measured. The calibration factor, $N_\mathrm{fact}$, is given by:

$$N_\mathrm{fact} = H_\mathrm{o}/G_{H\mathrm{corr}} \tag{4}$$

where

$G_{H\mathrm{corr}}$ is the indication/reading, given in units of the quantity to be measured;

$H_\mathrm{o}$ is the conventional quantity value or the best estimate of dose equivalent of the reference radiation field.

If the indication or reading of the device is not expressed in terms of the quantity to be measured, then the corrected instrument indication, $G_\mathrm{corr}$, has to be converted to the same units as the measurand by applying an instrument constant, $c_\mathrm{i}$, before the calibration factor is applied. Equation (4) becomes:

$$N_\mathrm{fact} = H_\mathrm{o}/(G_\mathrm{corr} \cdot c_\mathrm{i}) \tag{5}$$

The value of $c_\mathrm{i}$ will have dimensions, for example milligrays per coulomb (measurement by an ionization chamber). The instrument constant, $c_\mathrm{i}$, and the calibration factor, $N_\mathrm{fact}$, need not be identified separately, but can be applied together as the calibration coefficient, $N_\mathrm{coeff}$, that has dimensions:

$$N_\mathrm{coeff} = H_\mathrm{o}/G_\mathrm{corr} \tag{6}$$

The calibration coefficient, $N_\mathrm{coeff}$, is the factor used to multiply the corrected dosemeter indication (when not expressed in terms of the quantity to be measured), $G_\mathrm{corr}$, to obtain the value of the quantity being measured.

Substituting $M$ for $H_\mathrm{o}$ in Equations (5) and (6) gives the measured quantity value for the measuring instrument under reference conditions. Reference conditions are those defined conditions under which the calibration is performed and valid. In the case of non-reference conditions, these can be considered by an additional correction factor, $k$, leading to:

$$M = G_\mathrm{corr} \cdot N_\mathrm{coeff} \cdot k \tag{7}$$

or

$$M = G_{\mathrm{corr}} \cdot c_{\mathrm{i}} \cdot N_{\mathrm{fact}} \cdot k \tag{8}$$

The response, $R$, is the quotient of the corrected (direct) dosemeter indication, $G_{\mathrm{corr}}$, by the conventional quantity value, $H_{\mathrm{o}}$, determined under the given conditions:

$$R = G_{\mathrm{corr}}/H_{\mathrm{o}} \tag{9}$$

Thus, any value of the response needs the specification of the kind of value and the kind of quantity, e.g. response of the corrected direct indication, $G_{\mathrm{corr}}$, to the ambient dose equivalent, $H^*(10)$, as shown in Equation (10):

$$R_{H^*(10)} = G_{\mathrm{corr}}/H^*(10) \tag{10}$$

Depending on the kind of quantity value, the response might have a dimension or be dimensionless.

If the radiation field is a single specified reference radiation field, for example $^{137}$Cs or $^{241}$Am-Be, and the dose equivalent value and all other influence quantities have the specified reference values, then the term calibration may be used in the restricted sense of determining a single calibration factor for a single set of reference conditions. This restricted definition not only fixes the values of the non-dosimetric influence quantities, but also includes fixed values of dose and dose rate. The single calibration factor may then be combined with a number of correction factors (a matrix of correction factors or a correction function) to be applied in specific conditions of use. The combination of a single calibration factor and a matrix of correction factors is equivalent to a matrix of calibration factors. To avoid any misunderstanding, the term “reference calibration” is used for this restricted use of the term calibration.

Determination of the dosimetric characteristics of the instrument (which may be a single device or a combination of devices) and its reference calibration are closely interlinked. The result of a response characterization is the detailed description of the dosimetric properties of a given instrument. This includes the dependence of the response on particle type, particle energy and angle of radiation incidence on temperature and so on. A reference calibration without a prior dosimetric characterization can be misleading, as the calibration can be misinterpreted as applying to the radiation field in aircraft without correction.

Where an instrument consists of more than one detector or more than one signal channel, the result of any algorithm used to calculate the measured value shall be treated as the instrument indication in all determinations of the calibration coefficient or factor or response.

All instruments shall have periodic laboratory reference calibrations, traceable to national metrology institutes, typically at intervals of about one to two years, or as required by the regulations. To confirm the stability of the dosimetric performance of the instrument at more frequent intervals, there shall be calibration checks by a fixed procedure using a stable source or radiation field.

The particle fluence or air kerma rate of a radiation field established for a calibration in accordance with this part of ISO 20785 shall be traceable to a recognized national or international standard. The method used to provide this calibration link is dependent upon the type of reference radiation field, but measurement traceability is usually achieved through the utilization of a transfer standard. This could be, for example, a radionuclide source, an accelerator-based source or an agreed-upon transfer instrument. The calibration of the field is valid in exact terms only at the time of the calibration and, thereafter, can be inferred from, for example, a knowledge of the half-life and the isotopic composition of a radionuclide source, knowledge of the stability of an accelerator-produced field, or knowledge of the properties of the transfer instrument.

The measurement technique used by a calibration laboratory for calibrating a radiation-measuring device shall also be approved in the way required by national or international regulations. An instrument of the same, or similar, type to that routinely calibrated by the calibration laboratory shall be calibrated by both a reference laboratory recognized by a country's approval body or institution and the calibration laboratory. These measurements shall be performed within each laboratory, using the laboratory's own approved calibration methods. In order to demonstrate that adequate traceability has been achieved, the calibration laboratory shall obtain the same calibration factor, within agreed limits, as that obtained by the reference laboratory.

As discussed in Part 1 of this International Standard, and in Clause 4 above, because of the several types of particle contributing to the measurement quantity, and their large energy ranges, it is usually necessary to use more than one measuring device or to use a measuring device operating in more than one mode, for example a tissue-equivalent proportional counter where different ranges of energy deposition event sizes are treated differently. In principle, for all such cases, the combination of measuring devices, or operating modes, together with any algorithm, shall be treated as one measuring assembly and calibrated as such. In practice, based on prior knowledge of the response characteristics, it might be acceptable to calibrate components of the measuring assembly separately, but then attention shall be paid to the effect of other radiation types (see 5.2.4) and the algorithm.

## 5.2 Characterization of an instrument

### 5.2.1 Determination of the dosimetric characteristics of an instrument

In accordance with ISO 29661, the instrument dosimetric characteristics, i.e. the energy and angle dependence of response, can be determined in terms of a calibration coefficient function or a response function. The calibration coefficient function, $N(E,\alpha)$, is given by:

$$N(E,\alpha) = C_\mathrm{f}(E,\ \alpha) \cdot c_\mathrm{i} \tag{11}$$

where

$C_\mathrm{f}(E,\alpha)$ is the calibration factor function;

$c_\mathrm{i}$ is the instrument constant.

Depending on the defined number of reference or standard radiation fields, the calibration coefficient function, $N(E,\alpha)$, can be expressed in the following two ways:

a) One reference radiation energy, $E_\mathrm{ref}$, and one reference angle of incidence, $\alpha_\mathrm{ref}$, are defined for which a reference calibration coefficient, $N_\mathrm{coeff\ ref}$, and a calibration factor, $N_\mathrm{fact\ ref}$, respectively, are determined. The calibration coefficient function, $N_\mathrm{coeff}(E,\alpha)$, for the $j$ radiation energies, $E_l$, and angles of incidence, $\alpha_l$, i.e. $N_\mathrm{coeff}(E_l,\alpha_l)$ ($l$ = 1, …, $j$), is then given by the product:

$$N_\mathrm{coeff}(E_l,\alpha_l) = N_\mathrm{coeff\ ref} \cdot k(E_l,\alpha_l) \quad \text{with } l = 1,\ \ldots,\ j \tag{12}$$

or expressed with the calibration factor, $N_\mathrm{fact\ ref}$, by:

$$N_\mathrm{coeff}(E_l,\alpha_l) = N_\mathrm{fact\ ref} \cdot c_\mathrm{i} \cdot k(E_l,\alpha_l) \quad \text{with } l = 1,\ \ldots,\ j \tag{13}$$

where

$N_\mathrm{coeff\ ref}$ is the calibration coefficient (under reference conditions);

$k(E_l,\alpha_l)$ is the correction factor for the radiation energy, $E_l$, and the angle of incidence, $\alpha_l$, and under reference conditions for all other influence quantities;

$N_\mathrm{fact\ ref}$ is the calibration factor (under reference conditions);

$c_\mathrm{i}$ is the instrument constant.

NOTE 1 There might be one reference radiation energy for each of more than one radiation type. For example, an instrument might have an $N_\mathrm{coeff\ ref}$ or $N_\mathrm{fact\ ref}$ for both $^{137}$Cs and $^{241}$Am-Be, both of which would be included in the measurement equation.

NOTE 2 The correction factor, $k(E_l,\alpha_l)$, is dimensionless. For the single set of reference conditions for which the corresponding calibration coefficient, $N$, is determined, the correction factor is unity.

b) Alternatively, several reference or standard radiation fields, differing only in how the reference radiation energy and the reference angle of incidence are defined, are used. For each of the $j$ sets of energy and angle, a calibration coefficient is determined, resulting in $j$ calibration coefficients. The calibration coefficient function, $N_{\text{coeff}}(E,\alpha)$, for these $j$ sets of reference radiation energies, $E_l$, and reference angles, $\alpha_l$, i.e. $N_{\text{coeff}}(E_l,\alpha_l)$ ($l = 1, \ldots, j$), is given by the corresponding calibration coefficients, $N_{\text{coeff}\ l}$:

$$N_{\text{coeff}}(E_l,\alpha_l) = N_{\text{coeff}\ l} \quad \text{with } l = 1, \ldots, j \tag{14}$$

or expressed with the corresponding calibration factors, $N_{\text{fact}\ l}$, by:

$$N_{\text{coeff}}(E_l,\alpha_l) = N_{\text{fact}\ l} \cdot c_{\text{i}} \quad \text{with } l = 1, \ldots, j \tag{15}$$

where

$N_{\text{fact}\ l}$ is the calibration factor for the reference radiation energy, $E_l$, and the reference angle, $\alpha_l$;

$c_{\text{i}}$ is the instrument constant.

The determination of the calibration coefficient function shall be performed at constant dose and dose rate, respectively. When calibrating an instrument, the conditions, e.g. dose, dose rate and axis of rotation, for which the calibration coefficient function was determined shall be specified.

The above considerations can be applied to the determination of the response characteristics of the instrument. The response is defined as the quotient of the output signal of the detector assembly and the corresponding conventional quantity value for specified conditions. The output signal can be the indication, $G$, or the corrected indication, $G_{\text{corr}}$. For each response value, it is necessary to specify to which output signal it refers and for which specified conditions, e.g. radiation energy, $E$, and angle of incidence, $\alpha$, it was determined. The response with respect to the indication of the instrument, $R(E,\alpha)_G$, is given by:

$$R(E,\alpha)_G = G/H_{\text{o}} \tag{16}$$

The response related to the corrected indication, $R(E,\alpha)_{G_{\text{corr}}}$, is defined analogously.

During calibration measurements, the zero indication to be taken into account includes the indication at zero external radiation, i.e. the inherent measuring-assembly background, the indication given by the residual external radiation at the measurement position, and the indication given by scattered radiation. The latter effect is the major source of background during neutron irradiation. Radiation is scattered by the floor and walls of the laboratory in a complex way (see 5.2.3).

A more detailed description of methods of performing the calibration and determining the response is given in ISO 29661.

### 5.2.2 Reference radiation fields

In terms of the quantities ambient dose equivalent and effective dose, the radiation field at aviation altitudes is dominated by neutrons, electrons, positrons, protons, photons and muons. In principle, to fully characterize instrumentation, reference radiations are required for neutrons from a few hundred keV up to several hundred MeV, protons from a few tens of MeV to a few GeV, electrons and positrons from a few MeV to a few hundred MeV and photons up to a few tens of MeV.

The response of devices used for the determination of the ambient dose equivalent for the cosmic radiation fields in aircraft shall be determined, where possible, in ISO reference radiations (see ISO 4037-1, ISO 6980-1, ISO 8529-1, ISO 12789-1 and ISO 12789-2). However, these reference radiations do not entirely cover the energy range of photons, neutrons and electrons which account for the majority of the contributions to total ambient dose equivalent, and additional calibration fields are required. Also, calibrations are required in proton radiation fields for some devices. For all calibration fields, account shall be taken of any energy and direction distribution of the field over the sensitive volume of the device. Radiation fields used for calibration are listed in Annex B.

For non-ISO fields, calibrations 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[14].

To determine the response 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, e.g. 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 of the ISO high-energy photon reference field. This addresses the particular problems associated with the setting of the low-LET threshold of TEPCs and other devices. To determine the response of devices for neutrons of energies greater than that available, about 200 MeV, measurements can sometimes be made in mono-energetic proton beams in combination with calculation, or in broad energy distribution neutron fields, also in combination with calculation.

### 5.2.3 Scattered radiation

Calibration measurements shall refer to the free-field quantities fluence or ambient dose equivalent, as appropriate, and corrections shall be made for the influence of scattered radiation on the reading given by the instrument during the calibration. Radiation is scattered by the floor and walls of the laboratory. This contribution to the reading of an instrument can be determined by transport calculations or by measurements at specific laboratory conditions, i.e. shadow cone measurements. Room scatter is likely to be the most important source of scattered radiation. For all scatter contributions, the energy and direction distribution is different from that of the original source spectrum. Thus the relative contribution of scattered radiation to the reading of the device is dependent upon the energy and angle dependence of the response of the device.

### 5.2.4 Effect of other types of radiation

The effect of influence quantities, in particular the response of the device to types of radiation other than that for which it is being characterized, shall be determined.

For instance, devices which are intended to measure only the photon component generally exhibit unwanted response to neutrons, particularly high-energy neutrons. Those intended to measure only the neutron component can also be sensitive to other particles.

As mentioned above, different correction factors can be applied to different regions of an instrument's response, and this can be used to take into consideration these unwanted effects.

### 5.2.5 Requirements for characterization in non-reference conditions

#### 5.2.5.1 General

Owing to the complexity of the radiation field at aviation altitudes, a set of radiation types, $A_l$ (photons, electrons/positrons, muons, protons, neutrons, ions), and energies, $E_l$ (which are relevant at aviation altitudes), have to be used for additional measurements. From these sets of radiation types and energies, a calibration function, a response matrix, or a correction function, $k(A_l,E_l,\alpha_l)$, shall be determined. These calibration functions or correction factors are an essential ingredient for measurements in the real field.

#### 5.2.5.2 Dose and dose rate response

The response of the dosemeters shall be investigated at dose and/or dose rate conditions which can be found at aviation altitudes. Therefore, the dose rate response, $R_{\dot{H}}$, of an instrument shall be measured at dose rates between about 0,1 μSv·h$^{-1}$ and 100 μSv·h$^{-1}$. For passive devices which are able to measure doses only, the dose response, $R_H$, shall be measured between about 0,01 mSv and 20 mSv.

#### 5.2.5.3 Energy and angle dependence of response

Each instrument shall be characterized at different energies and angles of the incident particles. The energies for each particle shall be such that the majority of contributions to ambient dose equivalent are included. The angle of incidence, $\alpha$, is defined by the direction of the incident particle and is antiparallel to the normal vector at the instrument's surface. The irradiations shall be performed at several angles of incidence, $\alpha$, between 0°

and 90°, depending on the instrument design. The energy and angle response, $R(\alpha,E)$, of an instrument shall be measured at representative dose rates and total doses. Use can be made of numerical simulations to assist in characterizing instrument response for particle types and energies for which reference fields are not available.

#### 5.2.5.4 Air pressure response

The air pressure inside an aircraft is adjusted to take into account the outside air pressure because the pressure difference between inside and outside the aircraft structure is not allowed to exceed specified limits for each aircraft type. In standard passenger aircraft, the inside pressure at flight altitudes between 8 km and 12 km is of the order of 800 hPa. If the measurement system has a significant pressure dependence, a corresponding correction factor, with uncertainties, shall be determined and included in the analysis.

### 5.2.6 Use of numerical simulations

The best method of instrument response characterization is to combine experimental determination, as described above, with numerical simulation of the instrument's response to the entire particle type, energy and direction distributions at aviation altitudes.

## 5.3 Instrument-related software

### 5.3.1 Software development procedures

The use of software in controlling measuring instruments and in processing the measurements has increased substantially in recent years, from field-programmable gate arrays controlling the very functioning of the device to off-line analysis of the acquired data. This has made such devices much easier to operate, more reliable and ultimately more accurate in their output. However, the inherent complexity of many of these software components can easily lead to errors in processing and output. Hence, both the users and the developers of such systems shall be aware of the risks involved and take appropriate precautions.

It is clearly neither desirable nor practicable to follow stringent, safety-critical procedures for software development in all cases. Hence, a graded system of development methods and process checks is recommended (see, for instance, Reference [15]). This approach considers the software in the context of three questions:

- what is the criticality of its use (from “for indication only” to “safety-critical process control”)?
- what is the complexity of hardware control (from “software is passive” to “software controls all aspects of device”)?
- what is the complexity of the data processing (from “linear scaling” to “complex, developer-designed algorithms”)?

The answers to the above questions will indicate what degree of stringency is required in the software development procedure. Nevertheless, version control and appropriate documentation will be required for all but the most basic of software tools.

### 5.3.2 Software testing

As with developing the software, the degree of testing required will be dictated by the use and functionality of the software. Such techniques can be as simple as a code review or as complex as system-level software functional testing which tests every aspect of the code functionality. Again, these are discussed in detail in Reference [15].

### 5.3.3 Data analysis using spreadsheets

Although developing a spreadsheet for data analysis will be covered by the general requirements of software development outlined above, it is important to recognize that some spreadsheet functions are better defined than others. Guidance on the specific development and testing of spreadsheet applications can be found in Reference [16].

## 6 Uncertainties

For the determination of uncertainties, ISO/IEC Guide 98-1 and ISO/IEC Guide 98-3 shall be used. The statement of uncertainty shall be consistent with the approaches recommended by these documents and their supplements.

## 7 Remarks on performance tests

Regular test measurements are required to be performed for quality assurance purposes. These tests shall provide a clear indication that the response of the instruments does not deviate from the characterization procedure.

In-flight comparison with reference instruments and/or intercomparisons between instruments as well as measurements on the ground at high elevations, as described in Annexes C and B, respectively, are recommended.

# 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

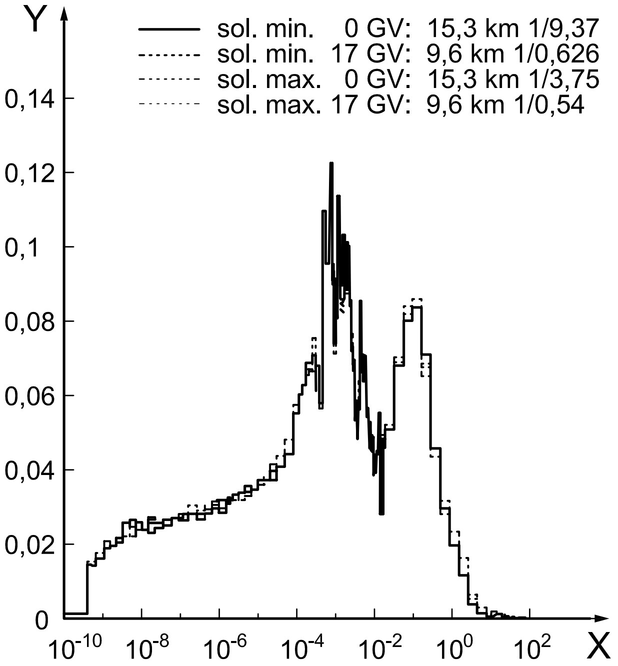
NOTE The figures in this annex are taken from Reference [9].

Figures A.1 to A.6 depict the calculated energy distribution of 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 to the extreme values which could be expected for civilian aircraft. These values are:

- minimum and maximum solar activity, described by the solar deceleration potential (= 465 MV and 1 700 MV, respectively), which presumably covers the entire dynamic range of solar modulation;
- minimum and maximum geomagnetic cut-off rigidity, $r_{\mathrm{c}}$ (= 0 GV and 17 GV, respectively);
- minimum and maximum 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 energy distribution of the particle fluence rate, i.e. the particle fluence per time interval, d$t$, and energy interval, d$E$, in $\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}\cdot\mathrm{GeV}^{-1}$, has been multiplied by the energy, $E$, and normalized to the energy-integrated fluence rate (the normalization factors are given in each figure for the respective curves).

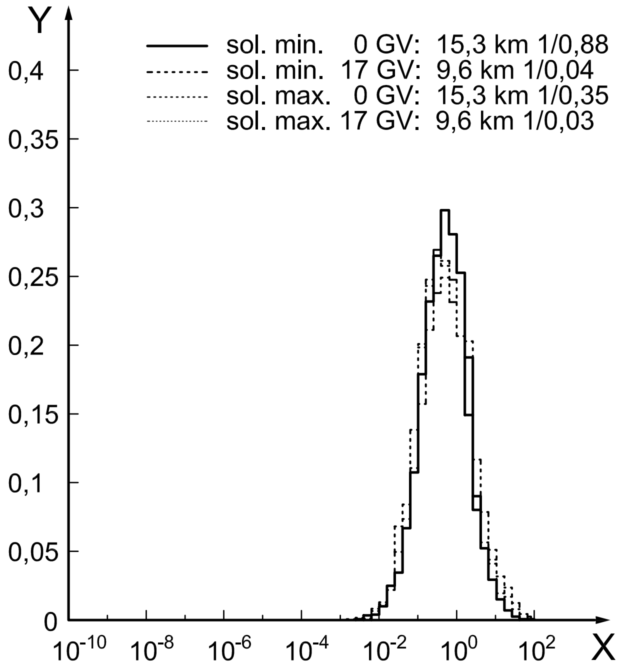


**Key**

X energy (GeV)

Y normalized fluence rate of neutrons

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

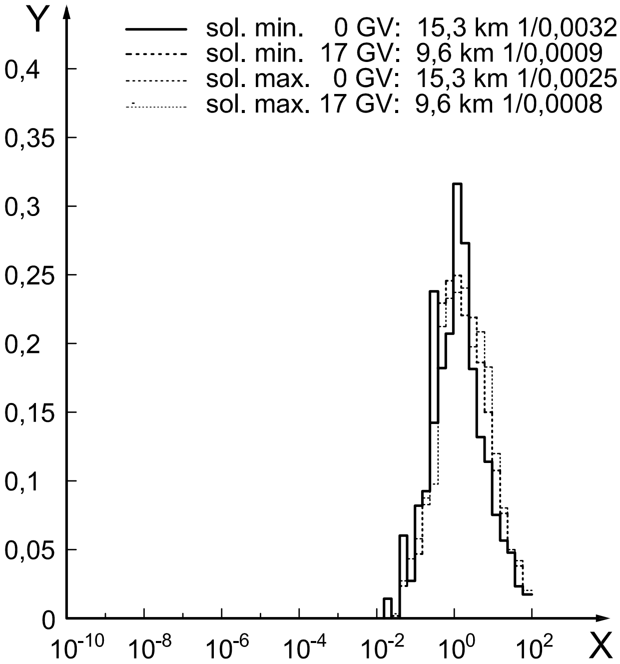


**Key**

X energy (GeV)

Y normalized fluence rate of protons

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

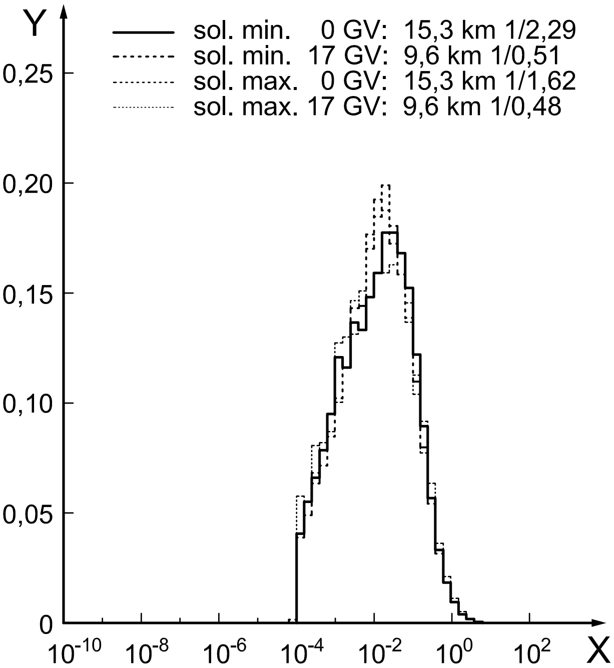


**Key**

X energy (GeV)

Y normalized fluence rate of charged pions

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

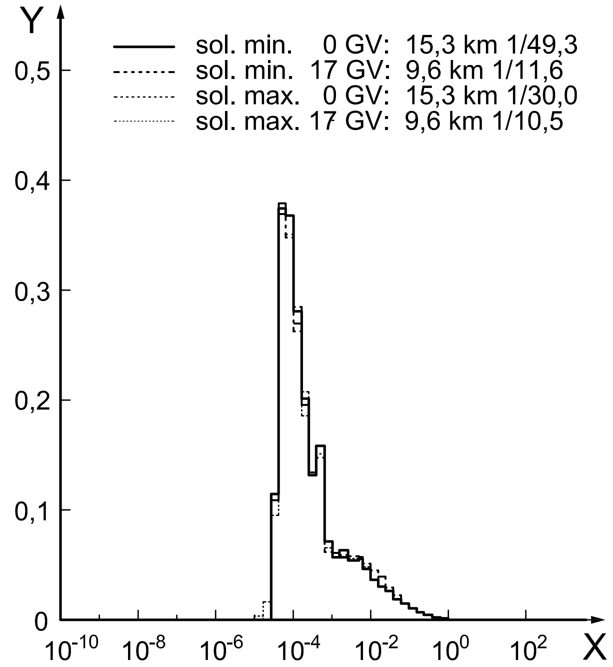


**Key**

X energy (GeV)

Y normalized fluence rate of electrons

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

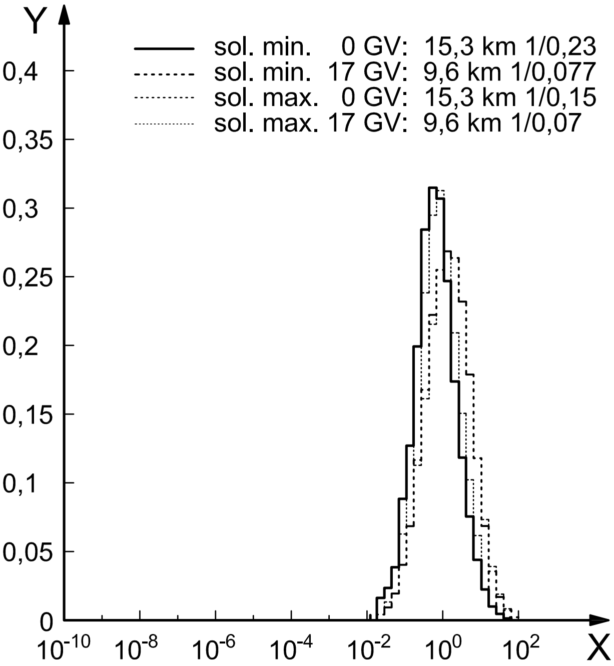


**Key**

X energy (GeV)

Y normalized fluence rate of gamma photons

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



**Key**

X energy (GeV)

Y normalized fluence rate of muons

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

# Annex B
(informative)

# Radiation fields recommended for use in calibrations

## B.1 Photon fields

The major fraction of the photon component of total ambient dose equivalent for all fields considered is for energies less than 10 MeV. This energy range is covered by the ISO reference radiations (see ISO 4037-1). The response of instruments to higher-energy photons might be adequately covered by calibration in the ISO reference radiation 6 MeV to 7 MeV photon field (see 5.2.2).

Traceability should be provided by using a transfer instrument which has been agreed upon by the calibration and the reference laboratories. The transfer instrument should be used in the same manner as when it was calibrated, and the proper corrections should be applied. The laboratories' transfer and monitoring instruments should be checked at intervals as required by national regulations and the results recorded.

## B.2 Neutron fields

### B.2.1 Radionuclide and mono-energetic neutron fields with $E < 20$ MeV

This energy range is covered by the ISO reference radiations (see ISO 8529-1). Dosimetry and procedures are provided in ISO 8529-2 and ISO 8529-3.

For calibrations using neutron fields produced by radionuclide neutron sources, traceability should be provided either by using a radionuclide source whose angular source strength has been determined by a reference laboratory (see ISO 8529-1) or by determining the fluence rate at the instrument test position using an agreed-upon transfer instrument calibrated at a reference laboratory. If the source is encapsulated in accordance with the recommendations in ISO 8529-1:2001, Clause 4, it may then be assumed that the spectral neutron fluence from the source is sufficiently similar to the appropriate spectral fluence given in ISO 8529-1 that the recommended fluence-to-dose equivalent conversion coefficients can be used.

For accelerator-produced fields, traceability should be provided by using a transfer instrument which has been agreed upon by the calibration and the reference laboratories. The transfer instrument should be used in the same manner, for similar neutron fields, as when it was calibrated, and the proper corrections should be applied. The laboratories' transfer and monitoring instruments should be checked at intervals as required by national regulations, and the results recorded.

### B.2.2 High-energy neutron fields, $E > 20$ MeV

#### B.2.2.1 General

Above 20 MeV, there are no ISO reference radiations available. There are no mono-energetic neutron fields, but quasi-mono-energetic fields, consisting of a peak with a low-energy tail. If the response of the device under test to the low-energy tail cannot be excluded by timing methods, the response to this component will have to be evaluated from *a priori* knowledge of the energy and direction distribution of the component and the device response, and then subtracted. It might be possible to establish traceability to national standards on occasions[18] to [25].

The following facilities have been used for response characterization and might be available for future use.

### B.2.2.2 UCL cyclone facility

A description of the neutron fields provided at the Université Catholique de Louvain (UCL) cyclone facility may be found in different papers by Dupont, *et al.*,[26] and Schuhmacher, *et al.*[18]. Two beams are provided at the facility, with peak neutron energies in the range 25 MeV to 70 MeV. Typically, the full width at half maximum of the peak is about 2 MeV. The beam is monitored with a $^{238}$U fission chamber and an NE102 plastic scintillator. The absolute neutron fluence is determined using a proton recoil telescope. The fluence energy distribution above 5 MeV is re-determined on frequent occasions using an NE213 spectrometer, the $^{238}$U fission chamber, and time-of-flight techniques. A scanning device can be provided by arrangement. The fluence and energy distribution measurements are made at the point of test with the instrument scanning device in position. Below 5 MeV, the energy distribution of the neutron fluence $\Phi_E$ is assumed constant. Typically, the relative uncertainty in the total fluence is about 7 %. For a peak energy of 60 MeV, for example, the fraction of neutron fluence within the peak ($E_n > 55$ MeV) has been determined as 0,327 (24) [fraction of $H^*(10)$ of 0,26]. The beam metrology is traceable to national standards via the fluence and energy distributions made by the Physikalisch-Technische Bundesanstalt (PTB).

### B.2.2.3 iThemba LABS

Detailed information on the quasi-mono-energetic fields at the iThemba Laboratory for Accelerator Based Sciences (iThemba LABS), Faure (South Africa) (previously, the National Accelerator Centre), can be found in the papers by McMurray, *et al.*[20] and Nolte, *et al.*[21]. Neutron beams with peak energies up to 200 MeV at 0° and 16° have been characterized by time-of-flight spectrometry, using a proton recoil telescope for the measurement of the fluence in the peak for lower energies and a $^{238}$U fission chamber for higher energies. The relative fluence energy distribution was measured up to 70 MeV with a scintillation detector, and above this energy by a combination of scintillation detector and fission chamber. For the 97 MeV beam, the full width at half maximum of the peak is about 4 MeV and the fraction of the total fluence within the peak is about 0,4. This fraction can be effectively increased to 0,7 by using a difference method, subtracting the instrument response for the 16° beam. For the 16° beam, the peak is greatly reduced, but with much less reduction in the lower-energy continuum. The beam metrology is traceable to national standards via the fluence and energy distributions made by PTB.

### B.2.2.4 TSL facility

A description of the neutron fields provided at the The Svedberg Laboratory (TSL) can be found in the paper by Condé, *et al.*[19]. The average energies of the peaks of the fluence distributions for the neutron beams which can be provided range from 68 MeV to 173 MeV, with a full width at half maximum of about 2 MeV. The neutron beam is monitored by means of a thin-film breakdown counter[27][28]. There are some data on the neutron energy distribution of the lower-energy component, but only above about 30 MeV, determined from both measurements and calculations (see Reference [29] and the references therein). Below about 40 MeV, the energy distribution of the neutron fluence $\Phi_E$ has to be extrapolated to lower energies with $\Phi_E$ constant. The ratio of peak fluence to total fluence depends on the peak energy, but is about 0,4. The uncertainty in the peak fluence is typically about 10 %. The uncertainties in the total fluences are estimated to be 30 % to 35 %, when the significant uncertainties in the energy distributions are taken into account.

### B.2.2.5 Facilities in Japan

Several neutron beam irradiation facilities have been developed in Japan: CYRIC of Tohoku University, TIARA of the Japan Atomic Energy Agency (JAEA), RRC of RIKEN and RCNP of Osaka University (see Annex D). At these facilities, neutrons are produced through the $^{7}$Li(p,n)$^{7}$Be reaction from energetic protons accelerated in a cyclotron. The energy ranges of the beams produced are 20 MeV to 90 MeV in CYRIC, 30 MeV to 90 MeV in TIARA, 70 MeV to 200 MeV in RRC and 250 MeV to 390 MeV in RCNP. The neutron energies are measured by the time-of-flight method, using fast-response detectors such as liquid scintillation counters. A detailed description of each facility can be found in papers by Terakawa, *et al.*[22] (for CYRIC), Baba, *et al.*[23] (for TIARA), Nakao, *et al.*[24] (for RRC) and Taniguchi, *et al.*[25] (for RCNP).

## B.3 Charged particles

### B.3.1 Electrons, muons and pions

There are no ISO reference fields available other than for electron energies up to a few MeV.

Traceability should be provided by using a transfer instrument which has been agreed upon by the calibration and the reference laboratories. The transfer instrument should be used in the same manner as when it was calibrated, and the proper corrections should be applied. The laboratories' transfer and monitoring instruments should be checked at intervals as required by national regulations, and the results recorded. Fields used for characterization and intercomparisons of energetic electrons are listed in Annex D.

### B.3.2 Protons

There are no ISO reference fields available for protons. There are a number of facilities (see Annex D) at which response characterization can be undertaken for high-energy protons (> 50 MeV).

Because the protons produced in an accelerator have the same energy at the beam exit, the irradiation dose can be determined precisely by counting the numbers of particles or by measuring ionization with the laboratories' monitoring instruments. These instruments should be checked at intervals as required for the calibration with photons or electrons.

### B.3.3 Heavy charged particles

Although there is little contribution to the ambient dose equivalent or effective dose at civil aviation altitudes from particles heavier than protons, some passive devices which determine particle fluence and LET in order to derive the dose equivalent require characterization in terms of particle type and LET. There are a number of facilities (see Annex D) at which response characterization can be undertaken for high-energy heavy ions (> 50 MeV).

Because the heavy charged particles produced in an accelerator have the same energy at the beam exit, the irradiation dose can be determined precisely by counting the numbers of particles or by measuring ionization with the laboratories' monitoring instruments. The instruments should be checked at intervals as required for the calibration with photons or electrons.

## B.4 Simulated workplace fields

Instrument response measurements and intercomparisons can be made in a simulated cosmic radiation neutron field designed at a high-energy accelerator. At the moment, the most popular is the one designed and provided at CERN. The facility has been developed and characterized jointly with the European Commission and is known as the CERF (CERN-EU high-energy Reference Field) facility[30], described also in ISO 12789-1. The fields are created by beams of high-energy protons and pions with moments 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 the 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 the component of other hadrons) of the radiation field at each calibration position has been calculated using the Monte Carlo code FLUKA. A number of multisphere spectrometry measurements have also been carried out.

Potentially, similar high-energy reference fields can be designed at other high-energy particle accelerators.

One such field was realized and characterized at the phasotron of the Joint Institute of Nuclear Research (JINR) at Dubna, Russia[31]. It was designed behind a 2-m-thick concrete wall on which primary 680 MeV protons impinge. The high-energy component spectrum is similar to that at CERF behind concrete[32]. The neutron spectrum was measured by a multisphere spectrometer in combination with ${}^{12}\mathrm{C} \rightarrow {}^{11}\mathrm{C}$ activation.

Studies of the characterization of another field of that type have been carried out in Cave A behind the shield of the SIS heavy-ion synchrotron forming part of the GSI accelerator facility, with $^{12}C$ as the primary charged particles with an energy of 400 MeV per nucleon hitting a graphite target. Multisphere neutron spectrometry measurements, other complex experimental studies and Monte Carlo calculations have also been made there[33][34][35][36].

Neither calibration procedures nor traceability to national standards have yet been established for this type of field.

## B.5 Natural fields

The cosmic radiation fields on the ground at high elevation are the radiation fields closest to those in aircraft[37][38] but, as with accelerator-produced simulated aircraft fields, the difference between these fields and 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, is not exactly the same as the cosmic radiation field at aviation altitudes. The fraction of the dose from muons is higher at lower altitudes, and 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 20 MeV, and more at thermal energies[39] to [44]. Different materials in or on the “ground” — soil, water or snow, concrete or other building materials — scatter neutrons differently and affect the shape of the spectrum as well as the general exposure level. Differences between radiation fields in aircraft at altitude and those in simulated fields and natural fields on mountains have to be taken into account.

There are several stations on mountains where the studies of cosmic radiation dosimetry characteristics can be continuously or occasionally performed: Chacaltaya (Bolivia), Jungfraujoch (Switzerland), Zugspitze (Germany), Cervino and others (Italy), Moussala (Bulgaria), Lomnický štít (Slovakia), Norikura and Fuji (Japan) and others. The results of continuous measurements of cosmic neutron spectra at Zugspitze have been presented[37]. Another recent publication has presented the results of studies of the influence of the choice of the measurement point inside the building of the Lomnický štít observatory on cosmic radiation dosimetry characteristics[45].

# Annex C
(informative)

# Comparison measurements

## C.1 In-flight comparison with reference instruments

Tissue-equivalent proportional counters (TEPCs) are considered to be the reference instrument for the measurement of the onboard aircraft radiation field at altitude that results from galactic cosmic rays and solar particle events[27] to [29][46] to [53]. Different types of TEPC system have been used for in-flight measurements, including:

a) a HAWK system (and earlier variations of this system)[48][49], as well as other portable systems[27][53], in which a pulse height spectrum that is proportional to the deposited energy is transformed into an absorbed dose distribution as a function of the linear energy transfer (LET);

b) a Sievert instrument[50] that determines a dose-mean lineal energy according to a variance method.

A low-LET threshold in the range 0,3 keV·μm$^{-1}$ to 0,5 keV·μm$^{-1}$ is observed in the widely used HAWK system due to electronic limitations. Monte Carlo calculations with FLUKA have therefore been employed to investigate the TEPC response so that appropriate corrections can be made for calibration of this instrument[51].

Several groups have performed different types of measurement on board aircraft with a variety of dosemeters, both active and passive, that can be compared to the well-characterized TEPCs[41][42][53] to [56]. The low- and high-LET components of the in-flight radiation field can be further measured separately and summed, providing a direct comparison with reference measurements made with the TEPC[27][28][46][57] to [59]. The complete mixed-radiation field has also been measured with a semiconductor spectrometer for comparison with TEPC measurements[60][61][62].

## C.2 Intercomparisons

In-flight calibrations and/or comparisons of different detector systems, generally involving several research groups, have been performed on board flights to assess the systematic differences between the various devices. These intercomparison flights provide a further opportunity to assess the different calibration and measurement procedures. The following intercomparison flights have been carried out:

a) The AIR (Atmospheric Ionizing Radiation) project was an international collaborative project, involving 12 laboratories from six countries, which employed 14 instruments [multisphere neutron spectrometer, ionization chamber, scintillation counters, two TEPCs, two particle telescopes, bubble detectors, three kinds of plastic nuclear track detector, two different kinds of thermoluminescent detector (TLD) and a solid-state neutron-sensitive pocket dosemeter (PDM-303)] on six flights of a National Aeronautics and Space Administration ER-2 aircraft in June 1997[11]. These flights covered latitudes of 18°N to 60°N and altitudes from 16 km to 21 km.

b) An Air France round-trip cargo flight between Paris and Tokyo via Fairbanks in April 2002, with passive and active detectors [TEPCs, Si (Liulin) spectrometer, TLDs, bubble detectors, bismuth fission detectors, etched-track detectors, Geiger-Mueller counter and electronic personal dosemeters] from nine laboratories were used for this intercomparison study[41][63]. The standard deviation in the integral ambient dose equivalent measured with the different systems for the round trip was ~10 %.

c) In the CAATER (Coordinated Access to Aircraft for Transnational Environmental Research) project, eight institutes were involved with an in-flight comparison of four well-characterized flights in May 2003 at constant altitudes (9,8 km and 12,2 km) and latitudes (56°N and 42°N), which employed five TEPC systems (including one that used a variance-covariance method) and an Si-diode spectrometer[41][64]. The relative standard deviation in the normalized ambient dose equivalent rates of all groups ranged from 6 % to 21 %.

d) There have also been several other bi- and/or multilateral studies to compare different passive and active dosimetry systems in order to evaluate passenger and aircrew exposure on intercontinental routes[63][65].

The typical overall dispersion of results obtained with different dosimetry systems is estimated to be between 10 % and 15 % (combined standard uncertainty). This agreement is satisfactory, considering that each system uses a specific technique and is calibrated in an independent way. Therefore, the measured value of the instruments should agree to within ±20 % (combined standard uncertainty).

# Annex D
(informative)

## Charged-particle irradiation facilities

The following list gives examples of facilities that have been used for response characterization and could be available for future use.

| Place | Country | Species | Energy |
|---|---|---|---|
| HIMAC, NIRS | Japan | p, He, C, …, Fe, Kr, Xe | ~800 MeV/u |
| J-PARC, JAEA/KEK | Japan | p, muons | ~3 GeV, ~50 GeV(p) |
| GSI | Germany | p, C, …, Xe, U | ~2 GeV/u |
| AGS, BNL | USA | p, …, Fe, Au | ~1,3 GeV/u |
| BAF, BNL | USA | p, …, Fe, Au | ~3 GeV/u |
| Loma Linda Univ. | USA | p | ~230 MeV |
| SPS, CERN | Switzerland | p, muons | 450 GeV(p) |
| NIRS | Japan | p, …, C | ~80 MeV(p)<br>~110 MeV(C) |
| RIKEN | Japan | p, …, Ni | ~210 MeV/u |
| JAEA | Japan | p, …, Au | ~90 MeV(p), ~460 MeV(Au) |
| Tohoku Univ. | Japan | p, …, Xe | ~90 MeV(p), ~750 MeV(Xe) |
| Osaka Univ. | Japan | p | ~400 MeV |
| GANIL | France | C, …, U | ~ 96 MeV(C), ~24 MeV(U) |
| UCL | Belgium | p, …, He | ~80 MeV(p), ~110 MeV(He) |
| Texas A&M Univ. | USA | p, …, U | ~70 MeV(p), ~3,5 GeV(U) |
| Univ. California at Davis Crocker Lab. | USA | p, …, He | ~68 MeV(p), ~130 MeV(He) |
| Michigan State Univ. | USA | p, …, U | ~200 MeV/u |
| Indiana Univ. | USA | p | ~205 MeV |
| Dubna | Russia | p, …, Fe, … | ~6 GeV/u |
| TRIUMF | Canada | p | ~520 MeV |
| PSI | Switzerland | p | ~250 MeV |
| TSL | Sweden | p | 65 MeV to 200 MeV |
| INFN, LNF | Italy | e, $e^+$ | 50 MeV to 750 MeV |

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