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Dosimetry for exposures to cosmic radiation in civilian aircraft —

Part 1: Conceptual basis for measurements

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

Partie 1: Fondement théorique des mesurages

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Foreword

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This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiation protection*.

This third edition cancels and replaces the second edition (ISO 20785-1:2012), which has been technically revised. The main changes are as follows:

— revision of the terms and definitions;

— updated references.

A list of all the parts in the ISO 20785 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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 (ICRP) in Publication 60[1], confirmed by Publication 103[2], the European Union (EU) introduced a revised Basic Safety Standards Directive[3] and International Atomic Energy Agency (IAEA)[4] issued a revised Basic Safety Standards. Those standards included exposure to natural sources of ionizing radiation, including cosmic radiation, as occupational exposure. The EU Directive requires account to be taken of the exposure of aircraft crews liable to receive more than 1 mSv per year. It then identifies the following four protection measures:

a) to assess the exposure of the crew concerned;

b) to take into account the assessed exposure when organizing working schedules with a view to reducing the doses of highly exposed crews;

c) to inform the workers concerned of the health risks their work involves; and

d) to apply the same special protection during pregnancy to female crews in respect of the "child to be born" as to other female workers.

The EU Council Directive has already been incorporated into laws and regulations of EU Member States and is being included in the aviation safety standards and procedures of the Joint Aviation Authorities and the European Air Safety Agency. Other countries such as Canada and Japan have issued advisories to their airline industries to manage aircraft crew exposure.

For regulatory and legislative purposes, the radiation protection quantities of interest are the equivalent dose (to the foetus) and the effective dose. The cosmic radiation exposure of the body is essentially uniform and the maternal abdomen provides no effective shielding to the foetus. As a result, the magnitude of equivalent dose to the foetus can be set equal to that of the effective dose received by the mother. Doses on board aircraft are generally predictable, and events comparable to unplanned exposure in other radiological workplaces cannot normally occur (with the rare exceptions of extremely intense and energetic solar particle events). Personal dosimeters for routine use are not considered necessary. The preferred approach for the assessment of doses of aircraft crews, where necessary, is to calculate directly the effective dose per unit time, as a function of geographic location, altitude and solar cycle phase, and to 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 Publications 75[5] and 132[6].

The role of calculations in this procedure is unique in routine radiation protection and it is widely accepted that the calculated doses should be validated by measurement. The effective dose is not directly measurable. The operational quantity of interest is ambient dose equivalent, $H^*(10)$. In order to validate the assessed doses obtained in terms of effective dose, calculations can be made of ambient dose equivalent rates or route doses in terms of ambient dose equivalent, and values of this quantity determined from measurements. Traceability should be provided for a reasonable number of particle types and energies of the atmospheric radiation field, corrections included for differences between the calibration fields and the total atmospheric radiation field, and related uncertainties properly taken into account. The validation of calculations of ambient dose equivalent for a particular calculation method may be taken as a validation of the calculation of the effective dose by the same computer code, but this step in the process may need to be confirmed. The alternative is to establish a priori that the operational quantity ambient dose equivalent is a good estimator of effective dose and equivalent dose to the foetus for the radiation fields being considered, in the same way that the use of the operational quantity personal dose equivalent is justified for the estimation of effective dose for ground-based 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 should be performed using accurate and reliable methods that ensure the quality of readings provided to workers and regulatory authorities. This document gives a conceptual basis for the characterization of the response of instruments for the determination of ambient dose equivalent in aircraft.

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

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

Dosimetry for exposures to cosmic radiation in civilian aircraft —

Part 1: Conceptual basis for measurements

1 Scope

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

2 Normative references

There are no normative references in this document.

3 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at http://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1 General terms

3.1.1
calibration
operation that, under specified conditions, establishes a relation between the conventional quantity, H_0, and the indication, G

Note 1 to entry: A calibration 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 to entry: Calibration should not be confused with adjustment of a measuring system, often mistakenly called "self-calibration", or with verification of calibration.

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

3.1.2
response
response characteristic
R
quotient of the indication, G, or the corrected indication, G_{corr}, and the conventional quantity value to be measured

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

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

Note 3 to entry: 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 to entry: The response usually varies with the energy and direction distribution of the incident radiation. It is, therefore, useful to consider the response as a function, $R(E,\Omega)$, of the radiation energy, E, and of the direction, Ω of the incident monodirectional radiation. $R(E)$ describes the "energy dependence" and $R(\Omega)$ the "angle dependence" of response; for the latter, Ω may be expressed by the angle, α, between the reference direction of the detector assembly and the direction of an external monodirectional field.

3.2 Quantities and units

3.2.1
particle fluence
fluence
Φ
number, dN, at a given point in space, of particles incident on a small spherical domain, divided by the cross-sectional area, da, of that domain:

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

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

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

3.2.2
particle fluence rate
fluence rate
$\dot{\Phi}$
rate of the *particle fluence* (3.2.1) expressed as

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

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

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

3.2.3
absorbed dose
D
for any ionizing radiation,

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

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

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

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

3.2.4
kerma
K
for indirectly ionizing (uncharged) particles, the mean sum of the initial kinetic energies dE_{tr} of all the charged ionizing particles liberated by uncharged ionizing particles in an element of matter, divided by the mass dm of that element:

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

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

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

3.2.5
dose equivalent
H
at the point of interest in tissue,

$$H = DQ$$

where

D is the absorbed dose;

Q is the quality factor at that point, and

$$H = \int_{L=0}^{\infty} Q(L) D_L \, dL$$

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

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

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

3.2.6
lineal energy
y
quotient of the energy, ε_s, imparted to the matter in a given volume by a single energy deposition event, by the mean chord length, $\bar{l}$, in that volume:

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

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

3.2.7
dose-mean lineal energy
$\bar{y}_D$

expectation

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

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

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

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

3.2.8
ambient dose equivalent
$H^*(10)$
dose equivalent (3.2.5) at a point in a radiation field, that would be produced by the corresponding expanded and aligned field, in the ICRU sphere at 10 mm depth on the radius opposing the direction of the aligned field

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

3.2.9
standard barometric altitude
pressure altitude
altitude determined by a barometric altimeter *calibrated* (3.1.1) with reference to the International Standard Atmosphere (ISA) (ISO 2533[7], *Standard Atmosphere*) when the altimeter's datum is set to 1 013,25 hPa

Note 1 to entry: ISO/IEC Directives Part 2 Clause 9 requires ISO documents to use SI units and to conform with ISO 80000[8] so the default should be metres. However, in aviation, the flight level is mostly given as FLxxx, where xxx is a three-digit number representing multiples of 100 feet of pressure altitude, based on the ISA and a datum setting of 1013,25 hPa; for instance FL350 corresponds to 35 000 ft or, using 1 foot = 0,304 8 m, 10 668 m.

3.2.10
vertical geomagnetic cut-off rigidity
vertical cut-off
cut-off
rc
minimum magnetic rigidity a vertically incident particle can have and still reach a given location above the Earth

3.3 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 rays
cosmic radiation (3.3.1) incident from space at the Earth's orbit

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 rays* (3.3.2) interacting, with the atmosphere or other matter

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

3.3.4
galactic cosmic radiation
galactic cosmic rays
GCR
cosmic radiation (3.3.1) originating outside the solar system

3.3.5
solar particles
solar cosmic radiation
solar cosmic rays
cosmic radiation (3.3.1) 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

Note 1 to entry: Solar particle events are directional.

3.3.7
ground level enhancement
GLE
sudden increase of *cosmic radiation* (3.3.1) observed on the ground by at least two neutron monitor stations recording simultaneously a greater than 3 % increase in the five-minute-averaged count rate associated with solar energetic particles

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

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

3.3.8
solar cycle
period during which the solar activity varies with successive maxima separated by an average interval of about 11 years

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

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

3.3.9
solar maximum
time period of maximum solar activity during a *solar cycle* (3.3.8), usually defined in terms of relative sunspot number

3.3.10
solar minimum
time period of minimum solar activity during a *solar cycle* (3.3.8), usually defined in terms of relative sunspot number

3.3.11
cosmic radiation neutron monitor
large detector used to measure the time-dependent relative fluence rate of high-energy *cosmic radiation* (3.3.1), in particular the secondary neutrons generated in the atmosphere (protons, other hadrons and muons can also be detected)

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

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[9][10]. Galactic cosmic radiation (GCR) can have energies up to 10^{20} eV, but lower energy particles are the most frequent. After the GCRs penetrate the magnetic field of the solar system, the peak of their energy distribution is at a few hundred MeV to 1 GeV per nucleon, depending on solar magnetic activity, and the spectrum follows a power function of the form $E^{-2,7}$ eV up to 10^{15} eV; above that energy, the spectrum steepens to E^{-3} eV. The fluence rate of GCR entering the solar system is fairly constant in time, and these energetic ions approach the Earth isotropically.

The magnetic fields of the Earth and Sun alter the relative number of GCR protons and heavier ions reaching the atmosphere. The GCR ion composition on the fluence basis for low geomagnetic cut-off and low solar activity is approximately 90 % protons, 9 % He ions, 1 % heavier nuclei; at a vertical cut-off of 15 GV, the composition is approximately 83 % protons, 15 % He ions, and nearly 2 % heavier ions[11][12].

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

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

