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Dosimetry for exposures to cosmic radiation in civilian aircraft —

Part 3: Measurements at aviation altitudes

Dosimétrie pour les expositions au rayonnement cosmique à bord d'un avion civil —

Partie 3: Mesurages à bord d'avions

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technology, and radiological protection*, Subcommittee SC 2, *Radiological protection,* in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 430, *nuclear energy, nuclear technologies and radiological protection,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

This second edition cancels and replaces the first edition (ISO 20785-3:2015), which has been technically revised.

The main changes are as follows:

— revision of the definitions of the terms;

— updated references.

A list of all 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[3], confirmed by Publication 103[4], the European Union (EU) introduced a revised Basic Safety Standards Directive[5] 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:

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 crew;

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

d) to apply the same special protection during pregnancy to female crew in respect of the ‘child to be born’ as to other female workers; after declaration of pregnancy, to ensure that the additional dose to the embryo/foetus would not exceed 1 mSv.

The EU Council Directive has to be incorporated into laws and regulations of EU Member States and has to be 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. ICRP has recommended a graded approach for radiological protection of flyers by setting three groups: aircraft crews, frequent flyers, and occasional flyers and encourages frequent flyers to perform self-assessment of their doses from cosmic radiation so that they could consider adjustment of their flight frequency as necessary[6].

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 effective dose rate, as a function of geographic location, altitude and solar cycle phase, and to fold these values with flight and staff roster information to obtain estimates of effective doses for individuals. This approach is supported by guidance from the European Commission, the ICRP in Publication 75[7] and the ICRU in Report 84[8].

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. As effective dose is not directly measurable, the operational quantity of interest is ambient dose equivalent, $H^*(10)$. Although the new recommendations on operational quantities have recently been published by ICRU[9], there would be a delay before being introduced into future ISO and IEC standards. As indicated in particular in ICRU Report 84, the ambient dose equivalent is considered to be a conservative estimator of effective dose if isotropic or superior isotropic irradiation can be assumed. 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 may need to be confirmed. The alternative is to establish, *a priori*, that the operational quantity ambient dose equivalent is a good estimator of effective dose and equivalent dose to the foetus for the radiation fields being considered, in the same way that the use of the operational quantity personal dose equivalent is justified for the estimation of effective dose for radiation workers. Ambient dose equivalent rate as a function of geographic location, altitude and solar cycle phase is then calculated and folded with flight and staff roster information.

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

Dosimetry for exposures to cosmic radiation in civilian aircraft —

Part 3: Measurements at aviation altitudes

1 Scope

This document gives the basis for the measurement of ambient dose equivalent at flight altitudes for the evaluation of the exposures to cosmic radiation in civilian aircraft.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements 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/IEC 80000-10, *Quantities and units — Part 10: Atomic and nuclear physics*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO/IEC 80000-10 for consistent uses of quantities and units, and the following apply.

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

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

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

3.1 Quantities and units

3.1.1
particle fluence
fluence
Φ
differential quotient of N with respect to a, where N is the number of particles incident on a sphere of cross-sectional area a:

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

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) $\Phi_{E,\Omega}(E,\Omega)$, where the subscripts characterize the variables (quantities) for differentiation and where the symbols in the brackets describe the values of the variables. The values in the brackets are needed for special function values (e.g. the energy distribution of the particle fluence at the energy $E = E_0$ is written as $\Phi_E(E_0)$). If no special values are indicated, the brackets may be omitted.

3.1.2
particle fluence rate
fluence rate
$\dot{\Phi}$

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

where dΦ is the mean increment of the *particle fluence* (3.1.1) during an infinitesimal time interval with duration dt

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

3.1.3
linear energy transfer
LET
L_Δ
quotient of the mean energy dE_Δ lost by the charged particles due to electronic interactions in traversing a distance, dl, minus the mean sum of the kinetic energies in excess of Δ, of all the electrons released by the charged particles and dl:

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

where

L_∞, i.e. with $\Delta = \infty$, is termed the unrestricted linear energy transfer in defining the quality factor

L_Δ is also known as the restricted linear collision stopping power

Note 1 to entry: The unit of the linear energy transfer is $\mathrm{J}\cdot\mathrm{m}^{-1}$, a frequently used unit is $\mathrm{keV}\cdot\mu\mathrm{m}^{-1}$.

3.1.4
dose equivalent
H
product of the absorbed dose D to tissue at the point of interest and the quality factor Q at that point:

$$H = DQ$$

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:

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

where $D_L = \mathrm{d}D/\mathrm{d}L$ is the distribution of D in L at the point of interest.

Note 2 to entry: The relationship of Q and L is given in Reference [4].

Note 3 to entry: The unit of dose equivalent is $\mathrm{J}\cdot\mathrm{kg}^{-1}$, called sievert (Sv).

3.1.5
ambient dose equivalent
$H^*(10)$
dose equivalent at a point in a radiation field, that would be produced by the corresponding expanded and aligned field, in the ICRU sphere at 10 mm depth on the radius opposing the direction of the aligned field

Note 1 to entry: The unit of ambient dose equivalent is $J \cdot kg^{-1}$, called sievert (Sv).

3.1.6
correction factor
K
factor applied to the indication to correct for deviation of the measurement conditions from reference conditions

3.1.7
standard barometric altitude
altitude determined by a barometric altimeter calibrated with reference to the International Standard Atmosphere (ISA) when the altimeter's datum is set to 1 013,25 hPa

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

3.1.8
geomagnetic cut-off rigidity
cut-off rigidity
$r_{\mathbf{c}}$
minimum magnetic rigidity an incident particle can have and still penetrate the geomagnetic field to reach a given location above the Earth. Magnetic rigidity, P, means the momentum per charge (of a particle in a magnetic field) given by:

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

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

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

3.1.9
vertical cut-off
cut-off
minimum magnetic rigidity a vertically incident particle can have and still reach a given location above the Earth

3.1.10
deceleration potential
ϕ
cosmic ray modulation parameter deduced from space observations of the abundance variation of the different species in function of the solar cycle epoch

Note 1 to entry: The deceleration potential could be deduced either from the sunspot index or from Climax neutron monitor output, using simple linear formula depending upon the phase of the solar cycle.

3.2 Atmospheric radiation field

3.2.1
cosmic radiation
cosmic rays
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

3.2.2
secondary cosmic radiation
particles which are created directly or in a cascade of reactions caused by interactions with the cosmic radiation incident from space and the atoms in the atmosphere

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.

3.2.3
galactic cosmic radiation
galactic cosmic rays
GCR
cosmic radiation (3.2.1) originating outside the solar system

3.2.4
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.

3.2.5
ground level enhancement
GLE
sudden increase of *cosmic radiation* (3.2.1) observed on the ground by at least two neutron monitoring 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.

3.2.6
solar modulation
change of the GCR field (outside the Earth's magnetosphere) caused by change of solar activity and consequent change of the magnetic field of the heliosphere

3.2.7
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 the average period of successive 11 years 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.

3.2.8
relative sunspot number
Wolf number
measure of sunspot activity, computed from the expression $k(10g + f)$, where f 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)

3.2.9
solar maximum
time period of maximum solar activity during a *solar cycle* (3.2.7), usually defined in terms of relative sunspot number

3.2.10
solar minimum
time period of minimum solar activity during a *solar cycle* (3.2.7), usually defined in terms of relative sunspot number

4 General considerations

4.1 General description of the cosmic radiation field in the atmosphere

The primary galactic cosmic radiation (and energetic solar particles) interact with the atomic nuclei of atmospheric constituents, producing a cascade of interactions and secondary reaction products that contribute to cosmic radiation exposures that decrease in intensity with depth in the atmosphere from aviation altitudes to sea level[10]. 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[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, protons, electrons/positrons, 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 as an 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.

