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Passive neutron dosimetry systems —

Part 2: Methodology and criteria for the qualification of personal dosimetry systems in workplaces

Systèmes dosimétriques passifs pour les neutrons —

Partie 2: Méthodologie et critères de qualification des systèmes dosimétriques individuels aux postes de travail

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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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Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation on the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see the following URL: www.iso.org/iso/foreword.html.

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

A list of all the parts in the ISO 21909 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

ISO 21909-1 provides laboratory-based type tests, and performance requirements for passive neutron dosimetry systems to be used for measurement of personal dose equivalent, $H_p(10)$, for neutrons ranging from thermal energy to approximately 20 MeV[1]. No distinction between the different techniques available in the marketplace is made in the description of the tests. ISO 21909 (series) aims at covering all passive neutron detectors that can be used as a personal dosemeter in parts of, or in the complete above-mentioned neutron energy range.

The main objective of ISO 21909 series is to achieve correspondence between performance tests and conditions of use at the workplaces. Dosimetry systems complying totally with ISO 21909-1 should give consistent dosimetry results in workplace environments without the requirement of precise information on the characteristics of the radiation fields (neutron energy and direction distributions).

For the case that a dosimetry system does not comply with the full range of requirements in ISO 21909-1 with regard to the dependence of the response on the energy and direction distributions of the neutron fluence, it remains necessary to evaluate the performance of the dosimetry system for the conditions of the workplace. That means that this document is systematically used to qualify at workplaces a dosimetry system that does not fulfil the criteria of ISO 21909-1 on the dependence of the response on neutron energy and direction of incidence.

This document aims to address dosimetry systems with responses that show energy and directional dependencies that do not comply with the test requirements in ISO 21909-1, but that are able to give consistent and reliable dosimetry results at selected workplaces. In this case, a specific study of the workplace where the dosimetry systems are used is necessary to demonstrate that the dosimetry systems are suited for the workplace of application and, if needed, to determine the appropriate corrections to be applied. This document gives requirements for the qualification of the dosimetry system as well as methods for evaluating its performance and qualifying it for use in the workplace.

In cases where the dosimetry system meets the requirements of ISO 21909-1, it may still be desirable to perform a similar study at the workplace to improve the performance of the neutron dosemeters. It is also recommended that this document may be implemented, not only for passive dosimetry systems, but for active dosimetry systems as well.

No qualification or correction of the dosimetry system at a workplace is required if the dosimetry system fulfils the criteria of ISO 21909-1.

All the estimations of the uncertainties in this document have to be considered in accordance with the GUM[2]. Uncertainties quoted in this document are provided using a coverage factor k=2.

Passive neutron dosimetry systems —

Part 2:
Methodology and criteria for the qualification of personal dosimetry systems in workplaces

1 Scope

This document provides methodology and criteria to qualify the dosimetry system at workplaces where it is used. The criteria in this document apply to dosimetry systems which do not meet the criteria with regard to energy and direction dependent responses described in ISO 21909-1.

The qualification of the dosimetry system at workplace aims to demonstrate that:

— either, the non-conformity of the dosimetry system to some of the requirements on the energy or direction dependent responses defined in ISO 21909-1 does not lead to significant discrepancies in the dose determination for a certain workplace field;

— or, that the correction factor or function used for this specific studied workplace enables the dosimetry system to accurately determine the conventional dose value with uncertainties similar to the ones given in ISO 21909-1.

NOTE This document is directed at all stakeholders who are involved: IMSs, accreditation or regulatory bodies, and users of the particular dosimetry (the user is meant as the entity which assigns the dosimetry system to the radiation worker and records the assigned dose.)

The methodologies to characterize the work place field in order to perform the qualification of the dosimetry system are given in Annex A. Annex B is complementary as it gives the practical methods to follow, once one methodology is chosen.

The provider of the dosimetry system shall provide the type test results corresponding to ISO 21909-1. However, when the dosimetry system to be qualified does not comply with all the criteria of ISO 21909-1 dealing with the energy and angle dependence of the response, some tests of the ISO 21909-1 can be not performed.

The links between ISO 21909-1 and ISO 21909-2 are described in Annex E.

This document only addresses neutron personal monitoring and not criticality accident conditions.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitute 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 21909-1:2021, *Passive neutron dosimetry systems — Part 1: Performance and test requirements for personal dosimetry*

ISO 8529-2:2000, *Reference neutron radiations — Part 2: Calibration fundamentals of radiation protection devices related to the basic quantities characterizing the radiation field*

ISO 8529-3:1998, *Reference neutron radiations — Part 3: Calibration of area and personal dosimeters and determination of response as a function of energy and angle of incidence*

3 Terms, definitions and symbols

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 and definitions

3.1.1
detector
radiation detector
apparatus or substance used to convert incident ionizing radiation energy into a signal suitable for indication and/or measurement

[SOURCE: IEC 60050-394:2007, 394-24-01, modified — the term “detector” has been added as the first preferred term]

3.1.2
dosemeter
dosimeter
device having a reproducible, measurable response to radiation that can be used to measure the absorbed dose or dose equivalent quantities in a given system

[SOURCE: ISO 12749-2:2013, 5.5]

3.1.3
personal dosemeter
meter designed to measure the personal dose equivalent (rate)

Note 1 to entry: A personal dosemeter can be worn on the trunk (whole-body personal dosemeter), at the extremities (extremity personal dosemeter) or close to the eye lens (eye lens dosemeter).

[SOURCE: ISO 29661:2012, 3.1.21]

3.1.4
individual monitoring service
IMS
organization that operates a personal-dosimetry system which includes the evaluation of the reading of dosemeters after their use and may include:

— providing the user with dosemeters;

— recording the results;

— reporting the results to the user

3.1.5
dosimetry system
system used for measuring absorbed dose or dose equivalent, consisting of dosemeters, measurement instruments and their associated reference standards, and procedures for the system’s use

[SOURCE: ISO 12749-4:2015, 3.1.3, modified — the wording of the definition was slightly modified.]

3.2 Quantities

3.2.1
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: The unit of dose equivalent is joule per kilogram ($J \cdot kg^{-1}$), and its special name is sievert (Sv).

[SOURCE: ISO 80000-10:2019, 10-83, modified — Note 1 to entry added.]

3.2.2
neutron fluence
Φ
differential quotient of *N* with respect to *a*, where *N* is the number of neutrons incident on a sphere of cross-sectional area *a*:

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

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

[SOURCE: ISO 80000-10:2019, 10-43, modified — the wording of the definition was slightly modified.]

3.2.3
energy distribution of the neutron fluence
Φ_E
quotient of $\mathrm{d}\Phi$ by $\mathrm{d}E$, where $\mathrm{d}\Phi$ is the fluence of neutrons with energy between E and $E + \mathrm{d}E$

$$\Phi_E = \frac{\mathrm{d}\Phi}{\mathrm{d}E}$$

Note 1 to entry: The SI unit of the energy distribution of the neutron fluence is ($m^{-2} \cdot J^{-1}$); a widely-used unit is ($cm^{-2} \cdot MeV^{-1}$).

Note 2 to entry: The energy distribution of the neutron fluence rate ϕ_E is the quotient of $\mathrm{d}\Phi_E$ by $\mathrm{d}t$, where $\mathrm{d}\Phi_E$ is the increment of the energy distribution of the fluence in time interval $\mathrm{d}t$. The unit is ($m^{-2} \cdot J^{-1} \cdot s^{-1}$); a widely-used unit is ($cm^{-2} \cdot MeV^{-1} \cdot s^{-1}$).

3.2.4
energy and direction distribution of the neutron fluence
$\Phi_{\mathrm{E},\Omega}$
quotient of $\mathrm{d}\Phi$ by $\mathrm{d}E$ and $\mathrm{d}\Omega$, where $\mathrm{d}\Phi$ is the *fluence* of neutrons with energy between E and $E + \mathrm{d}E$ and propagating within a solid angle $\mathrm{d}\Omega$ around a specified direction, Ω, expressed as

$$\Phi_{E,\Omega} = \frac{\mathrm{d}^2\Phi}{\mathrm{d}E\Omega}$$

Note 1 to entry: The SI unit of the energy and direction distribution of the neutron fluence is $m^{-2} \cdot J^{-1} \cdot sr^{-1}$; a widely-used unit is ($cm^{-2} \cdot MeV^{-1} \cdot sr^{-1}$).

Note 2 to entry: The energy and direction distribution of the neutron fluence rate $\Phi_{E,\Omega}$ is the quotient of $\mathrm{d}\Phi_{\mathrm{E},\Omega}$ by $\mathrm{d}t$, where $\mathrm{d}\Phi_{E,\Omega}$ is the increment of the energy and direction distribution of the fluence in time interval $\mathrm{d}t$. The unit is ($m^{-2} \cdot J^{-1} \cdot sr^{-1} \cdot s^{-1}$); a widely-used unit is ($cm^{-2} \cdot MeV^{-1} \cdot sr^{-1} \cdot s^{-1}$).

3.2.5
personal dose equivalent
$H_p(d)$
dose equivalent in soft tissue at an appropriate depth, *d*, below a specified point on the human body

Note 1 to entry: The unit of personal dose equivalent is joule per kilogram ($J \cdot kg^{-1}$) and its special name is sievert (Sv).

Note 2 to entry: The specified point is usually given by the position where the individual's dosimeter is worn.

[SOURCE: ICRP 103:2007]

3.2.6
ambient dose equivalent
$H^*(10)$, $H'(0{,}07)$ or $H'(3)$
dose equivalent that would be produced by the corresponding aligned and expanded field in the *ICRU sphere* at a depth, *d*, on the radius opposing the direction of the aligned field

[SOURCE: IAEA – Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards - Interim Edition IAEA Safety Standards Series GSR Part 3, 2011]

3.2.7
conversion coefficient
$h_{p\Phi}(10,E,\alpha)$
quotient of the personal dose equivalent at 10 mm depth, $H_p(10)$, and the *neutron fluence*, Φ, at a point in the radiation field used to convert neutron fluence into the personal dose equivalent at 10 mm depth in the ICRU tissue slab phantom, where E is the energy of the incident neutrons impinging on the phantom at an angle α

Note 1 to entry: The unit of the conversion coefficient is $Sv \cdot m^2$. A commonly used unit of the conversion coefficient is $pSv \cdot cm^2$.

3.3 Calibration and evaluation

3.3.1
conventional true value for the neutron personal dose equivalent
H^{conv}
quantity value attributed by agreement to a quantity for a given purpose

Note 1 to entry: The conventional value H^{conv} is the best estimate of the quantity to be measured, determined by a primary standard or a secondary or working measurement standard which are traceable to a primary standard.

Note 2 to entry: in this document, the quantity is the neutron personal dose equivalent.

[SOURCE: ISO/IEC Guide 99:2007, 2.12, modified — the term was changed.]

3.3.2
calibration
operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding readings with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication

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

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

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

[SOURCE: ISO/IEC Guide 99:2007, 2.39]

3.3.3
calibration factor
N
quotient of the *conventional quantity value*, H^{conv}, (3.3.1) divided by the reading, *M*, derived under standard test conditions, given by the formula:

$$N = \frac{H^{conv}}{M}$$

Note 1 to entry: mathematical functions, in some cases families of functions, can be used to provide calibration factors over a range of conditions. Several different calibration functions can be defined for the same dosimetry system and possibly be used for different conditions of exposure.

3.3.4
correction factor or function
numerical value or function by which the indication is multiplied to compensate for the deviation of measurement conditions from reference conditions or for a systematic effect

Note 1 to entry: In this document, it corresponds to the factor or function, noted $k_{n,E,\Omega}$, defined for a specific workplace field, that is applied to the value of the measured dose equivalent in order to take into account the systematic effect induced by the dose response of the dosimetry system.

[SOURCE: ISO 29661:2012, 3.1.9, modified — the wording of the definition was slightly modified.]

3.3.5
measured dose equivalent
H_M
product of the reading, *M*, and the calibration factor, *N*:

$$H_M = M \cdot N$$

Note 1 to entry: More elaborate algorithms may also be used.

Note 2 to entry: This definition is only valid for a calibration field. To extend it to any other field, the correction factor of function $k_{n,E,\Omega}$, needs to be added. In that case, the formula becomes:

$$H_M = M \cdot N \cdot k_{n,E,\Omega}$$

3.3.6
phantom
object constructed to simulate the scattering and absorption properties of the human body for a given ionizing radiation

Note 1 to entry: For calibrations for whole body radiation protection considerations, the ISO water slab phantom is employed. It is made with polymethyl metacrylate (PMMA) walls (front wall 2,5 mm thick, other walls 10 mm thick), of outer dimensions 30 cm x 30 cm x 15 cm and filled with water.

Note 2 to entry: In the cases of very non-uniform irradiation conditions, an extremity cylinder, pillar or rod phantom may be used as described in ICRU report 66.

[SOURCE: ISO 12749-2: 2013, 4.1.6.1 modified — Notes 1 and 2 to entry added]

3.3.7
reading
M
quantitative indication of a detector or dosemeter when it is read out, generally corrected for background, ageing, fading and non-linearity of the process or the read out system

3.3.8
dose equivalent response
response
R
measured dose equivalent, H_M, divided by the *conventional quantity value,* H^{conv}, (3.3.1) of the dose equivalent, as given by the following formula:

$$R = \frac{H_M}{H^{conv}}$$

Note 1 to entry: The reading, *M*, is converted into dose equivalent, H_M, by multiplying *M* by an appropriate conversion coefficient or by using a more elaborate algorithm.

Note 2 to entry: In this document, the quantity is personal dose equivalent: $R = \frac{H_p^M(10)}{H_p^{conv}(10)}$

Note 3 to entry: In this document, for the sake of brevity, $H_M = H$ is used.

Note 4 to entry: The reciprocal of the response at *reference conditions* is equal to the calibration coefficient.

Note 5 to entry: In radiation metrology, the term response, abbreviated for this application from "response characteristic" (VIM), is defined as the ratio of the reading, *M*, of the instrument, to the value of the quantity to be measured by the instrument, for a specified type, energy and direction distribution of radiation. It is necessary, in order to avoid confusion, to state the quantity to be measured, e.g. the "fluence response" is the response with respect to the fluence, the "dose equivalent response" is the response with respect to dose equivalent.

[SOURCE: ISO 8529-3:1998, 3.2.10, modified]

3.4 Symbols

The list of the symbols used in this document is given in Table 1.

Table 1 — List of symbols

Symbol	Meaning	Unit
α	angle of incidence of the irradiation field	degree
d	Depth in ICRU 4-element or soft tissue. Recommended depths are 0,07 mm, 3 mm, and 10 mm.	mm
E	Neutron energy	eV
Φ	Neutron fluence	m^{-2}
H	Dose equivalent	Sv
$H^*(10)$	Ambient dose equivalent at 10 mm depth	Sv
H^{conv}	Conventional true value for the neutron personal dose equivalent	Sv
H_{HD}	Personal dose equivalent whose value is chosen in the range: $0,8\ mSv < H_{HD} < 2\ mSv$	Sv
H_M	Measured dose equivalent	Sv
$H_p(d)$	Personal dose equivalent at a depth d	Sv
$H_p(10)$	Personal dose equivalent at 10 mm depth	Sv
H_p^{conv}	Conventional true value for the neutron personal dose equivalent.	Sv
$h_p(d,E,\alpha)$	Fluence-to-personal-dose-equivalent conversion factor	$Sv \cdot m^2$
R	Dose-equivalent response	-
U_{H_M}	Expanded uncertainty of the measured personal dose equivalent	As quantity
$U_{H^{conv}}$	Expanded uncertainty of the conventional true value for the personal dose equivalent	As quantity

Table 1 *(continued)*

Symbol	Meaning	Unit
U_{com}	Expanded uncertainty of a combined quantity of conventional quantity values. This uncertainty is equivalent to the half-width of the confidence interval about the combined quantity at a confidence level of 95 %	As quantity

This document uses SI units. However, the following units of practical importance for time and energy are used when necessary:

— days (d) and hours (h) for time;

— electron-volt (eV) knowing that 1 eV = 1,602 × 10^{-19} J.

The SI unit of dose equivalent is J·kg^{-1} but the dedicated name for the unit of dose equivalent is sievert (Sv).

4 Documentation and communication to the users

The IMS (individual monitoring service) shall specify in its documentation whether the dosimetry system complies or not with requirements in ISO 21909-1 in terms of its energy and angular dependence. If the dosimetry system is not in compliance, the dosimetry system shall be qualified for the workplace in which it is to be used. The IMS should inform the user (responsible for the workers monitoring, i.e., employer, RPO…) on the energy and angular range for which the dosimetry system does not fulfil the criteria of ISO 21909-1 and that the dosimetry system shall be qualified for the workplace in which it is used. The qualification of the dosimetry system at the workplace shall be done in accordance with this document.

The IMS should also indicate the need to qualify the dosimetry system in the situation in which the dosimetry system is deployed to different workplaces or even different worker's locations, each requiring a unique correction. A specific note shall be given to the users, explaining that a dosimetry system for which the response is corrected for one specific workplace cannot be used at several workplaces except if it is qualified globally for those several workplaces.

In the situation where the IMS is not in charge of performing the qualification, it shall give to the user all the results of the characterisation in accordance with ISO 21909-1.

5 Recommendations about the workplace to consider

When characterizing a specific workplace, the variability in energy or directional distributions of the neutron field shall be taken into account. To achieve this objective, the exposure situations that show the highest differences in terms of neutron fluence rate or neutron dose rate, different shielding materials and thicknesses, surfaces of scattering, have to be considered.

In case that the spectral neutron fluence can be significantly different for the possible locations of the workers in one given workplace, the effect of these different exposure situations on the response of the dosimetry system shall be considered. If needed, several workplaces can be defined taking the different worker's locations into account. The attention to this issue is essential to insure the robustness and reliability of the dosimetry system at this workplace.

Moreover, in case that the workplace field varies with time, i.e., neutron sources and/or shielding and/or locations of exposure change, the effect of the new exposure situation on the response of the dosimetry system shall be considered. Only different exposure situations for which it was already shown that the dosimetry system fulfils the requirements with the same correction function (if needed) are acceptable without a new study.

NOTE 1 The definition of the workplace is conceptually simple. In the case when a worker is working in front of a glovebox, it is easy to define one specific workplace. However, in some situations, for example around a transport container, the spectrum can be very different at the edge of the container compared to the middle of the container.

The workplace conditions have a significant impact on the neutron fluence, energy and direction distributions. The following shall be considered in any evaluation of the performance of the dosimetry system in this environment: emission rate and energy distribution, mass, density, geometry, shielding, materials present at the workplace, location of work, typical orientation of worker, etc.

NOTE 2 An example where the neutron fluence, energy and direction distributions can be significantly modified at the same workplace is for storage facilities. Indeed the amount of neutron sources may vary, but also the geometrical configuration and the composition of the neutron emitters and the surrounding materials. To sum up, the type, the number and the locations of stored sources may vary. These modifications may induce high variations in terms of fluence rate, energy and directional distributions of the neutron field in such a workplace.

6 Methodologies and criteria to qualify the personal dosimetry system at a certain workplace

6.1 Choice of the methods to be used for the qualification at workplaces

Two methods a) and b) are described below to qualify the dosimetry system at a specific workplace. Choose and apply one of these two methods (see also Figure 1).

a) The first approach is based on a characterization in terms of the energy and direction distribution of the neutron fluence encountered at the workplace. The method consists of evaluating the impact of the non-compliance of the dosimetry system to the requirements of the dependence of the response on energy or direction of incidence defined in ISO 21909-1. For such dosimetry systems, specific correction at workplaces shall not be performed if it has been demonstrated that the non-compliance does not lead to significant discrepancies in the dose determination for the considered workplace field. The impact shall be quantified and the dosimetry system shall fulfil the requirements of 6.2.

b) The second approach is based on a qualification of the dosimetry system itself performed directly at the considered workplace. In that case, it should be demonstrated that the correction factor or function used for the specific workplace enables to accurately determine the conventional dose equivalent quantity with uncertainties similar to the ones required in ISO 21909-1. The required tests and the performance limits are given in 6.3.

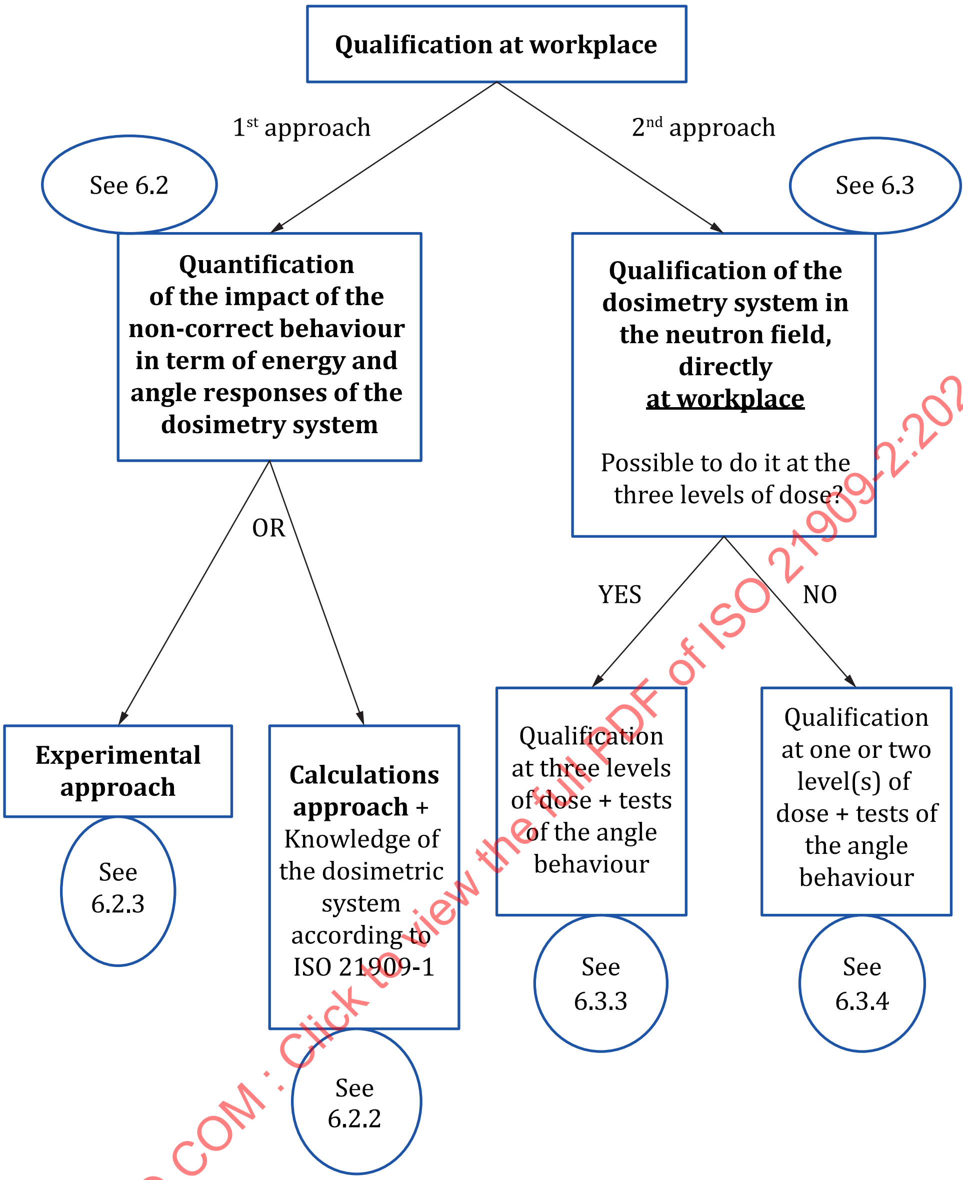


Figure 1 — Decision diagram to determine the method to use to qualify the dosimetry system at a workplace

6.2 Quantification of the impact of the non-correct behaviour in terms of energy and angle responses of the dosimetry system

6.2.1 General

This approach is restricted to dosimetry systems that show under-responses in regard to the criteria of ISO 21909-1:

— for the lower energies and/or the higher energies of the minimal rated energy range as defined in ISO 21909-1;

— or, for the higher angles of the angle range as defined in ISO 21909-1.

To demonstrate in this specific case, the small impact on dose equivalent measurement, two methods can be used: calculations (6.2.2) or experimental tools (6.2.3).

The location(s) at which the dosimetry system is qualified in the workplace shall be, at minimum, the one(s) representative for the usual locations of the workers in the room. In both approaches, it is acceptable to consider to characterizing the workplace field in terms of the energy dependence of the neutron fluence without taking into account the direction distribution of the neutron fluence (i.e., usual neutron spectrometers allowing the determination of $H^*(10)$ can be used.)

6.2.2 Computational approach

The approach consists in using both:

— the information on the characteristics of the workplace in terms of energy and direction distributions of the neutron fluence from calculations. Apply the numerical approach described in (A.2.2) to determine this information.

— and all the results of the tests of performance of the dosimetry system obtained from the type tests defined in ISO 21909-1, in order to qualify the dosimetry system at the workplace.

The dosemeters can be used at the workplace without corrections under the following conditions:

— a range of acceptable energy/angle responses against ISO 21909-1 shall be found by defining an upper and or lower energy limit; only mono-energetic beams demanded in ISO 21909-1 shall be considered for defining the limits;

— it shall be demonstrated by workplace calculations that $H_p(10)$ neutron dose contribution due to neutrons corresponding to energies/angles outside of the aforementioned defined range is lower than 10 % of the total neutron dose.

The criteria given in ISO 21909-1 for the mono-energetic neutron fields shall be used to define the lower or upper limit in useful energy response of the dosimetry system.

6.2.3 Experimental approach

The experimental approach is similar in concept to the computational approach but the dose contribution due to neutrons with energies below a threshold for low energies and/or above a threshold for high energies is assessed using experimental tool. Apply (A.2.1) to have the information on the energy distribution.

As stated previously, the workplace(s) in which the dosimetry system is to be qualified shall be the one(s) representative of the usual locations of the workers in the room.

6.3 Qualification based on experimental tests of the dosimetry systems at the workplace

6.3.1 General method

This approach is based on the assessment of $H_p(10)$ at the workplace. This personal dose equivalent value determined by the dosimetry system is compared to a reference value obtained from a reference measurement.

Firstly, the reference value $H_p(10)$ shall be assessed. To do so, apply Annex A to define which methodology to use, and apply the corresponding practical method in Annex B.

When a dosimetry system uses different correction functions or factors, choose the system that is the most adapted to the specific workplace.

Secondly, for the measurement of H_M by the dosimetry system to be qualified, a minimum of four dosemeters shall be placed on a phantom. Use the same phantom, and at the same position and at the same directional incidence, used to determine the reference value of $H_p(10)$, denoted as H^{conv}. The value H_M to be considered in the calculation of the response is the average of the four measurements.

The dosemeters shall be placed on the front face of the phantom. The phantom and irradiation geometry used in the experimental irradiation shall be in accordance with ISO 8529-3:1998, 6.2.

The phantom shall be positioned in order that the 0° incidence corresponds to the orientation the most representative of the worker's position.

NOTE 1 The correction factor or function can be estimated using several methods. The experimental results from this on-site qualification can be used, but supporting published information (see Annex D) or tests using simulated workplace fields can also be used, to help determine the appropriate correction factor or function.

The response R, is defined as the quotient of the mean measured dose equivalent value H_M, of the irradiated dosemeters with the correction factor or function applied if needed, and the reference value H^{conv}:

$$R = \frac{H_M}{H^{conv}}$$

The value of the response, R, shall meet the following criteria defined in 6.3.2.

The tests shall be performed at either one (see 6.3.4) or three (see 6.3.3) levels of dose equivalent H^{conv}.

NOTE 2 The choice between these two solutions depends mainly on the personal dose equivalent rate at the workplace.

The tests performed according to this method have to be completed by supplementary verifications based on tests performed following ISO 21909-1:

— In any case, it shall be checked that all the requirements of ISO 21909-1, except the ones concerning the dependence of the response on energy and direction of incidence, are still fulfilled when the correction factor or function is applied (see 6.3.4);

— Depending on the number of levels of personal dose equivalent chosen for the qualification at the workplace, complementary requirements regarding tests performed following ISO 21909-1 have to be fulfilled to validate the reliable performance of the dosimetry system in terms of angular dependence and linearity of the response (see 6.3.3 or 6.3.4).

6.3.2 Performance test criteria

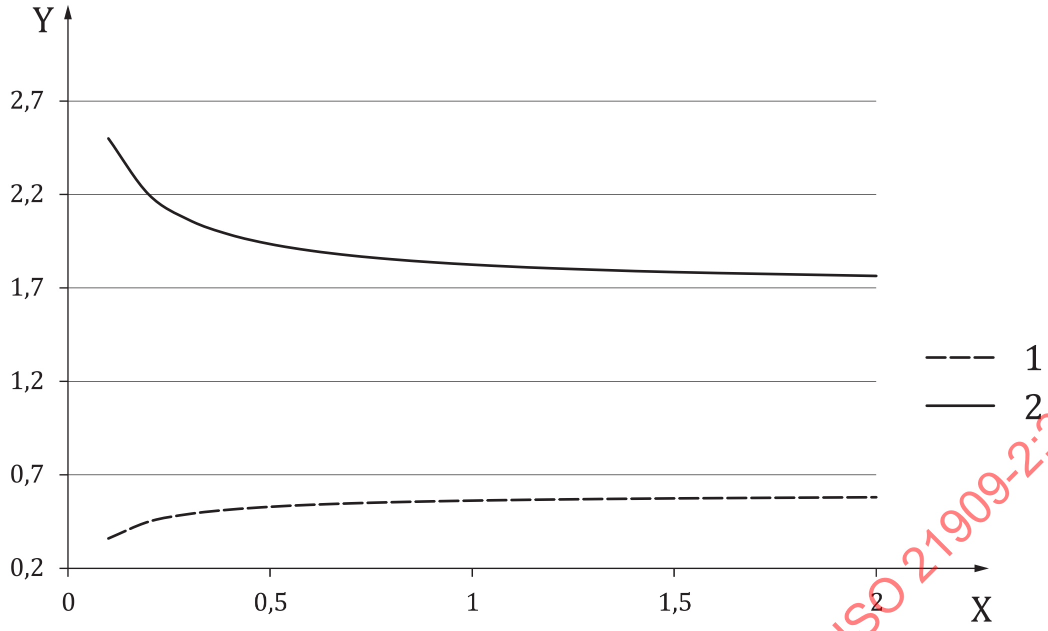
The value of the response, R shall meet the following criteria:

$$0{,}3 \cdot \left(1 - \frac{2 \cdot H_{low} / 1{,}5}{H_{low} / 1{,}5 + H^{conv}} \right) + 0{,}3 \leq R \pm U_{com} \leq \left(\frac{2 \cdot H_{low} / 1{,}5}{H_{low} / 1{,}5 + H^{conv}} \right) + 1{,}7$$

with $H_{low} = 0{,}1$ mSv,

$$\text{and with } U_{com} = \left(\frac{H_M}{H^{conv}} \right) \cdot \left[\left(\frac{U_{H_M}}{H_M} \right)^2 + \left(\frac{U_{H^{conv}}}{H^{conv}} \right)^2 \right]^{1/2}$$

Such performance limits are illustrated in Figure 2.



Key

1 minimum limit
2 maximum limit
X dose equivalent (mSv)
Y ratio $R = H_M/H^{conv}$

Figure 2 — Performance limits

6.3.3 First solution: tests at three levels of dose at the workplace

The qualification following the general method (see 6.3.1) is performed experimentally with measurements performed at three levels of dose:

— at a dose within the range [H_{min}; H_{min} + 40 %],

— at a dose within the range [(H_{min}+ 0,1 mSv) – 20 %; (H_{min} + 0,1 mSv) + 20 %],

— at a dose within the range [0,8 mSv; 2 mSv].

Moreover, it shall be demonstrated that, using a specific correction factor or function depending only on the considered neutron energy, the tests and the criteria of ISO 21909-1 are fulfilled for the three following energies: 144 keV, 250 keV, and ^{252}Cf or ^{241}Am-Be sources.

This means that, using a specific correction factor or function depending only on the considered energy, the criteria on the dependence of the response on energy and direction of incidence described in ISO 21909-1:2021, 7.5.3, shall be fulfilled.

Figure 3 gives the mandatory series of irradiations from the of ISO 21909-1:2021, Table 2 to perform, in addition to the tests performed directly at the workplace.

NOTE These tests provide confidence in the angle dependence of response of the dosemeters.

To illustrate this, one unique correction factor or function can be applied for all the tests described in columns C and K of ISO 21909-1:2021, Table 2. Another correction factor or function can be used for the tests of columns D and L. A third correction factor or function can be defined to fulfil the tests of columns J, M and N.

6.3.4 Second solution: tests at one level of dose at the workplace

If the qualification at the workplaces cannot be performed experimentally at the three levels of dose as specified in the first solution (see 6.3.3), then the following criteria shall be fulfilled:

All the tests of ISO 21909-1 shall be performed at the three levels of dose (see ISO 21909-1:2021, Table 2). Moreover, it shall be demonstrated that, using one unique correction factor or function depending only on the considered energy, all the tests and criteria defined in ISO 21909-1 are fulfilled.

NOTE At some workplaces, the personal dose equivalent rate can be very low and it might be very difficult for practical reasons to integrate the high level of dose [0,8 to 2] mSv. That is why this second method can be used instead.

Figure 3 gives the mandatory series of irradiations from ISO 21909-1:2021, Table 2 to perform, in addition to the tests performed directly at the workplace.

The tests shall be performed at minimum for the “mandatory” range as defined in ISO 21909-1:2021, Table 3 giving the mandatory series of irradiations as a function of the stated energy range of the dosimetry system. This means that the tests of all the columns from C to N included in the “mandatory” range shall be fulfilled, even if a different correction factor or function is required for each test field. If the neutron field encountered at the workplace has a thermal component, and/or fast energy respectively, then the dosimetry system shall comply with the tests of the columns A, B and Q (and/or respectively the column O).

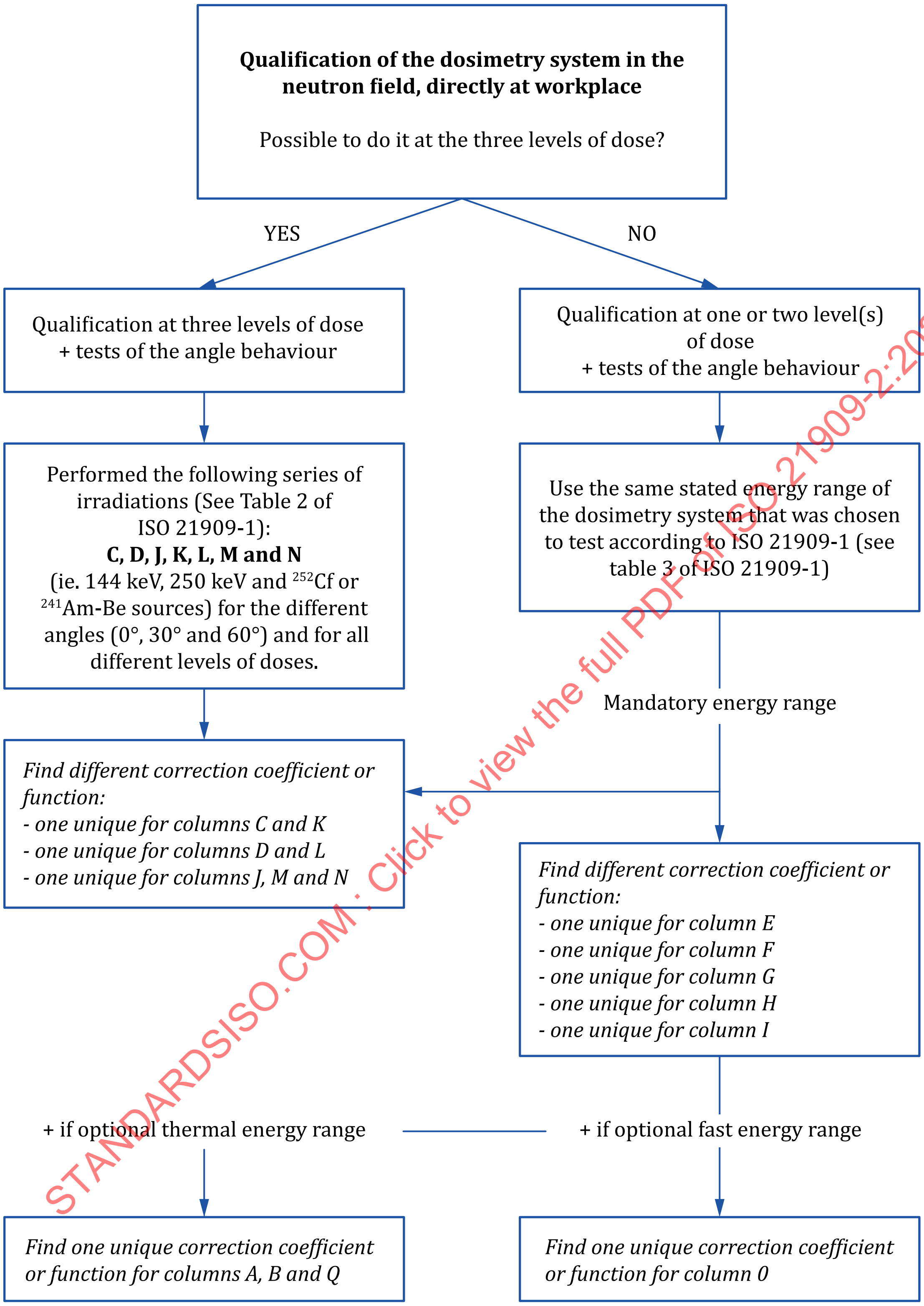


Figure 3 — Mandatory irradiations from ISO 21909-1 and specific requirements to fulfil, in addition to the tests performed directly at the workplace

6.3.5 Complementary tests based on ISO 21909-1

When defined and applied, the correction factor or function shall be verified. First, all the criteria of the tests of ISO 21909-1 shall be checked and fulfilled, except the ones concerning the dependence of the response on neutron energy and direction of incidence.

To do this verification, a recalculation of all the doses measured for all the tests of ISO 21909-1, shall be done, considering the correction factor or function. It shall be demonstrated that the dosimetry system fulfils all the requirements of ISO 21909-1 (except the ones on the dependence of the response on energy and direction of incidence). For dosimetry systems using correction factor or function, a general verification can be performed before any workplace qualification considering all the potential correction factors or functions routinely used by the IMS.

NOTE To illustrate the importance of doing this verification, consider the case of the tests for effects on unexposed dosemeters required by ISO 21909-1. To be more precise, the example of the test described in ISO 21909-1:2021, 8.3, which deals with the effect of storage for unexposed dosemeters, can be considered. Indeed, if a correction factor is applied after the qualification at the workplace, the result of this test can change and the criteria can be not fulfilled anymore. Before applying the correction factor or function, such a test would be fulfilled, but after the application of the correction factor or function, the test criteria would not be met any more.

6.3.6 Unique correction for several workplaces

This subclause addresses the specific case where the same dosemeter is worn by a worker at different workplaces. In that case, one unique correction factor or function should be used for all the considered workplaces.

A qualification shall be performed at each workplace. For each workplace, the most appropriate method for qualifying the dosimetry system shall be used. For instance, the choice is partly determined by the dose equivalent rate of each workplace. The methods are described in 6.3.

For each workplace, a correction factor or function is defined (if needed). But in order for the dosimetry system to be used by a worker at all these different workplaces, the applied correction factor or function on the dose reading is necessarily unique. As a consequence, one unique correction factor or function needs to be defined.

It shall be demonstrated that the value of the correction factor or function is acceptable at each workplace. To do so, it shall be shown (by recalculations) that the dosimetry system satisfies the performance test described in 6.3.1 at each workplace.

NOTE For instance, a single correction factor or function can be determined as the weighted mean of correction factors or functions (weighted by the dose equivalent rates). Another solution that can be used, for instance, is to take estimations of the percentage of duration of stay at the various workplaces as weighting factors.

Annex A
(normative)

Methodologies to characterize the workplace field

A.1 General

A neutron workplace field can be characterized completely by experimental studies and/or with computer simulations, i.e., to determine the energy distribution and direction distribution of the present neutron fluence rate. Depending on the objectives, however, a complete characterization is not always necessary or feasible. For the purpose of the validation or the correction of personal dosimetry systems, sometimes the knowledge of the energy distribution without detailed information on the directional distribution can be sufficient. Of course, only the complete characterization of the neutron field with its energy and direction distribution allows for the determination reference values of personal dose equivalent $H_p(10)$ by folding the neutron fluence with energy and angle dependent fluence-to–personal-dose-equivalent conversion coefficients as specified by the ICRU and ICRP reports (ICRU report n°57, ICRP Publication 74).

The reference instrument shall be adapted to the specific context (energy range, pulse source term...).

The following sub clauses give a description of the different approaches.

Choose one of the approaches (A.2) or (A.3), according to the technical capabilities and possibilities at the workplace.

A.2 Determination of energy and direction distribution of the neutron fluence

A.2.1 Experimental approach

Ideally, the determination of the energy and direction distribution of the neutron fluence should be performed through spectrometers in capacities to measure such distributions.

NOTE In the past, one experimental campaign was performed using such a type of spectrometer. See informative Annex C.

For the neutron energy distribution, spectrometers that are commercially available shall be used to perform direct measurements: Bonner Sphere systems, ROSPEC, Bubble Detector Systems ... or any other experimental means provided there is enough control of the uncertainties.

When the knowledge of the direction distribution is needed, then a complete analysis shall be performed.

But, no commercial system allows the determination of the directional distribution. Simultaneous measurements of the energy and direction distribution of the neutron field are complicated and systems dedicated to do such measurements are unavailable. However, ISO 12789-2 explains that some pragmatic methods can be used, such as positioning several dosimetry systems on the different faces of a phantom.

Without access to an experimental system allowing the direct determination of the directional distribution, choose one of the three methods described in B.1 and then comply with it.

A combination with calculations can be used to complete the experimental results, complying with (A.2.2) in that case.

A.2.2 Numerical approach

Numerical tools exist to determine the energy and direction distributions of the neutron fluence, such as Monte Carlo codes. Only internationally tested computer codes, or those that have been compared to measurements, shall be used. The version, or update number, of the code shall be indicated, and also the version of the cross-section data set which is used. The initial conditions shall be documented in order to facilitate the inter-comparison of results between laboratories.

NOTE 1 As stressed in ISO 12789-2:2008, 6.1, it is difficult to estimate the overall uncertainty associated with Monte Carlo calculations.

NOTE 2 At a minimum, sufficient histories shall be accumulated to reduce the statistical uncertainty. However, a small value for the statistical uncertainty does not necessarily indicate a small overall uncertainty. These tools can notably be used to complete experimental systems in order to get the directional distribution.

An experimental check of the numerical tools shall be performed.

NOTE 3 This enables verification that the physical models, geometrical description, source description, etc. are correct. Such a check can be the comparison of the fluence dose rate or fluence rate at a specific point.

A.3 Determination of the reference value for $H_p(10)$

A.3.1 General

Several approaches are proposed to assess the reference value of $H_p(10)$. One of the three approaches described in (A.3.2), (A.3.3) or (A.3.4) shall be chosen and used. The corresponding method described in Annex B shall be applied for the practical implementation.

A.3.2 From complete characterization of the neutron field

This method, based on the complete characterization of the neutron field, involves two steps:

Firstly, perform a complete characterization of the energy and direction distribution of the neutron fluence according to (A.2.1).

Secondly, determine reference values for the personal dose equivalent $H_p(10)$ by folding the neutron fluence with energy and angle dependent fluence-to–personal-dose-equivalent conversion coefficients as specified by the ICRU and ICRP reports[18][19].

Calculations using Monte Carlo codes can also be used to determine the neutron fluence. They can also provide values for $H_p(10)$. However, calculated results have to be validated by experimental checks.

NOTE Such a method was used during the EVIDOS project (see Annex C).

A.3.3 From neutron energy distribution or $H^*(10)$ measurement and basic information on the direction distribution

This method consists in using the neutron energy distribution or $H^*(10)$ measurement and basic information on the direction distribution.

The neutron field at the workplace can be complex. In some cases, the neutron radiation comes mainly from one direction (one located neutron source). In more complex cases, the field is a superposition of direct neutrons from a source and scattered neutrons from walls, floor and ceiling. Conceptually, a measurement of $H^*(10)$ is conducted with an adequate instrument and this value is corrected to determine the conventional value of $H_p(10)$ from basic information on the direction distribution of the neutron field[20].

In the situation of a directed neutron field where the contribution to $H_p(10)$ from non-AP directions is negligible, $H_p(10)$ is determined from a measured value of $H^*(10)$ with minor adjustments. To determine the reference values for the personal dose equivalent $H_p(10)$, apply (B.1.2) or (B.1.3).

NOTE Indeed, the fluence-to-personal dose-equivalent conversion coefficients and fluence-to-ambient-dose-equivalent conversion coefficients for neutrons are quite similar for normal incidence. At higher angles of incidence, the fluence-to-personal dose equivalent conversion coefficients decrease.

In the complex situation (non-direct neutron field), some quantitative information about directional distribution of neutrons in every direction shall be estimated. Practically, dosemeters are fixed on different sides of a phantom. In that case, to determine the reference values for the personal dose equivalent $H_p(10)$, apply (B.1.3).

A.3.4 From direct $H_p(10)$ reference measurements

This method consists in the determination a reference value for the personal dose equivalent $H_p(10)$, using a personal dosemeters that measure $H_p(10)$. In that case, (B.2) shall be applied.

Annex B
(normative)

Determination of the neutron personal dose equivalent Hp(10) – Practical methods

B.1 Determination of $H^*(10)$ and the basic directional distribution

B.1.1 General

As described in A.3.3, a method to assess the reference value of $H_p(10)$ is to measure $H^*(10)$ and estimate $H_p(10)$ via hypothesis on the direction distribution of the field.

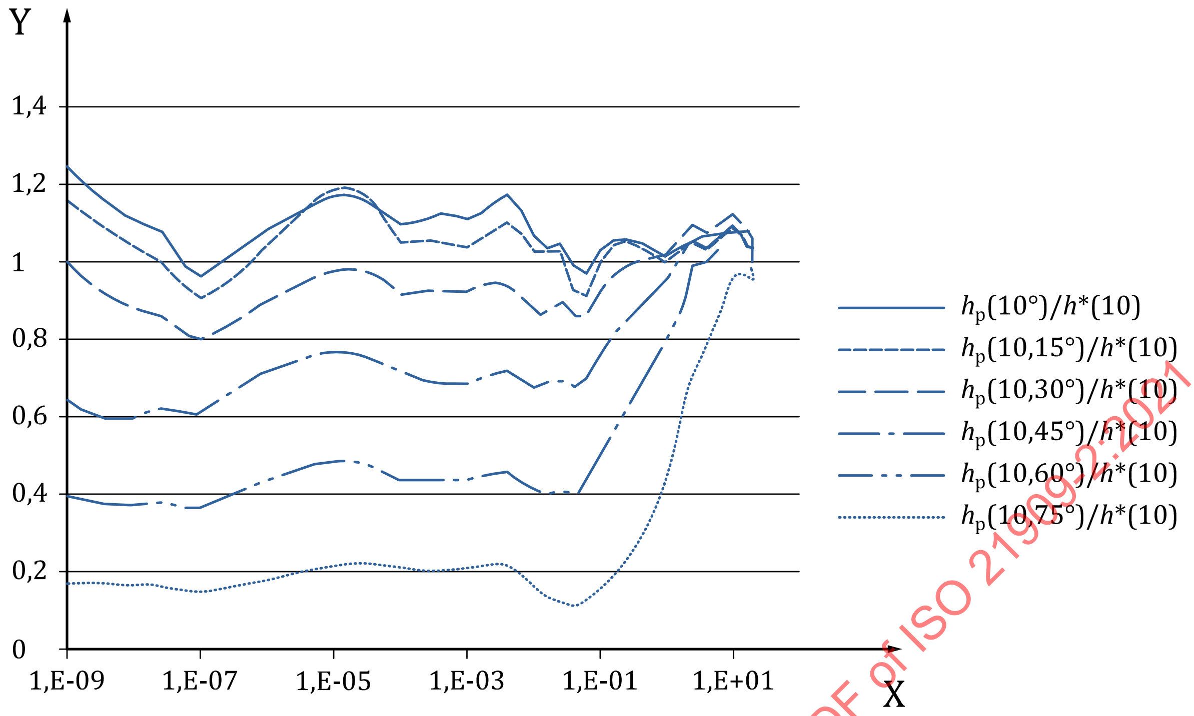
Two situations are distinguishable: the first one where the neutron field is coming mainly from one direction and a more complex situation where the neutrons are incident from several directions. In both situations, it is possible to determine a reference value of $H_p(10)$ from a $H^*(10)$ measurement. A correction factor shall be applied to estimate the reference value of $H_p(10)$ as a function of the direction distribution of the field. The estimation of this correction factor or function is different for the two situations.

B.1.2 Directed neutron field

For a directed neutron field, the 0° incidence is defined by the direction from which the neutrons are emitted. The values of fluence-to-personal-dose equivalent conversion coefficients and fluence-to-ambient dose equivalent conversion coefficients for neutrons are quite similar for normal incidence. At higher angles of incidence, the fluence-to-personal dose equivalent conversion coefficients decrease (see Figure B.1).

NOTE 1 This example is typical for a worker standing in front on a glove box. Indeed, the measurement performed to estimate $H_p(10)$ with a phantom directed towards the main direction of incidence of the neutron source corresponds also with the way the worker usually stands.

A correction factor, called R, applied to $H^*(10)$ measurement is deduced from the basic information on the directional distribution of the field. Then, the reference value of $H_p(10)$ is equal to $H^*(10)$ multiplied by R. This coefficient R is deduced from the ratio of the fluence-to-personal-dose equivalent conversion coefficients at an angle to be defined, $h_p(10,\alpha)$, on the fluence-to-ambient dose equivalent conversion coefficients, $h^*(10)$ and according to the information on the energy spectrum.



Key

X neutron energy (MeV)

Y ratio of the conversion coefficients (no unit)

Figure B.1 — Ratio of the fluence-to-personal-dose equivalent conversion coefficients $h_p(10,\alpha)$ and fluence-to-ambient-dose equivalent conversion coefficients $h^*(10)$ for neutrons in function of the neutron energy and for different angle α

A rough estimation of the importance of the scattered neutron field at this specific workplace and coming from all the other directions shall be estimated, according to the following steps:

a) The main direction where the neutrons are emitted shall be defined according to the knowledge of the presence of the sources at the workplace (i.e., the 0° incidence is defined).

b) Then a measurement of $H^*(10)$ is performed using a radiameter. This neutron ambient dose equivalent meter shall be able to measure $H^*(10)$ at the workplace with an uncertainty smaller than 20 %. Available information on the energy distribution of the neutron fluence at the workplace should be used to choose one radiameter rather than another one. This first measurement is called M_T.

c) Then, a second measurement is performed at the same position, using the same radiameter but with a shadow cone placed between the radiameter and the source (see ISO 8529 for the choice of the adapted shadow cone). This second measurement is then called M_S. The specifications for the shadow cone technique are detailed in ISO 8529-2:2000, Annex E.

These two measurements shall be done with a sufficiently long integration time in order to minimize the statistical uncertainties.

The part of the field measured with the shadow cone, M_S, is reasonably estimated to come from angles between 15° and 60° and the part directly from the source, (M_T - M_S), between 0° and 15°. With these considerations the reference value of $H_p(10)$ is calculated as:

$$H_p(10) = (M_T - M_S) + R_1 \times M_S \quad \text{(B.1)}$$

Where R_1 a coefficient corresponding to the average ratio of the fluence-to-personal-dose equivalent conversion coefficients, $h_p(10,\alpha)$ on the fluence-to-ambient-dose equivalent conversion coefficients, $h^*(10)$ considering a flat directional distribution between 15° and 60°.

$$\text{Then, since } H_p(10) = R \times M_T,\ R = 1 + (M_S/M_T) \times (R_1\text{-}1) \quad \text{(B.2)}$$

According to Table B.2, R_1 can be estimated to 0,75 for instance.

$$R = 1 - 0{,}25 \times (M_S/M_T) \quad \text{(B.3)}$$

It is then possible to give a reference value for $H_p(10)$ according to Formula (B.4):

$$H_p(10) = M_T - 0{,}25\ M_S \quad \text{(B.4)}$$

Table B.2 — Values of R_1 in function of the neutron energy – For information, the values of R for the main neutron field coming from 0° and 15° are also given as a function of the neutron energy

For scattered neutrons, distributed between 15° and 60° in a homogeneous way

	Neutron energy			
	10 keV	**100 keV**	**500 keV**	**1 MeV**
$\langle h_p(10)/h^*(10)\rangle$	0,66	0,72	0,84	0,88

For direct neutrons, distributed between 0° and 15° in a homogeneous way

	Neutron energy			
	10 keV	**100 keV**	**500 keV**	**1 MeV**
$\langle h_p(10)/h^*(10)\rangle$	1,05	1,01	1,03	1,01

NOTE 2 Spectrometer measurement results could supplement the measurement of $H^*(10)$. The ratios R and R_1 can then be estimated more precisely taken into account the energy distribution of the neutron field.

B.1.3 Complex neutron field

B.1.3.1 General

To determine the neutron personal dose equivalent $H_p(10)$ in a complex neutron field (i.e. non directional), choose and apply one of the two methods below (B.1.3.2) or (B.1.3.3).

B.1.3.2 Method using 6 dosemeters on a phantom

A method to estimate the reference value of $H_p(10)$ in a complex neutron field is based on the measurement of $H^*(10)$ and on the estimation of the direction distribution via dosimetry measurements on the different faces on a phantom i.e. ISO water phantom or a PMMA phantom.

NOTE 1 Such method is used in References [7], [8], [9] and [20]. In these articles, the ambient dose equivalent $H^*(10)$ was determined at workplaces at power plants using commercial neutron monitors, whose readings were corrected taking into account spectral information in rough energy intervals from a commercial spectrometer. Basic information on the directional distribution of neutron fluence was obtained from the readings of several personal neutron dosemeters attached to a phantom.

This sub clause describes a practical method to estimate the conventional dose equivalent $H_p(10)_{reference}$ value when the neutron field is not directional, or when no information is available a priori on the direction distribution of the neutron field to qualify. The following steps shall be applied:

a) First, estimate the ambient dose equivalent $H^*(10)$.

To do so, neutron spectrometry shall be performed in order to determine the energy distribution of the neutron fluence (e.g., using spectrometers such as Bonner sphere system, ROSPEC or Microspec-2 Nprobe, etc.). With the neutron spectrum, the value of $H^*(10)$ is then deduced using the fluence-to-ambient-dose-equivalent conversion coefficients from the ICRP Publication 74.

However, performing neutron spectrometry is very time consuming and it could be impossible to do at some workplaces. In order to simplify the method, it is allowed to measure the ambient dose equivalent $H^*(10)$ with a radiometer instead. In that case, a neutron ambient dose equivalent meter shall be chosen in order to measure $H^*(10)$ at the workplace with an uncertainty smaller than 25 %. Available information of the energy distribution of the neutron fluence at the workplace should be used to choose one radiameter over another one.

b) Then, expose six dosemeters on a PMMA phantom.

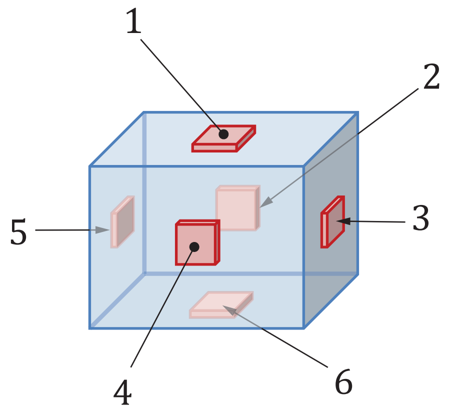
The dosemeters should preferably be in accordance with ISO 21909-1. Otherwise the dosemeters used should be able to indicate the personal dose equivalent with uncertainties in the same range as required in ISO 21909-1.

NOTE 2 These measurements enable the estimation of the directional contribution of the neutron spectrum.

Six dosemeters should be located above, below and on the four different sides of a PMMA phantom to get six readings of $H_p(10)$ (see Figure B.2).

NOTE 3 The sum of the value of these readings associated with a geometrical correction factor allows determining a value close to an estimation of $H^*(10)$.

NOTE 4 It was demonstrated that a separation into 6 directions is slightly conservative compared to a separation into 18 directions[23].



Key

1	dosemeter “up”	90° up ± dα°
2	dosemeter “Back”	180° ± dα°
3	dosemeter “Right”	90° right ± dα°
4	dosemeter “Front”	0° ± dα°
5	dosemeter “Left”	90° left ± dα°
6	dosemeter “Down”	90° down ± dα°

Figure B.2 — Position of the dosemeters on the PMMA phantom

If $H_p(10,x)$ is noted with x = 0°, 180°, 90°Left, 90°Right, 90°Up, 90°Down the six values of dose equivalent measured by the six dosemeters placed on the PMMA phantom, then a “similar H*(10)” is calculated with a geometrical correction factor:

$$H_p(10,4\Pi)=\frac{4\Pi}{6\Omega}\cdot\left[H_p(10,0°\text{Front})+H_p(10,90°\text{Right})+H_p(10,90°\text{Left})+H_p(10,90°\text{Up})+H_p(10,180°\text{Back})+H_p(10,90°\text{Down})\right]$$ (B.5)

$$\Omega=2\Pi\left[1-\cos\left(\beta\cdot\frac{\Pi}{180°}\right)\right] \quad \text{(B.6)}$$

NOTE 5 This correction factor means that each dosemeter measure the personal dose equivalent under a solid angle of Ω, defined by the angle β.

For practical reasons, it is also allowed to use only 5 dosemeters (with no dosemeter beneath the phantom), the measurement at 90°Down being assumed to be equal to the one at 180°. The formula to be used is:

$$H_p(10,4\Pi)=\frac{4\Pi}{6\Omega}\cdot\left[H_p(10,0°\text{Front})+H_p(10,90°\text{Right})+H_p(10,90°\text{Left})+H_p(10,90°\text{Up})+2\cdot H_p(10,180°\text{Back})\right]$$ (B.7)

c) Estimate the reference for the personal dose equivalent, i.e. the conventional dose equivalent, using the Formula (B.8):

$$H_p(10)_{\text{reference}}=\frac{H^*(10)_{\text{radiameter}}}{H_p(10,4\Pi)}\cdot H_p(10,0°) \quad \text{(B.8)}$$

It is highly recommended to place at least 2 dosemeters (preferably 3) on each face in this method, in order to avoid the risk of any outlier measurements that could occur. If several dosemeters are used, the average measurement could be used, enhancing the statistical quality of the value.

B.1.3.3 Single sphere method for albedo dosemeters with TL detectors

NOTE 1 The technique for albedo dosemeters with thermoluminescence detectors (TLD) to obtain an indication for the personal dose equivalent in workplace fields was proposed by Burgkhardt and Piesch[10][11][12]. It is used by all individual monitoring services in Germany[13] for the characterization of unknown workplace fields. The method is also suited for other types of dosemeters as shown in Reference [14] based on evaluation of the results of the EVIDOS project [4]. In accordance with cited literature, it is here denoted as single-sphere method.

Use the following method, developed by Reference [10]:

In a workplace field, a detector card with 4 TLDs (two with ^{6}Li and two with ^{7}Li) is inserted in the centre of a moderator sphere, 30 cm in diameter and made of high-density polyethylene, and two TLD albedo dosemeters are fixed on diametrically opposite sides on the sphere. The sphere serves as a moderator for the TLD card in the centre of the sphere and as a phantom for the albedo dosemeters on the surface. The central detectors provide a value for the neutron ambient dose equivalent H_{n}*(10) by applying a calibration factor $N_{\mathrm{n,c}}$ determined in neutron reference fields (e.g., ^{252}Cf, ^{252}Cf(D$_2$O mod), ^{241}Am-Be) to the neutron reading $H_{\mathrm{n,c}}$. Calibration measurements in these fields have shown that $N_{n,c}$ is varying only by ±20% (k = 2) and this method can be used therefore for determining a reference value for H*(10).

The neutron ambient dose equivalent H_{n}*(10) obtained from the central TL detectors, divided by the sum of the neutron albedo readings of the two albedo dosemeters, $H_{\mathrm{n,A,1}}$ and $H_{\mathrm{n,A,2}}$, yields the field-specific correction factor $k_{\mathrm{n},E,\Omega}$. The albedo dosemeter on the front of the sphere (A.1), is aligned with the main dose direction. In workplace fields, where the main dose direction is not known, albedo dosemeters can be fixed on four sides of the sphere and the dosemeter with the maximum neutron reading can be used as front dosimeter. The neutron reading of the dosemeter in front multiplied by $k_{\mathrm{n},E,\Omega}$ gives an indication of the personal dose equivalent $H_{\mathrm{p}}(10)$ of neutrons in the workplace field:

$$k_{\mathrm{n},E,\Omega} = H_{\mathrm{n}}^*(10)/(H_{\mathrm{n,A,1}} + H_{\mathrm{n,A,2}}) \quad \text{(B.9)}$$

$$H_{\mathrm{p}}(10) = H_{\mathrm{n,A,1}} \cdot H_{\mathrm{n}}^*(10)/(H_{\mathrm{n,A,1}} + H_{\mathrm{n,A,2}}) \quad \text{(B.10)}$$

In directed radiation fields, where the neutrons are strongly directed towards the front dosemeter, the personal dose equivalent $H_{\mathrm{p}}(10)$ is similar to the neutron ambient dose equivalent H*(10) within a few percent and no reading is expected for the dosemeter at the back (A.2). In this case, the personal dose equivalent is obtained with a good accuracy.

In isotropic neutron radiation fields, $H_{\mathrm{p}}(10)$ is up to a factor four smaller than H*(10) or the quantity $H_{\mathrm{p}}(10; 0°)$ for the corresponding directed and aligned field. The ratio H_{p}(10; isotropic) / $H_{\mathrm{p}}(10; 0°)$ has been calculated by Hollnagel[15]. It depends on the neutron energy and typical values are 0,22 to 0,24 (thermal to 100 keV), 0,24 to 0,32 (100 keV to 1 MeV), and 0,32 to 0,57 (1 MeV to 5 MeV). The neutron readings $H_{\mathrm{n,A,1}}$ and $H_{\mathrm{n,A,2}}$ of the two dosemeters mounted onto the front and the back of the reference sphere are equal in isotropic radiation fields. The field-specific correction factor $k_{\mathrm{n},E,\Omega}$ is then determined by relating one albedo dosemeter reading to a value of H*(10)/2. H*(10)/2 is a conservative estimate of H_{p}(10; isotropic) for workplace fields with neutrons having energies lower than a few MeV and the overestimate can reach a factor of two (see values of H_{p}(10; isotropic) / $H_{\mathrm{p}}(10; 0°)$ as given for neutrons with energies between thermal and 100 keV in Reference [15]).

NOTE 2 Since most practical fields are a combination of a directed and an isotropic part it can be anticipated that overestimates of $H_{\mathrm{p}}(10)$, which are expected in isotropic fields, are further reduced in the workplace field and over- and under-estimates are much lower in workplace fields with broad energy distributions. In workplaces of the nuclear industry and at radionuclide sources, the contribution of thermal neutrons is usually less than 15 %[16]. Thus, an overestimate of $H_{\mathrm{p}}(10)$ by a factor of 2 is not expected in workplace fields.

It is highly recommended to place at least 2 dosemeters (preferably 3) on each position in this method, in order to avoid the risk of any outlier measurements that could occur. Moreover, if several dosemeters are used, the average measurement could be used, enhancing the statistical quality of the value. If it is not possible for practical reasons to put at least 2 dosemeters (preferably 3) on each position, then it could be possible to repeat the experiment twice.

NOTE 3 The single-sphere method was even used successfully in the high-energy neutron field of CERF (Cern-EU high-energy Reference Field), because the scattered field has a considerable amount of neutron dose in the region of 100 keV to 1 MeV (roughly 50 %). These neutrons provide the readings of albedo dosemeters, which are generally not sensitive to neutrons with energies higher than 5 MeV[17].

The method is also applicable to pulsed radiation fields because of the use of passive integrating TL detectors. It also can be used at workplaces with a low neutron dose rate because the sphere can be placed for a time period of several weeks.

B.2 Direct $H_p(10)$ reference measurements

The dosemeter used for the direct $H_p(10)$ reference measurements shall fulfil the criteria defined in ISO 21909-1. The specification of the chosen instrument shall be adapted to the need (energy range of use and uncertainties).

The measurements shall be performed on a phantom at the same position used for the dosimetry system to be qualified.

When measurements are performed with passive individual dosemeters for the assessment of the reference value of $H_p(10)$, they should be performed at values of the personal dose equivalent higher than 0,5 mSv.

NOTE 1 A higher value is indispensable to obtain a smaller uncertainty on the value.

When possible, it is recommended to use the method in B.1 as a more accurate method.

NOTE 2 In the main part of the document, criteria are given to ensure an appropriate correction for specific workplaces, with some tests performed at three levels of dose equivalent. In this sub clause, the target is different: to estimate the reference value for $H_p(10)$ using a reference dosemeter, different from the one to qualify at the workplace. Thus, it is suggested to determine the reference value with such a dosemeter at a personal dose equivalent higher than 0,5 mSv, to limit the uncertainty of the reference. The duration of the dose integration enables to estimate the personal dose-equivalent rate and then, it is possible to define each reference dose equivalent for all the measurements done by the dosimetry system that is qualified in accordance with this document.

Annex C
(informative)

Example of a complete characterization of the workplace field

The combination of the use of a spectrometer and a directional spectrometer in order to have the neutron energy distribution in function of the considered direction is the most complete characterization that can be performed. Such measurements are very complex and may not be adapted to routine constraints. Moreover, no directional spectrometer is commercially available.

Such a method was used within the EVIDOS project [4][5]. In this project, measurements with spectrometers (energy and direction) were performed at several workplaces of the nuclear industry in Europe in order to derive reference values for the ambient dose equivalent $H^*(10)$ and personal dose equivalent $H_p(10)$ and to compare them to readings of dosemeters (personal dosemeters and ambient dose equivalent meters) for neutrons.

For the determination of the reference values $H^*(10)$, a well-characterised Bonner sphere spectrometer and, for the determination of $H_p(10)$, a newly developed directional spectrometer which consisted of 24 silicon detectors mounted in six capsules on the surface of a polyethylene sphere, were used. The response of the directional spectrometer had been determined with respect to neutron energy and direction in the neutron reference fields available at the German standard laboratory PTB (Physikalisch-Technische Bundesanstalt) and had been calculated by MCNP in the intermediate energy region, where measurements were not feasible[4]. Unfolding of the measured pulse height spectra was performed using the MAXED unfolding code and prior information on the energy distribution was obtained with the Bonner sphere spectrometer.

The ratios $H_p(10)/H^*(10)$ as derived from these distributions are given in Table C.1 in order to illustrate the possible range of ratios that can be potentially found at the workplace. They are calculated for six directions: the FRONT direction was in most cases the direction with the highest contribution to the dose equivalent. The other directions were the opposite direction (named BACK), the side directions (LEFT and RIGHT), and TOP and BOTTOM which correspond to upwards and downwards directions. Please note that at the position below the control rods (BWR SAR) of the Krümmel reactor and at the Venus research reactor, the highest value for the ratio $H_p(10)/H^*(10)$ is determined for TOP. Almost similar values for different directions are an indication of an isotropic field, and large differences for a more directed field.

Table C.1 — Ratios $H_p(10)/H^*(10)$ as determined in the workplaces investigated in the EVIDOS project for different directions (numerical values of Figure 10 of [5])

	FRONT	TOP	BOTTOM	LEFT	RIGHT	BACK
CANEL	0,83	0,36	0,26	0,18	0,19	0,07
SIGMA	0,91	0,26	0,44	0,20	0,19	0,18
BWR SAR	0,22	0,37	0,30	0,20	0,23	0,16
BWR T	0,60	0,26	0,24	0,21	0,19	0,04
VENUS F	0,29	0,39	0,29	0,34	0,35	0,33
PWR L	0,47	0,28	0,21	0,23	0,24	0,08
PWR A	0,31	0,23	0,20	0,16	0,35	0,18
Cask NTL M	0,70	0,30	0,30	0,26	0,26	0,05
Cask NTL S	0,52	0,29	0,33	0,16	0,41	0,14
Cask TN N	0,61	0,25	0,21	0,15	0,18	0,06
Cask TN D	0,73	0,22	0,31	0,17	0,20	0,03