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Measurement of radioactivity in the environment — Air: radon-222 —

Part 3:
Spot measurement method of the potential alpha energy concentration of its short-lived decay products

Mesurage de la radioactivité dans l'environnement — Air: radon 222 —

Partie 3: Méthode de mesure ponctuelle de l'énergie alpha potentielle volumique de ses descendants à vie courte

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Contents

Foreword

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

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

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ISO 11665-3 was prepared by Technical Committee ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

ISO 11665 consists of the following parts, under the general title *Measurement of radioactivity in the environment — Air: radon-222*:

— *Part 1: Origins of radon and its short-lived decay products and associated measurement methods*

— *Part 2: Integrated measurement method for determining average potential alpha energy concentration of its short-lived decay products*

— *Part 3: Spot measurement method of the potential alpha energy concentration of its short-lived decay products*

— *Part 4: Integrated measurement method for determining average activity concentration using passive sampling and delayed analysis*

— *Part 5: Continuous measurement method of the activity concentration*

— *Part 6: Spot measurement method of the activity concentration*

— *Part 7: Accumulation method for estimating surface exhalation rate*

— *Part 8: Methodologies for initial and additional investigations in buildings*

The following parts are under preparation:

— *Part 9: Method for determining exhalation rate of dense building materials*

— *Part 10: Determination of diffusion coefficient in waterproof materials using activity concentration measurement*

Introduction

Radon isotopes 222, 220 and 219 are radioactive gases produced by the disintegration of radium isotopes 226, 224 and 223, which are decay products of uranium-238, thorium-232 and uranium-235 respectively, and are all found in the earth's crust. Solid elements, also radioactive, followed by stable lead are produced by radon disintegration[1].

When disintegrating, radon emits alpha particles and generates solid decay products, which are also radioactive (polonium, bismuth, lead, etc.). The potential effects on human health of radon lie in its solid decay products rather than the gas itself. Whether or not they are attached to atmospheric aerosols, radon decay products can be inhaled and deposited in the bronchopulmonary tree to varying depths according to their size.

Radon is today considered to be the main source of human exposure to natural radiation. The UNSCEAR (2006) report[2] suggests that, at the worldwide level, radon accounts for around 52 % of global average exposure to natural radiation. The radiological impact of isotope 222 (48 %) is far more significant than isotope 220 (4 %), while isotope 219 is considered negligible. For this reason, references to radon in this part of ISO 11665 refer only to radon-222.

Radon activity concentration can vary by one to multiple orders of magnitude over time and space. Exposure to radon and its decay products varies tremendously from one area to another, as it depends firstly on the amount of radon emitted by the soil and the building materials in each area and, secondly, on the degree of containment and weather conditions in the areas where individuals are exposed.

Variations of a few nanojoules per cubic metre to several thousand nanojoules per cubic metre are observed in the potential alpha energy concentration of short-lived radon decay products.

The potential alpha energy concentration of short-lived radon-222 decay products in the atmosphere can be measured by spot and integrated measurement methods (see ISO 11665-1 and ISO 11665-2). This part of ISO 11665 deals with spot measurement methods. A spot measurement of the potential alpha energy concentration relates to the time when the measurement is taken and has no significance in annual exposure. This type of measurement does not therefore apply when assessing the annual exposure.

NOTE The origin of radon-222 and its short-lived decay products in the atmospheric environment and other measurement methods are described generally in ISO 11665-1.

Measurement of radioactivity in the environment — Air: radon-222 —

Part 3:
Spot measurement method of the potential alpha energy concentration of its short-lived decay products

1 Scope

This part of ISO 11665 describes spot measurement methods for determining the activity concentration of short-lived radon-222 decay products in the air and for calculating the potential alpha energy concentration.

This part of ISO 11665 gives indications for performing a spot measurement of the potential alpha energy concentration, after sampling at a given place for several minutes, and the conditions of use for the measuring devices.

This measurement method is applicable for a rapid assessment of the potential alpha energy concentration. The result obtained cannot be extrapolated to an annual estimate potential alpha energy concentration of short-lived radon-222 decay products. Thus, this type of measurement is not applicable for the assessment of annual exposure.

This measurement method is applicable to air samples with potential alpha energy concentration greater than 5 nJ/m^3.

NOTE This part of ISO 11665 does not address the potential contribution of radon-220 decay products.

2 Normative references

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

ISO 11665-1, *Measurement of radioactivity in the environment — Air: radon-222 — Part 1: Origins of radon and its short-lived decay products and associated measurement methods*

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

IEC 61577-1, *Radiation protection instrumentation — Radon and radon decay product measuring instruments — Part 1: General principles*

IEC 61577-3, *Radiation protection instrumentation — Radon and radon decay product measuring instruments — Part 3: Specific requirements for radon decay product measuring instruments*

3 Terms, definitions and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 11665-1 apply.

3.2 Symbols

For the purposes of this document, the symbols given in ISO 11665-1 and the following apply.

C_i	activity concentration of the nuclide i, in becquerels per cubic metre
$E_{\mathrm{AE},i}$	alpha particle energy produced by the disintegration of the nuclide i, in joules
$E_{\mathrm{AEt},i}$	total alpha particle energy potentially produced by the nuclide i, in joules
$E_{\mathrm{PAE},i}$	potential alpha energy of the nuclide i, in joules
$E_{\mathrm{PAEC},i}$	potential alpha energy concentration of the nuclide i, in joules per cubic metre
$E^{*}_{\mathrm{PAEC},i}$	decision threshold of the potential alpha energy concentration of the nuclide i, in joules per cubic metre
$E^{\#}_{\mathrm{PAEC},i}$	detection limit of the of the potential alpha energy concentration of the nuclide i, in joules per cubic metre
$E^{\triangleleft}_{\mathrm{PAEC},i}$	lower limit of the confidence interval of the potential alpha energy concentration of the nuclide i, in joules per cubic metre
$E^{\triangleright}_{\mathrm{PAEC},i}$	upper limit of the confidence interval of the potential alpha energy concentration of the nuclide i, in joules per cubic metre
I_j	j^{th} number of gross counts obtained between times t_j and $t_{\mathrm{c}j}$
$I_{0,j}$	j^{th} number of background counts obtained between times t_j and $t_{\mathrm{c}j}$
$k_{i,j}$	coefficient related to the j^{th} number of gross count for radon decay product i, depending on the decay constants of the radon decay products, the sampling duration, t_{s}, and the times t_j and $t_{\mathrm{c}j}$, per square second
N_i	number of atoms of the nuclide i
n	counting number depending on the gross alpha counting protocol used
Q	sampling flow-rate, in cubic metres per second
$t_{\mathrm{c}j}$	end time of counting j, in seconds
t_j	start time of counting j, in seconds
t_{s}	sampling duration, in seconds
U	expanded uncertainty calculated by $U = k \cdot u(\ )$ with $k = 2$
$u(\ )$	standard uncertainty associated with the measurement result
$u_{\mathrm{rel}}(\ )$	relative standard uncertainty
V	sampled volume, in cubic metres
ε_{c}	counting efficiency, in pulses per disintegration
λ_i	decay constant of the nuclide i, per second

4 Principle of the measurement method

Spot measurement of the potential alpha energy concentration of short-lived radon-222 decay products is based on the following elements:

a) grab sampling, at time t, of short-lived radon decay products contained in a volume of air representative of the atmosphere under investigation, using a high-efficiency filtering membrane;

b) repeated gross alpha measurements of the collected decay products using a detector sensitive to alpha particles; the counting stage starts after sampling has stopped;

c) calculation of the activity concentrations of the radon decay products using the laws of radioactive decay and the counting results from a preset duration, repeated at given times.

The gross alpha measurement method quantifies alpha particles emitted by short-lived radon decay products. The ^{222}Rn decay product chain shows that 99,98 % of the decays of ^{218}Po result in the emission of alpha particles. It can, therefore, be considered as a pure alpha emitter. ^{214}Pb and ^{214}Bi are not alpha emitters, but they contribute to the appearance of alpha particles from the decay of ^{214}Po.

After collecting the air sample, the gross alpha activity is measured for various counting durations. Because of the fast decay of radon decay products, the isotopic composition of a sample rapidly changes during collection as well as during the counting durations. Repeated measurements of the gross alpha activity are necessary in order to describe the decay of the sample and thereby calculate the amounts of the various decay products which were originally collected in the air sample.

NOTE Although ^{222}Rn and its decay products are usually found in higher quantity, environmental air samples can also contain significant activity of radonuclides of the ^{220}Rn decay chain as well as other airborne long-lived radionuclides. In such cases, the formulas and procedures given in this part of ISO 11665 need to be adapted to take into account these additional radionuclides.

5 Equipment

The apparatus shall include a sampling system and a detection system composed of a detector connected to a counting system (see Figure 1). The measuring devices used shall comply with IEC 61577-1 and IEC 61577-3.

The sampling system shall include the following components:

a) an open filter holder allowing fast and easy removal of the filter after sampling;

b) a pump;

c) a high-efficiency particulate air filter (HEPA filter with a minimum efficiency of 99,97 % for a particle size of 0,3 µm);

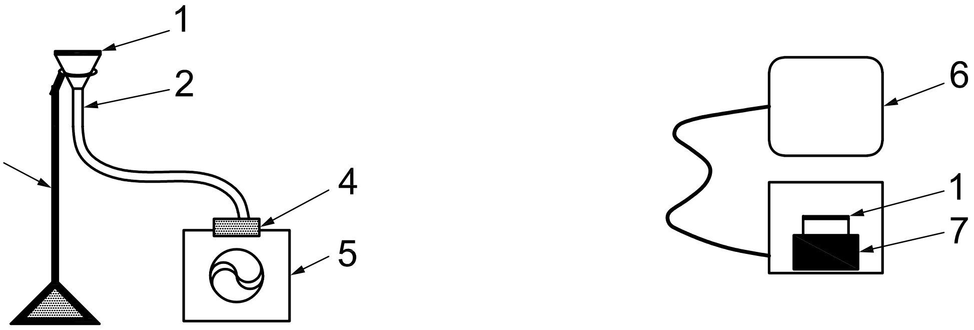
d) a flow-meter and a chronometer;

Possible detectors include the following:

— a photomultiplier associated with a sensitive scintillation surface [ZnS(Ag), for example];

— a silicon semi-conductor that is sensitive to alpha particles.

The detector, connected to a pulse counting system, shall have a sensitive detection surface at least equal in diameter to the filtering membrane.



a) Sampling system **b) Detection system**

Key

1 filtering membrane
2 filter holder
3 support
4 flow-meter and chronometer
5 pump
6 counting system
7 detector

Figure 1 — Functional diagram of a spot measuring system for potential alpha energy concentration of short-lived radon decay products

6 Sampling

6.1 General

Grab sampling is representative of the potential alpha energy concentration of short-lived radon-222 decay products at a given time and a given place.

6.2 Sampling objective

The sampling objective is to collect, without interruption, all the aerosols, regardless of their size (unattached and attached fractions), carrying short lived radon decay products and contained in the ambient air during a given sampling duration (less than one hour).

6.3 Sampling characteristics

The unattached and attached fractions of short-lived radon decay products shall be sampled without interruption from the atmosphere under investigation by pumping and filtering a known volume of air through a high-efficiency collection membrane located in an open filter holder. The air sampling shall be omni-directional.

In order to count the emitted alpha particles correctly, the sampling system shall conduct to the surface deposit of the radionuclides on the filter and shall prevent the aerosols from being buried.

The sampling system shall be used in conditions that preclude clogging of the filtering membrane, which would cause self-absorption of the alpha emissions of particles collected on the filter or a reduction in the sampling flow-rate over time.

6.4 Sampling conditions

6.4.1 General

Sampling shall be carried out as specified in ISO 11665-1. The sampling location, date and time shall be recorded.

6.4.2 Installation of sampling system

Installation of the sampling system shall be carried out as specified in ISO 11665-1.

6.4.3 Sampling duration

Given the short half-lives of the radon-222 decay products, particularly ^{218}Po, the sampling duration should normally be less than or equal to 20 min. A longer sampling duration would not improve the detection limit of the method.

6.4.4 Volume of air sampled

The volume of air sampled shall be ascertained by continuous measurement of the flow-rate during sampling with a calibrated system (for example, a sonic nozzle) (see IEC 61577-3).

7 Detection method

Detection shall be performed using silver-activated zinc sulphide ZnS(Ag) scintillation or a semi-conductor (alpha detection), as described in ISO 11665-1.

8 Measurement

8.1 Procedure

Measurement shall be carried out as follows.

a) Select the sampling duration, t_s.

b) Plan the counting stage, with n countings, and choose start time t_j and end time $t_{\mathrm{c}j}$ for each number of counts I_j. The different sets are organized from $j = 1$ to $j = n$. Before a set of counting, a specific waiting time can be required.

   NOTE Examples of gross alpha counting protocols are given in Annex A.

c) Install the detection system (detector and pulse counting system).

d) Determine the background level of the filtering membrane. Before carrying out sampling, position the virgin membrane opposite the detector, in accordance with manufacturer recommendations. Measure the virgin membrane by means of n successive gross alpha countings during specific counting durations $t_{\mathrm{c}j} - t_j$ according to the counting stage selected:

   1) $t = 0$ to $t = t_1$ standby, there is no count if $t_1 > 0$;

   2) $t = t_1$ to $t = t_{\mathrm{c}1}$ count $I_{0,1}$ is performed;

   3) $t = t_{\mathrm{c}j-1}$ to $t = t_j$ standby, there is no count if $t_j > t_{\mathrm{c}j-1}$;

   4) $t = t_j$ to $t = t_{\mathrm{c}j}$ count $I_{0,j}$ is performed.

   If $n > 1$, repeat stages 3) and 4) until $j = n$.

e) Record values of $I_{0,j}$ for $j = 1$ to $j = n$.

f) Select and locate the measuring point.

g) Install the sampling system.

h) Using grab sampling, obtain an air sample representative of the atmosphere under investigation during the sampling duration t_S.

i) Record the location and the time (date, hour and minutes) of sampling.

j) Once sampling is completed, remove the filtering membrane from the sampling system and position it opposite the detector, in accordance with manufacturer recommendations. Given the short half-lives of the radon-222 decay products, the alpha particles shall be detected on the sampling site within a few minutes of sampling.

k) Perform n successive gross alpha countings of the membrane with specific counting durations $t_{\mathrm{c}j} - t_j$ according to the counting stage selected:

   1) $t = 0$ to $t = t_1$ standby, there is no count if $t_1 > 0$;

   2) $t = t_1$ to $t = t_{\mathrm{c}1}$ count I_1 is performed;

   3) $t = t_{\mathrm{c}j-1}$ to $t = t_j$ standby, there is no count if $t_j > t_{\mathrm{c}j-1}$;

   4) $t = t_j$ to $t = t_{\mathrm{c}j}$ count I_j is performed.

   If $n > 1$, repeat stages 3) and 4) until $j = n$.

l) Record values of I_j for $j = 1$ to $j = n$.

m) Determine the potential alpha energy concentration by calculation.

8.2 Influence quantities

Various quantities can lead to measurement bias that could induce non-representative results. Depending on the measurement method and the control of usual influence quantities specified in IEC 61577-1 and ISO 11665-1, the following quantities shall be considered in particular:

a) influence of atmospheric pressure on the sampling process;

b) influence of the filtering membrane storage conditions before sampling starts; the storage conditions shall be so designed to avoid contamination of the filtering membrane with radon decay products;

c) detector surface contamination; the surface contamination of the detector shall be controlled before performing the measurement;

d) potential presence of other alpha emitters (radium, radon isotopes, etc.) on the filtering membrane or in the ambient air.

Manufacturer recommendations in the operating instructions for the measuring devices shall be followed.

8.3 Calibration

The entire measuring device (sampling system and detection system, i.e. detector and related electronics) shall be calibrated as specified in ISO 11665-1.

The relationship between the variable measured by the detection system and the potential alpha energy concentration of the radon decay products in the air shall be established by using reference radioactive sources or another standard (a reference atmosphere, for example) recognized through international inter-comparison programmes.

9 Expression of results

9.1 General

Calculation of the potential alpha energy concentration of short-lived radon-222 decay products is based on the activity concentration of each short-lived decay product as well as the total potential alpha energy concentration.

Calculation of the activity concentration of ^{218}Po, ^{214}Pb and ^{214}Bi is based on several gross alpha counts I_j, the detector background level $I_{0,j}$, the counting efficiency, the flow-rate and the sampling duration. The following hypotheses shall be applied:

a) the short-lived radon decay products are the only alpha-emitting nuclides present in the air being analysed;

b) their respective activity concentration does not change during sampling;

c) the counting efficiency is the same for each decay product.

The activity concentration of each decay product is calculated using equations that express the number of atoms of each decay product present on the filter at the end of the sampling process based on the gross alpha counts obtained over the different time intervals (see Annex B).

9.2 Potential alpha energy concentration

The potential alpha energy concentration of short-lived radon-222 decay products shall be calculated as given by Formula (1):

$$E_{\mathrm{PAEC,222}_{\mathrm{Rn}}} = \sum_i \frac{E_{\mathrm{PAE},i}}{V} = \sum_i \left(\frac{E_{\mathrm{AEt},i} \cdot N_i}{V_i} \right) = \sum_i \left(\frac{E_{\mathrm{AEt},i} \cdot C_i}{\lambda_i} \right) \tag{1}$$

$$E_{\mathrm{PAEC,222}_{\mathrm{Rn}}} = \omega \cdot \sum_j \sum_i \frac{E_{\mathrm{AEt},i} \cdot k_{i,j}}{\lambda_i} \cdot \left(I_j - I_{0,j} \right) \tag{2}$$

where

$$C_i = \frac{1}{\varepsilon_{\mathrm{c}} \cdot Q} \cdot \sum_j k_{i,j} \cdot \left(I_j - I_{0,j} \right) = \omega \cdot \sum_j k_{i,j} \cdot \left(I_j - I_{0,j} \right) \tag{3}$$

$$\omega = \frac{1}{\varepsilon_{\mathrm{c}} \cdot Q} \tag{4}$$

A method of calculation of $k_{i,j}$ is detailed in Annex B.

NOTE For ^{218}Po, $E_{\mathrm{AEt},i} = E_{\mathrm{AE,218}_{\mathrm{Po}}} + E_{\mathrm{AE,214}_{\mathrm{Po}}}$. For ^{214}Pb, ^{214}Bi and ^{214}Po, $E_{\mathrm{AEt},i} = E_{\mathrm{AE,214}_{\mathrm{Po}}}$.

9.3 Standard uncertainty

The uncertainties of the sampling flow-rate, the counting efficiency and the number of counts (including the background level) shall be taken into account.

The uncertainties of decay constants, sampling duration and counting durations are considered negligible. The uncertainty of $k_{i,j}$ is therefore considered negligible.

By hypothesis:

a) the variables are all independent;

b) the numbers of counts $I_{0,j}$ and I_j are normal variables according to Poisson’s law.

Under these conditions, the uncertainties of numbers of counts $I_{0,j}$ and I_j are expressed as follows:

$$u^2\left(I_{0,j}\right) = I_{0,j} \text{ and } u^2\left(I_j\right) = I_j \tag{5}$$

I_j depends on the activity of each decay product as well as on the time elapsed since the end of the sampling process. The counting uncertainty estimated from the variance of I_j therefore includes uncertainties associated with the variables on which I_j depends.

In accordance with ISO/IEC Guide 98-3, the standard uncertainty of $E_{\mathrm{PAEC},222_{\mathrm{Rn}}}$ shall be calculated as given by Formula (6):

$$u(E_{\mathrm{PAEC},222_{\mathrm{Rn}}}) = \sqrt{\omega^2 \cdot \sum_j \left[\left(K_{i,j}\right)\cdot\left(I_j + I_{0,j}\right)\right] + \left(E_{\mathrm{PAEC},222_{\mathrm{Rn}}}\right)^2 \cdot u_{\mathrm{rel}}^2(\omega)} \tag{6}$$

where

$$u_{\mathrm{rel}}^2(\omega) = u_{\mathrm{rel}}^2(\varepsilon_{\mathrm{c}}) + u_{\mathrm{rel}}^2(Q) \tag{7}$$

$$K_{i,j} = \left[\sum_i \left(\frac{E_{\mathrm{AEt},i} \cdot k_{i,j}}{\lambda_i}\right)\right]^2 \tag{8}$$

Calculation of the characteristic limits (see ISO 11929) requires calculation of $\tilde{u}\left(\tilde{E}_{\mathrm{PAEC},222_{\mathrm{Rn}}}\right)$, i.e. the standard uncertainty of $E_{\mathrm{PAEC},222_{\mathrm{Rn}}}$ as a function of its true value, calculated as given in Formula (9).

$$\tilde{u}\left(\tilde{E}_{\mathrm{PAEC},222_{\mathrm{Rn}}}\right) = \sqrt{\omega^2 \cdot \sum_j \left[\left(K_{i,j}\right)\cdot\left(\tilde{I}_j + I_{0,j}\right)\right] + \left(\tilde{E}_{\mathrm{PAEC},222_{\mathrm{Rn}}}\right)^2 \cdot u_{\mathrm{rel}}^2(\omega)} \tag{9}$$

9.4 Decision threshold

The decision threshold, $E^*_{\mathrm{PAEC},222_{\mathrm{Rn}}}$, is obtained from Formula (9) for $\tilde{E}_{\mathrm{PAEC},222_{\mathrm{Rn}}} = 0$ (see ISO 11929), i.e. each $\tilde{\mathrm{C}}_i = 0$ and $\tilde{I}_j = I_{0,j}$. This yields Formula (10):

$$E^*_{\mathrm{PAEC},222_{\mathrm{Rn}}} = k_{1-\alpha} \cdot \tilde{u}(0) = k_{1-\alpha} \cdot \omega \cdot \sqrt{2 \cdot \sum_j \left[\left(K_{i,j}\right) \cdot I_{0,j}\right]} \tag{10}$$

$\alpha = 0{,}05$ with $k_{1-\alpha} = 1{,}65$ is often chosen by default.

9.5 Detection limit

The detection limit, $E^{\#}_{\mathrm{PAEC},222_{\mathrm{Rn}}}$, is calculated as given in Formula (11) (see ISO 11929):

$$E^{\#}_{\mathrm{PAEC},222_{\mathrm{Rn}}} = a + \sqrt{a^2 + \left(k_{1-\beta}^2 - k_{1-\alpha}^2\right)\cdot \tilde{u}^2\left(\tilde{E}_{\mathrm{PAEC}} = 0\right)} = a + \sqrt{a^2 + \left(k_{1-\beta}^2 - k_{1-\alpha}^2\right)\cdot \tilde{u}^2(0)} \tag{11}$$

with

$$a = k_{1-\alpha} \cdot \tilde{u}(0) + \frac{1}{2} \cdot \left(\frac{k_{1-\beta}^2}{E_{\mathrm{PAEC}}}\right) \cdot \left[u^2\left(E_{\mathrm{PAEC}}\right) - \tilde{u}^2(0)\right] \tag{12}$$

If $\alpha = \beta$, then it follows that $E^{\#}_{\mathrm{PAEC}} = 2 \cdot a$.

$\alpha = \beta = 0{,}05$ with $k_{1-\alpha} = k_{1-\beta} = 1{,}65$ is often chosen by default.

9.6 Limits of the confidence interval

The lower, $E^{\triangleleft}_{\text{PAEC},222_{\text{Rn}}}$, and upper, $E^{\triangleright}_{\text{PAEC},222_{\text{Rn}}}$, limits of the confidence interval shall be calculated using Formulae (13) and (14) (see ISO 11929):

$$E^{\triangleleft}_{\text{PAEC},222_{\text{Rn}}} = E_{\text{PAEC},222_{\text{Rn}}} - k_p \cdot u\left(E_{\text{PAEC},222_{\text{Rn}}}\right); \quad p = \omega \cdot \left(1-\gamma/2\right) \tag{13}$$

$$E^{\triangleright}_{\text{PAEC},222_{\text{Rn}}} = E_{\text{PAEC},222_{\text{Rn}}} - k_q \cdot u\left(E_{\text{PAEC},222_{\text{Rn}}}\right); \quad q = 1-\omega \cdot \gamma/2 \tag{14}$$

where

$\omega = \Phi\,[y/u(y)]$, Φ being the distribution function of the standardized normal distribution;

$\omega = 1$ may be set if $E_{\text{PAEC},222_{\text{Rn}}} \geq 4 \cdot u\left(E_{\text{PAEC},222_{\text{Rn}}}\right)$, in which case:

$$E^{\triangleleft\triangleright}_{\text{PAEC},222_{\text{Rn}}} = E_{\text{PAEC},222_{\text{Rn}}} \pm k_{1-\gamma/2} \cdot u\left(E_{\text{PAEC},222_{\text{Rn}}}\right) \tag{15}$$

$\gamma = 0{,}05$ with $k_{1-\gamma/2} = 1{,}96$ are often chosen by default.

10 Test report

10.1 The test report shall be in accordance with the requirements of ISO/IEC 17025 and shall contain the following information:

a) reference to this part of ISO 11665, i.e. ISO 11665-3:2012;

b) measurement method (spot);

c) identification of the sample;

d) sampling characteristic (active);

e) start time of sampling (date, hour and minutes);

f) end time of sampling (date, hour and minutes);

g) duration of sampling;

h) sampling location;

i) units in which the results are expressed;

j) test result, $E_{\text{PAEC},222_{\text{Rn}}} \pm u\left(E_{\text{PAEC},222_{\text{Rn}}}\right)$ or $E_{\text{PAEC},222_{\text{Rn}}} \pm U$, with the associated k value.

10.2 Complementary information may be provided, such as the following:

a) purpose of the measurement;

b) probabilities α, β and (1-γ);

c) the decision threshold and the detection limit; depending on the customer request, there are different ways to present the result:

    1) when the potential alpha energy concentration of the short-lived radon-222 decay products is compared with the decision threshold (see ISO 11929), the result of the measurement shall be expressed as ≤ $E^{*}_{\text{PAEC},222_{\text{Rn}}}$ if the result is below the decision threshold;

   2) when the potential alpha energy concentration of the short-lived radon-222 decay products is compared with the detection limit, the result of the measurement shall be expressed as $\leq E^{\#}_{\mathrm{PAEC},222_{\mathrm{Rn}}}$ if the result is below the detection limit or, if the detection limit exceeds the guideline value, it shall be documented that the method is not suitable for the measurement purpose;

d) any relevant information likely to affect the results:

   1) weather conditions at the time of sampling;

   2) ventilation conditions for indoor measurement (mechanical ventilation system, doors and windows open or shut, etc.).

10.3 The results can be expressed in a similar format to that shown in 11665-1:2012, Annex C.

Annex A
(informative)

Examples of gross alpha counting protocols

There are several gross alpha counting protocols associated with spot measurement methods for the potential alpha energy concentration of short-lived radon-222 decay products described in this part of ISO 11665.

Some of them, that are suitable for the purposes of this part of ISO 11665, are listed in Table A.1.

Table A.1 — Examples of gross alpha counting protocols

Method	Duration of the different phases s						
	Sampling	Standby	1st count	Standby	2nd count	Standby	3rd count
Thomas[4]	300	120	180	60	840	60	540
Thomas[4] + Hartley[5][6]	Variable						
Markov[7]	300	60	180	180	180		
Nazaroff[8]	300	60	600	600	1 140		
Miller[9][10]	120	30	120				
Kusnetz[11]	300 to 600	2 400 to 5 400					
Rolle[12]	120	480	120				

Annex B
(informative)

Calculation of the coefficients $k_{^{218}\text{Po},j}$, $k_{^{214}\text{Pb},j}$ and $k_{^{214}\text{Bi},j}$

B.1 General

This annex deals with the method of determination for the coefficients $k_{^{218}\text{Po},j}$, $k_{^{214}\text{Pb},j}$ and $k_{^{214}\text{Bi},j}$.

NOTE For definitions of the symbols used in this annex, see Clause 3.

B.2 Determination method

B.2.1 Determination of the number of alpha disintegrations

After sampling is completed, the expected number of alpha disintegrations, n_α, during the time interval $t_{\text{c}j} - t_j$ is given by Formula (B.1):

$$\begin{aligned} n_\alpha = & \left[N_{^{218}\text{Po}} + \frac{\lambda_{^{214}\text{Pb}} \cdot \lambda_{^{214}\text{Bi}} \cdot N_{^{218}\text{Po}}}{\left(\lambda_{^{214}\text{Bi}} - \lambda_{^{218}\text{Po}}\right) \cdot \left(\lambda_{^{214}\text{Pb}} - \lambda_{^{218}\text{Po}}\right)} \right] \cdot \left(\text{e}^{-\lambda_{^{218}\text{Po}} \cdot t_j} - \text{e}^{-\lambda_{^{218}\text{Po}} \cdot t_{\text{c}j}} \right) \\ & + \left[\frac{\lambda_{^{218}\text{Po}} \cdot \lambda_{^{214}\text{Bi}} \cdot N_{^{218}\text{Po}}}{\left(\lambda_{^{218}\text{Po}} - \lambda_{^{214}\text{Pb}}\right) \cdot \left(\lambda_{^{214}\text{Bi}} - \lambda_{^{214}\text{Pb}}\right)} + \frac{\lambda_{^{214}\text{Bi}} \cdot N_{^{214}\text{Pb}}}{\lambda_{^{214}\text{Bi}} - \lambda_{^{214}\text{Pb}}} \right] \cdot \left(\text{e}^{-\lambda_{^{214}\text{Pb}} \cdot t_j} - \text{e}^{-\lambda_{^{214}\text{Pb}} \cdot t_{\text{c}j}} \right) \\ & + \left[\frac{\lambda_{^{218}\text{Po}} \cdot \lambda_{^{214}\text{Pb}} \cdot N_{^{218}\text{Po}}}{\left(\lambda_{^{218}\text{Po}} - \lambda_{^{214}\text{Bi}}\right) \cdot \left(\lambda_{^{214}\text{Pb}} - \lambda_{^{214}\text{Bi}}\right)} + \frac{\lambda_{^{214}\text{Pb}} \cdot N_{^{214}\text{Pb}}}{\lambda_{^{214}\text{Pb}} - \lambda_{^{214}\text{Bi}}} + N_{^{214}\text{Bi}} \right] \cdot \left(\text{e}^{-\lambda_{^{214}\text{Bi}} \cdot t_j} - \text{e}^{-\lambda_{^{214}\text{Bi}} \cdot t_{\text{c}j}} \right) \end{aligned} \qquad \text{(B.1)}$$

where $N_{^{218}\text{Po}}$, $N_{^{214}\text{Pb}}$ et $N_{^{214}\text{Bi}}$ are the number of atoms for ^{218}Po, ^{214}Pb and ^{214}Bi, collected on the membrane filter at the end of sampling.

To determine this number of alpha disintegrations, counting has to be performed once between t_j and $t_{\text{c}j}$.

The number of countings that it is necessary to perform depends on the gross alpha counting protocol used (see Annex A). From these counting results, $I_j - I_{0,j}$, the number of atoms of each radon decay product collected on the filter at the end of sampling ($N_{^{218}\text{Po}}$, $N_{^{214}\text{Pb}}$ and $N_{^{214}\text{Bi}}$) can be deduced.

B.2.2 Determination of the activity concentration of each radon decay product

The activity concentration of each radon decay product is obtained from Formula (3) (see 9.2). This yields Formulae (B.2), (B.3) and (B.4):

$$C_{^{218}\text{Po}} = \frac{1}{\varepsilon_\text{c} \cdot Q} \cdot \sum_{j=1}^{n} k_{^{218}\text{Po},j} \cdot (I_j - I_{0,j}) \qquad \text{(B.2)}$$

$$C_{^{214}\text{Pb}} = \frac{1}{\varepsilon_\text{c} \cdot Q} \cdot \sum_{j=1}^{n} k_{^{214}\text{Pb},j} \cdot (I_j - I_{0,j}) \qquad \text{(B.3)}$$

$$C_{^{214}\mathrm{Bi}} = \frac{1}{\varepsilon_\mathrm{c} \cdot Q} \cdot \sum_{j=1}^{n} k_{^{214}\mathrm{Bi},j} \cdot (I_j - I_{0,j}) \tag{B.4}$$

The activity concentration of each radon decay product is also calculated, for a sampling duration t_s, as given by Formulae (B.5), (B.6) and (B.7):

$$C_{^{218}\mathrm{Po}} = \frac{\lambda^2_{^{218}\mathrm{Po}}}{1 - e^{-\lambda_{^{218}\mathrm{Po}} \cdot t_\mathrm{s}}} \cdot \frac{N_{^{218}\mathrm{Po}}}{Q} \tag{B.5}$$

$$\begin{aligned} C_{^{214}\mathrm{Pb}} = {} & \frac{\lambda^2_{^{214}\mathrm{Pb}}}{1 - \mathrm{e}^{-\lambda_{^{214}\mathrm{Pb}} \cdot t_\mathrm{s}}} \cdot \frac{N_{^{214}\mathrm{Pb}}}{Q} - \left(\frac{\lambda_{^{214}\mathrm{Pb}} \cdot \lambda_{^{218}\mathrm{Po}}}{1 - \mathrm{e}^{-\lambda_{^{218}\mathrm{Po}} \cdot t_\mathrm{s}}} \right) \\ & \cdot \left(1 + \frac{\lambda_{^{214}\mathrm{Pb}}}{\lambda_{^{214}\mathrm{Pb}} - \lambda_{^{218}\mathrm{Po}}} \cdot \frac{\mathrm{e}^{-\lambda_{^{214}\mathrm{Pb}} \cdot t_\mathrm{s}} - \mathrm{e}^{-\lambda_{^{218}\mathrm{Po}} \cdot t_\mathrm{s}}}{1 - \mathrm{e}^{-\lambda_{^{214}\mathrm{Pb}} \cdot t_\mathrm{s}}} \right) \cdot \frac{N_{^{218}\mathrm{Po}}}{Q} \end{aligned} \tag{B.6}$$

$$\begin{aligned} C_{^{214}\mathrm{Bi}} = {} & \frac{\lambda^2_{^{214}\mathrm{Bi}}}{1 - \mathrm{e}^{-\lambda_{^{214}\mathrm{Bi}} \cdot t_\mathrm{s}}} \cdot \frac{N_{^{214}\mathrm{Bi}}}{Q} - \left(\frac{\lambda_{^{214}\mathrm{Bi}} \cdot \lambda_{^{214}\mathrm{Pb}}}{1 - \mathrm{e}^{-\lambda_{^{214}\mathrm{Pb}} \cdot t_\mathrm{s}}} \right) \cdot \left(1 + \frac{\lambda_{^{214}\mathrm{Bi}}}{\lambda_{^{214}\mathrm{Bi}} - \lambda_{^{214}\mathrm{Pb}}} \cdot \frac{\mathrm{e}^{-\lambda_{^{214}\mathrm{Bi}} \cdot t_\mathrm{s}} - \mathrm{e}^{-\lambda_{^{214}\mathrm{Pb}} \cdot t_\mathrm{s}}}{1 - \mathrm{e}^{-\lambda_{^{214}\mathrm{Bi}} \cdot t_\mathrm{s}}} \right) \\ & \cdot \frac{N_{^{214}\mathrm{Pb}}}{Q} - \left[\frac{\lambda_{^{214}\mathrm{Bi}} \cdot \lambda_{^{214}\mathrm{Pb}} \cdot \lambda_{^{218}\mathrm{Po}}}{\left(\lambda_{^{218}\mathrm{Po}} - \lambda_{^{214}\mathrm{Pb}} \right) \cdot \left(1 - \mathrm{e}^{-\lambda_{^{218}\mathrm{Po}} \cdot t_\mathrm{s}} \right)} \right] \\ & \cdot \left[\begin{aligned} & \frac{\mathrm{e}^{-\lambda_{^{214}\mathrm{Pb}} \cdot t_\mathrm{s}} - \mathrm{e}^{-\lambda_{^{218}\mathrm{Po}} \cdot t_\mathrm{s}}}{1 - \mathrm{e}^{-\lambda_{^{214}\mathrm{Pb}} \cdot t_\mathrm{s}}} + \frac{\lambda_{^{214}\mathrm{Bi}}}{\lambda_{^{218}\mathrm{Po}} - \lambda_{^{214}\mathrm{Bi}}} \cdot \frac{\mathrm{e}^{-\lambda_{^{214}\mathrm{Bi}} \cdot t_\mathrm{s}} - \mathrm{e}^{-\lambda_{^{218}\mathrm{Po}} \cdot t_\mathrm{s}}}{1 - \mathrm{e}^{-\lambda_{^{214}\mathrm{Bi}} \cdot t_\mathrm{s}}} \\ & + \frac{\lambda_{^{214}\mathrm{Bi}}}{\lambda_{^{214}\mathrm{Bi}} - \lambda_{^{214}\mathrm{Pb}}} \cdot \frac{\mathrm{e}^{-\lambda_{^{214}\mathrm{Bi}} \cdot t_\mathrm{s}} - \mathrm{e}^{-\lambda_{^{214}\mathrm{Pb}} \cdot t_\mathrm{s}}}{1 - \mathrm{e}^{-\lambda_{^{214}\mathrm{Bi}} \cdot t_\mathrm{s}}} \cdot \left(1 + \frac{\mathrm{e}^{-\lambda_{^{214}\mathrm{Pb}} \cdot t_\mathrm{s}} - \mathrm{e}^{-\lambda_{^{218}\mathrm{Po}} \cdot t_\mathrm{s}}}{1 - \mathrm{e}^{-\lambda_{^{214}\mathrm{Pb}} \cdot t_\mathrm{s}}} \right) \end{aligned} \right] \cdot \frac{N_{^{218}\mathrm{Po}}}{Q} \end{aligned} \tag{B.7}$$

B.2.3 Determination of the coefficients $k_{^{218}\mathrm{Po},j}$, $k_{^{214}\mathrm{Pb},j}$ and $k_{^{214}\mathrm{Bi},j}$

Using Formulae (B.2) to (B.7), along with the determination of $N_{^{218}\mathrm{Po}}$, $N_{^{214}\mathrm{Pb}}$ and $N_{^{214}\mathrm{Bi}}$, the values of $k_{^{218}\mathrm{Po},j}$, $k_{^{214}\mathrm{Pb},j}$ and $k_{^{214}\mathrm{Bi},j}$ can be obtained for each measurement method.

B.3 Application to the Thomas protocol

B.3.1 Measurement procedure

For the Thomas protocol[4], the sampling takes place over exactly $t_\mathrm{s} = 300$ s, to the second.

After the sampling phase, the number of alpha disintegrations of the collected decay products is measured.

The steps are as follows:

a) Determine the background number of counts. Before performing the sampling, the virgin membrane is measured by means of three gross alpha countings with counting durations $t_{\mathrm{c}1} - t_1 = 180$ s, $t_{\mathrm{c}2} - t_2 = 840$ s, $t_{\mathrm{c}3} - t_3 = 540$ s. The non-contamination of the detector when fitted with a virgin membrane is checked by a counting of at least 1 min prior to each measurement.

b) Carry out sampling.

c) Position the filtering membrane opposite the detector after the sampling process has been halted.

d) Perform three gross alpha countings of the membrane with specific durations according to the Thomas protocol:

    1) $t = 0$ s to $t_1 = 120$ s standby, there is no count;

    2) $t_1 = 120$ s to $t_{c1} = 300$ s count I_1 is performed;

    3) $t_{c1} = 300$ s to $t_2 = 360$ s standby, there is no count;

    4) $t_2 = 360$ s to $t_{c2} = 1\,200$ s count I_2 is performed;

    5) $t_{c2} = 1\,200$ s to $t_3 = 1\,260$ s standby, there is no count;

    6) $t_3 = 1\,260$ s to $t_{c3} = 1\,800$ s count I_3 is performed.

B.3.2 Determination of the coefficients $k_{^{218}\mathrm{Po},j}$, $k_{^{214}\mathrm{Pb},j}$ and $k_{^{214}\mathrm{Bi},j}$

If the sampling duration is known, the activity concentration of each radon decay product can be obtained from Formulae (B.5), (B.6) and (B.7). This yields Formulae (B.8), (B.9) and (B.10):

$$C_{^{218}\mathrm{Po}} = 2{,}112\,91 \times 10^{-5} \cdot \frac{N_{^{218}\mathrm{Po}}}{Q} \tag{B.8}$$

$$C_{^{214}\mathrm{Pb}} = 1{,}531\,78 \times 10^{-6} \cdot \frac{N_{^{214}\mathrm{Pb}}}{Q} - 9{,}849\,24 \times 10^{-7} \cdot \frac{N_{^{218}\mathrm{Po}}}{Q} \tag{B.9}$$

$$C_{^{214}\mathrm{Bi}} = 2{,}131\,71 \times 10^{-6} \cdot \frac{N_{^{214}\mathrm{Bi}}}{Q} - 1{,}328\,16 \times 10^{-7} \cdot \frac{N_{^{214}\mathrm{Pb}}}{Q} + 2{,}327\,55 \times 10^{-8} \cdot \frac{N_{^{218}\mathrm{Po}}}{Q} \tag{B.10}$$

From all times (start and end counting times) selected in the counting protocol and using Formula (B.1), the counting results can be expressed as given by Formulae (B.11), (B.12) and (B.13):

$$I_1 - I_{0,1} = \varepsilon_\mathrm{c} \cdot \left(0{,}316\,57 \cdot N_{^{218}\mathrm{Po}} + 0{,}085\,3 \cdot N_{^{214}\mathrm{Pb}} + 0{,}093\,37 \cdot N_{^{214}\mathrm{Bi}}\right) \tag{B.11}$$

$$I_2 - I_{0,2} = \varepsilon_\mathrm{c} \cdot \left(0{,}324\,93 \cdot N_{^{218}\mathrm{Po}} + 0{,}108\,01 \cdot N_{^{214}\mathrm{Pb}} + 0{,}314\,93 \cdot N_{^{214}\mathrm{Bi}}\right) \tag{B.12}$$

$$I_3 - I_{0,3} = \varepsilon_\mathrm{c} \cdot \left(0{,}095\,77 \cdot N_{^{218}\mathrm{Po}} + 0{,}095\,65 \cdot N_{^{214}\mathrm{Pb}} + 0{,}129\,65 \cdot N_{^{214}\mathrm{Bi}}\right) \tag{B.13}$$

From these counting results, the number of atoms of the radon decay products collected on the filter at the end of sampling ($N_{^{218}\mathrm{Po}}$, $N_{^{214}\mathrm{Pb}}$ and $N_{^{214}\mathrm{Bi}}$) can be deduced using, for example, the Cramer's rule:

$$N_{^{218}\mathrm{Po}} = \frac{1}{\varepsilon_\mathrm{c}} \cdot \left[4{,}930\,77 \cdot \left(I_1 - I_{0,1}\right) - 2{,}393\,32 \cdot \left(I_2 - I_{0,2}\right) + 2{,}262\,79 \cdot \left(I_3 - I_{0,3}\right)\right] \tag{B.14}$$

$$N_{^{214}\mathrm{Pb}} = \frac{1}{\varepsilon_\mathrm{c}} \cdot \left[4{,}930\,77 \cdot \left(I_1 - I_{0,1}\right) - 2{,}393\,32 \cdot \left(I_2 - I_{0,2}\right) + 2{,}262\,79 \cdot \left(I_3 - I_{0,3}\right)\right] \tag{B.15}$$

$$N_{^{214}\mathrm{Bi}} = \frac{1}{\varepsilon_\mathrm{c}} \cdot \left[-6{,}342\,40 \cdot \left(I_1 - I_{0,1}\right) + 9{,}012\,25 \cdot \left(I_2 - I_{0,2}\right) - 9{,}611\,52 \cdot \left(I_3 - I_{0,3}\right)\right] \tag{B.16}$$

Using Formulae (B.8) and (B.14), the activity concentration of ^{218}Po is expressed as given in Formula (B.17):

$$C_{^{218}\mathrm{Po}} = \frac{1}{\varepsilon_\mathrm{c} \cdot Q} \cdot \left[1{,}041\,83 \times 10^{-4} \cdot \left(I_1 - I_{0,1} \right) - 5{,}056\,86 \times 10^{-5} \cdot \left(I_2 - I_{0,2} \right) + 4{,}781\,06 \times 10^{-5} \cdot \left(I_3 - I_{0,3} \right) \right] \tag{B.17}$$

Using Formulae (B.9) and (B.15), the activity concentration of ^{214}Pb is expressed as given in Formula (B.18):

$$C_{^{214}\mathrm{Pb}} = \frac{1}{\varepsilon_\mathrm{c} \cdot Q} \cdot \left[7{,}494\,63 \times 10^{-7} \cdot \left(I_1 - I_{0,1} \right) - 1{,}268\,38 \times 10^{-5} \cdot \left(I_2 - I_{0,2} \right) + 3{,}027\,16 \cdot 10^{-5} \cdot \left(I_3 - I_{0,3} \right) \right] \tag{B.18}$$

Using Formulae (B.10) and (B.16), the activity concentration of ^{214}Bi is expressed as given in Formula (B.19):

$$C_{^{214}\mathrm{Bi}} = \frac{1}{\varepsilon_\mathrm{c} \cdot Q} \cdot \left[-1{,}389\,15 \times 10^{-5} \cdot \left(I_1 - I_{0,1} \right) + 1{,}892\,73 \times 10^{-5} \cdot \left(I_2 - I_{0,2} \right) - 2{,}325\,43 \times 10^{-5} \cdot \left(I_3 - I_{0,3} \right) \right] \tag{B.19}$$

Using Formulae (B.17), (B.18) and (B.19) and Formulae (B.2), (B.3) and (B.4), the values of $k_{^{218}\mathrm{Po},j}$, $k_{^{214}\mathrm{Pb},j}$ and $k_{^{214}\mathrm{Bi},j}$ are deduced:

$$k_{^{218}\mathrm{Po},1} = 1{,}041\,83 \times 10^{-4}\ \mathrm{s}^{-2}$$

$$k_{^{218}\mathrm{Po},2} = -5{,}056\,86 \times 10^{-5}\ \mathrm{s}^{-2}$$

$$k_{^{218}\mathrm{Po},3} = 4{,}781\,06 \times 10^{-5}\ \mathrm{s}^{-2}$$

$$k_{^{214}\mathrm{Pb},1} = 7{,}494\,63 \times 10^{-7}\ \mathrm{s}^{-2}$$

$$k_{^{214}\mathrm{Pb},2} = -1{,}268\,38 \times 10^{-5}\ \mathrm{s}^{-2}$$

$$k_{^{214}\mathrm{Pb}3} = 3{,}027\,16 \times 10^{-5}\ \mathrm{s}^{-2}$$

$$k_{^{214}\mathrm{Bi},1} = -1{,}389\,15 \times 10^{-5}\ \mathrm{s}^{-2}$$

$$k_{^{214}\mathrm{Bi},2} = 1{,}892\,73 \times 10^{-5}\ \mathrm{s}^{-2}$$

$$k_{^{214}\mathrm{Bi},3} = -2{,}325\,43 \times 10^{-5}\ \mathrm{s}^{-2}$$

Annex C
(informative)

Measurement method using gross alpha counting according to the Thomas protocol

C.1 General

This annex deals with the gross alpha counting method according to the Thomas protocol[4], which is one of several methods meeting the requirements of this part of ISO 11665 (see Annex A and IEC 61577-1).

It is assumed that influence due to the presence of radon-220 decay products in the air sampled is negligible.

C.2 Equipment

The apparatus includes the following:

a) an open filter holder linked to a pump;

b) a filtering membrane: pore size 0,8 µm, diameter 4,5 cm;

c) a volume flow-meter;

d) a chronometer;

e) a photomultiplier associated with a sensitive scintillation surface [ZnS(Ag)].

C.3 Sampling

The sampling device is installed in an open area at 1,50 m above the ground.

Sampling takes place over a period of exactly 300 s, to the second.

Two samples are taken at the same location at two different times.

The measured flow-rate is $Q = 5 \times 10^{-4}$ m^3/s.

C.4 Measurement procedure

The measurement procedure is as described in B.2.1.

C.5 Expression of results

C.5.1 Potential alpha energy concentration

The potential alpha energy concentration of short-lived radon-222 decay products is calculated as given in Formula (C.1):

$$E_{\text{PAEC},222_{\text{Rn}}} = E_{\text{PAEC},218_{\text{Po}}} + E_{\text{PAEC},214_{\text{Pb}}} + E_{\text{PAEC},214_{\text{Bi}}} \tag{C.1}$$

where

$$E_{\text{PAEC},218_{\text{Po}}} = \frac{\left(E_{\text{AE},218_{\text{Po}}} + E_{\text{AE},214_{\text{Po}}}\right) \cdot C_{218_{\text{Po}}}}{\lambda_{218_{\text{Po}}}} \tag{C.2}$$

$$E_{\text{PAEC},214_{\text{Pb}}} = \frac{E_{\text{AE},214_{\text{Po}}} \cdot C_{214_{\text{Pb}}}}{\lambda_{214_{\text{Pb}}}} \tag{C.3}$$

$$E_{\text{PAEC},214_{\text{Bi}}} = \frac{E_{\text{AE},214_{\text{Po}}} \cdot C_{214_{\text{Bi}}}}{\lambda_{214_{\text{Bi}}}} \tag{C.4}$$

where $C_{218_{\text{Po}}}$, $C_{214_{\text{Pb}}}$ and $C_{214_{\text{Bi}}}$ are given by Formulae (B.17), (B.18) and (B.19).

C.5.2 Standard uncertainty

The standard uncertainty of $E_{\text{PAEC},222_{\text{Rn}}}$ is obtained from Formula (6). This yields Formula (C.5):

$$u(E_{\text{PAEC},222_{\text{Rn}}}) = \sqrt{\omega^2 \cdot \sum_{j=1}^{3}\left[\left(K_{i,j}\right) \cdot \left(I_j + I_{0,j}\right)\right] + \left(E_{\text{PAEC},222_{\text{Rn}}}\right)^2 \cdot u_{\text{rel}}^2(\omega)} \tag{C.5}$$

where

$$u_{\text{rel}}^2(\omega) = u_{\text{rel}}^2(\varepsilon_{\text{c}}) + u_{\text{rel}}^2(Q) \tag{C.6}$$

$$K_{i,j} = \left[\sum_{i=1}^{3}\left(\frac{E_{\text{AEt},i} \cdot k_{i,j}}{\lambda_i}\right)\right]^2 \tag{C.7}$$

C.5.3 Decision threshold

The decision threshold, $E^*_{\text{PAEC},222_{\text{Rn}}}$, is obtained from Formula (10).

This yields Formula (C.8):

$$E^*_{\text{PAEC},222_{\text{Rn}}} = k_{1-\alpha} \cdot \tilde{u}(0) = k_{1-\alpha} \cdot \omega \cdot \sqrt{2 \cdot \sum_{j=1}^{3}\left[\left(K_{i,j}\right) \cdot I_{0,j}\right]} \tag{C.8}$$

$\alpha = 0{,}05$ with $k_{1-\alpha} = 1{,}65$ is often chosen by default.

C.5.4 Detection limit

The detection limit, $E^{\#}_{\mathrm{PAEC,222_{Rn}}}$, is calculated using Formula (11) with $\alpha = \beta$. This yields Formula (C.9):

$$E^{\#}_{\mathrm{PAEC,222_{Rn}}} = 2 \cdot E^{*}_{\mathrm{PAEC,222_{Rn}}} + \left(\frac{k^{2}_{1-\beta}}{E_{\mathrm{PAEC}}} \right) \cdot \left\{ \left(\omega^{2} \cdot \sum_{j=1}^{3} \left[\left(K_{i,j} \right) \cdot \left(I_{j} + I_{0,j} \right) \right] + \left(E_{\mathrm{PAEC,222_{Rn}}} \right)^{2} \cdot u^{2}_{\mathrm{rel}}(\omega) \right) - \left(\frac{E^{*}_{\mathrm{PAEC,222_{Rn}}}}{k_{1-\alpha}} \right)^{2} \right\} \tag{C.9}$$

$\alpha = \beta = 0{,}05$ with $k_{1-\alpha} = k_{1-\beta} = 1{,}65$.

C.6 Example

Two samples are performed outdoor in the region of Limousin (France).

The counting results of these two samples, using the Thomas protocol, are given in Table C.1.

Table C.1 — Counting results

Date and time	Counting results (pulses)					
	$I_{0,1}$	I_1	$I_{0,2}$	I_2	$I_{0,3}$	I_3
17/08/1999 – 10:35	3	867	10	2 735	7	1 558
18/08/1999 – 19:00	2	693	9	2 318	6	1 258

The measurement results of the potential alpha energy concentrations of short-lived radon-222 decay products are given in Table C.2:

Table C.2 — Measurement results

Date and time	$E_{\mathrm{PAEC,222_{Rn}}}$ nJ/m^3	$u\left(E_{\mathrm{PAEC,222_{Rn}}}\right)$ nJ/m^3	$E^{*}_{\mathrm{PAEC,222_{Rn}}}$ nJ/m^3	$E^{\#}_{\mathrm{PAEC,222_{Rn}}}$ nJ/m^3
17/08/1999 – 10:35	239	21	2	9
18/08/1999 – 19:00	181	17	2	8

where

$Q = 5 \times 10^{-4}$ m^3/s and $u^{2}_{\mathrm{rel}}(Q) = 0{,}05$

$\varepsilon_{\mathrm{c}} = 0{,}5$ and $u^{2}_{\mathrm{rel}}(\varepsilon_{\mathrm{c}}) = 0{,}05$

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