INTERNATIONAL STANDARD

ISO 16641

First edition
2014-10-01

Measurement of radioactivity in the environment — Air — Radon 220: Integrated measurement methods for the determination of the average activity concentration using passive solid-state nuclear track detectors

Mesurage de la radioactivité dans l'environnement — Air — Radon 220: Méthode de mesure intégrée pour la détermination de l'activité volumique moyenne avec des détecteurs passifs solides de traces nucléaires

Reference number
ISO 16641:2014(E)

Contents

Page

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www.iso.org/patents).

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 meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 85, *Nuclear energy, nuclear technologies, and radiological protection*, Subcommittee SC 2, *Radiological protection*.

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, are all found in the earth's crust. Solid elements, also radioactive, followed by stable lead are produced by radon disintegration.[1]

Radon is considered to be the main source of human exposure to natural radiation. The UNSCEAR (2006) report[2] suggests that, at the international level, radon accounts for around 52 % of the global average exposure to natural radiation. Isotope 222 (48 %) is far more significant than isotope 220 (4 %), while isotope 219 is considered negligible.

Recent studies on indoor radon-222 and lung cancer in Europe, North America, and Asia provide strong evidence that radon-222 causes a substantial number of lung cancers in the general population. Current estimates of the proportion of lung cancers attributable to radon-222 range from 3 % to 14 %, depending on the average radon-222 concentration in the country concerned and the calculation methods.[3]

Indoor radon-222 concentration is mainly measured by passive detectors that can measure both radon-222 and radon-220 signals.[4] If the readings are overestimated, the lung cancer risk is given as a biased estimate when epidemiological studies are carried out. Radon-222 and radon-220 parallel measurements have been carried out in several countries[4]-[11] (See Table A.1). Experiences from field work indicate that there is no correlation among radon-222 and radon-220 and its decay products' concentrations. This implies that one parameter cannot be estimated from the other. Unless radon-220 activity concentration is measured, a correct radon-222 concentration cannot be given with a single use of radon-222 measuring device. Therefore, a specific measurement of radon-220 is justified.

Due to its short half-life, radon-220 disappears very rapidly in the atmosphere. An activity concentration gradient is observed from the walls or grounds to the inner space of the room. Depending on the objective of the measurement (building characteristics, construction material characterization, etc.), the sampling location is to be chosen after taking into account this gradient.

Due to a highest level of radon-222 in air, radon-220 is very difficult to measure alone. This International Standard proposes a measuring method of radon-220 activity concentration using a dual system considering radon-222 and radon-220.

There are many ways of measuring the activity concentration of radon-220 and its decay products. The measuring technique proposed is an integrated measurement method for radon-220 only.

Measurement of radioactivity in the environment — Air — Radon 220: Integrated measurement methods for the determination of the average activity concentration using passive solid-state nuclear track detectors

1 Scope

This International Standard covers integrated measurement techniques for radon-220 with passive sampling only. It provides information on measuring the average activity concentration of radon-220 in the air, based on easy-to-use and low-cost passive sampling, and the conditions of use for the measuring devices.

This International Standard covers samples taken without interruption over periods varying from a few months to one year.

This type of measurement is also applicable for determination of radon-222 activity concentration.

2 Normative references

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

ISO 11665-1:2012, *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 11929, *Determination of the characteristic limits (decision threshold, detection limit and limits of the confidence interval) for measurements of ionizing radiation — Fundamentals and application*

ISO/IEC 17025:2005, *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*

3 Terms, definitions, and symbols

3.1 Terms and definitions

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

3.1.1
activity
number of spontaneous nuclear disintegrations occurring in a given quantity of material over a reasonably short time interval, divided by this time interval

[SOURCE: ISO 921:1997, 23]

Note 1 to entry: Activity is expressed by the relationship:

$$A = \lambda \times N$$

The decay constant is linked to the radioactive half-life (T) by the relationship:

$$\lambda = \frac{\ln 2}{T}$$

3.1.2
activity concentration
activity per unit volume

[SOURCE: IEC 61577-1]

3.1.3
average activity concentration
exposure to activity concentration divided by the sampling duration

3.1.4
radon exposure
integral with respect to time of radon activity concentration accumulated during the exposure time

Note 1 to entry: Exposure to radon is expressed by:

$$e = \int_0^t C \mathrm{d}t$$

3.1.5
integrated measurement
measurement obtained by accumulating over time physical variables (number of nuclear tracks, number of electric charges, etc.) linked to the disintegration of radon and/or its decay products, followed by analysis at the end of the accumulation period

3.1.6
measurand
particular quantity subject to measurement

[SOURCE: ISO/IEC Guide 99]

3.1.7
passive sampling
sampling using no active device like pumps for sampling the atmosphere

[SOURCE: IEC 61577-1]

Note 1 to entry: In this case, the sampling is in most instruments mainly made by diffusion.

3.1.8
primary standard
standard designed or widely acknowledged as having the highest metrological qualities and whose value is accepted without reference to other standards of the same quantity

[SOURCE: IEC 61577-1]

Note 1 to entry: The concept of primary standard is equally valid for base quantities and derived quantities.

3.1.9
reference atmosphere
radioactive atmosphere in which the influencing parameters (aerosols, radioactivity, climatic conditions, etc.) are sufficiently well-known or controlled to allow its use in a testing procedure for thoron or its decay products' measuring instruments

[SOURCE: IEC 61577-1]

Note 1 to entry: The parameter values concerned shall be traceable to recognized standards.

3.1.10
reference source
radioactive secondary standard source for use in the calibration of the measuring instruments

[SOURCE: IEC 61577-1]

3.1.11
sampling duration
time interval between the installation and removal of the sampling device at a given point

3.1.12
sampling plan
precise protocol that, depending on the application of the principles of the strategy adopted, defines the spatial and temporal dimensions of sampling, the frequency, the sample number, the quantities sampled, etc., and the human resources to be used for the sampling operation

3.1.13
sampling strategy
set of technical principles that aim to resolve, depending on the objectives and site considered, the two main issues which are the sampling density and the spatial distribution of the sampling areas

Note 1 to entry: The sampling strategy provides the set of technical options that are required in the sampling plan.

3.1.14
radon-220 decay products
polonium-216 (^{216}Po), lead-212 (^{212}Pb), bismuth-212 (^{212}Bi), polonium-212 (^{212}Po), and thallium-208 (^{208}Tl)

Note 1 to entry: See Figure A.1.

3.2 Symbols

For the purposes of this document, the following symbols apply.

λ decay constant of the nuclide i, in per second

$\bar{C}$ average activity concentration, in becquerel per cubic metre (e.g. $\overline{C_{Tn}}$ radon-220 activity concentration)

$\tilde{C}$ true value of the average activity concentration

t sampling duration, in hours

e exposure to radon, in becquerel per cubic metre hour

$\tilde{u}$ standard uncertainty of the estimator of the true value $\tilde{C}$

$u()$ standard uncertainty associated with the measurement result

U expanded uncertainty calculated by $U = k \times u()$ with $k = 2$

$\bar{C}^*$ decision threshold of the average activity concentration, in becquerel per cubic metre

$\bar{C}^\#$ detection limit of the average activity concentration, in becquerel per cubic metre

$\bar{C}^\triangleleft$, $\bar{C}^\triangleright$ lower and upper limit of the confidence interval, respectively, of the average activity concentration, in becquerel per cubic metre

ω_1 factor linked to the calibration factor f_{Tn2} and the sampling duration

ω_2 factor linked to the calibration factor f_{Tn1} and the sampling duration

ω_3 factor linked to the calibration factor f_{Rn1} and the sampling duration

ω_4 factor linked to the calibration factor f_{Rn2} and the sampling duration

d_L track density for low air-exchange rate chamber in tracks per square centimetre

d_H track density for high air-exchange rate chamber in tracks per square centimetre

$\bar{b}$ track density due to background in tracks per square centimetre

f_{Tn1} calibration factor for radon-220 in a low air-exchange rate chamber in (tracks per square centimetre per hour) per (becquerel per cubic metre)

f_{Tn2} calibration factor for radon-220 in a high air-exchange rate chamber in (tracks per square centimetre per hour) per (becquerel per cubic metre)

f_{Rn1} calibration factor for radon-222 in a low air-exchange rate chamber in (tracks per square centimetre per hour) per (becquerel per cubic metre)

f_{Rn2} calibration factor for radon-222 in a high air-exchange rate chamber in (tracks per square centimetre per hour) per (becquerel per cubic metre)

4 Principle of the measurement method

The integrated measurement of the average radon-220 activity concentration using a solid-state nuclear track detector (SSNTD) is based on the following:[12]

— passive sampling using two chambers with different air-exchange rates during which the alpha particles, including those produced by the disintegration of radon-220, radon-222, and their decay products, transfer their energy by ionizing or exciting the atoms in the polymer or plastic. This energy transferred to the medium leaves areas of damage called “latent tracks”. Because of their different half-lives, radon-222 and radon-220 can be separated using these two chambers. In the high air-exchange rate chamber, both isotopes are detected. In the low air-exchange rate chamber, however, radon–222 is mainly detected with only a small quantity of radon-220 (see Figure 1);

  The high air-exchange rate should be set as high as possible so that the calibration factor of radon-220 is ideally the same as that of radon-222. On the contrary, the low air-exchange rate should be set as low as possible with a high diffusion barrier.

— transport of the exposed detectors to the laboratory for the appropriate chemical processing which transforms the latent tracks into “visible tracks” counted via an optical system. The number of these visible tracks per unit surface area is linked to the exposure value of the radon-220 and its decay products by the calibration factor defined for detectors in the same batch processed chemically and counted under the same conditions;

— determination of the radon-220 average activity concentration from the exposure value of both chambers and the sampling period.

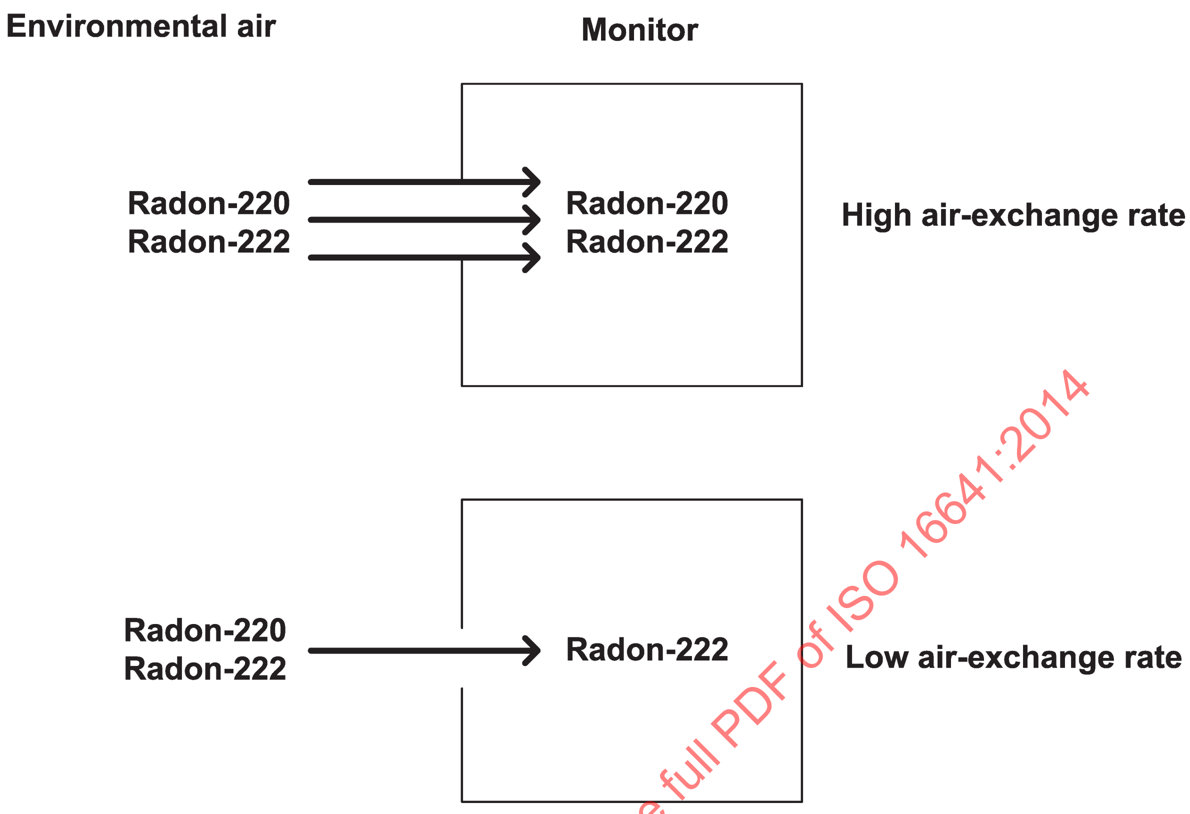


Figure 1 — Principle of radon-thoron separation technique

5 Equipment

The apparatus includes the following.

5.1 A device composed of two closed accumulation chambers with different air-exchange rates.

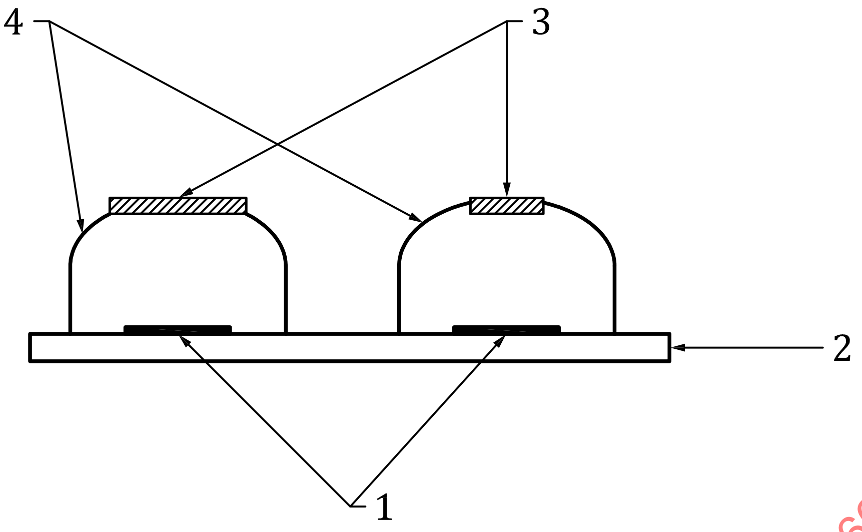
Each of them is associated with a solid state nuclear track detector. Each closed accumulation chamber has a filter through which the radon-220 and radon-222 diffuse. This filter is set to prevent access of the aerosols present in the air at the time of sampling, especially the solid radon-220 and radon-222 decay products (see Figure 2).

The SSNTD shall come from the same sheet of plastic to avoid different results. Nevertheless each SSNTD batch is calibrated.

5.2 The equipment and suitable chemical reagents for etching the detector.

See ISO 11665-4.

5.3 An optical microscope and associated equipment, for scanning and counting the etched tracks.



Key

1 solid state nuclear track detector (SSNTD)
2 support
3 filter or diffusion barrier
4 accumulation chamber

Figure 2 — Example of the design of a radon-222/radon-220 discriminative measuring device

6 Sampling

6.1 Sampling objective

The sampling objective is to place the measuring device, without interruption, in an air sample representative of the atmospheric medium under investigation.

6.2 Sampling characteristics

The sampling is passive and is performed through a filtering medium. Depending on the air-exchange rate of the accumulation chamber, one or two radon isotopes can diffuse into the chamber. If the air-exchange rate is low, only radon-222 can diffuse into the chamber. If the air-exchange is high, both radon-222 and radon-220 can diffuse into the chamber. The sampling shall be performed in conditions that preclude clogging of the filtering medium, which would result in modified measuring conditions. If the filtering medium clogs there is a risk of the air in the chamber not being renewed.

6.3 Sampling conditions

6.3.1 Installation of sampling device

The installation of the measuring device shall be carried out as specified in ISO 11665-1.

In the specific case of an indoor measurement, the measuring device is installed as follows:

— in an area not directly exposed to solar radiation;

— away from a heat source (radiator, picture windows, electrical equipment, chimney, etc.);

— away from traffic areas, doors and windows, and natural ventilation sources (it could, for example, be sited on an item of furniture like a shelf or sideboard);

— sheltered from weather conditions.

6.3.2 Sampling duration

The sampling duration is equal to the time interval between the installation and removal of the measuring device at the sampling point.

The dates and times of the installation and removal of the measuring device shall be recorded.

The sampling duration is adjusted to suit the phenomenon under investigation, assumed to be the activity concentration of radon-220 and radon-222.

It is important that the period of measurement is commensurate with the desired outcome. For example, indoor concentrations vary not only during a day but also between days of the week because of variations in occupancy and weather conditions. Depending on the intended use of the measurement results, the sampling duration shall be chosen according to ISO 11665-1:2012, Clause 6.

Users should be aware of the saturation characteristics of their devices because etch tracks are overlapped due to many tracks in a small area. Therefore, they should arrange their sampling regime to ensure that saturation does not occur.

6.3.3 Volume of air sampled

For passive sampling, direct measurement of the air volume sampled is not needed.

7 Detection method with solid-state nuclear track detectors (SSNTD)

An alpha particle triggers ionization as it passes through some polymer or plastic nuclear detectors (such as cellulose nitrate, polycarbonate). Ion recombinations are not complete after the particle has passed through the detecting materials. Appropriate etching acts as a developing agent. The detector then shows the tracks as etching holes or cones, in a quantity proportional to the number of alpha particles detected.

8 Measurement procedure

8.1 General

The measurement is performed as follows:

a) choosing and locating the measuring point;

b) installing the measuring device;

c) recording the location, date, and time of the installation of the measuring device;

d) collecting an air sample that is representative of the atmosphere under investigation;

e) removing the measuring device;

f) recording the date and time of the removal of the measuring device;

g) processing the measuring as soon as possible;

In case that the detectors are positioned by laboratory/company who is not responsible for the etching, they should be sent to the laboratory for processing following the procedure described by the laboratory who performs the etching and following procedures.

h) removing the SSNTD from the measuring device;

i) developing the SSNTD by etching with a suitable chemical treatment. The latent tracks caused by the alpha particles produced by the disintegration of the radon-220, radon-222, and their decay products are converted into "visible tracks";

j) scanning the SSNTD under an optical microscope and counting the number of etched tracks;

k) determining the background noise of the SSNTD. Several (for example 10) detectors, from the same batch, are revealed and counted as described from step i) up to j);

l) determining the average activity concentration by calculation.

8.2 Influencing variables

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

a) direct exposure of a sensor to solar radiation;

b) humidity which can clog a filter of the chamber and consequently reduce particularly radon-220 diffusion into the chamber;

c) the ageing effect of the SSNTD. In order to avoid the effect of ageing, the sensor shall be used before the expiry date given by the manufacturer.

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

8.3 Calibration

The entire measuring system (sampling system, detector, and related electronics) is calibrated as specified in ISO 11665-1. Additional requirements for the devices used for particular methods are contained in the relevant annexes.

The relationship between the physical parameter measured by the detection device (number of etched tracks) and the activity concentration of the radon-220/radon-222 and its decay products in the air, shall be established based on the measurement of a radon-220/radon-222 reference atmosphere. The radon-220/radon-222 activity concentration in these reference atmospheres shall be traceable to a primary radon-220/radon-222 gas standard.[13] [14]

If the calibration factor is not provided by manufacturer, each batch of detectors is calibrated upon receipt.

For a batch of detectors:

— calibration involves exposing 10 randomly chosen devices to reference atmospheres and applying the same chemical processing and track counting as used for measurement samples;

— the calibration factor is the ratio between the density of the tracks per unit of time (tracks · cm^2 · h^{-1}) and the activity concentration (Bq · m^{-3}) of the reference atmosphere. This calibration factor is expressed in (tracks per square centimetre per hour) per (becquerel per cubic metre) (tracks · cm^{-2} · h^{-1} · Bq^{-1} · m^3);

— at the same time as the calibration, the background noise is measured on 10 detectors from the same batch.

9 Expression of results

9.1 Average thoron activity concentration

For dual measurements of radon-222 and radon-220, the average radon-222 and radon-220 concentrations are calculated as given in Formulae (1) and (2), respectively:

$$\overline{C_{Rn}} = \left(d_L - \bar{b}\right) \cdot \frac{f_{Tn2}}{t \cdot \left(f_{Rn1} \cdot f_{Tn2} - f_{Rn2} \cdot f_{Tn1}\right)} - \left(d_H - \bar{b}\right) \cdot \frac{f_{Tn1}}{t \cdot \left(f_{Rn1} \cdot f_{Tn2} - f_{Rn2} \cdot f_{Tn1}\right)} = \left(d_L - \bar{b}\right) \cdot \omega_1 - \left(d_H - \bar{b}\right) \cdot \omega_2$$

$$\text{with } \omega_1 = \frac{f_{Tn2}}{t \cdot \varepsilon} \text{ and } \omega_2 = \frac{f_{Tn1}}{t \cdot \varepsilon} \text{ where } \varepsilon = f_{Rn1} \cdot f_{Tn2} - f_{Rn2} \cdot f_{Tn1} \qquad (1)$$

$$\overline{C_{Tn}} = \left(d_H - \bar{b}\right) \cdot \frac{f_{Rn1}}{t \cdot \left(f_{Rn1} \cdot f_{Tn2} - f_{Rn2} \cdot f_{Tn1}\right)} - \left(d_L - \bar{b}\right) \cdot \frac{f_{Rn2}}{t \cdot \left(f_{Rn1} \cdot f_{Tn2} - f_{Rn2} \cdot f_{Tn1}\right)} = \left(d_H - \bar{b}\right) \cdot \omega_3 - \left(d_L - \bar{b}\right) \cdot \omega_4$$

$$\text{with } \omega_3 = \frac{f_{Rn1}}{t \cdot \varepsilon} \text{ and } \omega_4 = \frac{f_{Rn2}}{t \cdot \varepsilon} \qquad (2)$$

For the most accurate value, $\bar{b}$ is determined experimentally by reading the number of tracks on the SSNTD that have not been exposed to radon and have been processed under the same physico-chemical and counting conditions. A nominal value may also be given by the manufacturer.

9.2 Standard uncertainty

According to ISO/IEC Guide 98-3, the standard uncertainty of $\overline{C_{Rn}}$ is calculated as given in Formula (3):

$$u\left(\overline{C_{Rn}}\right) = \sqrt{\begin{aligned}&\omega_1^{\,2}\left(u^2(d_L) + u^2(\bar{b})\right) - 2\omega_1\omega_2 u^2\left(\bar{b}\right) + \omega_2^{\,2}\left(u^2\left(d_H\right) + u^2\left(\bar{b}\right)\right) + \left(d_L - \bar{b}\right)^2 u^2\left(\omega_1\right)\\ &+ \left(-d_H + \bar{b}\right)^2 u^2\left(\omega_2\right)\end{aligned}} \qquad (3)$$

with

$$u^2\left(\omega_1\right) = \frac{1}{\varepsilon^4 t^2}\left\{\left(\varepsilon - f_{Rn2} f_{Rn1}\right)^2 u^2\left(f_{Tn2}\right) + f_{Tn2}^{\;\;4} u^2\left(f_{Rn1}\right) + f_{Tn1}^{\;\;2} f_{Tn2}^{\;\;2} u^2\left(f_{Rn2}\right) + f_{Rn2}^{\;\;2} f_{Tn2}^{\;\;2} u^2\left(f_{Tn1}\right)\right\}$$

and

$$u^2\left(\omega_2\right) = \frac{1}{\varepsilon^4 t^2}\left\{\left(\varepsilon + f_{Rn1} f_{Tn2}\right)^2 u^2\left(f_{Tn1}\right) + f_{Tn2}^{\;\;4} u^2\left(f_{Rn2}\right) + f_{Tn1}^{\;\;2} f_{Tn2}^{\;\;2} u^2\left(f_{Rn1}\right) + f_{Rn1}^{\;\;2} f_{Tn1}^{\;\;2} u^2\left(f_{Tn2}\right)\right\}$$

The standard uncertainty of $\overline{C_{Tn}}$ is calculated as give in Formula (4):

$$u(\overline{C_{Tn}}) = \sqrt{\begin{aligned}&\omega_3^2\left(u^2(d_H) + u^2(\bar{b})\right) - 2\omega_3\omega_4 u^2(\bar{b}) + \omega_4^{\,2}\left(u^2(d_L) + u^2(\bar{b})\right) + \left(d_H - \bar{b}\right)^2 u^2(\omega_3)\\ &+ \left(-d_L + \bar{b}\right)^2 u^2(\omega_4)\end{aligned}} \qquad (4)$$

with

$$u^2\left(\omega_3\right) = \frac{1}{\varepsilon^4 t^2}\left\{\left(\varepsilon - f_{Rn1} f_{Tn1}\right)^2 u^2(f_{Rn1}) + f_{Rn1}^{\;\;4} u^2(f_{Tn2}) + f_{Rn1}^{\;\;2} f_{Tn1}^{\;\;2} u^2(f_{Rn2}) + f_{Rn1}^{\;\;2} f_{Rn2}^{\;\;2} u^2(f_{Tn1})\right\}$$

and

$$u^2(\omega_4)=\frac{1}{\varepsilon^4 t^2}\left\{(\varepsilon+f_{Rn2}f_{Tn1})^2 u^2(f_{Rn2})+f_{Rn2}{}^4 u^2(f_{Tn1})+f_{Rn2}{}^2 f_{Tn2}{}^2 u^2(f_{Rn1})+f_{Rn1}{}^2 f_{Rn2}{}^2 u^2(f_{Tn2})\right\}$$

where the uncertainty of the exposure time is neglected.

The calculation of the characteristic limits (ISO 11929) requires the calculation of $\tilde{u}(\tilde{C}_{\mathrm{Rn}})$ and $\tilde{u}(\tilde{C}_{\mathrm{Tn}})$, i.e. the standard uncertainty of $\overline{C_{Rn}}$ and $\overline{C_{Tn}}$ as a function of their true value, calculated as given in Formulae (5) and (6), respectively:

$$\tilde{u}(\tilde{C}_{Rn})=\sqrt{\begin{array}{l}\omega_1^2\left(u^2(d_L)+u^2(\bar{b})\right)-2\omega_1\omega_2 u^2(\bar{b})+\omega_2^2\left(u^2(d_H)+u^2(\bar{b})\right)\\+\dfrac{\left(d_H^2-2\bar{b}d_H+\bar{b}^2\right)\omega_2^2+\tilde{C}_{Rn}\left(2d_H-2\bar{b}\right)\omega_2+\tilde{C}_{Rn}^2}{\omega_1^2}u^2(\omega_1)+\left(-d_H+\bar{b}\right)^2 u^2(\omega_2)\end{array}} \quad (5)$$

$$\tilde{u}(\tilde{C}_{Tn})=\sqrt{\begin{array}{l}\omega_3^2\left(u^2(d_H)+u^2(\bar{b})\right)-2\omega_3\omega_4 u^2(\bar{b})+\omega_4^2\left(u^2(d_L)+u^2(\bar{b})\right)\\+\dfrac{\left(d_L^2-2\bar{b}d_L+\bar{b}^2\right)\omega_4^2+\tilde{C}_{Tn}\left(2d_L-2\bar{b}\right)\omega_4+\tilde{C}_{Tn}^2}{\omega_3^2}u^2(\omega_3)+\left(-d_L+\bar{b}\right)^2 u^2(\omega_4)\end{array}} \quad (6)$$

9.3 Decision threshold

The decision thresholds $\overline{C}_{Rn}^*$ and $\overline{C}_{Tn}^*$ are obtained from the Formulae (2) and (3) for $\tilde{C}_{Rn}=0$, $\tilde{u}(d_L)=0$, $\tilde{C}_{Tn}=0$ and $\tilde{u}(d_H)=0$ (see ISO 11929).

These yield Formulae (7) and (8):

$$\overline{C}_{Rn}^*=k_{1-\alpha}\cdot\tilde{u}(0)=k_{1-\alpha}\sqrt{\begin{array}{l}\omega_1^2 u^2(\bar{b})-2\omega_1\omega_2 u^2(\bar{b})+\omega_2^2\left(u^2(d_H)+u^2(\bar{b})\right)\\+\dfrac{\left(d_H{}^2-2\bar{b}d_H+\bar{b}^2\right)\omega_2^2}{\omega_1^2}u^2(\omega_1)+\left(-d_H+\bar{b}\right)^2 u^2(\omega_2)\end{array}} \quad (7)$$

$$\overline{C}_{Tn}^*=k_{1-\alpha}\cdot\tilde{u}(0)=k_{1-\alpha}\sqrt{\begin{array}{l}\omega_3^2 u^2(\bar{b})-2\omega_3\omega_4 u^2(\bar{b})+\omega_4^2\left(u^2(d_L)+u^2(\bar{b})\right)\\+\dfrac{\left(d_L{}^2-2\bar{b}d_L+\bar{b}^2\right)\omega_4{}^2}{\omega_3^2}u^2(\omega_3)+\left(-d_L+\bar{b}\right)^2 u^2(\omega_4)\end{array}} \quad (8)$$

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

9.4 Detection limit

The detection limit, $\overline{C}_{Rn}^{\#}$ and $\overline{C}_{Tn}^{\#}$, are calculated as given in Formulae (9) and (10) (see ISO 11929):

$$\overline{C}_{Rn}^{\#}=\overline{C}_{Rn}^*+k_{1-\beta}\cdot\tilde{u}\left(\overline{C}_{Rn}^{\#}\right)$$

$$=\overline{C}_{Rn}^*+k_{1-\beta}\cdot\sqrt{\begin{array}{l}\omega_1^2\left(u^2(d_L)+u^2(\bar{b})\right)-2\omega_1\omega_2 u^2(\bar{b})+\omega_2^2\left(u^2(d_H)+u^2(\bar{b})\right)\\+\dfrac{\left(d_H^2-2\bar{b}d_H+\bar{b}^2\right)\omega_2^2+\tilde{C}_{Rn}\left(2d_H-2\bar{b}\right)\omega_2+\tilde{C}_{Rn}^2}{\omega_1^2}u^2(\omega_1)+\left(-d_H+\bar{b}\right)^2 u^2(\omega_2)\end{array}} \quad (9)$$

$$\bar{C}_{Tn}^{\#} = \bar{C}_{Tn}^{*} + k_{1-\beta} \cdot \tilde{u}\left(\bar{C}_{Tn}^{\#}\right)$$

$$= \bar{C}_{Tn}^{*} + k_{1-\beta} \cdot \sqrt{\omega_3^2\left(u^2(d_H)+u^2(\bar{b})\right) - 2\omega_3\omega_4 u^2(\bar{b}) + \omega_4^2\left(u^2(d_L)+u^2(\bar{b})\right) + \frac{\left(d_L^2 - 2\bar{b}d_L + \bar{b}^2\right)\omega_4^2 + \tilde{C}_{Tn}\left(2d_L - 2\bar{b}\right)\omega_4 + \tilde{C}_{Tn}^2}{\omega_3^2} u^2(\omega_3) + \left(-d_L + \bar{b}\right)^2 u^2(\omega_4)} \quad (10)$$

The detection limit can be calculated by solving Formulae (6) and (7) for $\bar{C}^{\#}$ or, more simply, by iteration with a starting approximation $\bar{C}^{\#} = 2 \times \bar{C}^{*}$ in terms of the right side of Formulae (11) and (12).

One obtains $\bar{C}^{\#}$ with $k_{1-\alpha} = k_{1-\beta} = k$:

$$\bar{C}_{Rn}^{\#} = \frac{2 \cdot \bar{C}_{Rn}^{*} + k^2 \left\{ \frac{\left(2d_H - 2\bar{b}\right)\omega_2 u^2(\omega_1)}{\omega_1^2} \right\}}{1 - k^2 \frac{u^2(\omega_1)}{\omega_1^2}} \quad (11)$$

$$\bar{C}_{Tn}^{\#} = \frac{2 \cdot \bar{C}_{Tn}^{*} + k^2 \left\{ \frac{\left(2d_L - 2\bar{b}\right)\omega_4 u^2(\omega_3)}{\omega_3^2} \right\}}{1 - k^2 \frac{u^2(\omega_3)}{\omega_3^2}} \quad (12)$$

Values $\alpha = \beta = 0{,}05$ and therefore $k_{1-\alpha} = k_{1-\beta} = 1{,}65$ are often chosen by default.

9.5 Confidence limits

The lower, $\bar{C}^{\triangleleft}$, and upper, $\bar{C}^{\triangleright}$, confidence limits are calculated using Formulae (13) and (14) (see ISO 11929):

$$\bar{C}^{\triangleleft} = \bar{C} - k_p \times u\left(\bar{C}\right) \; ; p = \omega \times \left(1 - \gamma/2\right) \quad (13)$$

$$\bar{C}^{\triangleright} = \bar{C} + k_q \times u\left(\bar{C}\right) ; q = 1 - \omega \times \gamma/2 \quad (14)$$

where $\omega = \Phi\left(y/u(y)\right)$, with Φ being the distribution function of the standardized normal distribution.

$\omega = 1$ may be set if $\bar{C} \geq 4 \cdot u\left(\bar{C}\right)$. In this case:

$$\bar{C}^{\triangleleft\triangleright} = \bar{C} \pm k_{1-\gamma/2} \times u\left(\bar{C}\right) \quad (15)$$

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

9.6 Example

The number of tracks after a radon-222/radon-220 discriminative measuring device has been exposed for 90 days reaches $d_H = 900 \pm 30$ and $d_L = 500 \pm 23$ tracks for a count over 1 cm^2.

The number of tracks, determined on 10 non-exposed SSNTD from the same batch, caused by the background noise is $\bar{b} = 50$ tracks over 90 days for a count over 1 cm^2.

The calibration factors are $f_{Rn1} = 1{,}65 \pm 0{,}01$, $f_{Tn1} = 0{,}03 \pm 0{,}01$, $f_{Rn2} = 1{,}70 \pm 0{,}03$, and $f_{Tn2} = 0{,}95 \pm 0{,}12$ in tracks · cm^{-2} · h^{-1} · kBq^{-1} · m^3.

Thus, the average radon-222 and radon-220 activity concentrations, calculated from Formula (1) and Formula (2), are:

$$\overline{C_{Rn}} = 123\ \text{Bq}\cdot\text{m}^{-3}$$

$$\overline{C_{Tn}} = 195\ \text{Bq}\cdot\text{m}^{-3}$$

The standard uncertainty of the average radon-222 and radon-220 activity concentrations, calculated from Formulae (3) and (4), are:

$$u\left(\overline{C_{Rn}}\right) = 64\ \text{Bq}\cdot\text{m}^{-3}$$

$$u\left(\overline{C_{Tn}}\right) = 81\ \text{Bq}\cdot\text{m}^{-3}$$

Thus, the average radon-222 and radon-220 activity concentrations are:

$$\overline{C_{Rn}} = (123 \pm 64)\ \text{Bq}\cdot\text{m}^{-3}$$

$$\overline{C_{Tn}} = (195 \pm 81)\ \text{Bq}\cdot\text{m}^{-3}$$

The decision threshold, $\overline{C}^{*}_{Rn}$ and $\overline{C}^{*}_{Tn}$ obtained from Formulae (7) and (8) are $\overline{C}^{*}_{Rn} = 12\ \text{Bq.m}^{-3}$ and $\overline{C}^{*}_{Tn} = 88\ \text{Bq}\cdot\text{m}^{-3}$, respectively.

The detection limit, $\overline{C}^{\#}_{Rn}$ and $\overline{C}^{\#}_{Tn}$ calculated by Formulae (9) and (10) are $\overline{C}^{\#}_{Rn} = 24\ \text{Bq}\cdot\text{m}^{-3}$ and $\overline{C}^{\#}_{Tn} = 183\ \text{Bq}\cdot\text{m}^{-3}$.

10 Test report

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

a) a reference to this International Standard (i.e. ISO 16641);

b) purpose of measurement;

c) measurement method (integrated);

d) identification of the sample;

e) sampling characteristic (passive);

f) sampling date and time;

g) duration of sampling period;

h) sampling location;

i) units in which the results are expressed;

j) test result, $\overline{C} \pm u\left(\overline{C}\right)$ or $\overline{C} \pm U$, with the associated k value.

Complementary information can be provided such as the following:

a) probabilities α, β, and $(1 - \gamma)$;

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

— when the average radon-220 activity concentration is compared with the decision threshold (see ISO 11929), the result of the measurement shall be expressed as $\leq \bar{C}_{Tn}^{*}$ when the result is below the decision threshold;

— when the average radon-220 activity concentration is compared with the detection limit, the result of the measurement can be expressed as $\leq \bar{C}_{Tn}^{\#}$ when the result is below the detection limit. If the detection limit exceeds the guideline value, it shall be documented that the method is not suitable for the measurement purpose;

c) any relevant information likely to affect the results, for example:

— weather conditions at the time of sampling;

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

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