INTERNATIONAL STANDARD

ISO 11665-7

First edition
2012-07-15

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

Part 7:
Accumulation method for estimating surface exhalation rate

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

Partie 7:
Méthode d'estimation du flux surfacique d'exhalation par la méthode d'accumulation

Reference number
ISO 11665-7:2012(E)

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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.

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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 11665-7 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].

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.

The radon-222 half-life (3,8 days) is long enough for it to migrate from the rock producing it, through the soil, to the air[3]. The radon atoms in the soil are produced by the disintegration of the radium-226 contained in the mineral grains in the medium. Some of these atoms reach the interstitial spaces between the grains: this is the phenomenon of emanation. Some of the atoms produced by emanation reach the soil's surface by diffusion and convection: this is the phenomenon of exhalation[3][4][5]. These mechanisms are also brought into play in materials (building materials, walls, etc.).

The quantity of radon-222 reaching the open air per unit of time and per unit of surface is called the radon-222 surface exhalation rate and depends on the physical characteristics of the soil and weather conditions. When the ground is covered in snow or a layer of water, or is frozen, this surface exhalation rate can become very weak.

Values of the radon-222 surface exhalation rate observed in France, for example, vary between 1 mBq/m^2/s and about 100 mBq/m^2/s[6][7]. In uranium-bearing ground, radon-222 surface exhalation rates in the order of 50 000 mBq/m^2/s can be observed. By way of comparison, the United Nations Scientific Committee estimates the average surface exhalation rate on the surface of the globe at 20 mBq/m^2/s[8].

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 7: Accumulation method for estimating surface exhalation rate

1 Scope

This part of ISO 11665 gives guidelines for estimating the radon-222 surface exhalation rate over a short period (a few hours), at a given place, at the interface of the medium (soil, rock, laid building material, walls, etc.) and the atmosphere. This estimation is based on measuring the radon activity concentration emanating from the surface under investigation and accumulated in a container of a known volume for a known duration.

This method is estimative only, as it is difficult to quantify the influence of many parameters in environmental conditions. This part of ISO 11665 is particularly applicable, however, in case of an investigation, a search for sources or a comparative study of exhalation rates at the same site. This part of ISO 11665 does not cover calibration conditions for the rate estimation devices.

The measurement method described is applicable for radon exhalation rates greater than 5 $mBq/m^2/s$.

NOTE The uncertainty relating to the estimation of the result obtained by applying this part of ISO 11665 cannot guarantee that the true flux value is included in the uncertainty domain.

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 11665-5, *Measurement of radioactivity in the environment — Air: radon-222 — Part 5: Continuous measurement method of the activity concentration*

ISO 11665-6, *Measurement of radioactivity in the environment — Air: radon-222 — Part 6: Spot measurement method of the activity concentration*

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*

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 and the following apply.

3.1.1
accumulation container
recipient with known geometric characteristics used to accumulate the radon, with one open face in contact with the surface under investigation

3.1.2
accumulation duration
time elapsed between installation of the container after air tightness is achieved and the end of sampling

3.1.3
back diffusion
mechanism responsible for the transport of radon from the accumulation container atmosphere into the material under investigation

3.1.4
effective surface
internal surface of the open face of the container that is in contact with the surface under investigation

3.1.5
effective volume
available internal volume for radon accumulation after the container is installed

3.2 Symbols

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

C	activity concentration in the accumulation container at time t, in becquerels per cubic metre
S	effective surface, in square metres
t	elapsed time since the start of the accumulation process, in seconds
U	expanded uncertainty calculated by $U = k \cdot u(\ )$ with $k = 2$
$u(\ )$	standard uncertainty associated with the measurement result
$u_{\text{rel}}(\ )$	relative standard uncertainty
V	effective volume, in cubic metres
λ_B	time constant of back diffusion, per second
λ_i	decay constant of the nuclide i, per second
λ_V	time constant of leakage, per second
ϕ	surface exhalation rate, in becquerels per square metre per second
ϕ^*	decision threshold of the surface exhalation rate, in becquerels per square metre per second
$\phi^\#$	detection limit of the surface exhalation rate, in becquerels per square metre per second
$\phi^\triangleleft$	lower limit of the confidence interval of the surface exhalation rate, in becquerels per square metre per second
$\phi^\triangleright$	upper limit of the confidence interval of the surface exhalation rate, in becquerels per square metre per second

4 Principle of the measurement method for estimating surface exhalation rate

The measurement method for estimating the radon surface exhalation rate is based on the following elements:

a) accumulating radon in a radon-free accumulation container applied to the surface under investigation for a known duration;

b) sampling a volume of air representative of the air contained in the accumulation container;

c) measuring the radon activity concentration in this air sample;

d) calculating the surface exhalation rate.

An estimate of the surface exhalation rate is calculated from the following elements:

— the variation in the radon activity concentration inside the accumulation container between two given moments;

— the effective surface of the accumulation container in contact with the surface under investigation;

— the effective volume of the accumulation container.

The radon activity concentration in the accumulation container increases over time depending on the surface-related exhalation rate, the volume of the accumulation container and influencing factors such as inadequate air tightness (leakage) and back diffusion.

The increase of radon activity concentration can be fitted with an exponential function:

$$C(t) = \frac{\phi \cdot S}{V \cdot \lambda} \cdot \left(1 - \mathrm{e}^{-\lambda t}\right) \tag{1}$$

where

$$\lambda = \lambda_{\mathrm{Rn}222} + \lambda_B + \lambda_V \tag{2}$$

Since the background radon activity concentration in the container is close to zero at the beginning of the accumulation process, the initial slope of the curve is independent of back diffusion[9][10]. Assuming that radon loss by leakage is negligible, the accumulation phase can be approximated by a linear increase of radon activity concentration in the accumulation container (see the example in Figure 1) as described by Formula (3):

$$C(t) = \frac{\phi \cdot S}{V} \cdot t \tag{3}$$

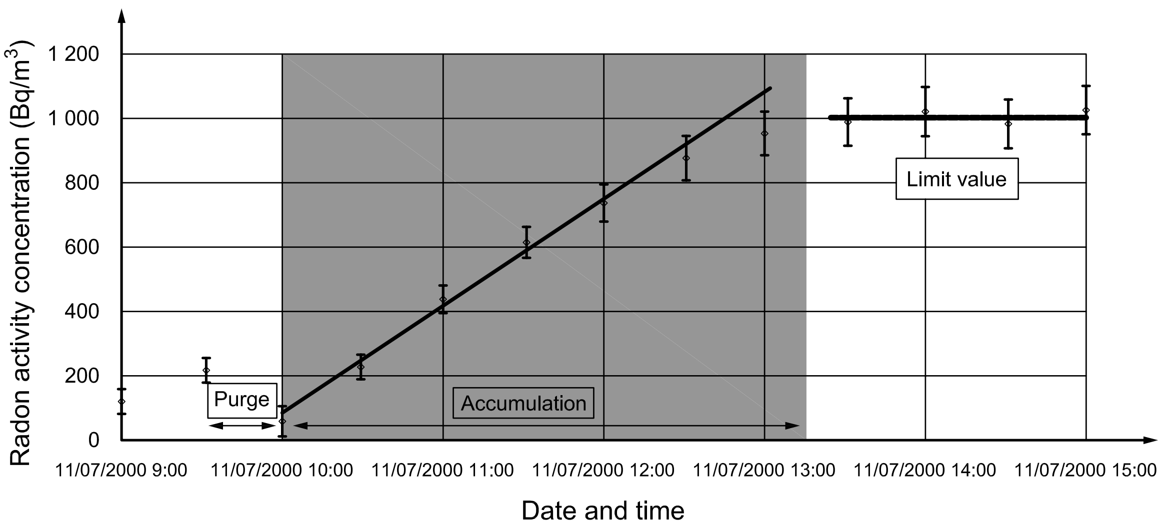


Figure 1 — Example of changes in radon activity concentration in the accumulation container

For outdoor measurements, the analysis of the measurement results can require detailed knowledge of climatic conditions. For example, the radon surface exhalation rate measurements carried out during snow or rain are only representative of these weather conditions.

For soil investigations, the surface area, topography, geology, pedology, vegetation, etc. all need to be taken into account. The humidity content of the ground at the time of sampling may be determined (see ISO 11465).

Several measurement methods meet the requirements of this part of ISO 11665. They can be distinguished by the way the air is sampled from the accumulation container.

5 Equipment

The apparatus shall include the following components.

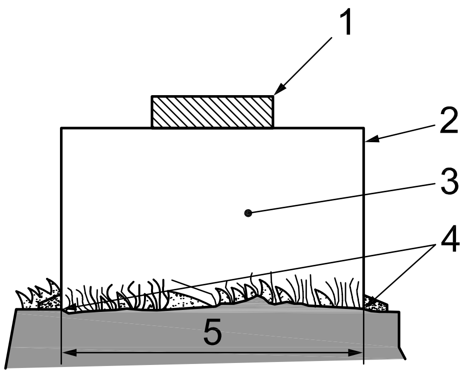
a) An accumulation container with known geometric characteristics (see Figure 2): The accumulation container characteristics shall be chosen so that any irregularities of the surface under investigation do not introduce an uncertainty of more than 10 % into the effective volume of the accumulation container. The effective surface of the accumulation container shall be selected to ensure that measurements are the most representative possible of the surface under investigation (i.e. the effective surface shall be appropriate for the surface area under investigation). The effective volume of the accumulation container shall be at least 10 times greater than the volume of air sampled from the accumulation container by the radon measuring device. The material used in the accumulation container shall not allow the radon to be diffused towards the outside of the container during the accumulation period. Neither the accumulation container material nor colour shall encourage a rise in temperature in the effective volume in the event of exposure to sunlight. The accumulation container shall have one or two orifices with a closing system for sampling purposes. When the accumulation container is placed on the material under investigation these orifices shall be open to prevent overpressure in the container.

b) A homogenization system in the accumulation container: Depending on its dimensions, the container may have a system to homogenize the entire volume of the container.

c) An air sampling device.

d) A measuring device adapted to the physical quantity to be measured.

The necessary equipment for specific measurement methods is specified in Annexes B and C.



Key

1 measuring device
2 accumulation container
3 effective volume
4 contact surface
5 effective surface

Figure 2 — Example set-up of apparatus

A single model of accumulation container shall be used when investigating a site in order to find the zones with the highest exhalation rates.

6 Accumulation of radon in a container

6.1 Accumulation characteristics

The open face of the accumulation container shall be positioned on the surface of the material under investigation (soil, rock, building material, etc.). The accumulation container geometry shall suit the surface under investigation. The contact surface shall be arranged so as to ensure uniform contact between the base of the accumulation container and the surface under investigation (weeds, pebbles, roots removed) (see Figure 2). Any alteration to the surface under investigation shall be recorded on the results sheet (see Annex A). Whenever possible, the surface under investigation shall be chosen so that its irregularities do not introduce an uncertainty of more than 10 % into the effective volume of the accumulation container.

After installing and before making the accumulation container air tight on the surface under investigation, the container shall be purged with radon-free air to ensure that the radon activity concentration is close to zero at the beginning of the accumulation process.

6.2 Accumulation duration

The experimental results show that accumulation takes between 1 h and 3 h depending on the volume of the accumulation container.

7 Sampling

7.1 Sampling objective

The sampling objective is to place an air sample representative of the air contained in the accumulation container in contact with the detector of the radon measuring device.

7.2 Sampling characteristics

7.2.1 General

Sampling may be either active via pumping or passive via natural diffusion. It shall not disturb the accumulation phenomenon.

Sampling characteristics depend on the measuring device used (see ISO 11665-5, ISO 11665-6 and Annexes B and C).

7.2.2 Grab sampling

When grab sampling is used, the sampling shall be carried out at the beginning and before the end of the accumulation phase. Sampling shall be carried out as specified in ISO 11665-6.

7.2.3 Continuous sampling

Continuous sampling may be

a) active, whereby the pump integrated in the radon activity concentration measuring device provides continuous air circulation between the measuring device and the accumulation container, or

b) passive by diffusion.

Sampling shall be carried out as specified in ISO 11665-5.

7.3 Sampling duration

The sampling duration depends on the measuring method used (see ISO 11665-5, ISO 11665-6 and Annexes B and C).

7.4 Volume of air sampled

The volume of air sampled depends on the measuring method used (see ISO 11665-5, ISO 11665-6 and Annexes B and C). It shall be determined accurately. To avoid alteration of the exhalation process in the case of grab sampling, the total volume of sampled air shall not exceed 10 % of the effective volume of the container.

8 Detection method

Various detection methods may be used to measure the radon activity concentration of the sampled air from the accumulation container.

For grab sampling, detection methods shall be in accordance with ISO 11665-6.

For continuous sampling, detection methods shall be in accordance with ISO 11665-5.

9 Measurement

9.1 Procedure

Measurement shall be carried out as follows.

a) Select and locate the measuring place.

b) Record the location of the measuring place.

c) Prepare the surface under investigation by removing rocks, roots, etc. if necessary.

d) Install the accumulation container on the surface of the material under investigation.

e) Purge the accumulation container with radon-free air.

f) Ensure the connection between the accumulation container and the surface under investigation is air tight.

g) Record the start time (date and hour) of the accumulation process.

h) Wait for the accumulation of radon in the container.

i) Take an air sample that is representative of the air of the container.

j) Record the time (date and hour) of sampling.

k) Measure the radon activity concentration of the sampled air. In the case of continuous sampling, measurement of the radon activity concentration shall be carried out during the accumulation process.

l) Determine the radon surface exhalation rate by calculation.

Interpretation of the results requires knowledge of the sampling and environmental conditions.

The measurement procedure for each measurement method, distinguished by the type of sampling, is specified in Annexes B and C.

9.2 Influence quantities

9.2.1 General

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 influence quantities specifed in 9.2.2 and 9.2.3 shall be considered in particular.

9.2.2 Influence quantities in the accumulation

The presence of the accumulation container on the surface under investigation systematically causes a disturbance in the free surface exhalation rate.

The following quantities can have a significant influence on the final estimations and shall be limited.

a) The variations in conditions (pressure, temperature, humidity) inside and outside the accumulation container: To minimise their effect, accumulation shall take place over a period of time with little variation in the external and internal container conditions (heavy rain and showers shall be avoided). However, the accumulation container may be thermally insulated.

b) Inadequate air tightness (leakages) and back diffusion induce radon loss. To minimize the effect of leakages, improving air tightness is recommended. To minimize the effect of back diffusion, the container shall be purged with radon-free air before beginning the accumulation process and the calculation of the exhalation rate shall be based on the initial slope of the curve of accumulation.

9.2.3 Influence quantities in measuring the radon activity concentration

The influence quantities specified in ISO 11665-5 for continuous measurement and in ISO 11665-6 for spot measurement shall be taken into consideration, as appropriate.

NOTE When the mass activity concentrations of radium-226 and radium-228 in the soil are the same, the radon-220 exhalation rate will be about two orders of magnitude higher than that of radon-222. Using measuring devices that do not discriminate between these two nuclides will generate a false result.

10 Expression of results

10.1 Radon surface exhalation rate

In accordance with the measurement procedure described in 9.1, the radon surface exhalation rate, estimated from the initial variation in radon activity concentration in the accumulation container according to time, is given by Formula (4):

$$\phi = \frac{C(t) \cdot V}{S \cdot t} \quad (4)$$

10.2 Standard uncertainty

The standard uncertainty of ϕ is calculated according to ISO/IEC Guide 98-3. Examples of the calculations of uncertainties are detailed in the various parts of ISO 11665 for each measurement method described (see ISO 11665-5, ISO 11665-6 and Annexes B and C).

10.3 Decision threshold and detection limit

The characteristic limits associated with the measurand are calculated according to ISO 11929. Examples of the calculations of characteristic limits are detailed in the various parts of ISO 11665 for each measurement method described (see ISO 11665-5, ISO 11665-6 and Annexes B and C).

10.4 Limits of the confidence interval

The lower, $\phi^{\triangleleft}$, and upper, $\phi^{\triangleright}$, limits of the confidence interval shall be calculated using Formulae (5) and (6) (see ISO 11929):

$$\phi^{\triangleleft} = \phi - k_p \cdot u(\phi);\ p = \omega \cdot (1 - \gamma/2) \quad (5)$$

$$\phi^{\triangleright} = \phi + k_q \cdot u(\phi);\ q = 1 - \omega \cdot \gamma/2 \quad (6)$$

where

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

$\omega = 1$ may be set if $\phi \geq 4u(\phi)$, in which case:

$$\phi^{\triangleleft\triangleright} = \phi \pm k_{1-\gamma/2} \cdot u(\phi) \quad (7)$$

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

11 Test report

11.1 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 11665-7:2012;

b) measurement method (continuous, spot);

c) accumulation container characteristics (geometry, height, diameter, effective surface, effective volume);

d) accumulation container location;

e) accumulation container location characteristics (characteristics of the surface under investigation, etc.);

f) time of installation of the container (date and hour);

g) accumulation duration;

h) identification of the sample;

i) sampling characteristic (active or passive);

j) sampling time (date and hour);

k) duration of sampling;

l) measuring time (date and hour);

m) units in which the results are expressed;

n) test result, $\phi \pm u(\phi)$ or $\phi \pm U$, with the associated k value.

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

a) purpose of the measurement;

b) probabilities α, ß 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 radon-222 surface exhalation rate is compared with the decision threshold (see ISO 11929), the result of the measurement shall be expressed as $\leq \phi^*$ if the result is below the decision threshold;

   2) when the radon-222 surface exhalation rate is compared with the detection limit, the result of the measurement shall be expressed as $\leq \phi^\#$ 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 the accumulation phase (rain, snow, storm, humidity, atmospheric pressure, surrounding air temperature, etc.);

   2) ventilation conditions for indoor measurement (mechanical ventilation system, doors and windows open or shut, etc.) prior to sampling (over a period of a few hours) and at the time of sampling.

11.3 The results can be expressed in a similar format to that shown in Annex A.

Annex A
(informative)

Example of a sample results sheet

Estimation of ^{222}Rn surface exhalation rate at the interface with the atmosphere (ISO 11665-7)			
Identification	**Reference to the relevant part of ISO 11665**		
	Purpose of measurement		
	Measurement method		
Accumulation container			
Characteristics	Serial no.		
	Geometry		
	Height and diameter		
	Effective surface		
	Effective volume		
Installation conditions	**Date and time**	Accumulation start	Date (day/month/year): Time (hour:minute):
		Accumulation end	Date (day/month/year): Time (hour:minute):
	Site	Country/administrative region	
		Commune/named locality	
		Postcode	
	Interface formed by the ground	Ground characteristics: — ground type — plant formation — other (specify)	sandy – loamy – clayey – etc.
		Topography: — slope — aspect	
		Any changes to the surface under investigation	
	Other interfaces	Nature	inside floor – wall – rock – concrete – parquet – breeze block – rubble stone – etc.
		Surface state	fissured – porous – etc.
		Other (specify)	finish covering (paint – wallpaper – etc.)

Sampling			
Characteristics	**Identification of the sample**		
	Sampling characteristics		passive – active
	Date and time	Start	Date (day/month/year): Time (hour:minute):
		End	Date (day/month/year): Time (hour:minute):
	Sampling duration		
Additional information	Ground humidity Ground temperature		Specify whether an observation or a measurement
Weather conditions	Observations in situ		rain – storm – snow – frost – fog – sun – drought – etc.
	National or local data		
	Temperature		
	Pressure		

RADON ACTIVITY CONCENTRATION MEASURING RESULTS

Date and time of the first measurement					
Activity concentration	$C_1 =$	Bq/m^3	Uncertainty ($k =$):		Bq/m^3
Date and time of the second measurement					
Activity concentration	$C_2 =$	Bq/m^3	Uncertainty ($k =$):		Bq/m^3
ESTIMATION OF SURFACE EXHALATION RATE					
Surface exhalation rate	$\phi =$	Bq/m^2/s	Standard uncertainty:		Bq/m^2/s
Comments					

Annex B
(informative)

Estimation of radon surface exhalation rate using a continuous measurement method

B.1 General

This annex deals with estimating the radon surface exhalation rate using a continuous method via circulation or diffusion.

Estimating the radon surface exhalation rate at a given place using a continuous measuring method involves measuring variations in the radon activity concentration as a function of time, in an accumulation container with known geometric characteristics and with one open face applied to the surface under investigation (soil, rock, building material, wall, etc.).

The accumulation duration is taken to be short enough that back diffusion can be considered negligible. The air tightness of the accumulation container is assumed to have been improved so that the ventilation due to leakages can also be considered negligible.

For the purposes of this annex, the symbols given in Clause 3 and the following apply.

C_i radon activity concentration at time t_i, in becquerels per cubic metre

$\bar{C}_i$ average value of radon activity concentrations C_i, in becquerels per cubic metre

C_0 background radon activity concentration of the measuring device, in becquerels per cubic metre

t_i time of the i^{th} measurement, in seconds

$\bar{t}_i$ average value of times t_i, in seconds

Δt time interval used for estimating the surface exhalation rate, in seconds

B.2 Principle of the measurement method

B.2.1 Circulation measurement method

The apparatus (see Figure B.1) includes an accumulation container and a continuous radon measuring device through circulation.

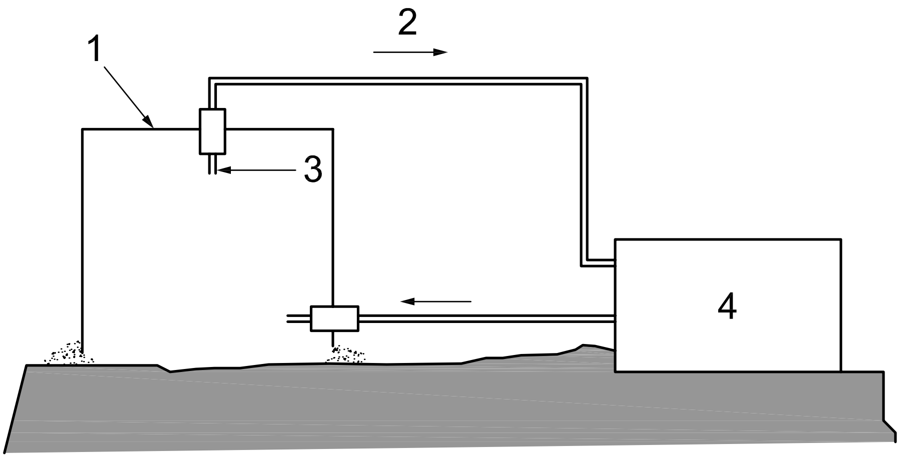
The accumulation container is a polypropylene cylinder with its external face covered by a layer of aluminium to reflect as much light as possible and thus prevent overheating. Two orifices are available for continuous air sampling to measure the radon activity concentration. The pump integrated into the measuring device keeps the air circulating with a sampling flow-rate at low intensity (equal to 0,5 l/min) in order to avoid actively sucking radon from the soil air.

The accumulation container dimensions could be as follows:

a) height: 14 cm;

b) diameter: 16 cm;

or equivalent dimensions based on scientific principles.



Key

1 accumulation container

2 high-density polyethylene tube

3 sampling point

4 continuous radon measuring device with pump

Figure B.1 — Outline drawing of a device for estimating radon surface exhalation rate using a continuous circulation measurement method

B.2.2 Diffusion measurement method

The apparatus (see Figure B.2) includes the following components:

a) an accumulation container;

b) an instrument, housed in a detection chamber, which samples, continuously and under diffusion conditions, a volume of air in the accumulation chamber and measures the radiations emitted by radon and its decay products.

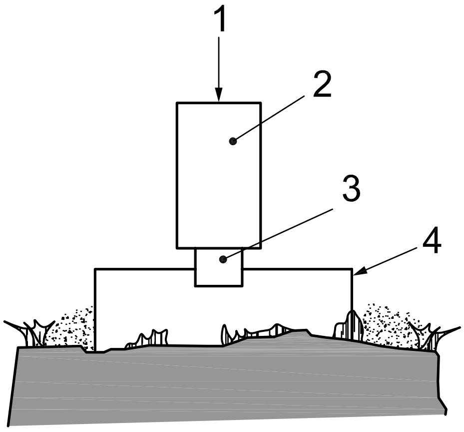
The accumulation container is a stainless steel cylinder with a device on its upper face that easily accommodates the radon measuring device.

The accumulation container dimensions could be as follows:

— height: 4,5 cm;

— diameter: 60 cm;

or equivalent dimensions based on scientific principles.



Key

1 continuous radon measuring device

2 detector electronics

3 detector

4 accumulation container

Figure B.2 — Outline drawing of a device for estimating radon surface exhalation rate using a continuous diffusion measurement method

B.3 Measurement procedure

Measurement is performed as follows:

a) Select and locate the measuring place.

b) Record the location of the measuring place.

c) Prepare the surface to be investigated by removing rocks, roots, etc. if necessary.

d) Install the accumulation container.

e) Set the radon measuring device in place.

f) Purge the accumulation container with radon-free air.

g) Ensure air tightness between the accumulation container and the surface under investigation;

h) Allow radon to accumulate in the container and monitor the variations of the radon activity concentration measured by the continuous radon measuring device for a period of 1 h to 3 h;

i) Record the time (date and hour) of the accumulation process.

j) Read the data (radon activity concentration) recorded during the accumulation process and calculating the surface exhalation rate.

B.4 Expression of results

B.4.1 Surface exhalation rate

The radon surface exhalation rate is estimated using Formula (4) and expressed by the relationship given in Formula (B.1):

$$\phi = p \cdot \frac{V}{S} = p \cdot \omega_\mathrm{p} \quad \text{with} \quad \omega_\mathrm{p} = \frac{V}{S} \tag{B.1}$$

where

p is the slope of the linear regression straight line calculated from C_i and t_i over the time interval Δt and is given by the relationship:

$$p = \frac{\sum \left\{ \left(t_i - \bar{t}_i\right) \cdot \left[\left(C_i - C_0\right) - \left(\bar{C}_i - C_0\right) \right] \right\}}{\sum \left(t_i - \bar{t}_i\right)^2} \tag{B.2}$$

The reduction in the radon activity concentration in the container due to its radioactive decay, back diffusion and ventilation is considered negligible.

B.4.2 Standard uncertainty

The variables p, V and S are considered independent.

In accordance with ISO/IEC Guide 98-3, the standard uncertainty of ϕ shall be calculated as given in Formula (B.3):

$$u(\phi) = \sqrt{\omega_\mathrm{p}{}^2 \cdot u^2(p) + \phi^2 \cdot \left[u_\mathrm{rel}^2\left(\omega_\mathrm{p}\right) \right]} \tag{B.3}$$

with

$$u_\mathrm{rel}^2\left(\omega_\mathrm{p}\right) = u_\mathrm{rel}^2(V) + u_\mathrm{rel}^2(S) \tag{B.4}$$

$$u^2(p) = \frac{\sum \left\{ \left(t_i - \bar{t}_i\right)^2 \cdot \left[u^2(C_i) + u^2(\bar{C}_i) + 2 \cdot u^2(C_0) \right] \right\}}{\left[\sum \left(t_i - \bar{t}_i\right)^2 \right]^2} \tag{B.5}$$

The calculation of the characteristic limits (see ISO 11929) requires the calculation of $\tilde{u}(\tilde{\phi})$, i.e. the standard uncertainty of ϕ as a function of its true value, calculated as given in Formula (B.6):

$$\tilde{u}\left(\tilde{\phi}\right) = \sqrt{\omega_\mathrm{p}{}^2 \cdot u^2\left(p \middle| \phi = \tilde{\phi}\right) + \tilde{\phi}^2 \cdot u_\mathrm{rel}^2\left(\omega_\mathrm{p}\right)} \tag{B.6}$$

B.4.3 Decision threshold

The decision threshold, ϕ^*, is obtained from Formula (B.6) for $\tilde{\phi} = 0$ (see ISO 11929), i.e. $C_i = \bar{C}_i = C_0$ for all values of i.

This yields Formula (B.7):

$$\phi^* = k_{1-\alpha} \cdot \tilde{u}(0) = k_{1-\alpha} \cdot \sqrt{\omega_\mathrm{p}{}^2 \cdot \frac{4 \cdot u^2(C_0)}{\sum \left(t_i - \bar{t}_i\right)^2}} = 2 \cdot k_{1-\alpha} \cdot \omega_\mathrm{p} \cdot \sqrt{\frac{u^2(C_0)}{\sum \left(t_i - \bar{t}_i\right)^2}} \tag{B.7}$$

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

B.4.4 Detection limit

The detection limit, $\phi^{\#}$, is calculated as given in Formula (B.8) (see ISO 11929):

$$\phi^{\#} = a + \sqrt{a^2 + \left(k_{1-\beta}^2 - k_{1-\alpha}^2\right) \cdot \tilde{u}^2\left(\tilde{\phi} = 0\right)} = a + \sqrt{a^2 + \left(k_{1-\beta}^2 - k_{1-\alpha}^2\right) \cdot \tilde{u}^2(0)} \quad \text{(B.8)}$$

with

$$a = k_{1-\alpha} \cdot \tilde{u}(0) + \frac{1}{2} \cdot \left(\frac{k_{1-\beta}^2}{\phi}\right) \cdot \left[u^2(\phi) - \tilde{u}^2(0)\right] \quad \text{(B.9)}$$

If $\alpha = \beta$, then $\phi^{\#} = 2 \cdot a$ follows.

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

B.5 Example

The following example is based on an estimation of radon surface exhalation rate of a soil in the Haute-Vienne department (France).

The variations in the radon activity concentration in the accumulation container are represented in Figure B.3.

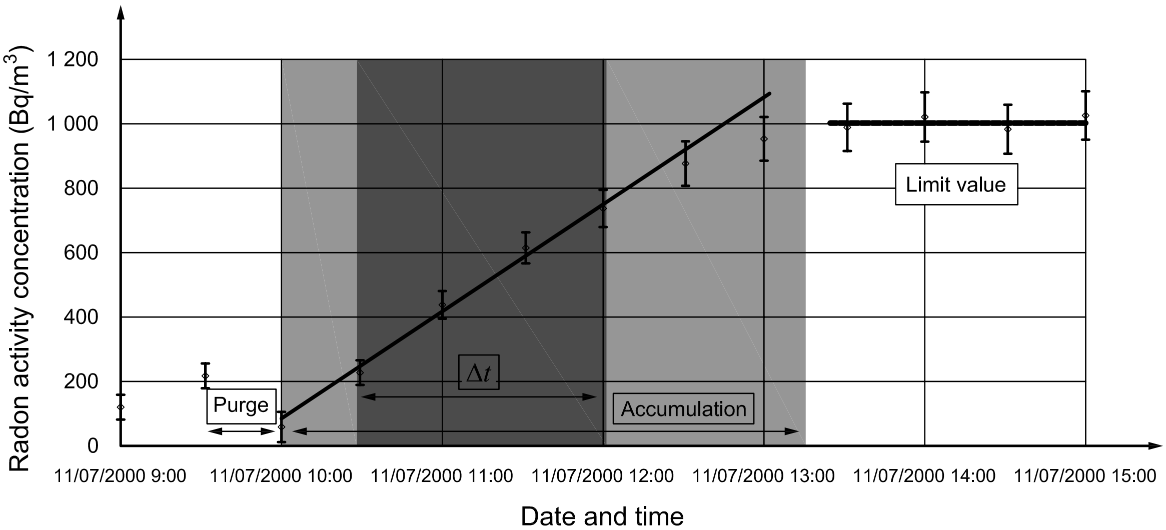


Figure B.3 — Variations in radon activity concentration in the accumulation container

The data used to calculate the initial slope of the accumulation curve are those comprised in time interval Δt and are assembled in Table B.1.

Table B.1 — Data used to calculate the slope of the accumulation curve

Date and time	Radon activity concentration Bq/m^3	Standard uncertainty
07/11/00 10:30	220	30
07/11/00 11:00	440	45
07/11/00 11:30	620	50
07/11/00 12:00	740	55

The background radon activity concentration of the radon measuring device, with its standard uncertainty, is:

$C_0 = 20 \pm 10$ Bq/m^3

The slope is calculated using Formula (B.2) and the related uncertainty using Formula (B.5).

The value obtained for the slope, with its standard uncertainty, is:

$p = 0{,}096\,7 \pm 0{,}013$ Bq/m^3/s

The following geometric characteristics of the accumulation container are involved in the calculation of the exhalation rate:

a) effective volume: $V = 12{,}7 \pm 1{,}25 \times 10^{-3}$ m^3;

b) effective surface: $S = 28{,}3 \pm 1{,}4 \times 10^{-2}$ m^2.

The uncertainty of the effective volume is considered equal to 10 %. This value takes into account the irregularities of the surface under investigation and the positioning of the accumulation container with respect to the ground (container more or less sunk into the ground).

The uncertainty of the effective surface is considered equal to 5 %. This value covers the irregularities of the surface under investigation.

The radon surface exhalation rate is calculated using Formula (B.1):

$$\phi = 4{,}34 \times 10^{-3} \text{ Bq/m}^2\text{/s}$$

The standard uncertainty of ϕ is calculated using Formula (B.3):

$$u(\phi) = 0{,}75 \times 10^{-3} \text{ Bq/m}^2\text{/s}$$

Thus, the result is expressed as:

$$\phi = 4{,}34 \pm 0{,}75 \text{ Bq/m}^2\text{/s}$$

The decision threshold, ϕ^*, is obtained from Formula (B.7):

$$\phi^* = 0{,}37 \times 10^{-3} \text{ Bq/m}^2\text{/s}$$

The detection limit, $\phi^\#$, is calculated using Formula (B.8) with $\alpha = \beta = 0{,}05$ and $k_{1-\alpha} = k_{1-\beta} = 1{,}65$:

$$\phi^\# = 1{,}06 \times 10^{-3} \text{ Bq/m}^2\text{/s}$$

Annex C
(informative)

Estimation of radon surface exhalation rate using a spot measurement method

C.1 General

This annex deals with estimating the radon surface exhalation rate using a spot measurement method.

Estimating the radon surface exhalation rate at a given place involves measuring changes in the radon activity concentration over a given period of time, in an accumulation container with known geometric characteristics and with one open face applied to the surface under investigation (soil, rock, building material, wall, etc.).

The accumulation container is purged with radon-free air before the accumulation process begins and the accumulation duration is taken to be short enough that back diffusion can be considered negligible. The air tightness of the accumulation container is assumed to have been improved so that the ventilation due to leakages can also be considered negligible.

The radon spot measurement method is performed with scintillation cells (see ISO 11665-6:2012, Annex A).

For the purposes of this annex, the symbols given in Clause 3 and the following apply.

C_0 background activity concentration in the accumulation container, in becquerels per cubic metre

$\bar{N}_s$ average number of gross counts of the cell used for the measurement of C

$\bar{N}_0$ number of background counts of the cell used for the measurement of C

$\bar{N}_s^0$ average number of gross counts of the cell used for the measurement of C_0

$\bar{N}_0^0$ number of background counts of the cell used for the measurement of C_0

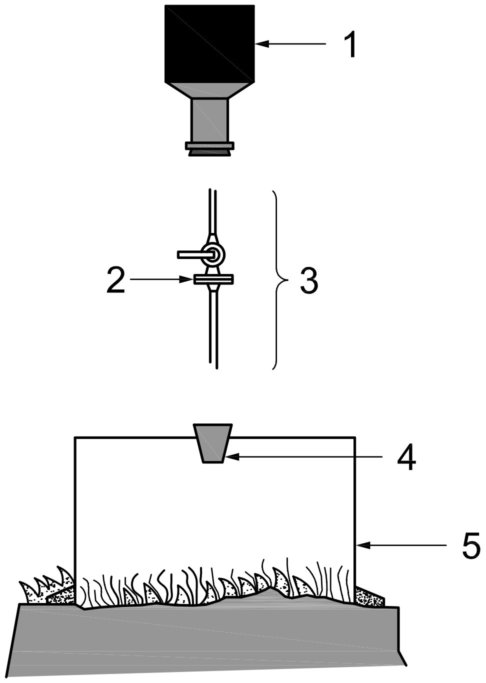
n number of countings of each sample

C.2 Equipment

The apparatus (see Figure C.1) includes the following components:

a) an accumulation container;

b) a spot radon measuring instrument (sampling device and scintillation cell).



Key

1 scintillation cell

2 filter

3 sampling device

4 plug

5 accumulation container

Figure C.1 — Outline drawing of a device for estimating radon surface exhalation rate using a spot measurement method

The accumulation container is stainless steel and cylindrical in shape, with an orifice closed by a rubber plug in its closed face.

The accumulation container dimensions could be as follows:

— height: 11 cm;

— diameter: 30 cm;

or equivalent dimensions based on scientific principles.

Given the installation conditions, the effective volume is estimated at $7{,}06 \times 10^{-3}$ m^3 and the effective surface is $7{,}06 \times 10^{-2}$ m^2.

C.3 Measurement procedure

Measurement is carried out as follows.

a) Select and locate the measuring place.

b) Record the location of the measuring place.

c) Prepare the surface to be investigated by removing rocks, roots, etc. if necessary.

d) Install the accumulation container.

e) Purge the accumulation container with radon-free air.

f) Ensure air tightness between the accumulation container and the surface under investigation.

g) Sample a volume of air representative of the air contained in the container at the beginning of the accumulation phase using one or two scintillation cells placed under vacuum in advance (see ISO 11665-6).

h) Record the time (date, hour and minute) of the first sampling procedure.

i) Waiting for the accumulation of radon in the container.

j) Sample a volume of air representative of the air contained in the accumulation container at the end of the accumulation duration (period of 1 h to 3 h) using one or two scintillation cells placed under vacuum in advance (see ISO 11665-6).

k) Record the time (date, hour and minute) of the second sampling procedure.

l) Wait until a radioactive equilibrium between the ^{222}Rn and its short-lived decay products (^{214}Po, ^{218}Po) is achieved in each cell. For optimal counting, a period of 3 h shall elapse after the sampling in order to achieve radioactive equilibrium (see ISO 11665-6).

m) Count the number of photons emitted by the scintillation medium when excited by the alpha particles that are produced by the disintegration of the radon and its short-lived decay products present in the cells. A pre-calibrated photomultiplier placed in a lightproof enclosure is used for the counting (see ISO 11665-6);

n) Calculate the radon surface exhalation rate.

NOTE Care needs to be taken that the total volume of samples remains less than 10 % of the effective volume of the accumulation container.

C.4 Expression of results

C.4.1 Surface exhalation rate

The radon surface exhalation rate is estimated from Formula (4).

If the reduction in the radon activity concentration in the container is considered negligible due to its decay, the radon surface exhalation rate can be simplified through a series expansion of the exponential and therefore becomes:

$$\phi = \frac{(C - C_0) \cdot V}{S \cdot t} = (C - C_0) \cdot \omega_c \quad \text{with} \quad \omega_c = \frac{V}{S \cdot t} \tag{C.1}$$

In accordance with ISO 11665-6, the radon activity concentrations C and C_0 are calculated as given in Formulae (C.2) and (C.3):

$$C = \left(\bar{N}_s - \bar{N}_0\right) \cdot \omega \tag{C.2}$$

$$C_0 = \left(\bar{N}_s^0 - \bar{N}_0^0\right) \cdot \omega \tag{C.3}$$

where ω depends on the cell volume, the calibration and correction factors, the counting duration and the number of alpha emitters present in the cell at the time of counting (see ISO 11665-6:2012, Annex A).

Formula (C.1) can therefore be expressed as follows:

$$\phi = \left(\bar{N}_s - \bar{N}_0 - \bar{N}_s^0 + \bar{N}_0^0\right) \cdot W \quad \text{with} \quad W = \omega \cdot \omega_c \tag{C.4}$$

C.4.2 Standard uncertainty

The variables $\bar{N}_s$, $\bar{N}_0$, $\bar{N}_s^0$, $\bar{N}_0^0$, V, S and t are considered independent.

In accordance with ISO/IEC Guide 98-3, the standard uncertainty of ϕ shall be calculated as given in Formula (C.5):

$$u(\phi) = \sqrt{\frac{W^2}{n} \cdot \left(\bar{N}_\mathrm{s} + \bar{N}_0 + \bar{N}_\mathrm{s}^0 + \bar{N}_0^0 \right) + \phi^2 \cdot u_\mathrm{rel}^2(W)} \quad \text{(C.5)}$$

where

$$u_\mathrm{rel}^2(W) = u_\mathrm{rel}^2(\omega) + u_\mathrm{rel}^2(\omega_\mathrm{c})$$

and

$$u_\mathrm{rel}^2(\omega_\mathrm{c}) = u_\mathrm{rel}^2(V) + u_\mathrm{rel}^2(S) + u_\mathrm{rel}^2(t)$$

Calculation of the characteristic limits (see ISO 11929) requires calculation of $\tilde{u}(\tilde{\phi})$, i.e. the standard uncertainty of ϕ as a function of its true value, calculated as given in Formula (C.6):

$$\tilde{u}(\tilde{\phi}) = \sqrt{\frac{W^2}{n} \cdot \left(\frac{\tilde{\phi}}{W} + 2\bar{N}_0 + 2\bar{N}_\mathrm{s}^0 \right) + \tilde{\phi}^2 \cdot u_\mathrm{rel}^2(W)} \quad \text{(C.6)}$$

C.4.3 Decision threshold

The decision threshold, ϕ^*, is obtained from Formula (C.6) for $\tilde{\phi} = 0$ (see ISO 11929).

This yields Formula (C.7):

$$\phi^* = k_{1-\alpha} \cdot \tilde{u}(0) = k_{1-\alpha} \cdot \sqrt{2 \cdot \frac{W^2}{n} \cdot \left(\bar{N}_0 + \bar{N}_\mathrm{s}^0 \right)} = k_{1-\alpha} \cdot W \cdot \sqrt{\frac{2 \cdot \left(\bar{N}_0 + \bar{N}_\mathrm{s}^0 \right)}{n}} \quad \text{(C.7)}$$

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

C.4.4 Detection limit

The detection limit, $\phi^\#$, is calculated as given in Formula (C.8) (see ISO 11929):

$$\phi^\# = \phi^* + k_{1-\beta} \cdot \tilde{u}\left(\phi^\#\right) = \phi^* + k_{1-\beta} \cdot \sqrt{\frac{W^2}{n} \cdot \left(\frac{\phi^\#}{W} + 2\bar{N}_0 + 2\bar{N}_\mathrm{s}^0 \right) + \phi^{\#2} \cdot u_\mathrm{rel}^2(W)} \quad \text{(C.8)}$$

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

The detection limit can be calculated by solving Equation (C.8) for $\phi^\#$ or, more simply, by iteration with a starting approximation of $\phi^\# = 2 \cdot \phi^*$ in terms of the right side of Formula (C.8).

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

$$\phi^\# = \frac{2 \cdot \phi^* + k^2 \cdot \left(W/n \right)}{1 - k^2 \cdot u_\mathrm{rel}^2(W)} \quad \text{(C.9)}$$

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

C.5 Example

The following example is based on an estimation of the radon surface exhalation rate of a soil in the Pyrénées-Atlantiques department (France).

The accumulation container is cylindrical in shape. Its geometric characteristics are as follows:

a) effective volume: $V = (7{,}06 \pm 0{,}7) \times 10^{-3}$ m^3;

b) effective surface: $S = (7{,}06 \pm 0{,}35) \times 10^{-2}$ m^2.

The accumulation duration t reaches (7 200 ± 60) s.

Values of ω and $u_{\text{rel}}^2(\omega)$ are the same as those used in ISO 11665-6:2012, Annex A:

$\omega = 24{,}69$ and $u_{\text{rel}}^2(\omega) = 0{,}01$

For a sample taken at $t = 0$ (at the beginning of the accumulation process):

$\bar{N}_0^0 = 1$ pulses (with $n = 2$ countings)

$\bar{N}_\text{s}^0 = 2$ pulses (with $n = 2$ countings)

For a sample performed at $t = 7\ 200$ s (at the end of the accumulation process):

$\bar{N}_0 = 3$ pulses (with $n = 2$ countings)

$\bar{N}_\text{s} = 274$ pulses (with $n = 2$ countings)

The radon surface exhalation rate is calculated using Formula (C.4):

$$\phi = 92{,}6 \times 10^{-3} \text{ Bq/m}^2\text{/s}$$

The standard uncertainty of ϕ is calculated using Formula (C.5):

$$u_\phi = 14{,}42 \times 10^{-3} \text{ Bq/m}^2\text{/s}$$

Thus, the result is expressed as follows:

$$\phi = (92{,}6 \pm 14{,}42) \text{ Bq/m}^2\text{/s}$$

The decision threshold, ϕ^*, is calculated using Formula (C.7):

$$\phi^* = 1{,}27 \text{ Bq/m}^2\text{/s}$$

The detection limit, $\phi^\#$, is calculated using Formula (C.9):

$$\phi^\# = 3{,}19 \text{ Bq/m}^2\text{/s}$$

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