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

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

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

Partie 1: Origine du radon et de ses descendants à vie courte, et méthodes de mesure associées

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Foreword

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

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

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

This second edition cancels and replaces the first edition (ISO 11665-1:2012), of which it constitutes a minor revision. The changes compared to the previous edition are as follows:

- update of the Introduction;
- in A.2.4, details added for change in radon activities concentration in time and space in buildings;
- update of the Bibliography.

A list of all the parts in the ISO 11665 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

Radon isotopes 222, 219 and 220 are radioactive gases produced by the disintegration of radium isotopes 226, 223 and 224, which are decay products of uranium-238, uranium-235 and thorium-232 respectively, and are all found in the earth's crust (see Annex A for further information). 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 [2][3][4][5].

Radon is today considered to be the main source of human exposure to natural radiation. UNSCEAR[6] 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 (see Annex A). For this reason, references to radon in this document refer only to radon-222.

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

As radon tends to concentrate in enclosed spaces like houses, the main part of the population exposure is due to indoor radon. Soil gas is recognized as the most important source of residential radon through infiltration pathways. Other sources are described in other parts of ISO 11665 and ISO 13164 series for water[59].

Radon enters into buildings via diffusion mechanism caused by the all-time existing difference between radon activity concentrations in the underlying soil and inside the building, and via convection mechanism inconstantly generated by a difference in pressure between the air in the building and the air contained in the underlying soil. Indoor radon activity concentration depends on radon activity concentration in the underlying soil, the building structure, the equipment (chimney, ventilation systems, among others), the environmental parameters of the building (temperature, pressure, etc.) and the occupants' lifestyle.

To limit the risk to individuals, a national reference level of 100 Bq·m^{-3} is recommended by the World Health Organization[5]. Wherever this is not possible, this reference level should not exceed 300 Bq·m^{-3}. This recommendation was endorsed by the European Community Member States that shall establish national reference levels for indoor radon activity concentrations. The reference levels for the annual average activity concentration in air shall not be higher than 300 Bq·m^{-3}[5].

To reduce the risk to the overall population, building codes should be implemented that require radon prevention measures in buildings under construction and radon mitigating measures in existing buildings. Radon measurements are needed because building codes alone cannot guarantee that radon concentrations are below the reference level.

ISO 11665 consists of several parts (see Figure 1) dealing with:

— measurement methods for radon-222 and its short-lived decay products (see ISO 11665-2, ISO 11665-3, ISO 11665-4, ISO 11665-5 and ISO 11665-6);

NOTE 1 There are many methods for measuring the radon-222 activity concentration and the potential alpha energy concentration of its short-lived decay products. The choice of measurement method depends on the expected level of concentration and on the intended use of the data, such as scientific research and health-related assessments[8][9].

— measurement methods for the radon-222 exhalation rate (see ISO 11665-7 and ISO 11665-9);

NOTE 2 ISO 11665-7 refers back to ISO 11665-5 and ISO 11665-6.

- measurement methods for the radon-222 in the soil (see ISO 11665-11);
- methodologies for radon-222 measurements in buildings (see ISO 11665-8);
- measurement methods for the radon-222 diffusion coefficient (see ISO/TS 11665-12 and ISO/TS 11665-13)

NOTE 3 ISO 11665-8 refers back to ISO 11665-4 for radon measurements for initial investigation purposes in a building and to ISO 11665-5, ISO 11665-6 and ISO 11665-7 for measurements for any additional investigation.

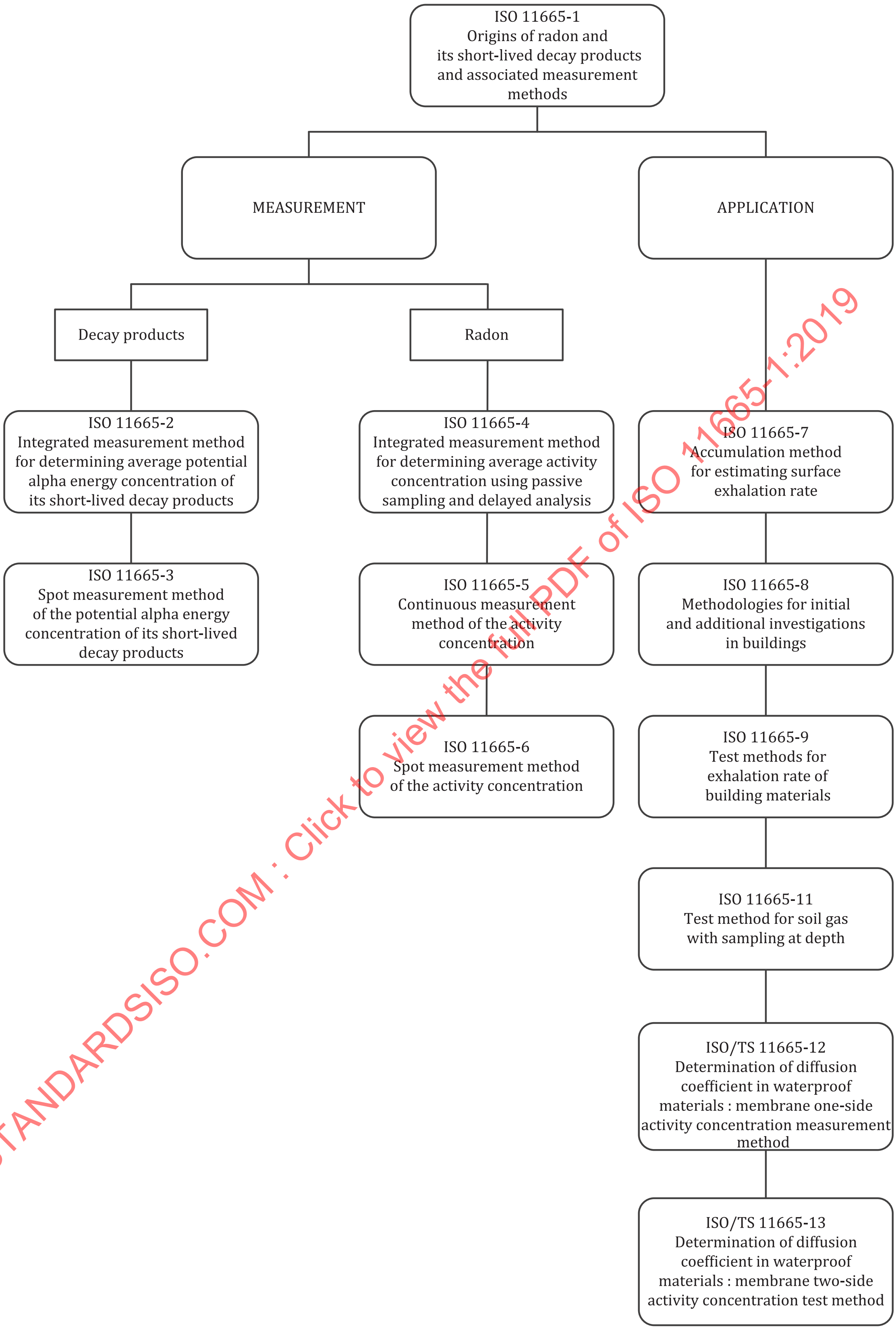


Figure 1 — Structure of the ISO 11665 series

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

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

1 Scope

This document outlines guidance for measuring radon-222 activity concentration and the potential alpha energy concentration of its short-lived decay products in the air.

The measurement methods fall into three categories:

a) spot measurement methods;

b) continuous measurement methods;

c) integrated measurement methods.

This document provides several methods commonly used for measuring radon-222 and its short-lived decay products in air.

This document also provides guidance on the determination of the inherent uncertainty linked to the measurement methods described in its different parts.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC 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 61577-2, *Radiation protection instrumentation — Radon and radon decay product measuring instruments — Part 2: Specific requirements for* ^{222}*Rn and* ^{220}*Rn measuring instruments*

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 following terms and definitions apply.

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

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

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

3.1.1
active sampling

sampling using active devices like pumps for sampling the atmosphere

[SOURCE: IEC 61577-1:2006, 3.2.22]

3.1.2
activity

disintegration rate

number of spontaneous nuclear disintegrations occurring in a given quantity of material during a suitably small interval of time divided by that interval of time

Note 1 to entry: Activity, A, is expressed by the relationship given in Formula (1):

$$A = \lambda \cdot N$$

where

λ is the decay constant per second;

N is the number of atoms.

Note 2 to entry: The decay constant is linked to the radioactive half-life by the relationship:

$$\lambda = \frac{\ln 2}{T_{1/2}}$$

where

$T_{1/2}$ is the radioactive half-life, in seconds.

3.1.3
activity concentration

activity per unit volume

[SOURCE: IEC 61577-1:2006, 3.1.2]

3.1.4
attached fraction

fraction of the potential alpha energy concentration of short-lived decay products that is attached to the ambient aerosol

[SOURCE: IEC 61577-1:2006, 3.2.15, modified]

Note 1 to entry: The sizes of the carrier aerosol to which most of the short-lived decay products are attached are generally in the 0,1 µm to 0,3 µm range of median values.

3.1.5
average activity concentration

exposure to activity concentration divided by the sampling duration

3.1.6
average potential alpha energy concentration

exposure to potential alpha energy concentration divided by the sampling duration

3.1.7
background noise
signals caused by something other than the radiation to be detected

Note 1 to entry: A distinction can be made between signals caused by radiation from sources inside or outside the detector other than those targeted for the measurements and signals caused by defects in the detection system electronic circuits and their electrical power supply.

3.1.8
continuous measurement
measurement obtained by taking a sample continuously (or at integration intervals typically in range of 1 min to 120 min) with simultaneous or slightly delayed analysis

Note 1 to entry: The sampling duration shall be adapted to the dynamics of the phenomenon studied to monitor the evolution of radon activity concentration over time.

Note 2 to entry: See Annex B for further information.

3.1.9
diffusion length
distance crossed by an atom due to diffusion forces before decaying

Note 1 to entry: Diffusion length, l, is expressed by the relationship given in Formula (3):

$$l = \left(\frac{D}{\lambda}\right)^{1/2}$$

where

D is the diffusion coefficient, in square metres per second;

λ is the decay constant per second.

3.1.10
equilibrium factor
ratio of the potential alpha energy concentration of short-lived radon decay products in a given volume of air to the potential alpha energy concentration of these decay products if these are in radioactive equilibrium with radon in the same volume of air

Note 1 to entry: The short-lived ^{222}Rn decay products present in an atmosphere are very rarely in radioactive equilibrium with their parent (through being trapped on the walls or eliminated by an air renewal system, for example) and the equilibrium factor is used to qualify this state of "non-equilibrium".

Note 2 to entry: The equilibrium factor is between 0 and 1. The equilibrium factor in buildings typically varies between 0,1 and 0,9, with an average value equal to 0,4[4][6].

Note 3 to entry: The equilibrium factor, F_{eq}, is expressed by Formula (4):

$$F_{\mathrm{eq}} = \frac{E_{\mathrm{PAEC},222_{\mathrm{Rn}}}}{5{,}57 \cdot 10^{-9} \times C_{222_{\mathrm{Rn}}}}$$

where

$E_{\mathrm{PAEC},222_{\mathrm{Rn}}}$	is the potential alpha energy concentration of ^{222}Rn, in joules per cubic metre;
$5{,}57 \times 10^{-9}$	is the potential alpha energy concentration of the short-lived ^{222}Rn decay products for 1 Bq of ^{222}Rn in equilibrium with its short-lived decay products, in joules per becquerel;
$C_{222_{\mathrm{Rn}}}$	is the activity concentration of ^{222}Rn, in becquerels per cubic metre.

3.1.11

grab sampling

collection of a sample (i.e of air containing radon or aerosol particles) during a period considered short compared with the fluctuations of the quantity under study (i.e volume activity of air)

[SOURCE: IEC 61577-1:2006, 3.2.18]

3.1.12

guideline value

value which corresponds to scientific, legal or other requirements with regard to the detection capability and which is intended to be assessed by the measurement procedure by comparison with the detection limit

Note 1 to entry: The guideline value can be given, for example, as an activity, a specific activity or an activity concentration, a surface activity or a dose rate.

Note 2 to entry: The comparison of the detection limit with a guideline value allows a decision on whether or not the measurement procedure satisfies the requirements set forth by the guideline value and is therefore suitable for the intended measurement purpose. The measurement procedure satisfies the requirement if the detection limit is smaller than the guideline value.

Note 3 to entry: The guideline value shall not be confused with other values stipulated as conformity requests or as regulatory limits.

[SOURCE: ISO 11929-2:2019, 3.18]

3.1.13

integrated measurement

measurement performed by continuous sampling of a volume of air which, over time, is accumulating physical quantities (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

Note 1 to entry: See Annex B for further information.

3.1.14

long-term measurement

measurement based on an air sample collected within a period greater than one month

3.1.15

measurand

quantity intended to be measured

[SOURCE: ISO/IEC Guide 99:2007, 2.3]

3.1.16

measuring system

set of one or more measuring instruments and often other devices, including any reagent and supply, assembled and adapted to give information used to generate measured quantity values within specified intervals for quantities of specified kinds

[SOURCE: ISO/IEC Guide 99:2007, 3.2]

3.1.17

passive sampling

sampling using no active devices such as pumps for sampling the atmosphere, whereby in most instruments sampling is performed mainly by diffusion

[SOURCE: IEC 61577-1:2006, 3.2.21 modified]

3.1.18
potential alpha energy of short-lived radon decay products

total alpha energy emitted during the decay of atoms of short-lived radon decay products along the decay chain through to ^{210}Pb for the decay chains of the ^{222}Rn

Note 1 to entry: The potential alpha energy of short-lived ^{222}Rn decay products, $E_{\mathrm{PAE},222_{\mathrm{Rn}}}$, is expressed by Formula (5):

$$E_{\mathrm{PAE},222\,\mathrm{Rn}} = \left[\begin{array}{l}\left(E_{\mathrm{AE},218\,\mathrm{Po}} + E_{\mathrm{AE},214\,\mathrm{Po}}\right)\cdot\left(N_{218\,\mathrm{Po}}\right)\\ + E_{\mathrm{AE},214\,\mathrm{Po}}\cdot\left(N_{214\,\mathrm{Pb}} + N_{214\,\mathrm{Bi}}\right) + E_{\mathrm{AE},214\,\mathrm{Po}}\cdot\left(N_{214\,\mathrm{Po}}\right)\end{array}\right]$$

where

$E_{\mathrm{AE},218\,\mathrm{Po}}$	is the alpha particle energy produced by the disintegration of ^{218}Po, in joules;
$E_{\mathrm{AE},214\,\mathrm{Po}}$	is the alpha particle energy produced by the disintegration of ^{214}Po, in joules;
$N_{218_{\mathrm{Po}}}$	is the number of atoms of ^{218}Po;
$N_{214_{\mathrm{Pb}}}$	is the number of atoms of ^{214}Pb;
$N_{214_{\mathrm{Bi}}}$	is the number of atoms of ^{214}Bi;
$N_{214_{\mathrm{Po}}}$	is the number of atoms of ^{214}Po.

Note 2 to entry: The total alpha energy emitted during the decay of atoms of short-lived radon decay products along the decay chain through to ^{208}Pb for the decay chains of the ^{220}Rn is expressed by Formula (6):

$$E_{\mathrm{PAE},220\,\mathrm{Rn}} = \left[\begin{array}{l}\left(E_{\mathrm{AE},216_{\mathrm{Po}}} + 0{,}36\cdot E_{\mathrm{AE},212_{\mathrm{Bi}}} + 0{,}64\cdot E_{\mathrm{AE},212_{\mathrm{Po}}}\right)\cdot\left(N_{216_{\mathrm{Po}}}\right)\\ + \left(0{,}36\cdot E_{\mathrm{AE},212_{\mathrm{Bi}}} + 0{,}64\cdot E_{\mathrm{AE},212_{\mathrm{Po}}}\right)\cdot\left(N_{212_{\mathrm{Pb}}} + N_{212_{\mathrm{Bi}}}\right) + E_{\mathrm{AE},212_{\mathrm{Po}}}\cdot\left(N_{212_{\mathrm{Po}}}\right)\end{array}\right]$$

where

$E_{\mathrm{PAE},220_{\mathrm{Rn}}}$	is the potential alpha energy of ^{220}Rn, in joules;
$E_{\mathrm{AE},216\,\mathrm{Po}}$	is the alpha particle energy produced by the disintegration of ^{216}Po, in joules;
$E_{\mathrm{AE},212\,\mathrm{Bi}}$	is the alpha particle energy produced by the disintegration of ^{212}Bi, in joules;
$E_{\mathrm{AE},212\,\mathrm{Po}}$	is the alpha particle energy produced by the disintegration of ^{212}Po, in joules;
$N_{212_{\mathrm{Pb}}}$	is the number of atoms of ^{212}Pb;
$N_{212_{\mathrm{Bi}}}$	is the number of atoms of ^{212}Bi;
$N_{212_{\mathrm{Po}}}$	is the number of atoms of ^{212}Po.

3.1.19
potential alpha energy concentration of short-lived radon decay products

concentration of any mixture of short-lived radon decay products in air in terms of the alpha energy released during complete decay through ^{210}Pb and/or ^{208}Pb respectively

[SOURCE: IEC 61577-1:2006, 3.2.2, modified]

Note 1 to entry: The potential alpha energy concentration of the nuclide *i*, $E_{\text{PAEC},i}$, is expressed by Formula (7):

$$E_{\text{PAEC},i} = \frac{E_{\text{PAE},i}}{V}$$

where

$E_{\text{PAE},i}$	is the potential alpha energy of the nuclide *i*, in joules;
V	is the sampled volume, in cubic metres.

3.1.20
potential alpha energy concentration exposure

integral with respect to time of potential alpha energy concentration accumulated during the exposure time

Note 1 to entry: Exposure to potential alpha energy concentration, X_{PAEC}, is expressed by Formula (8):

$$X_{\text{PAEC}} = \int_{0}^{t} E_{\text{PAEC}} \cdot \mathrm{d}t$$

where

E_{PAEC}	is the potential alpha energy concentration, in joules per cubic metre;
t	is the sampling duration, in seconds.

3.1.21
primary standard

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

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

[SOURCE: IEC 61577-1:2006, 3.1.3]

3.1.22
radioactive equilibrium of radon-222 with its short-lived decay products

state of radon and its short-lived decay products whereby the activity of each radionuclide is equal

Note 1 to entry: In radioactive equilibrium, the activity of each short-lived decay product decreases over time like the radon activity.

3.1.23
radon emanation

mechanism whereby a radon atom leaves the individual particle of solid material in which it has been formed and reaches the free space of pores

3.1.24
radon exhalation

mechanism whereby a radon atom produced by emanation and transported (by diffusion or convection) towards the material surface is released from the material into the surrounding medium (air)

3.1.25
radon exhalation rate

value of the activity concentration of radon atoms that leave a material per unit time

Note 1 to entry: The radon exhalation rate under conditions whereby the radon activity concentration at the surface of the material equals zero is called free radon exhalation rate.

Note 2 to entry: The free radon exhalation rate is approximated from the radon exhalation rate if the radon activity at the surface of the material has a sufficiently low value.

3.1.26
radon surface exhalation rate

value of the activity concentration of radon atoms that leave a material per unit surface of the material per unit time

3.1.27
radon mass exhalation rate

value of the activity concentration of radon atoms that leave a material per unit mass of the material per unit time

3.1.28
radon exposure

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

Note 1 to entry: Exposure to radon, X, is expressed by Formula (9):

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

where

C is the activity concentration, in becquerels per cubic metre;

t is the sampling duration, in seconds.

3.1.29
reference atmosphere

radioactive atmosphere in which the influence quantities (aerosols, radioactivity, climatic conditions, etc.) are sufficiently well-known or controlled to allow its use in a testing procedure for measuring instruments for radon or short-lived decay products

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

[SOURCE: IEC 61577-1:2006, 3.2.26 modified – Last sentence of the definition changed to note 1 to entry.]

3.1.30
reference source

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

[SOURCE: IEC 61577-1:2006, 3.2.25]

3.1.31
sampling duration

time interval during which the sampling is performed at a given point

3.1.32
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

Note 1 to entry: See ISO/IEC 17025:2017, 7.3, for further information on sampling plans.

3.1.33
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.

3.1.34
sensor

element of a measuring system that is directly affected by a phenomenon body, or substance carrying a quantity to be measured

[SOURCE: ISO/IEC Guide 99:2007, 3.8]

Note 1 to entry: The term "detector" is also used for this concept.

3.1.35
short-lived decay products

radionuclides with a half-life of less than one hour produced by radon-222 disintegration (^{222}Rn): polonium-218 (^{218}Po), lead-214 (^{214}Pb), bismuth-214 (^{214}Bi) and polonium-214 (^{214}Po)

Note 1 to entry: See Figure A.1.

Note 2 to entry: Decay products of radon-220 disintegration such as polonium-216 (^{216}Po), lead-212 (^{212}Pb), bismuth-212 (^{212}Bi), polonium-212 (^{212}Po) and thallium-208 (^{208}Tl) can interfere with the radon-222 measurement (see Figure A.2).

3.1.36
short-term measurement

measurement based on an air sample collected within a period comparable to the duration of the half-life of radon

3.1.37
spot measurement

measurement based on a grab sample taken within a period of less than one hour, at a given point in space, together with an analysis (e.g. count) carried out simultaneously or after a set period of time

Note 1 to entry: See Annex B for further information.

3.1.38
unattached fraction of $E_{\text{PAEC},^{222}\text{Rn}}$

fraction of the potential alpha energy concentration of short-lived decay products that is not attached to the ambient aerosol

Note 1 to entry: The particle size concerned is in the order of magnitude of nanometres.

Note 2 to entry: In the case of ^{220}Rn, the relatively long half-life of ^{212}Pb can lead to cases where ^{220}Rn completely disappears before ^{212}Bi; in this case, the unattached fraction of short-lived radon-220 decay products cannot be defined.

[SOURCE: IEC 61577-1:2006, 3.2.14]

3.2 Symbols

For the purposes of this document the following symbols apply.

A_i	activity of the nuclide *i*, in becquerels
C_i	activity concentration of the nuclide *i*, in becquerels per cubic metre
$\bar{C}_i$	average activity concentration of the nuclide *i*, in becquerels per cubic metre
D	diffusion coefficient, in square metres per second
$E_{\text{AE},i}$	alpha particle energy produced by the disintegration of 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
$\bar{E}_{\mathrm{PAE},i}$	average potential alpha energy of the nuclide *i*, in joules
$\bar{E}_{\mathrm{PAEC},i}$	average potential alpha energy concentration of the nuclide *i*, in joules per cubic metre
F_{eq}	equilibrium factor (dimensionless)
l	diffusion length, in metres
N_i	number of atoms of the nuclide *i*
$T_{1/2,i}$	radioactive half-life of the nuclide *i*, in seconds
t	sampling duration, in seconds
U	expanded uncertainty calculated by $U = k \cdot u(\ )$ with $k = 2$
$u(\ )$	standard uncertainty associated with the measurement result
V	sampled volume, in cubic metres
X	exposure to radon, in becquerel-hours per cubic metre
X_{PAEC}	potential alpha energy concentration exposure, in joule-hours per cubic metre
Y	primary measurement result of the measurand
y^*	decision threshold of the measurand
$y^\#$	detection limit of the measurand
$y^\triangleleft$	lower limit of the confidence interval of the measurand
$y^\triangleright$	upper limit of the confidence interval of the measurand
ϕ	exhalation rate, in becquerels per square metre per second
ϕ_{f}	free exhalation rate, in becquerels per square metre per second
ϕ_{m}	mass exhalation rate, in becquerels per square metre per second
ϕ_{s}	surface exhalation rate, in becquerels per square metre per second
λ_i	decay constant of the nuclide *i*, per second

4 Principle

The measurement methods presented in this document are based on the following elements:

a) sampling a volume of air representative of the atmosphere under investigation;

b) detecting radiations produced by successive radioactive disintegrations of the radon isotopes and their decay products.

NOTE Examples of results for radon activity concentration measurements are given in Annex B.

5 Equipment

Equipment is specific to the different measurement methods and is described in the various parts of ISO 11665. Equipment shall be in accordance with IEC 61577-1, IEC 61577-2 and IEC 61577-3.

6 Sampling

6.1 General

Selection of the appropriate sampling method depends on the site under investigation (mines, outdoors, houses, buildings open to the public, workplaces, etc.), the intended use of the data and the anticipated level of radon activity concentration.

The radon activity concentration and the potential alpha energy concentration of its decay products vary tremendously over time (see Annex A). More than one order of magnitude in variation can be observed over time at the same place and thus measurement results depend on the sampling duration, which can extend from a few minutes to a few hours or several months[10] and on the sampling date (see Figure B.2).

The extrapolation from an average activity concentration obtained from a measurement performed during a given sampling duration at a given sampling time to an average activity concentration representative of a different sampling duration and/or sampling time requires knowledge of the radon activity concentration variability over the inferred period. In some cases, the uncertainty attached to this variability can be so large that such an extrapolation becomes meaningless for the objective of the measurement.

It is therefore important that the choice of sampling method and duration and time of sampling is compatible with the measurement objective and its required uncertainty. For these reasons, the measurement results following screening of an area over a short sampling period need to be interpreted with caution.

The sampling process is performed using different approaches or sampling strategies depending on the objective pursued. Whatever this objective might be, the sampling strategy should be carefully selected, as it determines a large number of decisions and can generate important and costly activities.

Radon activity concentration measurement results and the potential alpha energy concentration measurement results can only be correctly interpreted if the sample is representative of the air that is being characterized.

The definition of the sampling strategy shall follow, as far as possible, the following stages:

a) analysis of records to enable an historic study of the previous use of the sampling site;

b) site reconnaissance (in some cases, analytic investigation techniques using portable radioactivity detectors, may be used to identify the areas to be studied in detail);

c) identification of preferential migration pathways and/or accumulation areas;

d) site reconnaissance with respect to the sampling to be undertaken.

The implementation of this strategy, which also includes the definition of the data quality objectives according to the parameters to be analysed, gives rise to the sampling plan.

The sampling plan shall define the operations to be carried out as defined in ISO/IEC 17025.

6.2 Sampling objective

The objective of the sampling is to provide sufficient representative samples in order that the measurement results comply with their intended use.

6.3 Sampling characteristics

The sampling can be either active or passive.

The sampling time (date and hour), duration and location, and whether sampling is active or passive, shall be specified for all measurements of radon and decay products in the environment or in a confined atmosphere.

The sampling characteristics relating to each measurement method of radon and its decay products are described in the various parts of ISO 11665.

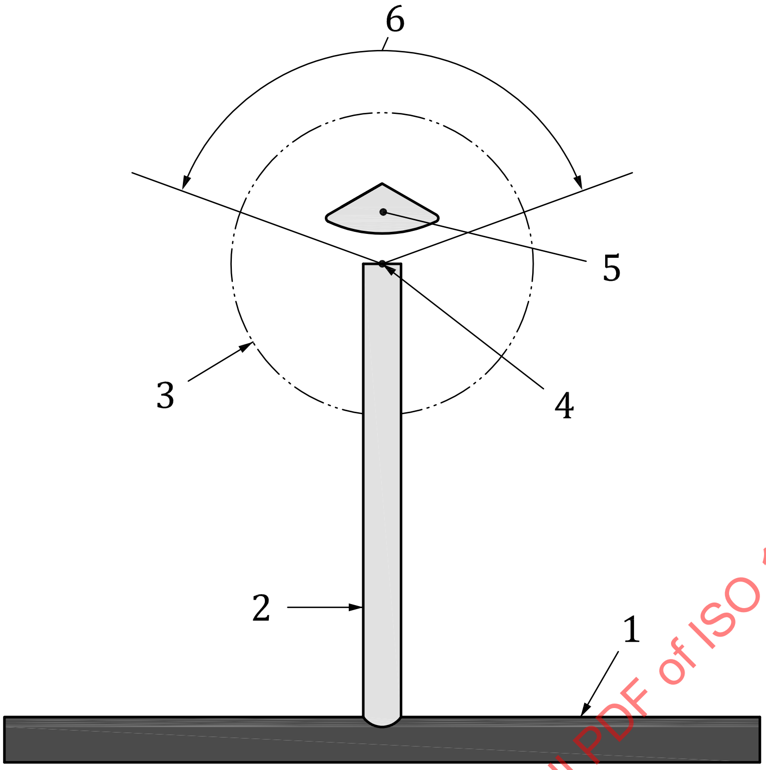
6.4 Sampling conditions

6.4.1 Installation of sampling device

6.4.1.1 Sampling outside a building

Sampling locations shall be distributed outside the building taking into account the following parameters: topography, prevailing winds, activity zones (urban, manufacturing, agricultural and domestic) and potential release points.

In an open area, sampling shall be representative of the air to be measured. Any natural and artificial obstacles (apart from weather shelters) shall be outside an inverted cone with a 140° opening at the top and the sampling point at the bottom tip, and outside a sphere with a 1 m diameter centred on the sampling location[11] (see Figure 2). The sampling location shall be between 1 m and 2 m above the supporting surface (e.g. ground). The installation shall not disturb the surrounding atmosphere.



Key

1	ground
2	bracket
3	sphere free of obstacles (1 m in diameter)
4	sampling place
5	weather shelter
6	cone free of obstacles (140°)

Figure 2 — Example of diagram of a sampling place outside a building

6.4.1.2 Sampling inside a building

The selected number of samples and their location inside a building is determined by the intended use of the measurement results (initial investigations, search for radioactive sources, radionuclide transfer study, verification of homogeneity of a parameter measured in an environment or identification of anomalies, assessment of human exposure, etc.) taking into account the architectural characteristics of the building (crawl space, basement, multiple storeys, earthen floor, building materials, etc.), the room characteristics and also the measuring equipment used (see ISO 11665-8).

6.4.2 Sampling duration

The sampling duration can vary from a few minutes to a few hours or several months.

Due to the great variability of both radon activity concentration and potential alpha energy concentration in time and space (see Annex A), the sampling duration shall be determined according to the intended use of the measurement results (see Table 1).

Table 1 — Sampling duration based on type of sampling

Measurement	Characteristics of sampling	Usual sampling duration	Characteristics of the measurement result
Spot	Grab	Less than one hour	Representative only of the activity concentration at a given moment and a given point
Continuous	Continuous	Variable	Representative of the activity concentration variation during the sampling at a given point. This sampling is used to monitor the temporal variation of radon activity concentration; the sampling duration and the integration interval shall be compatible with the dynamics of the phenomenon studied
Integrated short-term		Few days	Representative of the mean value of the activity concentration during the sampling at a given point
Integrated long-term		Several months	Estimation of the annual mean value of activity concentration at a given point. This measurement is often used to approximate human radon exposure

6.4.3 Volume of air sampled

For active sampling, the volume of air sampled shall be measured by a flow-meter corrected for temperature and pressure (expressed in cubic metres at a standard pressure and temperature of 1,013 hPa and 0 °C respectively).

For passive sampling, the direct measurement of the air volume sampled is not needed, since a calibration factor, in activity per unit volume, is used to compute the activity concentration.

7 Detection

Seven different types of detection can be used. See 7.1 to 7.7.

7.1 Silver-activated zinc sulphide ZnS(Ag) scintillation

Some electrons in scintillating media, such as ZnS(Ag), have the particular feature of emitting light photons by returning to their ground state when they are excited by an alpha particle. These light photons can be detected using a photomultiplier.

This is the principle adopted for scintillation cells (such as Lucas cells[12]) used for radon spot measurement.

ZnS(Ag) scintillation may also be used to detect radon decay products collected on a filter[13][14][15][16].

NOTE This detection principle is occasionally used for continuous sampling[17].

7.2 Gamma-ray spectrometry

The radon, adsorbed on activated charcoal encapsulated in a container,[18][19][10] is determined by gamma-ray spectrometry of its decay products (^{214}Bi and ^{214}Pb) after their equilibrium is reached[20].

7.3 Liquid scintillation

The radon, adsorbed on activated charcoal placed in a vial, is measured following the addition of a scintillation cocktail by counting alpha and beta particles emitted by the radon and its decay products (^{218}Po, ^{214}Bi, ^{214}Pb, ^{214}Po) after their equilibrium is reached[21].

7.4 Air ionization

When travelling through the air, each alpha particle creates several tens of thousands of ions pairs which, under some experimental conditions, produce an ionization current. Although very low, this current may be measured using an ionization chamber that gives the activity concentration of radon and its decay products. When the sampling is performed through a filtering medium, only radon diffuses into the ionization chamber and the signal is proportional to the radon activity concentration[22][23].

7.5 Semi-conductor (alpha detection)

A semi-conductor detector (made of silicon, for example) converts the energy from an incident alpha particle into electric charges. These are converted into pulses with an amplitude proportional to the energy of the alpha particles emitted by the radon and its short-lived decay products[24].

NOTE This detection principle is occasionally associated with electrostatic precipitation of the alpha emitter isotopes.

7.6 Solid-state nuclear track detectors (SSNTD)

An alpha particle triggers ionization as it passes through some polymer nuclear detectors (such as cellulose nitrate). Ion recombinations are not complete after the particle has passed through. 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 that have passed through the detector[25][26].

7.7 Discharge of polarised surface inside an ionization chamber

A polytetrafluoroethylene (PTFE) disc with a positive electric potential is inserted into an ionization chamber, of a given volume, made of plastic conductive material. The electrostatic field, thus created inside the chamber, collects the ions formed during the disintegration of the radon and its decay products on this disc. After the ions have been collected, the electric potential of the disc decreases according to the radon activity concentration. An electrometer measures this potential difference, which is directly proportional to the radon activity concentration during the exposure period[27][28].

8 Measurement

8.1 Methods

As mentioned in 6.1, the sampling duration is important for reaching the measurement objective and its required uncertainty. For the sake of presentation, the measurement methods can therefore be distinguished on the basis of the duration of the sampling phase: spot measurement method, continuous measurement method and integrated measurement method. The information that is provided by measurements of these three different types is described briefly below.

a) Integrated measurement method: This method gives indications for measuring the average activity concentration of the radon-222 or the average potential alpha energy concentration of short-lived radon decay products in the air over periods varying from a few days to one year. Long-term integrated measurement methods are applicable for approximation of human exposure to radon and its decay products.

b) Continuous measurement method: This continuous monitoring enables the assessment of temporal changes in radon activity concentration in the environment, in public buildings, in homes and in workplaces, as a function of ventilation and/or meteorological conditions.

c) Spot measurement method: This method gives indications for spot measuring, at the scale of a few minutes at a given point, the radon activity concentration or the potential alpha energy concentration of short-lived radon decay products in open and confined atmospheres.

The choice of measurement method depends on the objective and the intended use of the measurement results. The measurement method, sampling and detection described in the various parts of the ISO 11665 series are shown in Table 2.

Table 2 — Characteristics of the measurement methods described in ISO 11665

Measurement method	Sampling		Detection						
	Characteristic	Type	Ionization chamber	Alpha spectrometry	ZnS(Ag) scintillation	Liquid scintillation	Gamma spectrometry	SSNTD	Electret
Spot	Active	Grab			ISO 11665-6 ISO 11665-3[a] ISO 11665-7[b]		ISO 11665-6 ISO 11665-9[b]		
Continuous		Continuous	ISO 11665-5	ISO 11665-5	ISO 11665-7[b]				
Integrated short-term								ISO 11665-2[a]	
Integrated long-term								ISO 11665-2[a]	
Continuous	Passive	Continuous	ISO 11665-5 ISO 11665-10	ISO 11665-5 ISO 11665-10	ISO 11665-7[b]				
Integrated short-term							ISO 11665-4	ISO 11665-4	ISO 11665-4
Integrated long-term							ISO 11665-4	ISO 11665-4	ISO 11665-4

[a] Measurement method: radon decay products.

[b] Measurement method: exhalation rate.

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, the following quantities shall be considered:

a) temperature during the sampling at the location of sampling devices;

b) humidity on the collection capacity of the sampling device;

c) air turbulence during the sampling in the vicinity of sampling devices;

d) air flow-rate on sampling;

e) detector storage conditions before sampling;

f) stability of the sampling and detection system during the measurement;

g) sample and detector conservation and storage;

h) variations of radon activity concentration and/or potential alpha energy concentration of the short-lived radon decay products;

i) concentration of radon decay products when measuring radon isotopes;

j) the presence of other gaseous radionuclide emitters of alpha, beta or gamma radiations, in the detection volume, including other radon isotopes and their decay products;

k) radiation background during measurement;

l) measurement equipment background and its variation over time.

8.3 Calibration

Equipment calibration is required to establish the relationship between the variable measured by the detection system (current, counting rate) and the activity concentration of the radon and/or its decay products in the air by using reference radioactive sources or reference atmospheres, with controlled activity concentration of the radon and/or its decay products.

An instrument calibration result shall allow traceability of the measurement result against a primary standard. In the absence of a primary standard, a reference atmosphere included in the international comparison database is used (see IEC 61577-4).

8.4 Quality control

Measurement methods shall be selected and associated procedures performed by suitably skilled staff under a quality assurance and quality control programme.

Confidence in the measurement results is maintained by regular use of certified reference materials and participation in interlaboratory comparisons and proficiency testing (see ISO/IEC 17025).

Laboratory procedures shall ensure that laboratory and equipment contamination as well as sample cross-contamination is avoided.

9 Expression of results

The models of the evaluation of the measurand as well as the standard uncertainties and the characteristic limits associated with the measurand are calculated in accordance with ISO/IEC Guide 98-3 and ISO 11929 (all parts), as detailed in the various parts of ISO 11665 for each of the measurement methods described.

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 the relevant part of ISO 11665 used for the measurement;

b) measurement method (spot, integrated or continuous);

c) identification of the sample;

d) sampling characteristic (active or passive);

e) sampling time (date and hour);

f) duration of sampling;

g) sampling location;

h) units in which the results are expressed;

i) test result, $y \pm u(y)$ or $y \pm U$ (standard uncertainty or expanded uncertainty), 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 $(1-\gamma)$;

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

   1) when the measurand is compared with the decision threshold [see ISO 11929 (all parts)], the result of the measurement shall be expressed as $\leq y^*$ if the result is below the decision threshold;

   2) when the measurand is compared with the detection limit, the result of the measurement shall be expressed as $\leq y^\#$ 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 Annex C.

Annex A
(informative)

Radon and its decay products — General information

A.1 Radon isotopes

Radon has three natural isotopes produced by radionuclides in the earth's crust. Their respective abundance depends, therefore, on the type of sub-soil (^{235}U, ^{238}U and ^{232}Th content) and their radioactive half-life (see Figures A.1, A.2 and A.3).

Radon-222, a decay product of ^{238}U, emanates less than radon-220 (100 times less on average). It is nevertheless the most widespread isotope in the atmosphere, as its radioactive half-life (3,823 5 days) is long enough for it to migrate from the rock producing it, through the soil, to the air.

Radon-220 (thoron), a decay product of ^{232}Th, is the most abundant of the three isotopes released by the soil. It disappears very quickly due to its short radioactive half-life (55,8 s).

Radon-219 (actinon), a decay product of ^{235}U, is the least abundant of the three isotopes. The ^{235}U content in rocks and soil is around 0,73 %of that of ^{238}U. Owing to its short radioactive half-life (3,96 s), it is virtually undetected in the atmosphere and ground water.

The abundance of these isotopes can vary in some manufacturing sites.

The decay constant (λ) of radon-222 is 2,1 × 10^{-6} s^{-1}, with 1,25 × 10^{-2} s^{-1} for radon-220. An activity of 1 Bq (one disintegration per second) corresponds to 476 600 radon-222 atoms and 80 radon-220 atoms.

In ISO 11665, only radon-222 is considered.

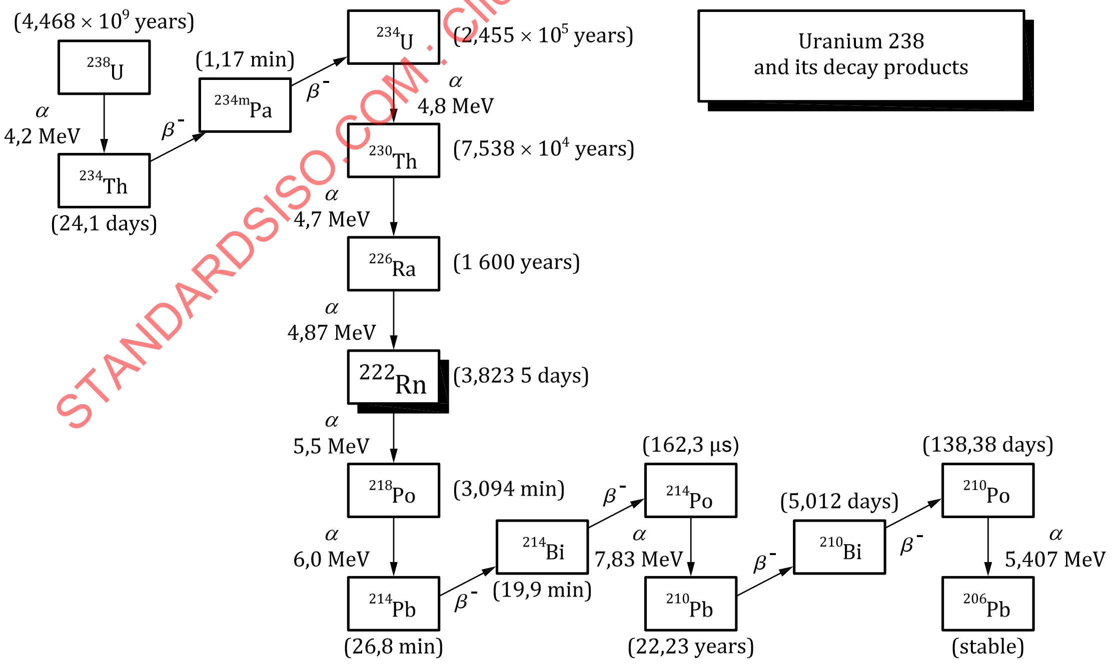


Figure A.1 — Uranium-238 and its decay products[1]

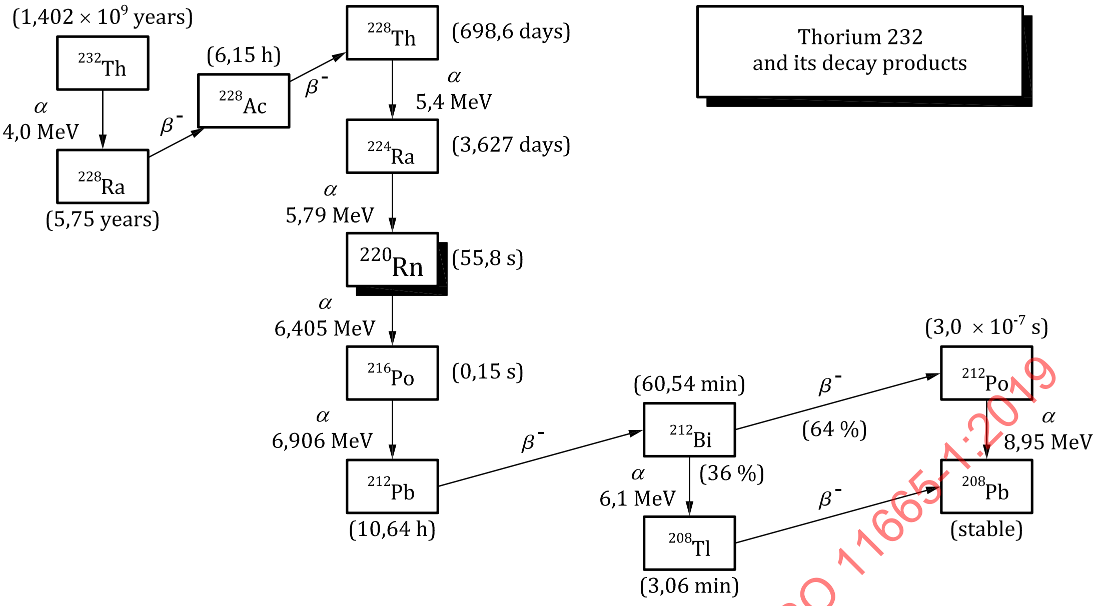


Figure A.2 — Thorium-232 and its decay products[1]

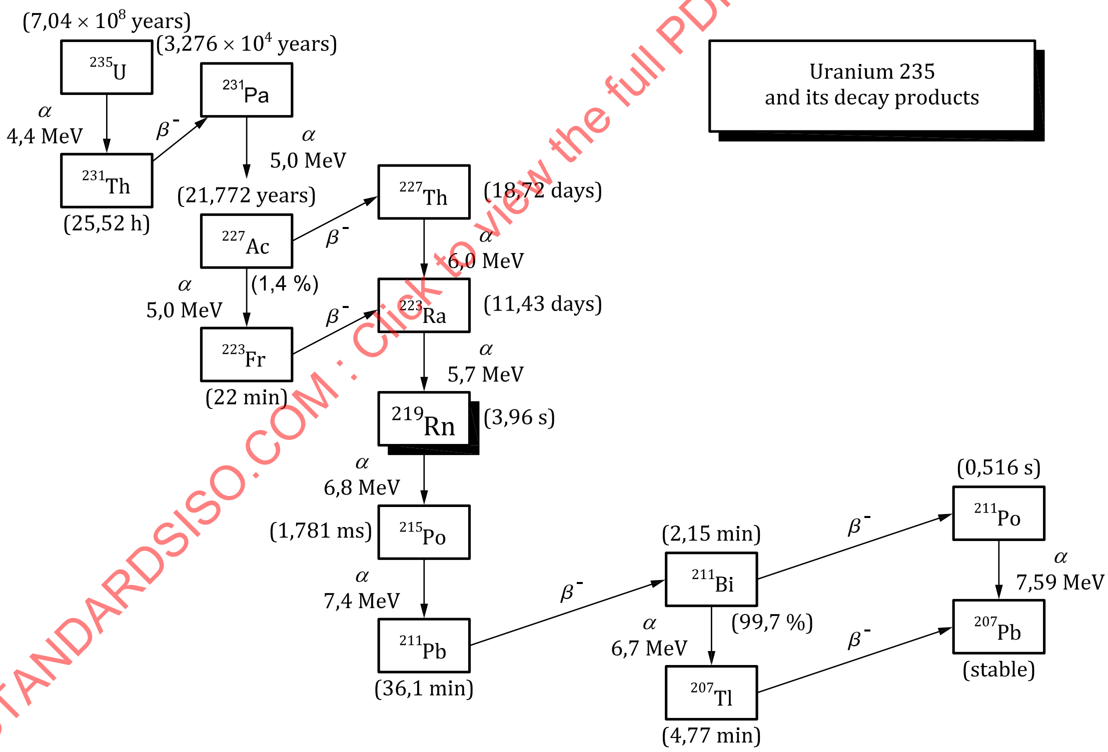


Figure A.3 — Uranium 235 and its decay products[1]

A.2 Changes in radon activity concentration

A.2.1 In the soil

Radon originates principally in the earth's crust where it is produced by the disintegration of radium atoms found in the minerals making up the rock. The quantity of radon-222 produced is directly proportional to the radium-226 content in the soil. Only a fraction manages to escape, however, with most atoms remaining trapped inside the crystalline lattice of the parent rock, where they disintegrate.

Depending on soil porosity, grain size, humidity and so on, the emanation rate varies considerably, from a few tenths of a percent to around 30 %. Once the radon atoms have escaped from the lattice, they are transported through the air or ground water over varying distances by diffusion or convection mechanisms. The radon-222 activity concentration in the soil varies in particular with vertical gradient and time, depending on weather conditions and intrinsic soil characteristics such as permeability, porosity, etc.

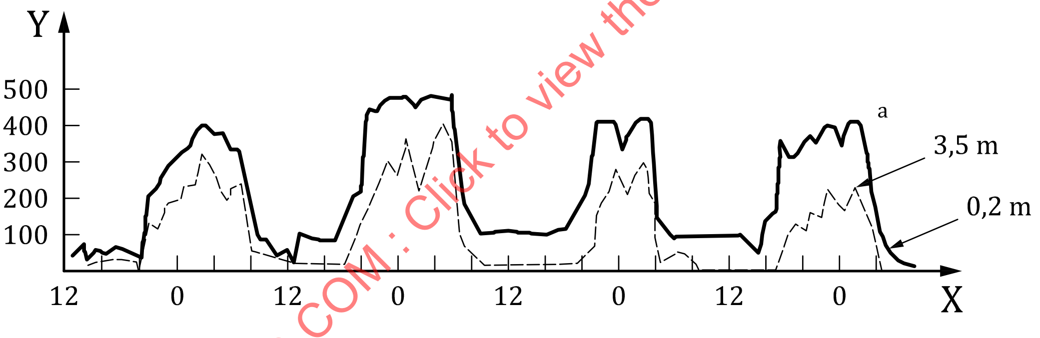
A.2.2 At the soil-atmosphere interface

The quantity of radon reaching the open air per unit time and per unit surface (called the radon-222 surface exhalation rate) depends on the radon activity concentration in the soils and weather conditions[29][30]. Thus, the radon-222 surface exhalation rate usually increases with soil humidity up to approximately 80 % and decreases with increasing atmospheric pressure. When the ground is covered with snow or a layer of water, or is frozen, this exhalation rate is very low.

The exhalation rate is a very useful explanatory parameter, as it is controlled by soil characteristics and weather conditions[31].

A.2.3 In the atmosphere

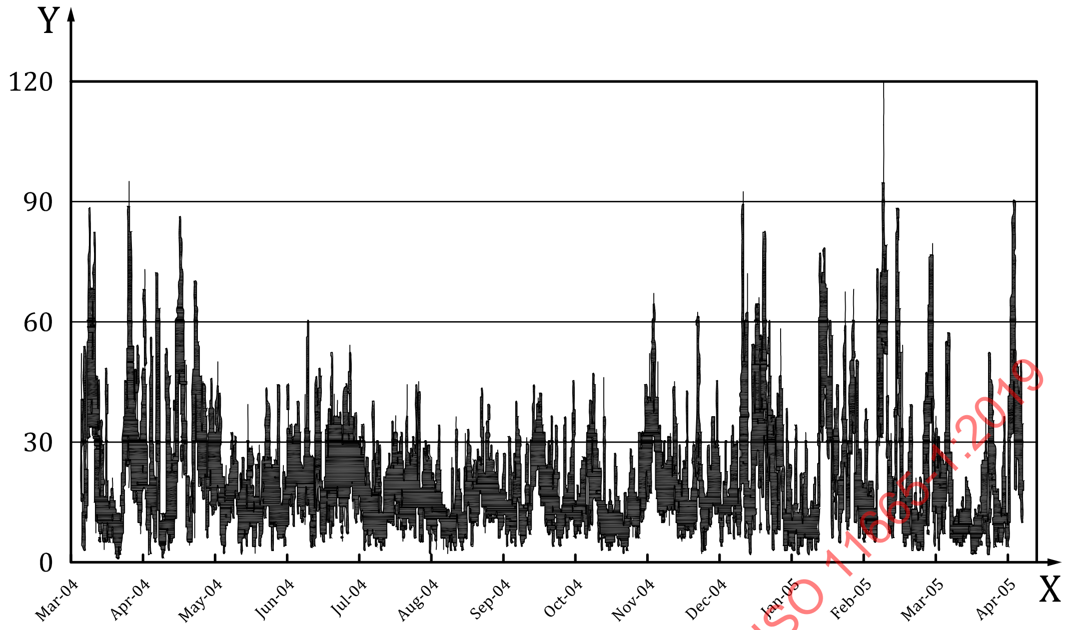
Once in the outside air, radon dilution/dispersion depends on atmospheric diffusion conditions relating to meteorology and topography[31]. A vertical gradient in activity concentration and time variations according to a daily cycle are commonly observed (see Figure A.4). Atmospheric dispersion is frequently higher during the daytime, and radon concentrations are relatively weak. Atmospheric dispersion is lower during night-time temperature inversions; radon accumulates and its activity concentration increases by a factor of 10 to 100 in the atmospheric layer in contact with the ground (see Figure A.5).



Key

X	time of the day
Y	^{222}Rn activity concentration (Bq/m^3)
a	Height of sampling probe.

Figure A.4 — Example of changes in daily cycle of radon activity concentration in the outside air[32]



Key

X	date
Y	^{222}Rn activity concentration (Bq/m^3)

NOTE Hourly average outdoor ^{222}Rn activity concentration measured in Britanny (France) over 1 year.

Figure A.5 — Example of time variation of outdoor radon activity concentration[33]

A.2.4 In buildings

In buildings, radon originates principally from the ground in contact with buildings and sometimes from building materials. More rarely, tap water can be radon-rich (for example, when drawn from a well in granitic terrain), in which case its degassing is a significant source. The outside atmosphere in different regions is also a possible source of radon.

Indoor radon activity concentration may vary significantly in time and space (see Figures A.6, A.7 and A.8) for various reasons.

For any specific space, it depends on:

— the amount of radon emitted by the soil (radium content and texture of the ground in contact with building slabs and walls) and in more rare instances by building materials or well water;

— the degree of negative pressure at any given time within the building that serves to drive entry of radon laden soil gas;

— the degree of passive and mechanically driven radon migration through the building; and

— the degree of containment in the areas where individuals are exposed.

For any specific time, it depends on:

— the building response to varying outdoor conditions in terms of the extent of negative indoor pressure compared to that in the soil which affects the volume of radon being pressure driven into a building;

— rates of ventilation with outdoor air and;

— mechanical system activity for heating, ventilation and cooling that serve to alter distribution and ventilation rates on different floors within a building and can also influence the degree of negative pressure within the building compared to that in the soil.

Radon activity concentration is usually higher in buildings than in the outside atmosphere because of the lower rate of air renewal (see Figure A.9). A daily cycle of variations in activity concentration in buildings is sometimes observed.

Due to higher indoor radon activity concentration, the radon exposure process of occupants is assessed as illustrated in Figure A.10.

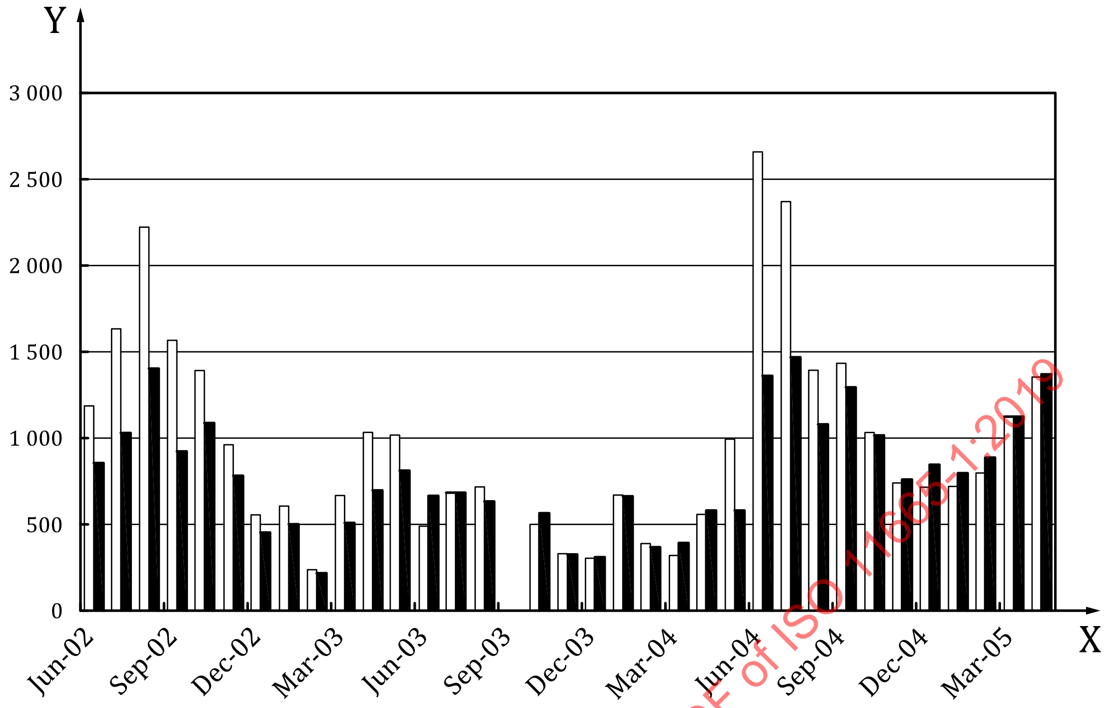
Key

X time of day

Y ^{222}Rn activity concentration (Bq/m^3)

NOTE Hourly variation of randon levels.

Figure A.6 — Example of indoor radon activity concentration over a period of 24 hours (Sweden)[34]

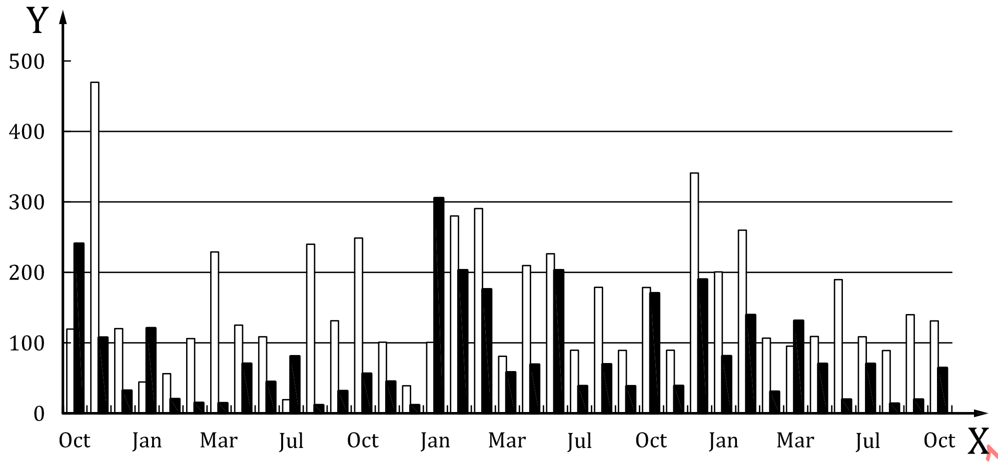


Key

X	date
Y	^{222}Rn activity concentration (Bq/m^3)
▭	basement
▬	1st floor

NOTE Monthly average indoor ^{222}Rn activity concentration measured in Britanny (France) over 3 years.

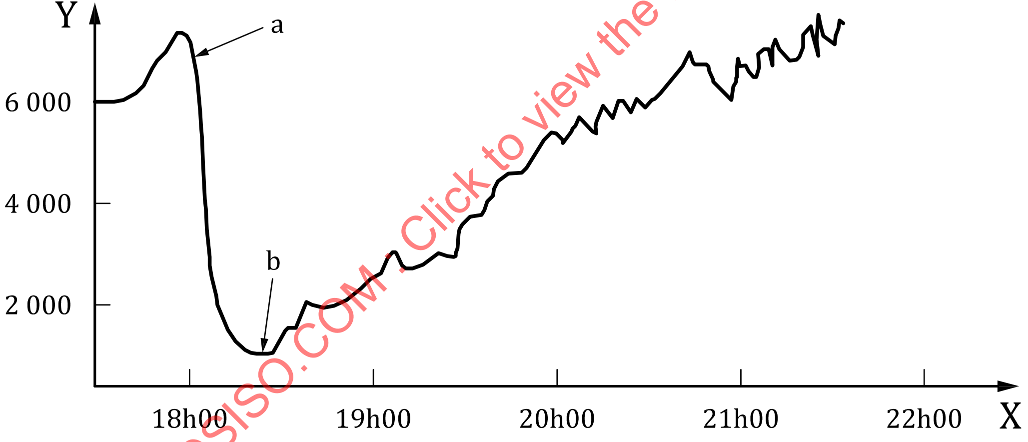
Figure A.7 — Example of monthly variation in indoor radon activity concentration measured at two different levels of a house[35]



Key

X	month
Y	radon concentration (Bq/m^3)
☐	site A
■	site B

Figure A.8 — Example of variations between monthly averages of radon activity concentration at two different sites less than 1 km apart[36]



Key

X	time of day
Y	^{222}Rn activity concentration (Bq/m^3)
a	Door and windows open.
b	Door and windows closed.

NOTE House with high randon activity concentration.

Figure A.9 — Example of changes in radon activity concentration in a house: a natural ventilation effect is revealed[37]

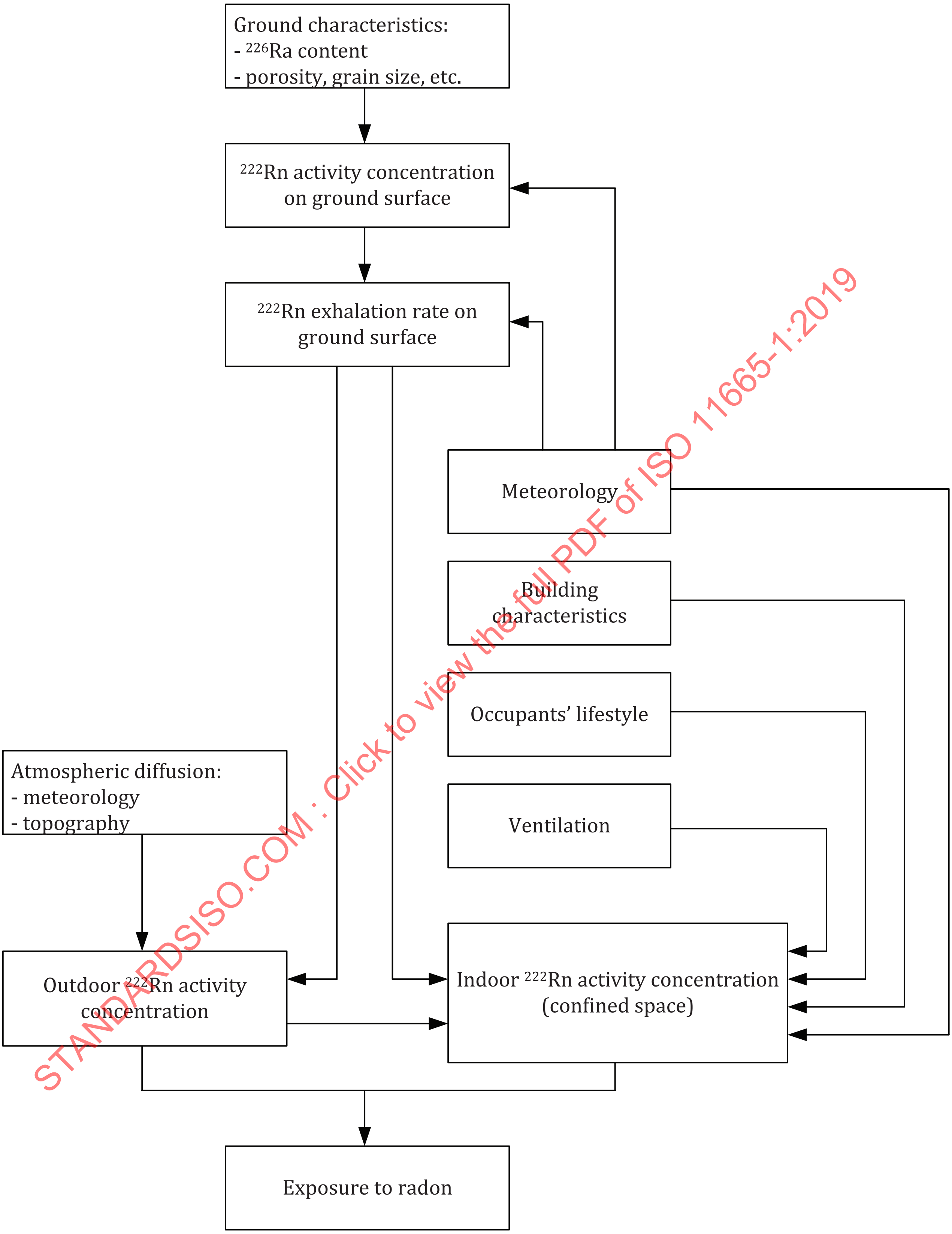


Figure A.10 — General diagram of radon exposure process