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Water quality — Radon-222 —

Part 1:
General principles

Qualité de l'eau — Radon 222 —

Partie 1: Principes généraux

Reference number
ISO 13164-1:2013(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.

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, www.iso.org/directives.

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The committee responsible for this document is ISO/TC 147, *Water quality*, Subcommittee SC 3, *Radioactivity measurements*.

ISO 13164 consists of the following parts, under the general title *Water quality — Radon-222*:

- *Part 1: General principles*
- *Part 2: Test method using gamma-ray spectrometry*
- *Part 3: Test method using emanometry*

The following part is under preparation:

- *Part 4: Test method using two-phase liquid scintillation counting*

This corrected version of ISO 13164-1:2013 incorporates the following corrections:

- Table 2: The check marks which printed out incorrectly in the last two columns have been changed to X's. The X's from the cells "Gamma spectrometry – On-site" and "Liquid scintillation – On-site" have been removed.
- Annex B: The examples of data record forms for B.2 and B.3 were inversed. They are now in the right places.

Introduction

Radioactivity from several naturally occurring and human-made sources is present throughout the environment. Thus, water bodies (surface waters, groundwaters, sea waters) can contain radionuclides of natural and human-made origin.

— Natural radionuclides, including potassium-40, and those of the thorium and uranium decay series, in particular radium-226, radium-228, uranium-234, uranium-238, lead-210, can be found in water for natural reasons (e.g. desorption from the soil and wash-off by rain water) or releases from technological processes involving naturally occurring radioactive materials (e.g. the mining and processing of mineral sands or phosphate fertilizer production and use).

— Human-made radionuclides such as transuranium elements (americium, plutonium, neptunium, curium), tritium, carbon-14, strontium-90 and gamma-emitting radionuclides can also be found in natural waters as they can be authorized to be routinely released into the environment in small quantities in the effluent discharged from nuclear fuel cycle facilities and following their used in unsealed form in medicine or industry. They are also found in water due to the past fallout of the explosion in the atmosphere of nuclear devices and the accidents at Chernobyl and Fukushima.

Drinking-water can thus contain radionuclides at activity concentration which could present a risk to human health. In order to assess the quality of drinking-water (including mineral waters and spring waters) with respect to its radionuclide content and to provide guidance on reducing health risks by taking measures to decrease radionuclide activity concentrations, water resources (groundwater, river, lake, sea, etc.) and drinking water are monitor for their radioactivity content as recommended by the World Health Organization (WHO).

Standard test methods for radon-222 activity concentrations in water samples are needed by test laboratories carrying out such measurements in fulfillment of national authority requirements. Laboratories may have to obtain a specific accreditation for radionuclide measurement in drinking water samples.

The radon activity concentration in surface water is very low, usually below 1 Bq l^{-1}. In groundwater, the activity concentration varies from 1 Bq l^{-1} up to 50 Bq l^{-1} in sedimentary rock aquifers, from 10 Bq l^{-1} up to 300 Bq l^{-1} in wells, and from 100 Bq l^{-1} up to 1 000 Bq l^{-1} in crystalline rocks. The highest activity concentrations are normally measured in rocks with high concentration of uranium (Reference [30]).

High variations in the activity concentrations of radon in aquifers have been observed. Even in a region with relatively uniform rock types, some well water may exhibit radon activity concentration greatly higher than the average value for the same region. Significant seasonal variations have also been recorded (see Annex A).

Water may dissolve chemical substances as it passes from the soil surface to an aquifer or spring waters. The water may pass through or remain for some time in rock, some formations of which may contain a high concentration of natural radionuclides. Under favourable geochemical conditions, the water may selectively dissolve some of these natural radionuclides.

Guidance on radon in drinking-water supplies provided by WHO in 2008 suggests that controls should be implemented if the radon concentration of drinking-water for public water supplies exceeds 100 Bq l^{-1}. It also recommended that any new, especially public, drinking-water supply using groundwater should be tested prior to being used for general consumption and that if the radon concentration exceeds 100 Bq l^{-1}, treatment of the water source should be undertaken to reduce the radon levels to well below that level (Reference [41]).

This International Standard is one of a series dealing with the measurement of the activity concentration of radionuclides in water samples.

Water quality — Radon-222 —

Part 1:
General principles

WARNING — Persons using this document should be familiar with normal laboratory practice. This document does not purport to address all of the safety problems, if any, associated with its use. It is the responsibility of the user to establish appropriate safety and health practices and to ensure compliance with any national regulatory conditions.

IMPORTANT — It is absolutely essential that tests conducted in accordance with this document be carried out by suitably qualified staff.

1 Scope

This part of ISO 13164 gives general guidelines for sampling, packaging, and transporting of all kinds of water samples, for the measurement of the activity concentration of radon-222.

The test methods fall into two categories:

a) direct measurement of the water sample without any transfer of phase (see ISO 13164-2);

b) indirect measurement involving the transfer of the radon-222 from the aqueous phase to another phase (see ISO 13164-3).

The test methods can be applied either in the laboratory or on site.

The laboratory is responsible for ensuring the suitability of the test method for the water samples tested.

2 Normative references

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

ISO 5667-1, *Water quality — Sampling — Part 1: Guidance on the design of sampling programmes and sampling techniques*

ISO 5667-3, *Water quality — Sampling — Part 3: Preservation and handling of water samples*

ISO 10703, *Water quality — Determination of the activity concentration of radionuclides — Method by high resolution gamma-ray spectrometry*

ISO 13164-2, *Water quality — Radon-222 — Part 2: Test method using gamma-ray spectrometry*

ISO 13164-3, *Water quality — Radon-222 — Part 3: Test method using emanometry*

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

ISO 80000-10, *Quantities and units — Part 10: Atomic and nuclear physics*

3 Terms, definitions, and symbols

3.1 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 80000-10 and the following apply.

3.1.1
activity

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

[SOURCE: ISO 921:1997,[1] 23]

3.1.2
activity concentration in water

activity per volume of water

Note 1 to entry: The activity concentration in water is expressed in becquerels per litre.

3.1.3
activity concentration in air

activity per volume of air following the degassing phase

Note 1 to entry: The activity concentration in air is expressed in becquerels per cubic metre.

3.1.4
test sample

part of the total sample subjected to analysis

3.1.5
Bunsen coefficient

volume of a gas dissolved at standard temperature (273,15 K) and standard partial pressure (0,1 MPa) divided by the volume of the solvent at a temperature, T, and standard pressure (0,1 MPa)

Note 1 to entry: Adapted from Reference [10], p. 239.

Note 2 to entry: Modern practice recommends that gas solubility be expressed as molality, mole fraction or mole ratio (see Reference [10]). However, in many studies dealing with radon measurement in water, the Bunsen coefficient appears frequently.

Note 3 to entry: The solubility of radon in water increases as the water temperature decreases (see Annex A).

3.1.6
continuous measurement of radon in water

measurement of the radon activity concentration of continuous samples at a given sampling point in the water environment

Note 1 to entry: This form of analysis is used to monitor variations in the activity concentration of radon in the water at the sampling point over time.

3.1.7
continuous sampling

process whereby samples are taken continuously from a body of water

[SOURCE: ISO 6107-2:2006,[3] 32, modified]

3.1.8
degassing

transfer of dissolved radon from water to air, usually by means of a physical process

3.1.9

direct *in-situ* measurement

automatic analysis system in which at least the measurement probe is immersed in the body of water

3.1.10

discrete sample

localized discrete sample

single sample taken from a body of water at a random time or place

3.1.11

dissolution

mixing of two phases with the formation of one new homogeneous phase

3.1.12

drinking water

potable water

water of a quality suitable for drinking purposes

[SOURCE: ISO 6107-1:2004,[2] 30]

3.1.13

groundwater

water which is held in, and can usually be recovered from, an underground formation

[SOURCE: ISO 6107-1:2004,[2] 41, modified]

3.1.14

intermittent sampling

process whereby discrete samples are taken from a body of water

3.1.15

mains water

water fed from a drinking water treatment station, spring or borehole into a distribution system or reservoir

3.1.16

Ostwald coefficient

volume of a gas dissolved at a given temperature and pressure divided by the volume of the solvent at the same temperature and pressure

Note 1 to entry: Adapted from Reference [10], p. 1147.

Note 2 to entry: Modern practice recommends that gas solubility be expressed as molality, mole fraction or mole ratio (see Reference [10]). However, in many studies dealing with radon measurement in water, the Ostwald coefficient appears frequently.

Note 3 to entry: The solubility of radon in a liquid increases as the liquid temperature decreases (see Annex A).

3.1.17

radon transport by permeation

transfer of radon from one medium to another across a third homogeneous medium (membrane)

3.1.18

raw water

water which has received no treatment whatsoever, or water entering a plant for treatment or further treatment

[SOURCE: ISO 6107-1:2004,[2] 59]

3.1.19
reservoir
construction, partially or wholly man-made, for storage or regulation and control of water

[SOURCE: ISO 6107-2:2006,[3] 107, modified]

3.1.20
surface water
water which flows over, or rests on, the surface of a land mass

[SOURCE: ISO 6107-1:2004,[2] 74]

3.1.21
sample
portion, ideally representative, removed from a specified body of water, either discretely or continuously, for the purpose of examination of various defined characteristics

[SOURCE: ISO 6107-2:2006,[3] 111]

3.1.22
sampling
process of removing a portion, intended to be representative, of a body of water for the purpose of examination of various defined characteristics

[SOURCE: ISO 6107-2:2006,[3] 114]

3.1.23
sampling point
precise position within a sampling location from which samples are taken

[SOURCE: ISO 6107-2:2006,[3] 117]

3.1.24
sampling zone
extent of a body of water over which samples are taken

3.1.25
short-lived ^{222}Rn decay products
radionuclides with a half-life <1 h produced by the decay of radon-222 (^{222}Rn), namely polonium-218 (^{218}Po), lead-214 (^{214}Pb), bismuth-214 (^{214}Bi), and polonium-214 (^{214}Po)

Note 1 to entry: See Figure 1.

3.1.26
spot measurement of radon in water
measurement of the radon activity concentration in a water discrete sample carried out either immediately or after a known delay

Note 1 to entry: The result obtained is only representative of the time the sample was taken.

3.1.27
transfer
displacement or transport of radon from one phase to another

3.2 Symbols

For the purpose of this document, the symbols given in ISO 80000-10 and the following apply.

c	activity concentration in air following degassing, in becquerels per cubic metre
c_A	activity concentration in water, in becquerels per litre

c_A^*	decision threshold, in becquerels per litre
$c_A^\#$	detection limit, in becquerels per litre
$c_A^{\triangleleft}, c_A^{\triangleright}$	lower and upper limits of the confidence interval, in becquerels per litre
c_l	activity concentration in a liquid, in becquerels per litre
L	Ostwald coefficient
$T_{\mathrm{H_2O}}$	temperature of water sample, in degrees Celsius
U	expanded uncertainty calculated by $U = k.u(\ )$ with $k = 2$
$u(c_A)$	standard uncertainty associated with the measurement result
V	volume of the test sample, in litres
α	Bunsen coefficient

4 Principle of the measurement method

Radon-222 (^{222}Rn) is a radioactive gas produced by the decay of radium-226 (^{226}Ra), which is one of the decay products of the uranium-238 (^{238}U) that is naturally present in the Earth's crust (see Annex A). The decay of radon-222 proceeds through a series of non-volatile radioactive elements resulting in stable lead-206 (see Figure 1) (Reference [9]).

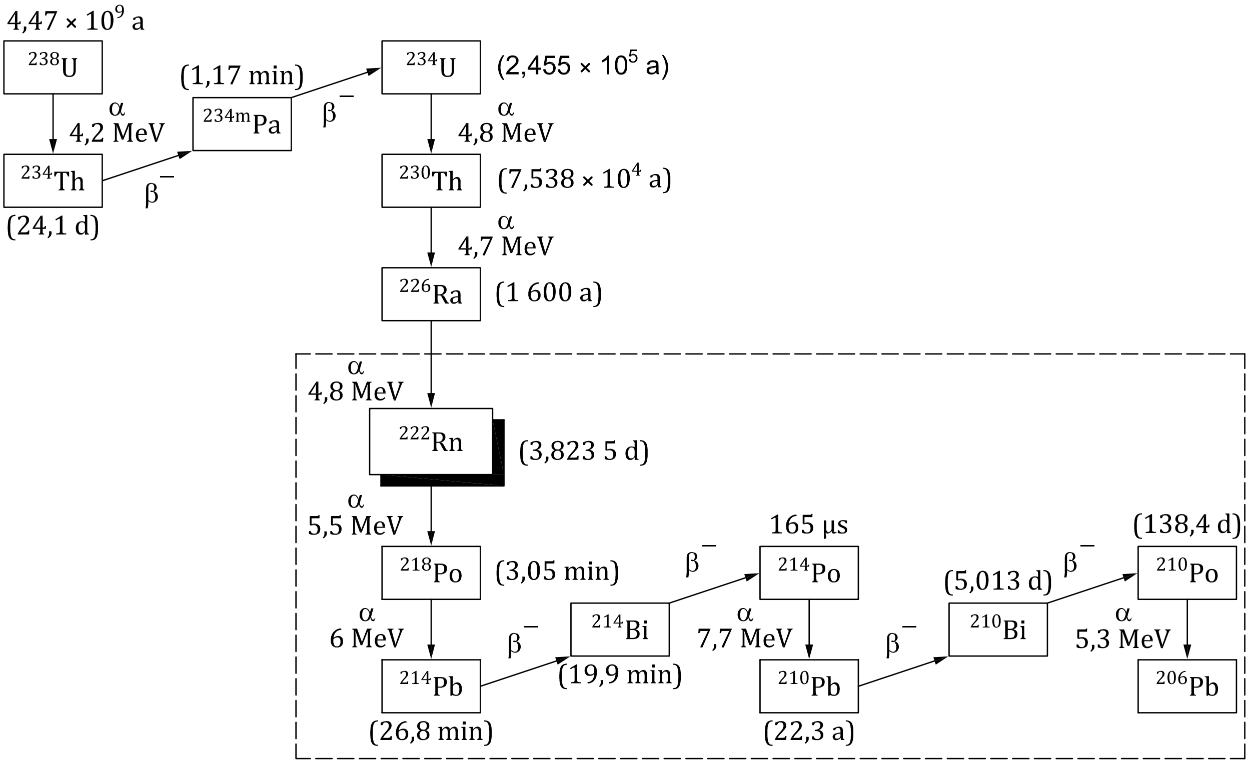


Figure 1 — Uranium-238 and its decay products

A large number of methods are available to measure the activity concentration of radon-222 in water.

The measurement of the activity concentration of radon-222 in water involves the following operations:

- collection of a representative sample of the water at time *t* in a suitable container;
- storage and the transportation of the sample, when the measurement is carried out in a laboratory;
- test sample preparation by transferring the radon dissolved in the water to another phase, when needed by the detection techniques (emanometric or a liquid scintillation counting);
- determination of the radon activity concentration in the water using a variety of detection techniques directly or through its decay products (see Figure 2).

The result of the measurement is expressed in becquerels per litre.

The methods specified in the different parts of this International Standard are applicable to all types of water (see Table 2), and the method is selected according to the purpose of the measurement, phenomenological observation or radiological impact assessment taking into account the level of the radon activity concentration expected in the raw sample.

5 Sampling

Sampling shall be carried out in accordance with ISO 5667-1 and ISO 5667-3.

The sampling conditions shall comply with ISO 5667-1, and shall also satisfy those specified in Table 1 in order to minimize as far as possible any exchange with the atmosphere and to maintain the radon in solution in the water sample.

The sample container shall be labelled.

The sampling location, date and time shall be recorded.

When measuring very low levels of radon activity concentration (<10 Bq l^{-1}), avoid any contact between the sample and the atmosphere when taking the sample.

When measurement methods require specific precautions, these are listed in the relevant parts of ISO 13164 (e.g. when using degassing techniques, the temperature of the water shall be recorded).

6 Transportation and storage

The transportation and storage conditions shall be adapted to keep the integrity of the sample.

The temperature of the transportation and storage of the sample shall be below that of the original water (but above 0 °C). The container shall be protected and sealed to avoid opening during transportation. The container shall be packed in an appropriate manner, especially around the cap, in order to prevent any leakage.

The sample shall be measured as soon as possible after sampling. When it is necessary to store the sample for an extended period of time prior to measurement, it shall be stored at low temperature in a refrigerator or similar storage facility in accordance with ISO 5667-1 and ISO 5667-3.

The duration of transportation and storage prior to analysis shall be as short as possible given the half-life of radon-222, the expected activity concentration, and the detection limit of the measurement method to be used.

Experience indicates that it is essential that the time between sampling and analysis not exceed 48 h.

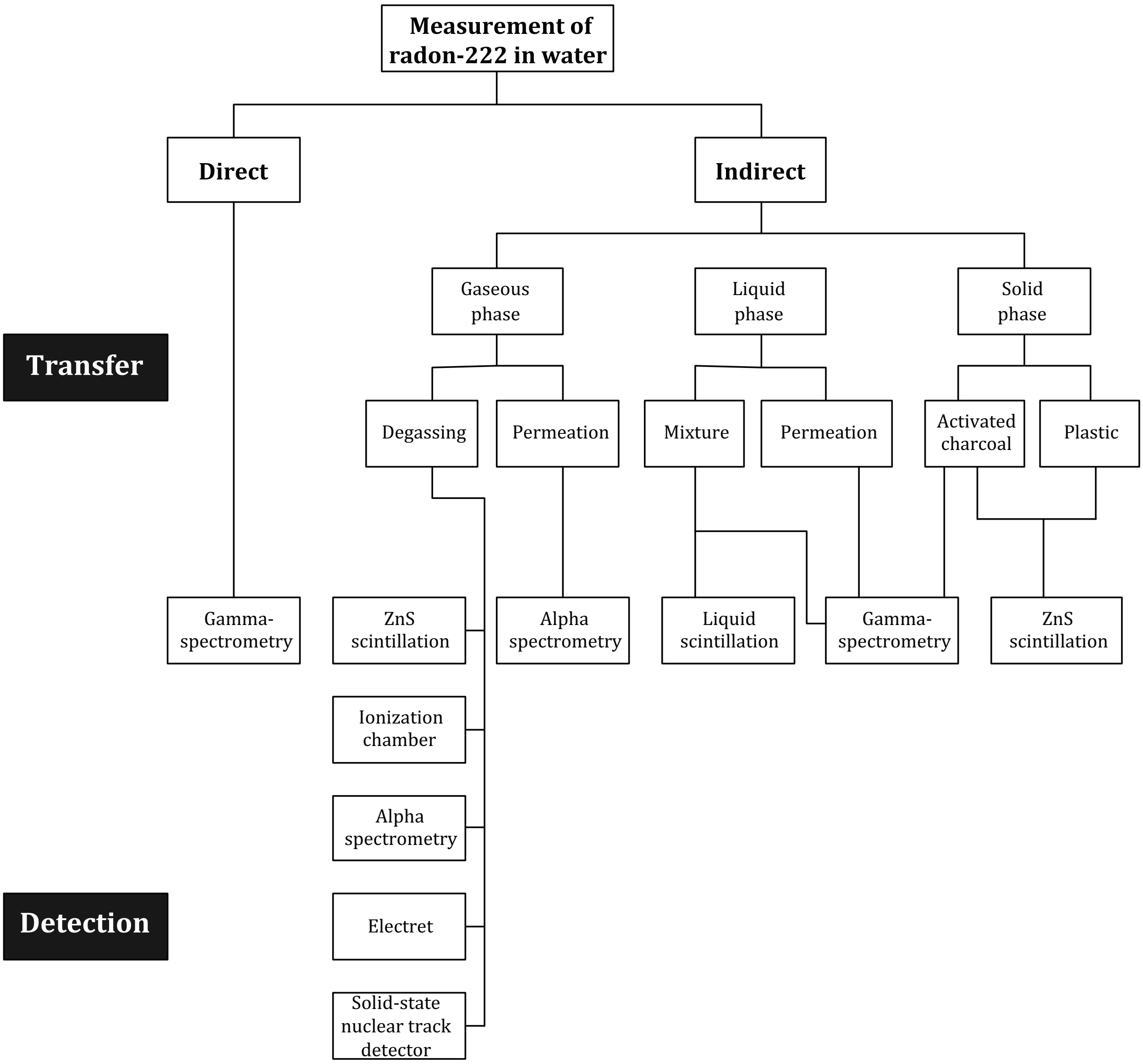


Figure 2 — Diagram illustrating the techniques used to measure radon in water

Table 1 — Sampling conditions

Sampling type	Container	Sampling steps
Sampling from an outlet (tap, spring, etc.)	— The container shall be made from a material that is non-porous to radon (e.g. aluminium). Avoid the use of highly hydrophobic materials in order to minimize the presence of gas bubbles on the walls of the container. Avoid the use of grease and oil because of the high solubility of radon in those substances. — The volume of the container shall be adapted to the test sample size needed for the chosen measurement method (refer to the relevant parts of this International Standard). — The sealing of the container shall be airtight (e.g. a cap with an aluminium cover). — The container shall be resistant to shock and pressure	— Prepare the equipment. — Open the tap to obtain a continuous flow to avoid turbulence at the outlet of the tap and on the walls of the container. — Take the sample carefully, allowing the stream of water to flow against the walls of the container. — Fill the container completely in order to avoid the presence of air in the container, but do not allow the container to overflow with turbulence. — Close the container. NOTE In some cases, it can be necessary to purge the supply system before taking the sample
Sampling by immersion in stagnant water	— Type and size of container, see above. — If necessary, the container shall be closed under water	— Prepare the equipment. — Ensure that the sampling point is representative of the body of water concerned. It is likely that stratification will make it necessary to take several samples at different lateral positions or depths. — Take the sample carefully, minimizing any turbulence. — Fill the container completely in order to avoid the presence of air. — Close the container
Sampling by immersion in flowing water	— Type and size of container, see above. — If necessary, the container shall be closed under water	— Prepare the equipment. — Ensure that the sampling point is representative of the body of water concerned. It is likely that stratification will make it necessary to take several samples at different lateral positions or depths. — Face the direction of the flow. — Take the sample carefully. — Fill the container completely in order to avoid the presence of air. — Close the container

7 Test sample preparation

7.1 Degassing techniques

Degassing techniques are used to transfer the radon dissolved in the water phase into the air phase so that it can be detected and measured using radon-in-air measuring devices.

As the Ostwald coefficient of radon in water is fairly low, the dissolved radon degasses naturally into the air with relatively slow kinetics (over a few hours).

In order to accelerate the degassing process, several means may be used:

- shaking the sample;
- aeration of the water sample using fine air bubbles to increase the air exchange surface;
- decreasing the pressure in the air phase.

7.2 Permeation technique

The permeation technique uses a physical barrier such as a membrane with physical and chemical properties that allow the transfer of radon from the water to the air on the far side of the membrane (see Reference [11]).

The permeation of radon through membranes involves a complex process comprising several successive stages:

- adsorption of the radon on one of the faces of the membrane;
- dissolution of the radon within the membrane;
- diffusion of the radon within the membrane under the influence of the concentration gradient;
- release of the radon at the opposite interface of the membrane.

7.3 Liquid extraction technique

Radon is more soluble in organic solvents than in water (see Annex A). To facilitate the extraction of radon from water and to concentrate it in the organic phase, organic solvents such as toluene or hexane may be used (see Reference [12]).

8 Detection techniques

8.1 Gamma-spectrometry

The activity concentration of the ^{222}Rn is derived from the gamma-lines of ^{214}Bi or ^{214}Pb measured using a NaI (sodium iodide) or Ge (germanium) detector.

The NaI detector is used for screening, semi-quantitative and semi-qualitative determination.

The Ge detector is used for qualitative and quantitative determination.

8.2 Silver-activated zinc sulfide ZnS(Ag) scintillation

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

This is the principle adopted for scintillation cells, such as Lucas cells (see Reference [13]), used for radon spot measurement (see ISO 11665-6[5]).

8.3 Air ionization

When it travels 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 can 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 (see References [14][15] and ISO 11665-5[4]).

8.4 Semiconductor (alpha-detection)

A semiconductor detector, e.g. made of silicon, converts the energy from an incident alpha-particle into electric charge. These charges 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 (see Reference [16]).

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

8.5 Liquid scintillation

This technique uses a homogeneous scintillating mixture by adding a liquid scintillation cocktail to the water sample. The alpha-particles resulting from the decay of the radon give up their energy to the scintillant, exciting the molecules. When the excited molecules return to their ground state, they emit photons that can be detected by a photodetector (see Reference [17]).

9 Measurement methods

9.1 General

The measurement methods fall into two categories:

- direct measurement of the water sample without any test sample preparation;
- indirect measurement involving the transfer of the radon-222 from the aqueous phase to another phase, before performing the measurement.

A summary of measurement methods taking less than 24 h, together with their respective field of application, is given in Table 2.

The selection of the measurement method depends on the objective of the request (see Table 2).

9.2 Gamma-spectrometry method

The activity concentration of radon-222 in the water is determined by direct gamma-analysis of the sample in a suitable container of known volume. The counting period starts after several hours when the ^{222}Rn has reached radioactive equilibrium with its short-lived decay products ^{214}Bi or ^{214}Pb (see References [18]–[20]).

This method is described in detail in ISO 13164-2.

9.3 Emanometric method

The activity concentration of radon-222 in the water is determined after degassing the radon from the aqueous phase to the air phase. When degassing is completed, a number of detection techniques can be used to quantify the activity concentration of radon in the air phase, including silver-activated zinc sulfide ZnS(Ag) scintillation (References [21][22]), air ionization (Reference [23]), or a semiconductor (alpha-detection) (References [24][25]).

This method is described in detail in ISO 13164-3.

Table 2 — Summary of techniques used to measure radon in water and their scope

Detection methods	Transfer of radon	Usual sampled volume l	Measurement range Bq l^{-1}	Relevant subclause	Measurement duration	Applications	Measurements	
							On-site	Lab
Gamma-spectrometry	No	0,5 to 2	1 to >100 000	See 9.2 and ISO 13164-2	Several hours	Routine measurement of the activity concentration of radon in water		X
Alpha-scintillation	Degassing	0,01 to 0,75	0,1 to >100 000	See 9.3 and ISO 13164-3	Less than 1 h[a]	Rapid and immediate testing for the presence of radon in the water	X	X
Ionization chamber		0,1	5 to 20 000		Less than 1 h	Rapid and immediate measurement of the activity concentration of radon in the water	X	X
Silicon detector		0,1 to 0,4	1 to 37 000		Less than 1 h	Rapid and immediate measurement of the activity concentration of radon in the water	X	X
Liquid scintillation	Yes/No[b]	1 to 2	0,1 to 100 000	See 9.4	Several hours	Routine measurement of the activity concentration of radon in water		X
Silicon detector	Permeation[c]	From a few litres to continuous sampling	0,5 to 100 000	See 9.5	Several hours	Discrete or continuous measurement of the activity concentration of radon in the water	X	X

[a] This method is used for the continuous on-site analysis of the activity concentration of radon in water by immersion.

[b] Depending on the type of scintillation cocktail used.

[c] After equilibrium of radon-222 with its decay products is achieved.

9.4 Liquid scintillation counting methods (LSC)

The activity concentration of radon-222 in the water is determined by adding a liquid scintillation cocktail to the water sample.

When a water-immiscible cocktail is used, a two-phase sample is produced. Radon-222 is transferred from the water to the cocktail by vigorous shaking due to the high solubility of radon in organic solvents. Other radionuclides, such as radon decay products which are mostly hydrophilic, remain in the water. Before measurement, the sample is stored for 3 h until equilibrium is reached between radon-222 and its alpha-emitting decay products.

In another direct method, water is mixed with the cocktail to attain a homogeneous test sample composition (Reference [26]). The disadvantage of the latter method is that other radionuclides present in water can also be efficiently detected.

The alpha- (5,49 MeV of ^{222}Rn, 6,0 MeV of ^{218}Po and 7,69 MeV of ^{214}Po) and beta- (endpoints ranging from 0,65 MeV of ^{214}Pb to 3,26MeV of ^{214}Bi) particles resulting from the decay of the radon can be counted by LSC with an efficiency close to 100 % (Reference [27]).

9.5 Permeation method

The activity concentration of radon-222 in the water is determined after transferring the radon from the aqueous phase to the air phase through a membrane. When transfer is completed, a number of detection techniques can be used to quantify radon in the air phase, including semiconductor detector (alpha-detection) (Reference [28]).

The permeation technique may be used for direct *in situ* measurement in the water or to perform a continuous measurement of the activity concentration of the dissolved radon (Reference [29]).

This method is not described in this International Standard.

10 Calibration

The relationship between the physical variable measured by the detection system (current, count, etc.) and the activity concentration of the radon or its decay products in the water should be established by using suitable reference radioactive sources.

The calibration conditions applicable to each measurement method are specified in ISO 13164-2 and ISO 13164-3.

11 Quality assurance and quality control programme

11.1 General

Quality operations shall meet the requirements of ISO/IEC 17025.

11.2 Influence quantities

Various quantities can lead to measurement bias that could induce non-representative results. Depending on the measurement method, influence quantities can affect the following stages in the test measurement process: sampling; transportation and storage of the sample; transfer of radon from the aqueous phase to another; and measurement of radon activity concentration.

The influence quantities affecting each measurement method are discussed in ISO 13164-2 and ISO 13164-3.

11.3 Instrument verification

Major instrument parameters (efficiency, spill over, background) shall be periodically checked within a quality assurance programme established by laboratory and following the manufacturer's instructions.

11.4 Method verification

Periodically verify method accuracy by:

- participating in intercomparison exercises;
- analysing reference materials.

Method repeatability should also be checked, e.g. by replicate measurements.

The acceptance limits of tests mentioned in the preceding should be defined.

11.5 Demonstration of analyst capability

If an analyst has not applied this procedure before, a precision and bias test shall be performed by duplicating the tests of a reference material. Acceptance limits for the test results shall be defined by the laboratory.

A similar test shall be performed by analysts routinely applying this procedure with a periodicity defined by the laboratory. Acceptance limits for the test results shall be defined.

12 Expression of results

The models of the evaluation of the activity concentration as well as the standard uncertainties and the characteristics limits associated with the activity concentration are calculated in accordance with ISO/IEC Guide 98-3[7] and ISO 11929[6] and are detailed in the different parts of this International Standard for each measurement method described.

For the gamma-spectrometry method (see ISO 13164-2), calculate the activity concentration as well as the standard uncertainties and the characteristic limits associated with the activity concentration in accordance with ISO 10703.

The reference date for the expression of the measurement results is the date and time of sampling.

13 Test report

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

a) the test method used, together with a reference to this part of ISO 13164 (ISO 13164-1:2013);

b) measurement method;

c) identification of the sample;

d) measuring date and time;

e) units in which the results are expressed;

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

Complementary information can be provided such as the following:

g) sampling date and time;

h) sampling location;

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

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

- when the activity concentration is compared with the decision threshold (see ISO 11929[6]), the result of the measurement shall be expressed as $\leq c_A^*$ when the result is below the decision threshold,
- when the activity concentration is compared with the detection limit, the result of the measurement can be expressed as $\leq c_A^\#$ when the result is below the detection limit — if the detection limit exceeds the guideline value, it shall be documented that the method is not suitable for the measurement purpose;

k) mention of any relevant information likely to have affected the results.

The results are expressed in a similar format to that shown in Annex B.

Annex A
(informative)

Radon and its decay products in water

A.1 Radon gas

Radon-222, radon-220 and radon-219 are radioactive gases produced by the decay of radium isotopes 226, 224 and 223, which are themselves decay products of uranium-238, thorium-232 and uranium-235 respectively, all of which are found in the Earth's crust. Radon decays through a series of solid radioactive isotopes to a stable isotope of lead.

Radon is a noble gas in the periodic table of the elements, along with helium, neon, argon, krypton, and xenon.

Radon is usually the main source of human exposure to natural radiation. Reference [30] suggests that, at the worldwide level, radon accounts for 54 % of the average of the total exposure to natural radiation. Radon-222 (50 %) is far more common than radon-220 (4 %), while the contribution of radon-219 is considered to be negligible.

Radon emits alpha-particles and generates non-volatile decay products, which are also radioactive (polonium, bismuth, lead, etc.). The potential radiological exposure of human population to radon is mainly due to its solid decay products. Whether or not radon decay products are attached to atmospheric aerosols, they can be inhaled and deposited at varying depths in the bronchopulmonary tree according to their size.

A.2 Radon in water

Radon is present in all occurring surface and groundwaters, with activity concentrations ranging from a few becquerels per litre (surface water) to several thousand becquerels per litre (deep aquifers, boreholes, geothermal springs, etc.).

The radon originates mainly from radon diffusion from rock into water and to a lesser extent from the radioactive decay of radium-226 dissolved in the water. The main factors affecting the value of radon activity concentration in groundwater are the emanation coefficient of reservoir rocks and the content of parent radium-226 in these rocks (Reference [31]).

The presence of radon in water is expressed in terms of the activity concentration, c_A (see 3.1.2), in becquerel per litre.

Knowledge of the quantity of radon in water is an important element in safety policies relating to the health risks caused by this gas.

In some spa treatment centres in particular, the amount of radon degassing from the large quantities of water used in crenotherapy can result in indoor air activity concentrations higher than several thousand becquerels per cubic metre (Reference [32]).

The use of water for washing and cooking in homes, public establishments, hotels, swimming pools, etc. can result in radon degassing into the atmosphere within a building. In a normal house, it is estimated that 10 Bq l^{-1} of radon-222 in the water contributes 1 Bq m^{-3} of air within the house (References [33]–[35]).

Measurements of the radon activity concentration in water are also of great interest to hydrogeologists. Knowledge of radon activity concentrations in deep aquifers provides important information on the structure of these aquifers, on the Earth's crust in general, and on the presence of uranium ores in the surrounding rock. They can also be used to discriminate between groundwater and surface water as the latter is more sensitive to the influence of rainfall.

As radon is an inert radioactive gas with a half-life of 3,82 d, it can move freely through a porous medium such as sand or fragmented rock. When the pores are saturated with water, as is the case in soil and in rock layers below the aquifer level, the radon dissolves in the water that carries it. Water-saturated ground with a porosity of 20 % and a radium concentration of 40 Bq kg^{-1} (the average value for the Earth's crust) results in an activity concentration of radon in the groundwater at equilibrium of around 50 Bq l^{-1} (Reference [36]).

Studies carried out in member states of the European Union (Reference [27]) have shown that the activity concentrations of radon in surface water are very low, usually well below 1 Bq l^{-1}. In groundwater, concentrations can range from 1 Bq l^{-1} to 50 Bq l^{-1} in sedimentary rock aquifers, from 10 Bq l^{-1} to 300 Bq l^{-1} in wells, and from 100 Bq l^{-1} to 1 000 Bq l^{-1} in crystalline rocks. The highest activity concentrations are normally found in rocks rich in uranium. There is a high variation in the activity concentrations in rock aquifers. Even in a region with relatively uniform rock types, some wells can exhibit an activity concentration greatly in excess of the average for the region. Significant seasonal variations have also been observed.

A.3 Solubility of radon in water

A.3.1 General

The solubility of radon in water is one of the most important factors to be taken into account when measuring radon in water. One of the main constraints during sampling is to prevent radon from degassing from the sample before it is measured.

A.3.2 Ostwald coefficient

When a liquid is in contact with air inside a closed space, the ratio of radon in the two phases is given by the Ostwald coefficient, L.

The Ostwald coefficient is defined as (see 3.1.16):

$$L = \frac{V_g\left(p, T_{H_2O}\right)}{V_l\left(T_{H_2O}\right)} \qquad \text{(A.1)}$$

where

V_g is the volume of gas at its partial pressure, p, and temperature, T_{H_2O};

V_l is the volume of solvent used to absorb the gas at temperature, T_{H_2O}.

Under the assumption that the volume of solvent is unchanged after absorption of the gas, the Ostwald coefficient may be calculated at a given temperature according to Formula (A.2) (Reference [37]):

$$L = \frac{c_l}{c} \qquad \text{(A.2)}$$

The ratio of the Ostwald coefficient for radon between an organic compound and water is often called the partition coefficient. Its use shows that radon activity concentrations are higher in many organic compounds than in water. Table A.1 gives the values of these coefficients for different organic compounds. The partition coefficient tends to increase with the length of the carbon chain. The low value of the Ostwald coefficient for water confirms the high volatility of the radon.

Table A.1 — Solubility of radon in organic compounds (References [37]–[39])

Organic compound		Ostwald coefficient	Temperature	Partition coefficient
Name	Formula		°C	
Water	H_2O	0,245	20	1
Ethanol	C_2H_6O	6,03	20	24,61
Acetone	C_3H_6O	6,1	20	24,89
Ethyl acetate	$C_4H_8O_2$	7,16	18	29,20
Benzene	C_6H_6	12,82	18	52,32
Toluene	C_7H_8	13,24	20	54,04
Ethyl ether	$C_4H_{10}O$	14,8	20	60,40
Chloroform	$CHCl_3$	14,6	20	59,59
		15,1	18	61,63
Hexane	C_6H_{14}	14,7	20	60,00
		16,56	18	67,59

A.3.3 Bunsen coefficient

The solubility of radon in water is sometimes expressed by the Bunsen coefficient.

The Bunsen coefficient is linked to the Ostwald coefficient by Formula (A.3):

$$\alpha = L\frac{273,15}{T_{H_2O}} \tag{A.3}$$

where the temperature T_{H_2O} is expressed in kelvin.

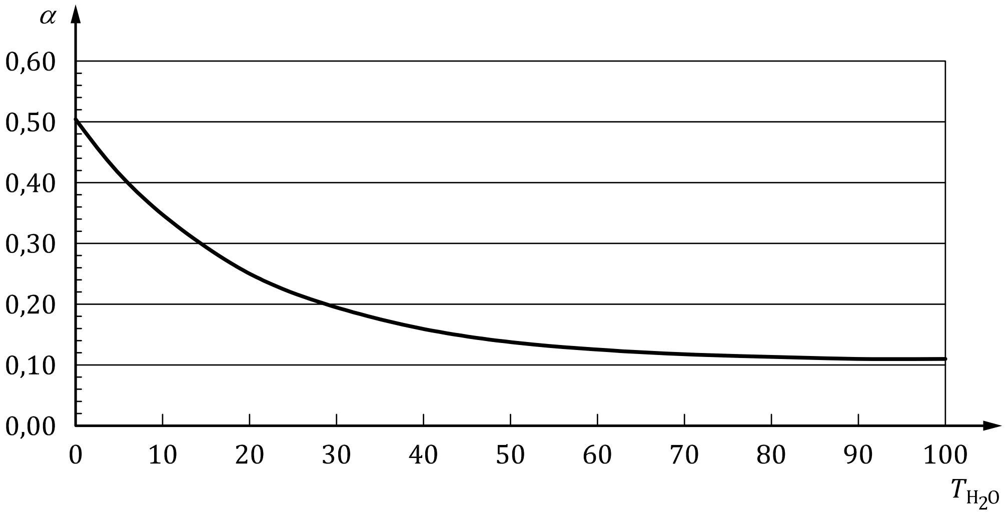
A.3.4 Parameters affecting the solubility of radon

One of the most influential parameters is the temperature of the liquid. The solubility of radon in a liquid decreases when the temperature of the liquid increases as shown for chloroform and hexane in Table A.1.

In the case of water, the decrease of the Ostwald coefficient with increase in water temperature (see Figure A.1) can be expressed by Formula (A.4) (Reference [37]):

$$L = 0,105 + 0,403\exp\left(-0,050\,2T_{H_2O}\right) \tag{A.4}$$

NOTE The same expression as Formula (A.4) is given in Reference [40] for the calculation of the Bunsen coefficient.



Key

α	Bunsen coefficient
T_{H_2O}	water temperature

Figure A.1 — Variation in the Bunsen coefficient for water as a function of water temperature using Formula (A.4)

The mineral composition of the water is also an influence quantity on the radon activity concentration. For example, radon is less soluble in sea water than in fresh water.

Annex B
(informative)

Examples of data record forms

B.1 Sampling

◉ **Identification**

Sampling sheet No.
Operator

◉ **Sampling point location**

Country
Department or county
Postcode
City or village
Place
Exact location of the sampling point

◉ **Origin of the water**

☐ surface ☐ ground ☐ mains ☐ other (specify)

◉ **Identification of the sampling device**

Container reference
Container type
Container mass (empty) G
Container internal volume L

◉ **Sampling conditions**

Sampling method ☐ tap ☐ immersion mechanical (pump, inlet pipe, etc.)

Other (specify)

Date of sampling ..../../..
Depth m
Time filling started ..:.
Time filling ended ..:.
Temperature of the sample °C
Container mass (full) g

◉ **Weather conditions**

◉ **Comments**

Name of sampler

Signature

B.2 Packaging, storage and transportation

◉ **Packaging** **Insulated pack**

◉ **Storage** Temperature °C

◉ **Reception at the analytical laboratory**

Date ..../../..

Time ..:.

Temperature °C

Condition

Signature

B.3 Measurement of the activity concentration of radon in water

◉ **Parameter measured**

◉ **Method used**

Name of the technique	
Standard reference	
Other (specify)	

◉ **Aliquot / Test sample**

Volume		**OR**	Mass	
Measurement started	**..../../..**	**.. h.**		
Measurement ended	**..../../..**	**.. h.**		
Radon activity concentration **Reference date**		Bq l^{-1}	Uncertainty	
Temperature		°C	Condition	
Interfering factors (if any)				
Comments				

Technical manager	**Signature**

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