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TECHNICAL REPORT

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Radiation protection instrumentation – Radon and radon decay product measuring instruments – Part 5: General properties of radon and radon decay products and their measurement methods

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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IEC TR 61577-5, which is a Technical Report, has been prepared by subcommittee 45B: Radiation protection instrumentation, of IEC technical committee 45: Nuclear instrumentation.

The text of this Technical Report is based on the following documents:

Enquiry draft	Report on voting
45B/912/DTR	45B/926/RVDTR

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts in the IEC 61577 series, published under the general title *Radiation protection instrumentation – Radon and radon decay product measuring instruments*, can be found on the IEC website.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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RADIATION PROTECTION INSTRUMENTATION – RADON AND RADON DECAY PRODUCT MEASURING INSTRUMENTS –

Part 5: General properties of radon and radon decay products and their measurement methods

1 Scope

This part of IEC 61577 provides basic data and technical information in order to support the design of instruments and their practical application for the measurement. The document covers ^{222}Rn as well as ^{220}Rn and the short-lived decay products of both. It is an accompanying document for the application of the technical standards series IEC 61577, and provides physical and technical fundamentals of the measurements methods. For more information, reference is made to the Bibliography.

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.

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*

IEC 61577-4, *Radiation protection instrumentation – Radon and radon decay product measuring instruments – Part 4: Equipment for the production of reference atmospheres containing radon isotopes and their decay products (STAR)*

IEC TR 62461:2015, *Radiation protection instruments – Determination of uncertainty in measurement*

3 Symbols, quantities and units

3.1 Symbols

L	Ostwald coefficient
$C_{Rn,liquid}$, C_{Rn}	Activity concentration of radon in a liquid, activity concentration of radon in air in Becquerels per cubic meter ($Bq \cdot m^{-3}$)
T_{H_2O}	Temperature of water in degrees Celsius (°C)
A, A_i	Activity, activity of radionuclide i in Becquerels (Bq)
λ_i	Radioactive decay constant of radionuclide i in per second (s^{-1})
q_i	Supply rate, production rate of radionuclide i in per second (s^{-1})
t, t_s	Time, sampling time in seconds (s)
V	Volume in cubic metres (m^3)
EEC, C_{eq}	Equilibrium equivalent concentration in Becquerels per cubic metres ($Bq \cdot m^{-3}$)
k_i	Weighting coefficient of radionuclide i
C_p	Potential alpha energy concentration in Joules per cubic metre ($J \cdot m^{-3}$)
F	Equilibrium factor
P_{Rn}	Exposure to radon in Becquerel hours per cubic metre ($Bq \cdot h \cdot m^{-3}$)
ε_p	Potential alpha energy in Joules (J)
N_i	Number of atoms of radionuclide i
P_p	Potential alpha energy exposure in Joule hours per cubic metre ($J \cdot h \cdot m^{-3}$)
$u(x)$	Standard uncertainty of quantity x
$U(x)$	Expanded uncertainty $U(x) = k \cdot u(x)$ with the coverage factor $k = 2$
v	Volume flow rate of air in litres per minute ($m^3\ s^{-1}$)
I_i	Number of counts of radionuclide i
ε , ε_s , ε_{si} , ε_c ε_{ci}	Efficiency, sampling efficiency, sampling efficiency of radionuclide i, counting efficiency of radionuclide i
α_k , α	Elapsed time after cessation of sampling until the beginning of time interval k, time at which the counting interval begins in seconds (s)
β_k , β	Elapsed time after cessation of sampling until the end of time interval k, time at which the counting interval ends in seconds (s)
D_k	Coefficients of vector **D**: Number of alpha disintegrations observed during the k^{th} time interval (counting period α_k to β_k)
$a_{k,i}(\alpha_k, \beta_k)$	Coefficients of matrix **A**: i^{th} coefficient of count determination k within the limits α_k and β_k
$N_i(t_s)$	Coefficients of vector **N**: the five unknown ^{222}Rn and ^{220}Rn short-lived decay products sampled and deposited onto the filter at time t_s
C_i	Coefficients of vector **C**: mean activity concentrations of the five short-lived decay products in the sampled air

$\mathbf{A}, \mathbf{A}^{\mathrm{T}}, \mathbf{C}, \mathbf{D}, \mathbf{N}, \mathbf{M}$	Matrices and vectors ($\mathbf{A}^{\mathrm{T}}$ is the transposed matrix of $\mathbf{A}$)
κ_k , $\eta_{k,l}$	Substitutions defined in the text
M	Output quantity of the linear model function, h
$h(X_1, \ldots, X_T)$	Linear model function with the input quantities $X_1, \ldots, X_T$
$X_1, \ldots, X_T$	Input quantities of the linear model function, h
$\hat{x}_1, \ldots, \hat{x}_T$	Best estimate of the input quantities
$u_{rel}(x)$	Relative standard uncertainty of a quantity x
$c_1, \ldots, c_T$	Sensitivity coefficient

The indices i refer to the following radionuclides:

index $i = 1$ refers to ^{218}Po

index $i = 2$ refers to ^{214}Pb

index $i = 3$ refers to ^{214}Bi/^{214}Po

index $i = 4$ refers to ^{212}Pb

index $i = 5$ refers to ^{212}Bi

index $i = 5'$ refers to ^{212}Po

3.2 Quantities and units

In this document, units of the International System (SI) are used[1]. The definitions of radiation quantities are given in IEC 60050-393 and IEC 60050-395. The corresponding old units (non SI) are indicated in brackets.

Multiples and submultiples of SI units will be used, when practicable, according to the SI system.

4 Radon in the environment

4.1 Origin, genesis and decay

The heavy metals uranium and thorium are natural components of the lithosphere. Both elements can be detected in different quantities in minerals, in soils and in water. The average concentration in the lithosphere for uranium is between 2,5 – 4 mg/kg and for thorium about 13 mg/kg [1][2]. Naturally occurring uranium is a mixture of three isotopes: 99,27 % ^{238}U, 0,72 % ^{235}U and 0,01 % ^{234}U. The primordial radionuclides ^{238}U and ^{232}Th are the mother nuclides of the decay chains by which ^{222}Rn and ^{220}Rn are formed, respectively.

The direct mother nuclide of ^{222}Rn is ^{226}Ra and of ^{220}Rn, it is ^{224}Ra. ^{226}Ra has formerly gained technical importance as luminescent paint for dials of watches and instruments. The alpha particles emitted by disintegration of radium excite a phosphor radiating luminescence light. ^{226}Ra was also applied as radiation source in medicine.

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1 International Bureau of Weights and Measures: The International System of Units, 8th edition, 2006.

2 Numbers in square brackets refer to the Bibliography.

In contradiction to all other radionuclides of the ^{238}U- and ^{232}Th-decay chains, radon isotopes are gaseous. Radon is soluble in water. Particularly, ^{222}Rn can be enriched in groundwater, if the aquifer layers contain elevated values of natural radioactivity (e.g. granite stone). A technical application of the radon isotopes is not known. In medicine, radon is used for the treatment of chronic diseases of the musculoskeletal system. As typical indication for a radon therapy, rheumatic diseases of the joints are often cited [2].

Elevated concentrations of radon have been mostly found at underground workplaces (mining), in radon spas or in water works. Elevated concentrations of ^{222}Rn in houses and other buildings can particularly occur, when a high concentration of ^{222}Rn in soil exists, and radon penetrates the house via entry paths in the below-ground structural elements. Elevated exposures to ^{220}Rn are mostly credited to thorium-containing building materials (e.g. limestone) [3].

The main source for the radiation effect is not attributed to the inhalation of radon itself but to the simultaneous inhalation of its short-lived decay products mostly attached to aerosol particles. The short-lived ^{222}Rn decay products are ^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po and those of ^{220}Rn are ^{216}Po, ^{212}Pb, ^{212}Bi and ^{212}Po. The short-lived decay products are deposited in the respiratory tract and decay there. Alpha particles emitted by ^{218}Po and ^{214}Po, or ^{212}Bi and ^{212}Po respectively, transfer their energy along the penetration way to the radiation sensitive cells, which cause possible health effects. ^{216}Po is an exemption. Because of its short half-life, it disintegrates during inhalation, and does therefore not markedly contribute to the exposure in the lung.

Whilst the ^{220}Rn decay chain ends up with the stable lead isotope ^{208}Pb, the ^{222}Rn decay chain has further stages following the short-lived decay products: Headed by ^{210}Pb, ^{210}Bi and ^{210}Po follows until it ultimately ends up with the stable lead isotope ^{206}Pb. Because of the long half-life of ^{210}Pb of more than 20 years, the remaining radionuclides are moved out of the respiratory tract by lung clearance, being excreted or deposited mainly in the mineral component of the bones [4]. In view of radiation protection, the radiation effects of the long-lived radionuclides are not relevant.

4.2 Radon in the rocks and soils and its transport towards the atmosphere

In rocks and soils, the permanent generation of radon is performed by alpha decay of radium. Radon atoms are subject to various processes on their path from the generation up to the atmosphere.

The emanation is the discharge of radon from the solid, mostly crystalline, phase of rocks and soils into the free pore volume, micro cracks, and fissures of the subsoil. The quantity, which defines the ratio between the number of radon atoms escaped the solid phase and the total number of radon atoms created in the solid phase, is the radon emanation coefficient. The process of discharge is initiated by the recoil due to alpha decay. The efficiency of this process depends on the distribution of radium in the mineral grain. The main part of radon escapes from radium located on the surface of the mineral grain or in the vicinity of the surface with depths lower than the recoil distance. A discharge of radon inside the mineral grain is only possible if sufficient pathways inside the grain are available. Very important for the emanation is therefore the grain size distribution.

The presence of water can increase the radon discharge. Due to adsorption of kinetic energy, radon atoms continue to stay in the pore water, from which it can attain the air-filled pore volume by diffusion. Soils and rocks reach the maximum of the radon emanation at various moistures. With the pore volume increasingly filling up with water, the part in the gas phase is getting lower, and the connectivity of the pore volumes by menisci is disturbed. Between dry and moisturized, the emanation can vary by a factor of 5 [5].

The movement of radon through rocks and soils is named migration. It is subject to geo-mechanical and hydrological conditions in the subsoil (permeability, fissions, flow of ground water and soil air). The main transport process is the diffusion, which can be supplemented by convection as an additional process. The diffusion is the mass transport of radon through inter-granular volumes, capillaries and fine pores caused by gradients of concentration. The coefficient of diffusion is a measure for the displacement forced by the gradient of concentration. In Table A.6, the effective diffusion coefficients for different materials are given. The coefficients take into account the prolongation of diffusion pathway due to ramifications of pores conducting the gas around the solid particles (tortuosity).

By convection, radon is transported together with carrier media, like ground waters or soil gases. The convective radon transport can result in radon anomalies. Within the bedrock, fissions and faults channelize the movement of radon-containing gases or ground waters, leading to an inhomogeneous distribution of the radon concentration far away from the origin of radon atoms.

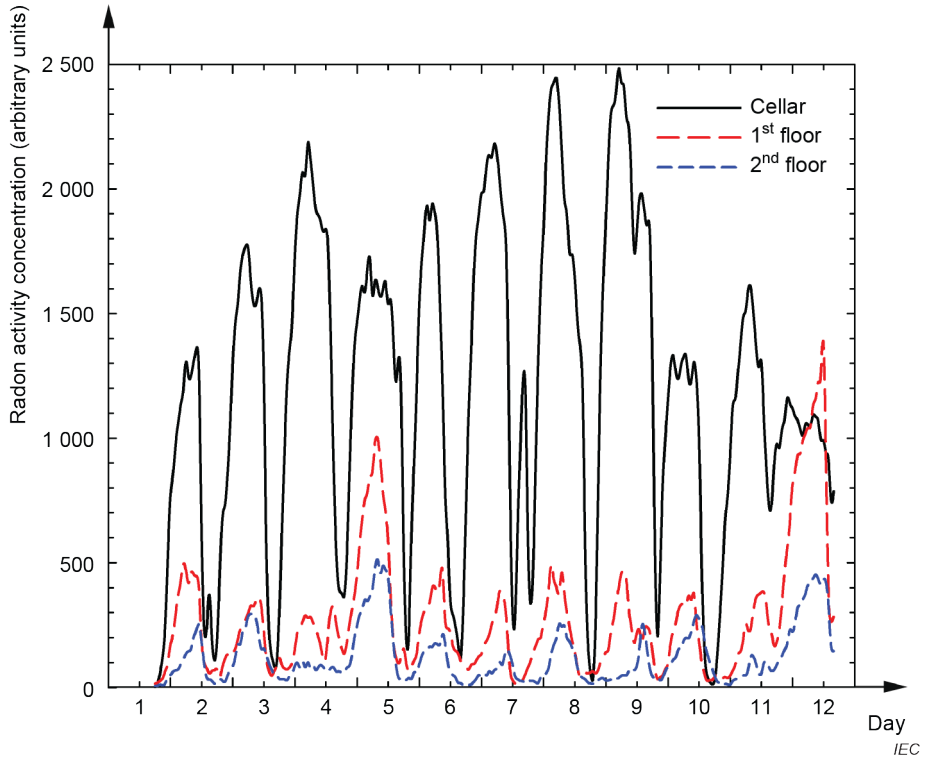
Besides the basic availability of radon by emanation and transport from the bedrock, the concentration of radon in the upper soil layers depends on the permeability, which in turn, depends on the pore size distribution and the degree of saturation with moisture, and can therefore locally and seasonally vary over several magnitudes. The discharge of radon from soil surface into air is denoted as exhalation.

4.3 Radon concentration in the outdoor air

Weather conditions with variations in air temperature from day to night cause variations in the outdoor radon concentration [6]. During the day the soil surface and the lower layers of the atmosphere heat up more intensively then the upper air layers by solar radiation, thus making the thermal stratification instable. The rising warm air results in a vertical intermixing of the atmosphere with low radon concentrations at the day. During the night and the early hours of the morning, the soil surface and the lower layers of the atmosphere cool down resulting in a stable stratification of the atmosphere (inversion at night). This process reduces the vertical intermixing of the atmosphere, which causes high radon concentration in the lower outdoor air layers. The variation of the radon concentration between day and night is greater, the greater the contrast in air temperature is. Measurements have shown that the day-to-night variations in the radon concentrations are mainly provoked by fluctuations of the vertical stratification in the atmosphere [7]. By contrast, the daily variations of the radon exhalation from the ground do not have substantial impact on the day-to-night variations in the outdoor radon concentrations [7].

4.4 Radon concentration in houses and at workplaces

Radon can enter a house through its substructure due to depressurization caused by the wind load or the temperature difference between indoor and outdoor. Indoor to outdoor temperature differences cause convective air flows, by which outdoor air flows into the building at the base



NOTE The maxima were measured in the early morning hours and the minima in the afternoon. The variations have a period of 24 h. The figure indicates the time lag of the variations and the reduced concentrations in the floors above the cellar [8].

Figure 1 – Diurnal variations of the radon activity concentration in the cellar, 1st and 2nd floor of a detached house measured over 12 days

and out of the building at the upper floors or the ceiling. The architecture of the house affects the distribution of radon throughout the building. In basements, radon-laden soil gas flows through cracks in the floor slab and walls, block wall cavities, plumbing connections, and sump wells. The radon concentration in the soil gas entering the house depends basically on the geology, the content of ^{226}Ra in the soil and its humidity. The transport of radon is enhanced when buildings are under significant negative pressure, particularly at floor level [6][7][9]. The indoor radon concentration undergoes diurnal and seasonal periods [10][11][12][13][14]. The long-term trends resulting from the use of the building or the relevant room(s) as well as from meteorological conditions are superimposed by stochastic fluctuations. Figure 1 represents an example of the diurnal variations of the radon activity concentration in the cellar, 1st and 2nd floor of a detached house measured over 12 days.

5 Radon decay products in the atmosphere

5.1 Physical processes of decay products in gaseous media

After the formation of radon decay products, they are subject to various physical and chemical processes. The processes are described here on the example of ^{218}Po, which has been investigated extensively [15][16][17]. Measurements have shown that after formation more than 10 % to – 60 % of ^{218}Po is positively charged. Different concurrent processes act on the fresh generated decay products: cluster formation, neutralization as well as attachment to aerosols and on surfaces. Within a short time (<1 s) after formation, the radionuclides attach to vapors (predominately H_2O) and to other trace gas molecules in the atmosphere. The thus generated radioactive clusters are denoted as the unattached fraction of the radon decay products, and have diameters between 0,5 nm and 3 nm [18].

Because of their small particle size and their high diffusion coefficient between 0,005 $cm^2 \cdot s^{-1}$ to 0,100 $cm^2 \cdot s^{-1}$ [18], the clusters possess a high mobility. Thus making the clusters almost independent to other transport processes in the air, as turbulence, convection, sedimentation and distraction by electromagnetic fields. A radioactive aerosol is formed by attaching the radioactive clusters to the existing aerosol particles in air. This process takes 1 s to 100 s [19]. The ratio of potential alpha energy of the short-lived radon progeny, which are unattached to aerosol particles, to the potential alpha energy of the attached short-lived radon progeny depends mainly on the aerosol particle concentration, and varies between 0,03 and 0,2 for dwellings [19]. The ratio decreases to below 0,01 in mines due to the increasing particle concentration [20].

5.2 Aerosol characteristics and ventilation

Atmospheric aerosol particle size distributions consist basically of three separate modes [21][22]:

a) the nucleation (or nuclei) mode for particles with diameters smaller than 100 nm and a modal peak in the range between 10 nm and 30 nm range,

b) the accumulation mode for particles with diameters between about 100 nm to about 1 µm and a modal peak at about 300 nm, and

c) the coarse mode corresponding to particles with diameters larger than 1 µm.

The nucleation mode appears if particles are freshly formed or emitted. This mode has a relatively short lifetime. By coagulation with other nuclei and accumulation mode particles, there sizes increase and end up in the next larger mode, the accumulation mode [21]. Several aerosol particle sources, such as cigarette smoke, gas stove, or candles, affect the particle distribution significantly according to the properties of the particles emitted. 10 % to 20 % of the attached activity could be assigned to the nucleation mode between 10 nm and 100 nm [19][23]. Aerosol particles with diameters below 100 nm are also denoted as ultrafine particles.

The accumulation mode results largely from the condensation of water and other vapours, and the attachment of particles by coagulation. This mode is stable with respect to deposition, and has a relative long atmospheric residence time.

The coarse mode particles are usually mechanically formed, or are resuspended particles such as windblown dust. This mode appears mainly in the outdoor environment or at workplaces.

The aerosol particle size distributions at workplaces are influenced by the local ventilation conditions and possibly different aerosol sources. The aerosol particle concentration depends strongly on work activity. During the work activities in mines, the radioactive aerosol particles tend to smaller diameters caused by the large number of particles emitted by diesel engines. At underground workplaces (mines, show caves) the activity size distribution of attached radon progeny can be described by a unimodal lognormal distribution specified by the activity median aerodynamic diameter and the geometric standard deviation [20]. Measurements at aboveground workplaces have identified a tri-modal aerosol size distribution with the focus on the accumulation mode [23]. Depending on the work activities, the particle sources and the ventilation, the nucleation and the coarse mode are more or less distinct [23].

In a radon atmosphere, a mixture of gaseous radon and radon decay products attached or unattached to aerosol particles exists. But not all the decay products are available in the air volume. Because of particle deposition and adhesion, a part of them is deposited to other surfaces, as walls, floors or the possible inventory of the site (e.g. room). This part of radioactivity is not inhaled and does, therefore, not contribute to the radiation effects. The radon equilibrium factor expresses the disturbance of equilibrium between radon and its short-lived decay products (for definition see 7.1). In real atmospheres, the equilibrium factor is below 1. Indoor measurements have shown that the equilibrium factor varies within a 95 % confidence interval from 0,2 to 0,7 around the mean value of 0,4 [24][25].