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RADON HAZARD GUIDELINE

S. Beaubien, S. Bigi, G. Ciotoli, B. Dehandschutter, A. Sciarra

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Executive Summary

The following report highlights various issues related to indoor radon and its eventual remediation.

The first chapter examines the legal framework of indoor radon. Considering the origin and eventual goals of the present work, focus is given to the European context. In particular, the European Directive 20213/59/Euratom, which laid out the background and requirements for member states to develop national laws related to ionizing radiation (including indoor radon), is used to introduce the present regulations that exist in Italy and Belgium that define acceptable dwelling and workplace radon concentrations, responsibilities, and penalties.

The second chapter describes how and where radon is formed and outlines the ways that it can enter and accumulate within indoor environments. The three main sources of soil, tap water and building materials are explained, given that the source pathway is critical to understand to choose the best and most effective remediation strategy.

Monitoring methods are reviewed in chapter 3, techniques that are important not only to understand if an indoor radon problem exists but also to monitor how values change as a function of any installed remediation system. Cumulative or dose integrating sensors are shown to be inexpensive, simple to use and effective for long term monitoring that assesses yearly dosage, while continuous or instantaneous radon detectors are more expensive but show how radon levels change as a function of occupant activities, environmental conditions, or other factors. Monitoring protocols established by world, national and regional health bodies are also described to illustrate how these sensors should be used to provide the most reliable results (considering the strong variability of indoor radon values).

Chapter 4 gives an overview of potential remediation methods, first describing how the radon can enter the building and then summarizing some of the more common approaches used to reduce radon in both dwellings and workplaces. The majority of methods focus on preventing the radon from entering the building in the first place, the preferred approach to obtain the lowest concentrations however only effective when the radon is coming from the soil beneath or surrounding the foundation. These include waterproof barriers and well as sub-living area depressurization or pressurization, which forces the radon to avoid the building and vent more directly into the atmosphere. Degassing of radon-rich well water used for tap water is briefly described for this entry vector, while ventilation methods (both passive and forced air) are described for when building materials are the main radon source. Finally, this chapter ends with a brief description of the technology developed within the LIFE-RESPIRE project, called the Respire Radon Remediation System, or R3S for short. This autonomous, flexible system using real-time radon monitoring to control any type of fan, such as sub-floor depressurization or living area ventilation, to lower radon concentrations. By actuating the fan only when radon values exceed a pre-set threshold (like that outlined in the European Directive), the system is energy efficient both in terms of consumption as well as heat management.

Table of Contents

1. LEGAL FRAMEWORK

1.1. INTERNATIONAL DIRECTIVES AND GUIDELINES

1.1.1. *The WHO Handbook on Radon*

This document, published in 2009, summarizes all available epidemiological evidence concerning the health risks and effects of radon exposure, particularly related to indoor radon in dwellings and places of work (risk increases 16% per 100 Bq/m³). The document provides detailed recommendations for radon measurements and preventive and corrective actions, information that can be used to develop nation radon programmes. According to the findings of WHO (2009), 100 Bq/m³ can be used as a reference level, with radon protective measures above this level being justified in all cases.

1.1.2. *The International Basic Safety Standards*

In 2014, the IAEA published the International Basic Safety Standards, addressing (in Requirement 50) radon as a source of concern for public health and occupational exposure. According to this document, information on the specific situations in a country shall be made public by the government. To accomplish this a programme must be developed that includes radon surveys, an estimate of the level of exposure, and the communication of protective and corrective measures, etc. In areas of concern, the governments shall aim to reduce radon exposure by coordinated actions defined in an action plan. Such actions include the establishment of an appropriate reference level that can be used to direct activities towards the reduction of radon activity concentrations to optimized levels (in existing and new buildings).

1.1.3. *EU BSS*

The European Directive (2013/59/Euratom, 2014, called hereafter the BSS) addresses radon in over 9 articles, classifying radon as an existing exposure situation. For the first time, the control of radon in dwellings is explicitly and in detail addressed in a European Directive on radiation protection. In particular, the concept of reference level is addressed for radon, with the Directive stating "… level of … activity concentration above which it is judged inappropriate to allow exposures to occur … even though it is not a limit that may not be exceeded". The value of the reference level should not exceed 300 Bq/m³ (unless justified by prevailing national circumstances) (Articles 54 and 74).

In workplaces, appropriate radon exposure reduction measures should be taken if the national reference level is exceeded (Articles 35 and 54). In dwellings, radon needs to be managed according to specifications defined in the national radon action plans setting out reference levels, using specific preventive and corrective measures, and an information strategy towards the public concerning radon has to be undertaken (article 74). In addition, art. 75 states that 1 mSv year^{-1} is the indoor limit of exposure to gamma radiation emitted by building materials, both for people and workers, and that the activity concentrations of radionuclides are determined before these materials are put on the market.

In application of Article 103 of the Directive 2013/59/Euratom, Member States shall establish a national action plan addressing long-term risks from radon exposure in dwellings, buildings with public access and workplaces for any radon source, whether from soil, building materials or water. The member states need to identify areas where the radon concentration is of specific concern.

Items to be considered and/or established when preparing a national action plan for long-term risks from radon exposures (as referred to in Articles 54, 74 and 103) include:

1) A strategy for conducting surveys of indoor radon concentrations (and/or associated soil gas concentrations) to determine areas at risk, for the management of measurement data and for the establishment of other relevant parameters (such as soil and rock types, permeability and radium-226 content of rock or soil).
2) Approach, data and criteria to be used to delineate areas or to define other parameters that can be used as proxies of potentially high radon exposure rates.
3) Identification of types of workplaces and buildings with public access (such as schools, underground workplaces, and those in high-risk areas) where measurements are required. This involves a risk assessment that also considers, for instance, occupancy hours.
4) The basis for the reference levels for dwellings and workplaces. If applicable, the basis for the different reference levels for different uses of buildings (dwellings, buildings with public access, workplaces) as well as for existing and new buildings.
5) Assignment of responsibilities (governmental and non-governmental), coordination mechanisms and available resources for implementation of the action plan.
6) Strategy for reducing radon exposure in dwellings and for prioritizing the situations identified under point 2.
7) Strategy for facilitating post construction remedial action.
8) Strategy, including methods and tools, for preventing radon ingress in new buildings, including identification of building materials with significant radon exhalation.
9) Schedules for reviews of the action plan.
10) Strategy for communication to increase public awareness and inform local decision makers, employers and employees of the risks of radon, including in relation to smoking.
11) Guidance on methods and tools for measurements and remedial measures. Criteria for the accreditation of measurement and remediation services shall also be considered.
12) Where appropriate, provision of financial support for radon surveys and for remedial measures, in particular for private dwellings with very high radon concentrations.
13) Long-term goals in terms of reducing lung cancer risk attributable to radon exposure (for smokers and non- smokers).
14) Where appropriate, consideration of other related issues and corresponding programmes, such as programmes on energy saving and indoor air quality.

1.2. REGULATORY FRAMEWORK IN ITALY

1.2.1. *Brief history of radon regulation in Italy*

In Italy, the history of ionizing radiation and radon regulation began with the **EU Directive 96/29/EURATOM**. The Directive concerned the protection of the population against exposure to radon in closed environments and recommended member states to create adequate systems to reduce indoor radon exposure. In particular, the Directive recommended a reference radiation level corresponding to an effective equivalent dose of 20 mSv per year. This dose, for practical purposes, can be considered equivalent to an average annual concentration of radon gas of 400 Bq m^{-3} in existing buildings. For new buildings the reference level was equal to an effective equivalent dose of 10 mSv per year, which corresponds to an average annual radon concentration of 100 Bq m^{-3}.

Furthermore, the Directive recommends that, due to daily and seasonal variations in indoor radon levels, decisions relating to radiation protection be based on the annual average of radon gas or its decay products in buildings and that such measurements be carried out using reliable measuring techniques by competent authorities. Finally, competent authorities should define criteria for the identification of regions, localities and construction characteristics that have a high probably of elevated radon levels in closed environments. Surveys of various parameters (e.g., soil and building material activity, soil permeability, etc.) can be used to help identify such exposure factors.

The EU Directive 96/29/EURATOM was adopted in Italy with **Legislative Decree 241/2000**, which gave indications for radon measurements in working places. This decree addressed natural sources of ionizing radiation and identified some work activities in which there is an obligation to carry out radon measurements (e.g., all underground work environments). The Action Level for workplaces, expressed in terms of "annual average concentration", was set both at 500 Bq m^{-3} of average annual radon activity concentration and 1 mSv per year of effective dose (Art. 10bis). The decree also establishes obligations that the operator must carry out remediation work if the measured radon concentration and estimated annual worker dosage, determined by an accredited company and Qualified Expert, exceeds the established limits

The Decree also established a technical commission for nuclear safety and health protection at the National Agency for Environmental Protection (ANPA, then ISPRA and now ISIN), which was to create guidelines for radon measurement and assessment of related exposures. The commission was not established within the legal timeframe established in the decree, however, leading to uncertainty for both administrators and industry. To deal with this non-compliance on the part of central institutions, in 2003 a group of regions (Emilia-Romagna, Lombardy, Tuscany, Umbria and Veneto) formed the Interregional Coordination to develop guidelines for underground workplaces measurements. In 2005, the Lazio region issued the **first regional law (n.14 31 March 2005)** about prevention and protection from radon risk, in which an action plan was developed to protect public health and safeguard the environmental heritage. The plan was aimed to measure radon in buildings, as well as the soil and in natural fractured zones, to define hazardous areas and buildings at risk where remediation actions are needed.

Radon regulation also included indications concerning the radiological quality of drinking water supplies with regard to radon and long-lived radon decay products. The **Legislative Decree n. 28** of 15 February 2016 transposed in Italy the **Euratom Recommendation 928/2001**. Representative investigations should be carried out to define the extent and nature of exposure to radon and long-lived radon decay products in domestic drinking water supplies, unless the information is already available. The survey should be designed so that the basic parameters can be identified to guide further action on the exposures, including, in particular, the geological / hydrological characteristics of the area, the radioactivity of the rock or soil and the type of wells. Regarding public or commercial water supply actions should be taken when above 100 Bq L^{-1}. Natural mineral waters and waters for medical use are excluded as special rules have already been defined for these types of water (see Council Directive 80/777 / EEC and Council Directive 65/65 / EEC).

After the **EU BSS Directive 2013/59/Euratom**, some other regions (e.g., Lombardia, Campania and Puglia) promoted regional laws for the reduction of exposure to natural radioactivity and the measuring of radon gas in confined environments. All these laws are now substituted by the recent Legislative Decree 101 of 31 July 2020 (see next section).

1.2.2. The Legislative Decree 31th July 2020, n.101

In Italy, the Legislative Decree n.101, 31th July 2020 transposes the EU BSS Directive 2013/59/Euratom, establishing basic safety standards relating to protection against the dangers arising from exposure to ionizing radiation and radon, thus repealing the older European directives (89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom e 2003/122/Euratom), as well as the national Legislative Decree 241/2000 and various regional laws. The regulatory framework that provides specific information and regulations for the ionising radiation from radon is reported in Title IV “Natural Sources of Ionizing Radiation” (Chapter I “Radon exposure” Section I. “General provisions”) of the Decree.

According to Legislative Decree n.101, the legislation and policy on ionizing radiation and radon defines the competence of various national, regional and local bodies. In particular, the National Inspectorate for Nuclear Safety (ISIN) manages the national database of environmental radioactivity, which includes radon concentration data relating to homes and workplaces as well as information on adopted remediation measures. ISIN guarantees data access to the Italian National Institute of Health (ISS), in which the National Radon Archive operates programs to prevent and reduce the health risk of pathologies resulting from exposure to radon. ISIN and ISS established a specific technical protocol concerning the contents and format of the data, as well as the interconnection between the two databases to ensure the mutual exchange of information. ISIN allows database access to all local administrations and national bodies for their respective institutional purposes (Figure 1). The regional and provincial agencies for the protection of the environment (ARPA / APPA), the Local Health Authorities (ASL) and the authorised dosimetry companies must transmit their data of the annual average concentration of indoor Rn detected in homes and workplaces to the ISIN database.

Companies that would like to carry out dosimetry service activities must be accredited by authorized institutes, which must consider the used measuring techniques, devices and quality control (see art. 15 of the Decree). Qualification procedures are established in accordance with the opinion of the ISIN, the Institute of Primary Metrology of Ionizing Radiation and the National Institute for Insurance against Accidents at Work (INAIL). In addition to ISIN and INAIL, the Atomic Defence Laboratory of the Department of Firefighters (VVF) is also an authorized institution.

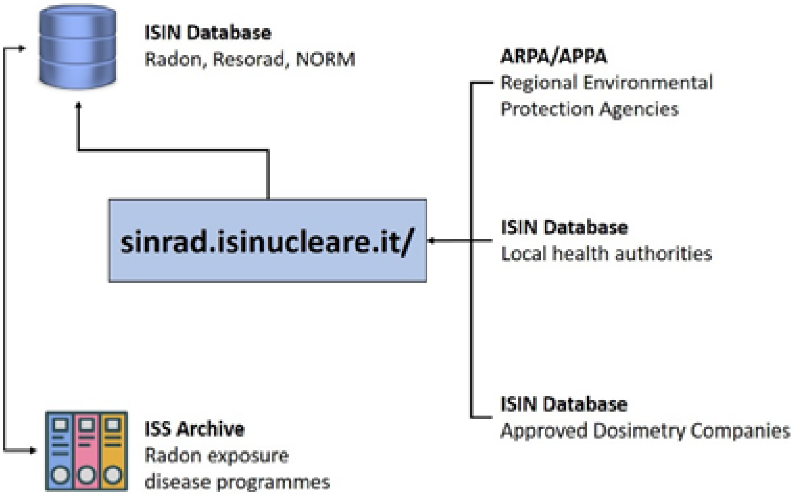

Figure 1. Flow chart of the national radon database showing the national, regional and local authorities involved.

According to art. 10 of Legislative Decree 31 July 2020 n.101, a decree of the President of the Council of Ministers, upon proposal from the Ministry of the Environment and Territorial Protection (MITE) and the Ministry of Health, together with the Ministries of Economic Development, Labour and Social Policies, and Infrastructure and Transport, in agreement with the State-Regions Conference, and with input from ISIN and ISS, constitutes a working group of experts to set up the Radon National Action Plan (currently under the approval by the Council of Ministers). The working group is composed of representatives of the involved institutions (MITE, ISIN, ISS) and INAIL. The Radon National Action Plan shall include:

- strategies aimed at measuring, preventing and reducing long-term risk to the population of radon exposure in existing or new homes, public buildings and places of work for any source of radon, be it the soil, building materials or water.
- the criteria to classify areas where the annual average radon concentration is likely to exceed the level of national reference in a significant number of buildings
- the technical rules and criteria for implementing measures to prevent radon from entering new buildings and renovation interventions on existing buildings in direct contact with the soil;
- the development of appropriate national and local information campaigns.

Articles 11 and 12 of the Decree define the criteria to be used to identify Radon Priority Areas (RPAs) and the reference radon levels for home and workplaces (as required by the article 103 of the EU Directive 59/2013/EURATOM). Based on the national radon plan, the Regions and the Autonomous Provinces of Trento and Bolzano will perform radon measurements, acquire the relevant data and identify the RPAs (defined as areas where it is estimated that >15% of the buildings exceed the annual average radon activity concentration of 300 Bq m^{-3}). The percentage of buildings is determined with investigations or measurements of radon performed on (or normalized to) the ground floor. In these areas intervention priorities should be defined to reduce the levels of concentration below the reference levels. The maximum reference levels for homes and places of work, expressed in terms of the average annual value of the concentration of radon activity in the air, are:

- 300 Bq m-3 for existing rooms;
- 200 Bq m-3 for houses built after 31 December 2024;
- 300 Bq m-3 for places of work;
- the reference level referred to in article 17, paragraph 4, is 6 mSv of annual effective dose.

Regulations regarding information and awareness campaigns are reported in **Article 14**. In particular, the Ministries of Health and Labour and Social Policies, ISIN, ISS and INAIL, the Regions and the Autonomous Provinces of Trento and Bolzano must make information available regarding exposure to indoor radon, the health risks of radon exposure (together with the associated risk of smoking), the importance of measuring the annual average radon concentration and the technical interventions available to reduce radon levels, based on indications of the National Action Plan for radon.

As reported above, experts and companies must be qualified to carry out radon measurements and remediation interventions (Art. 15 of the Decree). They must be able to adopt corrective measures for reducing the concentration of radon in buildings on the basis of the contents of the National Action Plan and on the basis of technical and international indications. The following workplaces are subject to the evaluation of exposure to radon risk (Art. 16 of the Decree): underground and semi-underground rooms or located on the ground floor, specific types of workplaces or RPAs identified by the radon National Action Plan, and spas.

In these workplaces, the employer is required to complete the measurements of the average annual concentration of radon activity in the air (Art. 17 of the Decree). In the case that the average annual radon level does not exceed the reference level, the Employer must prepare and store, for eight years, a document containing the results of the measurements. The Employer repeats the measurements every eight years, or whenever interventions involving structural work are carried out. In the case that the average annual radon value exceeds the reference level, the Employer must take corrective measures to reduce the concentration to the lowest achievable level. These measures must be completed within 2 years of the release of the technical report. The Employer must guarantee the maintenance of corrective measures over time and repeat the measurements every four years. In the case that, despite the adoption of corrective measures, the average annual radon concentration remains above the reference level, the Employer, making use of a radiation protection expert, evaluates the annual effective doses. The results of the assessments must be stored for a period of no less than 10 years. The Employer carries out measurements of the average annual concentration of radon activity in the air using the dosimetry services recognized in art. 155, with the release of a technical report.

The Employer is subject to penalties if all the measures provided for by the Decree have not been implemented. The penalties provided by the Decree range from imprisonment (6 months to 1 year) or a penalty ranging from € 5,000 to € 20,000 for the Employer who does not make use of an expert or does not implement the indicated corrective measures; imprisonment (1 to 6 months) or a penalty ranging from € 1,000 to € 15,000 for the Employer who does not carry out the measurements in the manner and within the deadlines indicated by Legislative Decree; administrative sanctions ranging from € 1,500 to € 10,000 for failure to comply with the transmission, information or communication obligations to the authorities (ISIN, ISS, ARPAs), as provided by art. 18 and 32 of the Decree.

1.3. REGULATORY FRAMEWORK IN BELGIUM

In Belgium, policy and regulations on ionising radiation are a federal competence overseen by the Federal Agency for Nuclear Control (FANC). Following various European and international recommendations, FANC set up a national radon action plan in 2009 and produced an associated dossier on this subject (link). The plan considers the activities and strategies (for surveys, communication, building protection, remediation, mapping, and management) that must be developed to achieve the goal of reduced radon exposure for the population and workers. This document completes the existing radon action plan with additional content following ANNEX XVIII of the EU BSS Directive 2013/59/Euratom. The action plan consists of relatively continuous items like strategy, definition of working fields and technical details plus periodic items like annual actions, with information being updated and published in the annual radon action plan each year.

The existing regulatory framework is essentially published in the FANC Law from 1994, the Royal Decree of 20 July 2001, the FANC Decree of 30 November 2015 and the procedures and guides published on the FANC web-site (link). At present the existing regulations are being updated in order to implement the scientific findings published after the 1990's (WHO, 2009, UNSCEAR 2009, ICRP 60, 65, 103, 115), the international Basic Safety Standards (IAEA BSS), and the European Directive 2013/59/Euratom. The current action plan uses the definitions, reference levels and dose values fixed in the EU BSS, while some of the above mentioned national documents are in the process of revision. The revision will be accomplished soon after the publication of the revised Royal Decree.

1.3.1. Radon risk management in workplaces

FANC has published specific regulations and guidelines for radon measurements in workplaces since 2012 (link). Based on extensive experience from radon measurements and inspections in workplaces, the guidelines serve as a tool for employers to comply with existing regulations.

The workplaces which have to measure the concentrations of radon and introduce a notification dossier are the ones situated in a municipality classified as class 2 (more than 5% of probability to exceed the reference level of 300 Bq/m^3) and enumerated on §6.1.3.

1.3.1.1. Reference Level

The reference level is defined as the annual average radon concentration above which it is judged inappropriate to allow exposures to occur, even though it is not a limit that may not be exceeded. The reference level for radon in workplaces (and in dwellings) has been fixed at 300 Bq/m^3. When the reference level is exceeded, a notification has to be submitted to FANC, in application of articles 4, 9 and 20 of the radiation protection regulation (RD 2001) and corrective measures must be implemented unless a risk analysis confirms that the maximum exposure level of 600 $kBqh/m^3$ is not exceeded.

1.3.1.2. Dose conversion coefficients

In order to estimate the (annual) exposure of the population to radon and the related risk, and for managing the health risks related to radon exposure in workplaces, it is necessary to calculate the time integrated exposure and to estimate annual doses resulting from radon exposure. In the EU BSS 2013/59/Euratom, this principle is specified in article 35.2, stating the necessity to manage radon in workplaces as a planned exposure (practices) if it is liable to exceed 6 mSv/y. To make this assessment, doses received from radon have to be calculated by converting from volumetric radon concentrations to time integrated exposure and dose. These dose conversion factors are fixed by international organisations, such as the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the National Academy of Sciences Biological Effects of Ionizing Radiation (BEIR) and the International Commission on Radiological Protection (ICRP). Belgium (FANC) uses the dose conversion factors published in ICRP 137. In short, the dose coefficient in most indoor exposure situations corresponds to $6.7\ 10^{-6}$ mSv $(Bq\ h\ m^{-3})^{-1}$. This results for workplaces (with a yearly working time of 2000h and equilibrium factor F=0.4[1]) in 1 mSv = 80Bq/m^3 (and 6 mSv ~ 450 Bq/m^3). Until the ICRP or Euratom Article 31 Expert Group publishes more definitive conversion factors, these will be used for dose estimation and risk calculations.

1.3.1.3. Identification of workplaces

Radon measurements have to be carried out in specific workplaces in Class 2 municipalities. The measurement protocol and the declaration of the measurement results to the competent authority (FANC) are specified in guideline documentation on the website (link) and in a specific document (link). The employer, responsible for measurements in the workplace, can order the radon detectors directly through the website www.radonatwork.be, or through the list of radon measurement service providers registered at FANC and published in a list on the FANC website (link). The following priority workplaces have to measure and report radon concentrations:

- Educational institutes, day-care centres, medical centres
- Public buildings (post, provinces, municipalities, police, libraries)
- Underground workplaces (galleries and caves open to the public)
- Water treatment facilities

1.3.1.4. Corrective measures

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[1] The equilibrium factor F is a measure of the disequilibrium which exists between the radon gas and its progeny due to ventilation and deposit on surfaces.

If the reference level for a specific declaration is exceeded, the employer must perform corrective measures, either directly by reducing the radon concentration (interventions in terms of ventilation in basements or crawl-spaces, sub-soil depressurisation, mechanical controlled ventilation systems, etc.), or through an intermediate step by carrying out a risk analysis that calculates the different exposure scenarios for the employees (Articles 4 and 9 of RD 2001). This generally requires a measurement campaign in the workplace premises using active and continuous radon monitors. Guidelines are published on the FANC website (link).

1.3.1.5. Assignment of responsibilities

FANC is responsible on the Belgian territory for the protection of workers due the effects of ionising radiation (RD 2001, Art. 4, 9, 20.3). Therefore FANC is the competent authority for everything related to radon measurements, follow-up, declarations and inspections in workplaces. FANC assures the implementation of the radon measurements in workplaces, the declaration of the results and the remedial and corrective measures related to possible high exposures and sets out responsibilities by the following means:

- Regular meetings with local employers such as municipalities, regional authorities, provinces, trade unions, services for prevention and protection at work.
- Information campaigns through road-shows, professional fairs and exposition events, mailings, bilateral contacts.
- A yearly inspection programme setting out the strategy and procedures to inspect compliance to the regulations of the targeted workplaces.

Guidance for the involved parties and stakeholders is provided on the regulatory system (link), the procedures for measurements (link) the procedures for declaration/notification of measurement results (link), measurement service providers (link), and technical assistance for implementing corrective measures (link). The information is also available through dedicated brochures available from local stakeholders (medical, preventive, local authorities, etc.) and the FANC web site (link).

1.3.2. Radon risk management in dwellings

1.3.2.1. Reference level

The reference radon levels in dwellings is based on information available from different surveys on the territory. It is important to note that it serves as a tool for optimisation of the protection of the public (and the workers). The reference level for dwellings (as for workplaces) is 300 Bq/m³. Optimisation has to be applied above as well as below the reference level, up to levels of exposure that have to be as low as reasonably achievable (As Low As Reasonably Achievable - ALARA), with the target level of 100 Bq/m³ (Figure 2). Instead, the intervention level is set at 600 Bq/m³, above which corrective measures must be put in place as soon as possible. Above the reference level, FANC provides detailed information on remedial actions as well as free control tests (detectors) to evaluate the efficiency after remediation. For new buildings, the target level is that which no new building should in principle exceed, provided that the correct preventive measures have been implemented.

Table 1 details the distribution of radon concentrations throughout Belgium, while Table 2 gives estimates of the number of buildings affected by the different radon concentration levels.

Figure 2. The use of the reference level as a tool for optimisation of the radiation protection.

Table 1. Average radon exposure of the Belgian population (population data for 2010). AM: arithmetic mean, MED: median, GM: geometric mean, GSD: geometric standard deviation. Values are in Bq/m³. RPA: radon prone areas. % gives the percentage of single family h

	Population	dwellings	AM	MED	GM	GSD	% >100	% >200	% >300	% >400	% >800
Belgium	10584534	3742000	57	44	46	1.7	10.0	2.1	0.9	0.6	0.2
Wallonia	3435879	1325000	84	60	75	1.7	26.0	4.5	2.6	1.6	0.4
Flanders	6117440	2191000	44	37	36	1.2	3.2	0.1	0.05	0.0	0.0
Brussels	1031215	226000	44	37	36	1.2	4.0	0.1	0.1	0.0	0.0
RPA	376568	130000	220	127	137	1.9	43.0	33.0	17.0	13.0	4.3

Table 2. Estimate of the number of single family houses in the different categories of radon exposure (Bq/m³).

	dwellings	>100	>200	>300	>400	>800
Belgium	3742000	360000	84000	36000	21000	5600
Wallonia	1325000	280000	79000	35000	21000	5600
Flanders	2191000	70000	some	some	0	0
Brussels	226000	9000	5000	some	0	0
Radon prone areas	130000	56000	43000	22000	17000	5500

The number of dwellings exceeding the level of 300 Bq/m³ is about 36000 while the number of affected workplaces is estimated to be about 3600. These data were published by the Superior Health Council in 2017. The radon reference level is a tool for optimisation and, specifically in workplaces, it is used to steer the graded approach of radiation protection. The legal level of radon exposure, as defined in Article 20.3 of the radiation protection regulations (RD 2001) is 600 kBqh/m³ per year. This means that a worker who is exposed over 2000 hours per year (approximate full-time employment) to more than 300 Bq/m³ (reference level of radon concentration) will exceed the exposure limit and is submitted to notification and corrective measures (Art. 9 RD 2001).

1.3.2.2. Assignment of responsibilities

FANC is the competent authority for the protection of the population and the environment against ionizing radiation in the event of exposure to radon (Art. 1 of RD 2001). One of its tasks is to determine the dose due to radon received by the population (Art. 70) and to reduce them if necessary (Art. 20.2

and 72bis). As such, FANC has the mission to act as the coordinating authority and to help organize activities aimed at applying the regulations, complying with the obligations and raising awareness of the actors involved in radon.

To achieve this, FANC collaborates closely with the following actors: the federal and regional public services of Employment, Health, Housing and Environment, the provinces, the municipalities, professional organizations (in the medical field, prevention services, construction professional organisations, etc.), academic and research institutes (universities, Scientific and Technical Center for Construction - CSTC, Belgian Nuclear Research Centre - SCK-CEN, National Institute of Radioelements - IRE, etc.), foreign and international organizations (European Union - EU, Dutch Authority for Nuclear Safety and Radiation Protection - ANVS, German Federal Office for Radiation Protection - BfS, French Nuclear Safety Authority - ASN, French Radiation Protection and Nuclear Safety Institute - IRSN, Heads of the European Radiological protection Competent authorities - HERCA, European Radon Association - ERA, International Radiation Protection Association - IRPA, Joint Research Centre - JRC, etc.) and the general public.

The coordinative role of FANC is important to ensure centralized coordination of all radon actions and uniformity of approaches, messages, measurements and interventions throughout the territory. In addition, this ensures compliance of all actions with the recommendations and current conclusions of international bodies in the field of radiation protection. Centralized coordination is the only way for good management and the statistical and scientific analysis of all data relating to radon (screening measures, control measures, remediation, cartography, epidemiology, etc.).

Guidance for the different involved parties and stakeholders is provided on the level of information about the regulatory system (link), the procedures for measurements (link), measurement service providers (link), and technical assistance for implementing corrective measures (link). The different information is also available in dedicated brochures available through local stakeholders (medical, preventive, local authorities, etc.) and the FANC web site (link).

1.3.2.3. Remediation of existing buildings

In the framework of the annual radon measurement campaigns (www.actionradon.be), house-owners are stimulated to carry out remedial actions by:

- Proposal of remedial actions for measurements around the reference level, through brochures (link) and the publication of a list of trained radon professionals (link).
- Proposal of radon inspection and diagnostic services by FANC in collaboration with local authorities for all measurements exceeding 600 Bq/m³.
- Proposal of free control measures after remedial actions.
- Financial intervention by the regional government for remedial actions (link).

Above the reference level, in the case of existing buildings, it may sometimes be impossible or too difficult to reasonably reduce the radon concentration below the reference level. In such cases, evaluated on a case-by-case basis, exposure situations can be locally accepted (Figure 2).

Finally, for communication purposes, the reference level can be represented on a continuous scale ranging from low risk to high risk (Figure 3).

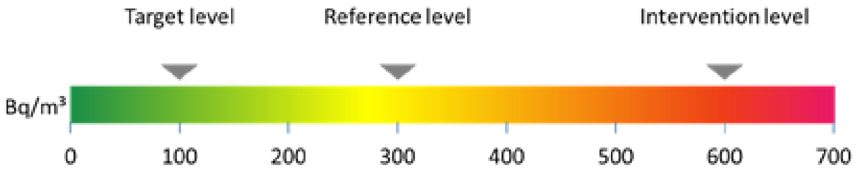

Figure 3. Radon Reference level on a continuous scale from low health risk to high health risk.

1.3.2.4. Prevention in new buildings

The protection of new buildings against radon ingress is very important to achieve the general long term objectives of the radon action plan. To achieve this, awareness campaigns are organised to inform the public on radon risk and on the protective measure to take during building construction. Besides informing the public by publications and interactive mapping applications, training of building professionals and local governmental administrations is essential. Including regulations on radon protection in the building codes, a regional competence, is essential to implement radon protection in a structural and sustainable way. Coordination with regional authorities on the implementation of these protective measures in the building codes is essential to attain the goals. The regional building code of the Walloon Region imposes a description of the radon protective measures by the responsible architect in the building permit (Case 13 in Annex 4 of the Building Code link).

2. ORIGIN AND MIGRATION OF RADON

Radon isotopes are noble gases produced via the uranium-thorium decay chain. They are emanated from mineral grains in the subsurface; if this occurs below the water table the radon can dissolve in the groundwater, whereas if it occurs in the unsaturated zone it can migrate towards the atmosphere. Of paramount importance is the emanation of ^{222}Rn, which is produced by the alpha decay of radium (^{226}Ra) and has a half-life (T) of 3.823 days. Isotopes like ^{220}Rn (T = 55 s) and ^{219}Rn (T = 4 s) are less relevant because their short half-lives mean that they decay to immobile solid phases before they can migrate and accumulate in the atmosphere. For simplicity, this document uses “radon” and “Rn” to refer to the dominant isotope ^{222}Rn, unless otherwise stated. The following summarizes how and where radon forms, and the processes that control its migration and accumulation in groundwater, in the gas filled pores in shallow, unsaturated rocks and soil, and in building materials.

2.1. RADON FORMATION

Geology is the most important factor controlling the source and distribution of radon (i.e. Miles and Appleton, 2005; Appleton and Miles, 2010), as some rock types are more enriched in uranium and radium than others and they tend to produce more radon. Relatively high levels of radon emissions are associated with light-coloured volcanic rocks, granites, dark shales (rich in organic materials), ironstones, reworked limestone (i.e. red lands), sedimentary rocks that contain phosphate, and some metamorphic rocks. Uranium can also be remobilized and concentrated along fractures in the rocks or along grain boundaries. Furthermore, the presence of radon in soil depends on the presence of radioactive minerals in the parent rock from which it is derived. There are two mechanisms that can transfer radon out of its parent mineral crystal and into the surrounding air- or water-filled pores or fractures: diffusion through the crystal lattice or alpha-recoil during formation.

2.1.1. Diffusion in the crystal lattice

Radon can diffuse through the crystal lattice of a mineral, however, the slow rate of diffusion through the solid matrix combined with the short radon half-life (3.82 days) does not allow a significant distance to be travelled. The concentration gradient due to diffusion alone in an isotropic medium can be calculated with the following formula, an expression of Fick’s law:

$$C(x) = C_o \cdot e^{\left(-\frac{x}{L}\right)}, \qquad L = \sqrt{\frac{D}{\lambda}}$$

where: C(x) is the radon concentration at a distance x from the origin (i.e. the point where it was produced); C_0 is the concentration at the origin; and L is the diffusion length, given by the square root of the ratio between the diffusion coefficient D and the ^{222}Rn decay constant.

Only 5% of the radon atoms can reach a distance equal to 5L from the point where they were produced; since L is only 0.7 nm, the migration capacity of radon by diffusion in the solid phase is very limited and essentially negligible compared to the contribution due to the alpha-recoil effect.

2.1.2. Alpha-recoil effect

When a ^{226}Ra nucleus alpha decays, the resultant ^{222}Rn nucleus undergoes a recoil, moving in the opposite direction to that of the ^{4}He nucleus with an energy equal to about 85 keV (98.1% of the energy released due to the decay). This energy is sufficient for the radon nucleus to travel between 20 and 70 nm in minerals, about 100 nm in water and about 6300 nm in air.

Tanner (1980) proposed a model to explain the alpha recoil effect. Only radium nuclei that decay at a distance from the grain surface that is less than the range of the radon recoil in the considered material can escape the crystal into the surrounding fluid (air or gas) that permeate the rock. Figure 4 shows the situations that can occur for different locations of the ^{226}Ra nuclei: the dotted and grey areas represent water and gas, respectively, present in the porosity of the rock.

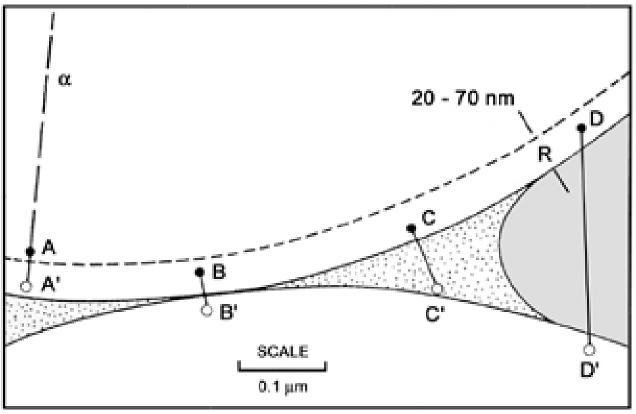

Figure 4. Schematic representation of the process of radon emanation due to the alpha-recoil effect.

As the figure shows, some of these nuclei (B and D), while abandoning the grain in which they are produced, can remain trapped in the solid matrix of the adjacent grains; in the case of nucleus B because they cross the separation surface between the two grains, in the case of core D because the gas may not be sufficient to stop the recoil nucleus before it reaches the adjacent grain.

The radon emanation factor of a rock is defined as the ratio between the quantity of ^{222}Rn that escapes from the solid matrix and the quantity of radon produced inside it, by radioactive decay, per unit volume. The emanation factor obviously assumes values lower than unity, therefore only a fraction of the radon produced inside the solid matrix, which varies with the solid matrix nature but is independent from the uranium and radium content, can leave the rock.

2.2. RADON IN GROUNDWATER

This radon can enter buildings via tap water. Radon in groundwater can originate either directly from uranium / radium decay in the solid phase and subsequent alpha-recoil into the water phase or from the decay of uranium / radium already dissolved in the groundwater itself. Both are a function of the uranium content in the rocks through which the groundwater is flowing (i.e., aquifer mineralogy).

As stated, certain rock types have higher uranium contents and thus the potential to produce more radon. For example, in terms of igneous rocks, waters interacting with granites have high radon concentrations up to 10^4 - 10^5 Bq/L (Banks et al., 1998; Akerblom & Lindgren, 1997; Skeppstrom & Olofsson, 2007; Talbot et al., 2000) whereas those in basalts have low concentrations of only about 10 - 20 Bq/L. Metamorphic rocks originate from the high pressure and temperature alteration of igneous and sedimentary rocks, and thus radon concentrations generated in these units are linked to the original rocks from which they were derived and the degree of alteration. The composition of clastic sedimentary rocks varies greatly in relation to the materials of origin, however the groundwater associated with them typically has relatively low radon concentrations which rarely exceed 40 Bq/L. Waters from limestone rocks are generally poor in radon, although higher concentrations may result from natural enrichment processes. Since radon decay rates are faster than those of ground water flow, high radon concentrations in ground water are often indicative of local uranium (radium) sources.

If decay of dissolved constituents is a dominant mechanism for the radon present in the groundwater, the mobility of these parent species will have an important impact on the radon distribution. In fact, dissolved radon typically shows poor correlation with dissolved uranium and radium (Veeger & Ruderman, 1998) because of their differing states, solubilities, sorption properties and redox dependencies. For example, the highest oxidation state of uranium tends to form more soluble compounds (e.g. uranile ion, $[UO_2]^{2+}$), whereas reducing conditions will tend to precipitate, and thus immobilize, the uranium. As such, radon activities in ground water are often much higher than can be accounted for by equilibrium decay of observed dissolved radium, suggesting the presence of additional radon from mineral sources (e.g. radium on adsorption sites or fracture precipitates).

For a given aquifer uranium content, higher radon concentrations in ground water are expected in rocks of lower porosity, higher density or higher emanation efficiency (Wanty et al., 1992). The extent of transport from a radium decay site is also determined by the permeability (primary or secondary) of the host rocks. High radon values are typically not found in high transmissivity aquifers due to reduced rock/water ratios and dilution of emanating radon (Lawrence et al., 1991). Once radon is in the ground water, its transport is controlled by advection and diffusion (Cinelli et al., 2019).

Compared to other gases, radon has a relatively high solubility. Temperature influences radon solubility (Figure 5), which is particularly important in controlling the release of indoor radon via the use of tap water (see Section 4.1). This relationship is expressed by Weigel (1978) as follows:

$$k = 0.105 + 0.405e^{-0.0502*T}$$

where k is the radon partition coefficient (ratio between the radon concentration in water and the radon concentration in air) and T is the water temperature in degrees Celsius.

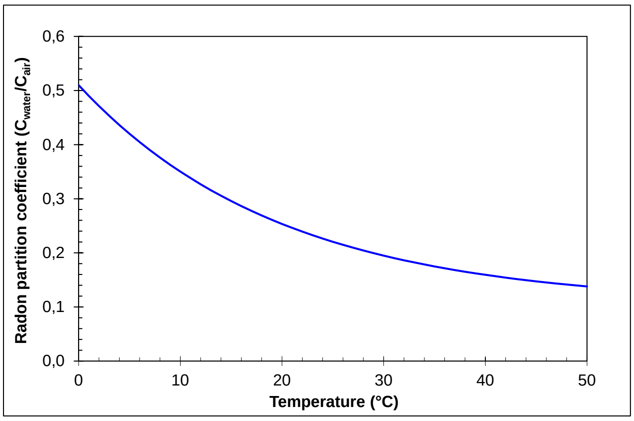

Figure 5. Plot of radon solubility in water as a function of the water temperature.

2.3. RADON IN UNSATURATED ROCK AND SOIL

This radon can enter buildings from the ground surrounding and beneath the foundation. Although radon can potentially migrate from deeper levels towards the surface, radon that enters buildings from the ground typically originates in the soil, sediments or rocks that occur at or relatively near the surface. This means that not all locations are at risk of elevated radon from the ground, but rather only those where the surface geological units are rich in uranium / radium. As mentioned above these can include, but are not restricted to, granites and acidic volcanic rocks like pyroclastic tuffs (common in central Italy), as well as the sediments or soils derived from these rocks.

Radon concentrations measured in soils usually range between 5 and 400 kBq m^{-3} for different rock types, while concentrations in the atmosphere directly above the soil surface only reach levels of tens of Bq m^{-3}. In addition to the rock type, gas-phase permeability is another important factor that can influence concentrations, as a highly permeable unit (like a gravel or a highly cracked soil) can allow for the rapid escape of radon to the atmosphere while, conversely, low permeable units can permit its accumulation. As described in more detail below, environmental conditions can change permeability, gas mobility, and gradients in the shallow subsurface, which in turn have an impact on radon values at both the seasonal and daily temporal scale. For example, precipitation and temperature can control soil-gas radon levels on a seasonal scale, whereas other climatic factors, such as barometric pressure, temperature, soil moisture and wind have an impact on a daily scale. This temporal variability of the radon source function can subsequently have an impact on the amount of radon that may enter a building during different periods or seasons.

2.3.1. Environmental effects

Rainfall makes soil radon concentrations increase (Pinault & Baubron, 1996) due to accumulation caused by a reduction of gas permeability in the soil, particularly when a saturated layer forms at the surface (i.e., the capping effect). Because of this, radon levels tend to increase during rainy seasons (e.g., during the winter and spring in Mediterranean climates) and decrease during the drier seasons as the soil dries out and the resultant increased gas permeability allows for migration to the atmosphere. Instead, at sites characterized by high intrinsic permeability, the water-saturated layer may quickly penetrate deeper in the ground, thus resulting in lower radon concentrations during the rainy season (King & Minissale, 1994) due to high radon solubility and the ingress of atmospheric air.

Barometric pressure is another important parameter, although it's effect is generally lower than that caused by soil moisture (i.e. precipitation) alone. Decreasing barometric pressure tends to draw soil gas upwards from deeper in the soil column, increasing the radon concentrations in the near-surface layers. This phenomenon is particularly pronounced in more permeable soils. Conversely, increasing barometric pressure forces atmospheric air into the soil, diluting the near-surface soil gas and driving radon deeper into the ground (Lindmark & Rosen, 1985; Kraner et al., 1964; Kovach, 1945).

Temperature shows a contrasting effect with respect to barometric pressure. Soil temperature variations can rapidly increase soil radon concentrations due to enhanced convection that increases the mobility of radon in soil gas and enhanced degassing from soil water due to decreased solubility at higher temperatures (Washington & Rose, 1992). A temperature increase may also augment production of some gas carriers (e.g., biological production of CO_2 and H_2O vapour), which again may increase radon transport from depth (Pinault & Baubron, 1996).

High wind velocities induce local depressurisation, which in turn decreases radon concentration in soil (Voltaggio, 2012) because the gas is drawn out of the soil and/or diluted by atmospheric air. Instead, strong wind turbulence and the Bernoulli effect across an irregular soil surface can draw soil gas upward from depths caused by alternating pumping between pressurization and depressurisation of the soil, similarly to that caused by barometric pressure (Kovach, 1945; Lindmark & Rosen, 1985).

2.3.2. *Transport Mechanisms*

Gas phase movement in the shallow subsurface can be controlled by diffusion, convection, and/or advection (Michel, 1998). Diffusion is driven by a concentration gradient and can be described using Fick’s Law (e.g., Section 2.1.1); because this process is slow compared to the rate of radon decay it is not considered significant for transferring radon from the soil into a building. Convection is driven by thermal gradients; because temperatures are relatively constant over the relatively shallow depths of building foundations, again this is not a significant transport mechanism for indoor radon entry.

Advection is caused by a pressure gradient, and while it can be caused by an increase in gas pressure at depth that pushes deep gases towards the surface (most notably geogenic CO_2), near surface changes in pressure are far more important in the context of indoor radon. To begin with, changes in barometric pressure, as described above, can induce both upwards and downwards gradients together with associated movement of gases in the soil (including radon). In terms of the built environment, temperature and wind effects can induce pressure gradients that cause advection of radon into a building. For example, heating a building results in an upward movement of warmer air, which depressurizes the lower levels and causes radon-enriched air from the surrounding soil to be drawn through cracks or openings in the foundation and into the structure. This is known as the “stack effect” or “chimney effect”, and it is a contributing factor (together with closed windows) to the higher indoor radon concentrations typically observed in the winter. Wind can also induce advection, as the down-wind side of a building will experience lower pressures which can once again create a pressure gradient that draws radon-rich soil air into the building. Because of these processes, advection is the most quantitatively important mechanism for the migration of radon from the soil to a building. Advection is governed by Darcy's law (Riley et al., 1999):

$$J_A = Cv = C\left(-\frac{k}{\varepsilon\mu}\frac{\delta P}{\delta x}\right)$$

where v is the Darcy's velocity (m/s), k is the effective medium permeability (m^2), μ is the dynamic viscosity of the medium (kg/ms), and P is fluid pressure (Pa) (Sabbarese et al., 2021).

2.4. RADON IN BUILDING MATERIALS

Building materials originating from soil and/or rock can contain elevated concentrations of uranium and radium. The radioactive decay of these elements produces radon (^{222}Rn) and thoron (^{220}Rn), which in turn can migrate into a building's living area and accumulate in high concentrations (Cinelli et al., 2019; European Commission, 2000). Higher permeability materials give rise to greater amounts of radon being transferred into rooms, while the fact that the entire surface area of walls / floors act as direct sources means that, in contrast to a soil origin, the short lived thoron isotope (220Rn) may also contribute to indoor radon impacts (Tuccimei et al., 2006). The radionuclide composition of rock-origin building materials represents the geology of the territory in which they occur. In general, magmatic rocks (effusive and intrusive) show very high radionuclide content, while metamorphic and sedimentary rocks highlight medium and low contents, respectively.

Numerous studies have examined radionuclide content in building materials as a way to assess potential risk of indoor radon from this source (Nuccetelli et al., 2017; Tositti et al., 2017; Marocchi et al., 2011; Capaccioni et al., 2012; Trevisi et al., 2018; Tuccimei et al., 2006). The work of Nuccetelli et al. (2017) is particularly noteworthy as it presents a database of ^{226}Ra, ^{232}Th and ^{40}K concentrations in 23,000 samples of bulk materials used in the construction industry. Cinelli et al. (2019) report data from these various authors to illustrate typical natural radionuclide concentrations in European building materials (Table 3). In terms of ^{226}Rn, the parent of ^{222}Rn, stone like volcanic tuff, pozzolana, pumic, shale, and syenite have the highest values (>120 Bq/kg) while travertine, limestone, gabbro, gypsum, and aggregates have the lowest (<20 Bq/kg).

Table 3. ^{226}Ra, ^{232}Th and ^{40}K activity concentration (Bq/kg) in natural stones, raw materials, and derived products (from Cinelli et al., 2019, reporting data from Nuccetelli et al., 2017, Tositti et al., 2017, Marocchi et al., 2011, Capaccioni et al., 2012, and Trevisi et al., 2018).

Building material	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)
Limestone	15	15	160
Travertine	7	20	3
Marlstone	35	11	273
Granite	79	93	1076
Syenite	146	106	971
Gabbro	17	20	324
Rhyolite	69	94	1239
Trachyte	96	126	1338
Basalt	81	117	892
Schist	36	42	668
Gneiss	123	61	962
Slate	49	66	617

Building material	^{226}Ra (Bq/kg)	^{232}Th (Bq/kg)	^{40}K (Bq/kg)
Tuff	147	224	1506
Clay	51	49	555
Chalk	15	15	112
Gypsum	18	16	105
Lime	19	11	109
Pozzolana	187	253	1397
Pumice	269	66	1073
Shale	174	131	493
Brick	51	49	555
Concrete	59	85	340
Cement	50	35	235
Aggregates	23	23	388

It is important to assess not only the radionuclide content of a building material but also its radon exhalation rate (usually expressed as Bq m^{-2} h^{-1}), since the efficiency of radon release from mineral grains (emanation) to the atmosphere (exhalation) depends on chemical and physical weathering and on the porosity and permeability of the material (Tuccimei et al., 2006; Petropolous et al., 1999). The radon exhalation rate in dry material increases steadily with increasing water content until it reaches 8 %, after which it decreases with increasing water content (Schery et al., 1989; Hosoda, 2007). It is intuitive how the exhalation rate increases as the porosity of the material increases and the size of the grains decrease. When the material temperature increases, the exhalation rate will also increase; this is because the thermal expansion of pore space air enhances convection (Schery et al., 1989; Stranden et al., 1984). Tuccimei et al. (2009) proposed a methodology to measure the radon exhalation of building material samples in the laboratory. The measurement allows simultaneous determination of ^{222}Rn and ^{220}Rn exhalation rates using the following equations:

$$E_{222} = \frac{(m + \lambda_{222}\, C_0)\, V}{S}$$

$$E_{220} = \frac{\lambda_{220}\, V_0}{S} \; \frac{C_m}{e^{-\lambda_{220}\,(V_1/Q)}}$$

where: E_{222} and E_{220} are ^{222}Rn and ^{220}Rn exhalation rates (Bq m^{-2} h^{-1}); m (Bq m^{-3} h^{-1}) is the initial slope of the radon growth curve; l_{222} and l_{220} are ^{222}Rn and ^{220}Rn decay constants (h^{-1}); C_0 is the initial radon concentration (Bq/m^3); V is the free total volume of the analytical system (m^3); S is the surface of the accumulation chamber (m^2); C_m is the equilibrium ^{220}Rn concentration (Bq/m^3); V_0 and V_1 (m^{-3}) are the free volume of the accumulation chamber and the volume between the outflow of the accumulation chamber and the inflow of the radon monitor; and Q is the flow rate in the system.

3. MONITORING

3.1. SENSOR TYPES

Monitoring sensors can be divided into two main types, those that provide a cumulative, total estimate of exposure over the time of deployment and those that progressively record radon concentration at pre-set time intervals. Cumulative (or dose integrating) sensors have been the standard methodology used for indoor radon monitoring due to their low cost, ease of use and robustness, as well as the fact that radon risk is linked to total exposure. Continuous radon monitors (or instantaneous detectors), instead, yield temporal data that can be used to better understand diurnal and seasonal trends as well as the impact of occupant activities. While used primarily in the past for research purposes due to their elevated costs, size and complexity, technological advances has led to the recent development of moderately priced, user-friendly commercial units that can potentially be used by both homeowners and remediation contractors.

3.1.1. *Cumulative (or dose-integrating or time-weighted average) sensors*

There are three main types of sensors in this group, including Alpha Track, Activated Charcoal and Electret Ionization Chamber detectors (Figure 6). Alpha track sensors are the most commonly used for long-term, large-scale indoor radon monitoring due to their robustness, low cost and monitoring range. Note that analytical precision can vary for all techniques as a function of laboratory quality control procedures and staff experience (PHE, 2020)

Table 4. Comparison of sensor types. After WHO, 2009.

Detector type	Passive / Active	Typical uncertainty	Typical sampling period	Cost
Alpha track detector	Passive	10-25	1-12 months	low
Activated charcoal detector	Passive	10-30	2-7 days	low
Electret ion chamber	Passive	8-15	5 days – 12 months	medium

Figure 6. Examples of different types of passive, cumulative radon sensors: a) alpha track; b) activated charcoal; c) electret ionization chamber.

Alpha Track Detectors (ATD) (or Track Etch or Solid State Nuclear Track Detectors)

Alpha Track detectors consist of a small container that is open to the atmosphere at one end and houses a plastic substrate that records the decay of individual radon atoms at the other. The open end is typically covered by a filter that allows the passage of gas but stops solid radon decay products and dust. The plastic substrate is typically made of polycarbonate (Makrofol), polyallyldiglycol carbonate (PADC or CR-39) or cellulose nitrate (LR-115) (WHO, 2009). When a radon atom decays in the chamber the released alpha particle can strike the substrate, creating a microscopic track; this track can then be chemically etched to enlarge it for manual or automated counting. The number of tracks per unit surface area are proportional to the cumulative radon exposure, which can be converted to a total or daily average concentration using a calibrated conversion factor. Cross-sensitivity to thoron can be reduced using chambers that require a longer diffusion time, thus resulting in thoron decay before its arrival at the sensing substrate.

Advantages:

- insensitive to humidity, temperature and background beta and gamma radiation
- low cost, small, robust and easy to deploy
- good response. Controlled tests against a precise continuous monitoring sensor yielded a slope of 1.01, an r^2 of 0.99 and a moderate offset of 35 Bq/m3 (Groves-Kirkby et al., 2006)
- wide range of deployment periods (from 1 month to 1 year)
- sensitive (minimum detectable concentration estimated to be 30 Bq/m3)

Disadvantages

- chemical etching procedure can be time consuming and labour intensive
- very sensitive to etching conditions and quality control procedures (Miles, 2004)
- response of the plastic to alpha particle damage can vary between batches (IAEA, 2015)

Activated Charcoal Detector (ACD) (or Activated Charcoal Adsorption Detectors)

These detectors consist of activated charcoal that can adsorb radon, with the host container being open to the air or covered with a gas permeable filter / diffusion barrier. Note that radon can also desorb from the charcoal and be lost, meaning that these detectors are not true integrators (Miles, 2004). After exposure for periods of 1-7 days the containers are sealed and the radon decay products allowed to equilibrate with the collected radon. The samples are then analysed directly using gamma counting of the short lived radon progeny or via liquid scintillation after sample preparation.

Advantages:

- sensitive (minimum detectable concentration estimated to be 20 Bq/m3).
- reasonable response. Controlled tests against a precise continuous monitoring sensor yielded a slope of 1, an r^2 of 0.96 and a small offset of 1.52 Bq/m3 (Groves-Kirkby et al., 2006)
- inexpensive

Disadvantages:

- deployment periods are only 1-7 days
- can give a good average radon estimate only if variations are small over the exposure period
- affected by humidity, range of Rn values, and temperatures, and thus must be calibrated under different conditions
- samples must be analysed quickly after collection (<8 days) due to the short radon half-life of 3.8 days

Electret Ion Chamber (EIC)

The EIC consists of a small electrically conducting plastic chamber that hosts an electret, i.e., a dielectric material that has a quasi-permanent electric charge that generates an external electric field. Alpha and beta particles released via radon decay collide with and ionize air molecules in the chamber, which in turn make contact with the electret, causing it to experience a voltage loss. As the electret is pre-charged during manufacture, the total charge loss during the exposure period can be equated to the cumulative (and daily average) amount of radon present using calibration factors (Kotrappa, 2008).

Advantages:

- re-usable, although for a limited total exposure which is a function of original voltage, radon concentration and deployment time.
- low failure rate (Denman et al., 2005)
- good response. Controlled tests against a precise continuous monitoring sensor yielded a slope of 1.07, an r^2 of 0.98 and a high offset of 105 Bq/m3 (Groves-Kirkby et al., 2006)
- no chemical processing required. Value can be read immediately, even on site, and intermediate measurements can be collected

Disadvantages

- affected by background gamma radiation, response is non-linear, high humidity can lead to water condensation on internal surface, the electret can be discharged by mechanical shocks or touching the electret's sensitive surface (IAEA, 2015)
- not recommended for long deployments at moderate or high concentrations (e.g., 12 months possible if concentration is less than 150 Bq/m3)
- cost per unit is higher than other passive sensors
- only one commercial EIC appears to be presently available (E-PERM®), which may impact on price, technology development and availability

3.1.2. Continuous Radon Monitors (CRM) (or Instantaneous Radon Monitors)

This class of sensors are capable of counting the decay of individual radon atoms, meaning that the amount of radon in the air can be quantified continuously at pre-set time intervals. In addition to calculating an average exposure over an entire deployment period, these monitors can thus also be used to define concentration variations due to changes in environmental parameters (e.g., barometric pressure, temperature, etc.) and occupant activities (e.g., opening windows, central heating, etc.).

In the past the only option for these types of sensors were professional-grade units that are very precise and flexible but tend to be expensive (thousands of euros), large and complex (Table 5). While they have been, and still are, used for indoor monitoring work, these units have a wide range of applications in other fields like uranium exploration, the study of faults, and groundwater research. Sorimachi et al. (2021) recently compared the response of three such units against an Alpha Track Detector (CR-39) at a low indoor radon concentrations, reporting that all CRM were within 15% of each other and within 20% of the ATD results.

Recently, miniaturization, improvements in electronics, and innovative designs has led to the development of a number of small, relatively inexpensive (hundreds of euros), user-friendly radon sensors specifically designed for the indoor radon consumer market (Table 6). Their quoted accuracy of 10-20% at typical indoor concentrations, the ability to immediately see how occupant behaviour and/or remediation interventions influence total radon exposure, the ability to collect data over very long periods or sequentially in different rooms, and the potential to use these sensors to control remediation systems means that these sensors may represent a valid alternative for some homeowners. Warkentin et al., 2020 found that all six consumer-grade detectors listed in Table 6 were valid options, yielding a level of accuracy from 10 to 30% under various test conditions and radon concentrations. These authors do note, however, that consumer grade detectors (unlike professional grade units) cannot be re-calibrated and thus it is possible that sensor accuracy and precision may change over the life-time of the monitor.

The development of such low-cost consumer-grade sensors has created the opportunity to integrate them into networks and smart home systems. Some manufacturers offer cloud services for users to access and track results on their sensors online (e.g., http://radonftlab.com/radon-sensor-product/radon-detector/new-rd200p-radon-detector/; https://www.airthings.com/en-gb/wave-plus). In addition, research has recently been conducted in the potential for ad hoc systems that monitor radon levels (Blanco-Novoa et al., 2018; Alvarellos et al., 2020) and also directly control radon remediation systems (Ruggiero et al., 2021).

Table 5. Characteristics of some professional-grade continuous radon monitors (After Sorimachi et al., 2021).

Manufacturer	Model name	Detector type	Sensitivity (cpm/Bq m^{-3})	Detection limit (Bq m^{-3})	Quoted Accuracy
Bertin Instruments	AlphaGuard	Pulse ionization chamber with air-diffusion	0.050	10.8	??
Durridge Co. Inc.	RAD7	Silicon semiconductor with electrostatic collection	0.013	7.3	??
Pylon Electronics Inc.	300A/AB-5	ZnS scintillation cell with flow-through	0.037	13.8	??

Table 6. Characteristics of some consumer-grade continuous radon monitors (After Warkentin et al., 2020). IC = ionization chamber; AS = alpha spectrometry.

Manufacturer	Model name	Detector type	Power	Data logging	T/RH	Alarm	Mobile link	Quoted accuracy
Safety Siren	Pro Series 3	IC	grid	no	no	no	no	±20%
Airthings	Corentium Home	AS	battery	no	no	no	no	±10%
Airthings	2900 Wave	AS	battery	yes	yes	yes	yes	±10%
Airthings	Wave plus	AS	battery	yes	yes	yes	yes	±10%
Radon Eye	Radon Eye Plus	IC	grid	yes	no	yes	yes	±10%
Radon Eye	Radon Eye RD200	IC	grid	yes	no	yes	yes	±10%

The technologies behind both the professional and consumer grade radon sensors can be broadly grouped into the following three types:

1) Solid state alpha detector. An example of this technology is the RAD7 (Durridge Inc.), which uses of a solid-state silicon alpha detector in a hemispherical electrical conductor. Charging of the conductor creates an electrical field which attracts positive ions, such as polonium-218, which is a radon-222 decay product. Subsequent decay of the short-lived polonium-218 releases an alpha particle that has a 50% probability of entering the detector, which then produces an electrical signal. As different isotopes release alpha particles that have different energy levels, the sensor can discriminate and quantify, for example, radon-222 (“radon”) and radon-220 (“thoron”); this method is known as alpha spectrometry (Durridge Inc., 2021).

2) Ionization chamber. This sensor consists of a chamber containing an anode and a cathode, across which is established a voltage potential to create an electric field in the surrounding gas (e.g., AlphaGuard). As radon decays it releases alpha particles which ionize air molecules into ion pairs. These ions move towards their charge-opposite electrodes and cause an ionization current that can be measured and converted into radon concentration. Independent signal processing can be performed to conduct alpha spectrometry (Bertin Technologies, 2019).

3) Scintillation cells. These sensors combine a scintillation cell with a photon detector and pulse counter (e.g., Pylon AB-5). The inner wall of the cell is coated with a material, such as ZnS (Ag), that releases a photon when struck by an alpha particle. This photon is detected by a photomultiplier tube or solid-state detector and the signal is converted to radon concentration (Pylon Elect., 2017). Because the conversion of alpha particles to photons is not selective, this technique cannot directly discriminate between radon and thoron. Sample introduction can be done passively by diffusion or actively using a pump for faster response times.

3.2. PROTOCOLS

The World Health Organization, in its wide-ranging radon handbook (WHO, 2009), has outlined a series of recommendations that local, regional or national governments can incorporate when creating indoor radon monitoring protocols. Monitoring periods are divided into “short-term” measurements lasting days or weeks and “long-term” measurements that cover one or more seasons during several months up to one year. The long-term monitoring approach is strongly recommended considering the significant temporal variations that can occur in radon values due to meteorological conditions and inhabitant activities, with radon measurement uncertainty, reference level and protocols also affecting decision reliability (WHO, 2009; IAEA, 2015). Measurements should be conducted in a room that is often occupied, on the lowest habitable level if the source is geological or in a room with the lowest airflow if the radon comes from the building materials. In large buildings like office complexes or schools, multiple rooms should be monitored, considering centralized heating, ventilation and cooling systems. Lower floors require more attention, as do the hours when the building is actually occupied. A short overview of some national or regional sampling protocols are given below to show how approaches (and level of detail) can differ between jurisdictions.

Implementation of the new Italian law focussed on protection against ionizing radiation (D.Lgs. 101/2020) is the responsibility of governments at the regional or autonomous region level. An example of adopted monitoring protocols can be found in a document published by the regional environmental protection agency of the autonomous region of Friuli Venezia Giulia (ARPA-FVG, 2020). The monitoring must be conducted during two consecutive 6-month periods, with a single Alpha Track Detector deployed at the same location for each semester. The ATDs are shipped individually just prior to deployment in aluminized bags, together with a document explaining the protocol to be followed, a form to be filled in with necessary information (name, location, exposure dates, etc.), and a shockproof bag for shipping to the analytical lab. Homeowners are instructed to place the ATD in the living room or bedroom and to avoid the kitchen, bathrooms and garage. Sensors should be placed far from drafts, heat sources and doors, with the recommendation to place them on the top of a wardrobe or other piece of furniture. Action levels are 300 Bq/m3 for existing homes, 200 Bq/m3 for homes built after January 1st, 2025, and 300 Bq/m3 for workplaces.

The protocol detailed by the Irish Environmental Protection Agency (EPA-Ireland, 2019a) states that measurements must be conducted over a period of no less than three months and no more than 12 months using a suitable device. The CR-39 ATD is mentioned but the protocol is not limited to this sensor. When the monitoring period is less than 12 months it is necessary to apply a seasonal adjustment factor, which involves dividing the measured value by the average of the appropriate monthly factors provided in the reference document. One sensor is to be deployed in a regularly used bedroom and a second placed in the living room. Sensors should be placed at least 1 m above the floor, avoiding sources of drafts (e.g., window sills) or heat (e.g., radiators, television, fireplace); detectors must not be moved or interfered with during the measurement period. If the seasonally adjusted average value exceeds the action level of 200 Bq/m3 but is less than 800 Bq/m3, the home-owner must receive a copy of the EPA booklet on radon, a list of registered radon remediation services, information on radon and health, advice for follow-up work after remediation, and advice to retest within 5 years. If values are greater than 800 Bq/m3, in addition to the previous, the homeowner must be contacted by phone to confirm correct placement of the detectors and explained health risks and information regarding how to reduce radon in the home. Information is also provided for workplace protocols and the associated action level of 300 Bq/m3. This includes the requirement to survey basement and ground floors, how to select a correct, representative number of rooms to measure, and the need to consider work area types when determining the number of detectors required. Different from dwellings, individual workplace and school values are not averaged, meaning that if any one measurement exceeds 300 Bq/m3 then remediation is needed for that workplace.

The most recent indoor monitoring protocols in the USA can be found in ANSI/AARST (2019), which only addresses a geological radon source and not radon coming from building materials. This document outlines two approaches. The first is a “time-sensitive testing protocol”, which is used when results are needed quickly (days or weeks). It is conducted over periods ranging from 2 to 90 days under “closed building” conditions, which requires that all windows and outside doors remain closed (aside from entering the building) on all levels, heating/cooling systems set to normal use, fireplaces or similar are not used unless they represent the primary heating source, no centralized ventilation and limited use of clothes dryers and bathroom exhaust fans. For tests lasting less than 4 days, closed building conditions must be established 12 hours prior. The second is an “extended testing protocol”, which is conducted over a longer time period (weeks or months) after an initial short-term test. For these tests longer than 90 days, closed-building conditions are not required. This protocol recommends deployment for a minimum of 6 months over different seasons, of which one is a heating season. Sensors, including either passive or continuous sensor types, should be put in the lowest floor in rooms where the occupants will spend a significant portion of their time. They should be located no less than 30 cm from walls, 50 cm from the floor and at least 1 m from doors and windows, avoiding drafts, heating vents, and high humidity rooms like bathrooms and kitchens. Measurements conducted by professional services require certification and the use of a Quality Assurance program. The time sensitive protocol requires two passive integrating sensors placed 10-20cm apart or the use of a single continuous monitor. The action level threshold above which remediation must be undertaken is 150 Bq/m3. When two collocated sensors are both above (or below) the action level, or when one sensor is below and one is above but no more than twice the value of the other sensor, the average value is used to decide if remediation is required. Instead it the above-threshold value is more than twice that of the below-threshold value the monitoring must be repeated.

4. REMEDIATION

4.1. ENTRY MECHANISMS

There are three main sources of indoor radon: the underlying soil / rock, tap water, and building materials (Figure 7). The selection of the best remediation intervention for a given site (see Section 4.2) will depend on which of these entry pathways predominate as well as the building characteristics.

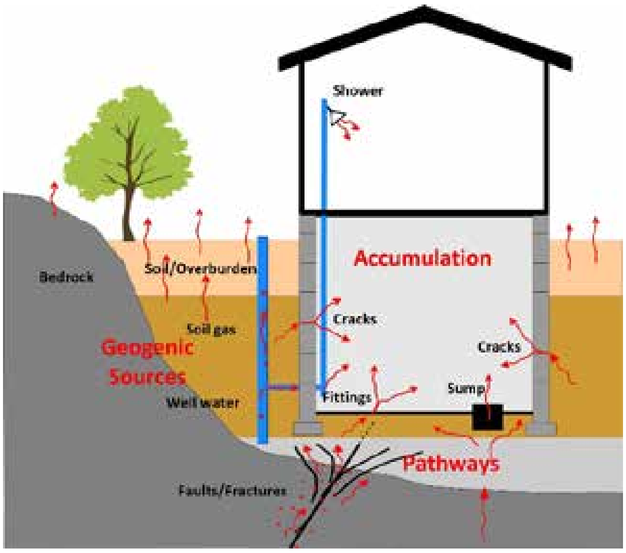

Figure 7. Main routes for radon entry the buildings.

4.1.1. Radon from the soil

The main pathways through which radon gas is able to move from the ground into a building are openings (like sumps or conduits), cracks or joints in the foundation, or particularly permeable surfaces (Figure 7). In this regard, building characteristics as well as occupant activities have a strong influence on eventual radon concentrations (Table 7).

Radon movement from the ground into a building can occur by simple diffusion however the majority is due to the slight pressure differential between the inside and outside of the building, which can be caused by wind (Figure 8a) or the difference between external and internal temperatures (i.e., the so called "chimney effect" or "stack effect") (Figure 8b). This pressure gradient draws air from outside (including radon-rich air from the ground) into the building. Due to the dependence on temperature differences and wind velocity, indoor radon concentration can be highly variable (depending on the weather conditions) and can present significant daily and seasonal variations. In addition, the pressure difference can also be increased by building factors such as extraction systems (kitchen hoods, fans in bathrooms, etc.) without a sufficient supply of air from the outside or the presence of chimneys without external air intakes. For sites where radon comes from the soil, concentrations rapidly decrease on the higher floors of the house, resulting in higher indoor Rn concentrations in basement and ground floor rooms.

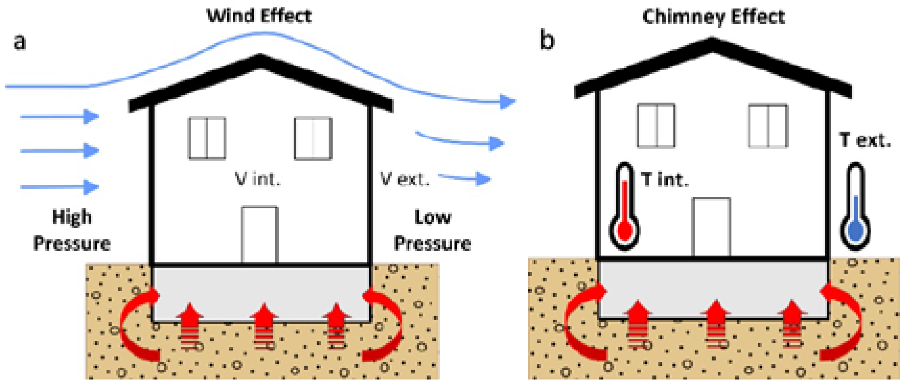

Figure 8. a) Wind effect: exposure to prevailing winds can create an overpressure zone and a depression zone in the sheltered side of the building. This effect accentuates air velocities between inside (V int.) and outside (V ext.) helping to reduce the internal

Table 7. Characteristics of the building that increase the probability of radon entry.

Type	Examples
Excavation of the foundation	- by explosive - in backfill area on gravel or sand - in foundation soils with cracks or very permeable
Type of ground contact	- direct contact of floor or walls with the ground - lack of ventilated crawl space
Permeable surfaces	- natural clay floors, pebbles, etc. - wooden floors - brick walls - stone walls
Infiltration points	- holes for cables and pipes - joints or cracks in floors and walls - manholes and other openings - electrical sockets in the cellar - fireplaces, etc.
Distribution of spaces	- underground or basement rooms used as a dwelling - presence of open stairs leading to the cellar
Building use	- no or poor ventilation of the underground rooms - poor ventilation of inhabited rooms - long stay in underground or basement rooms

4.1.2. Radon from tap water

Radon originating from tap water is less common, and is more likely to occur when the water is sourced from a private groundwater well. This is because municipal water supplies undergo transport, storage and aeration that causes the loss of most dissolved radon prior to arriving at a site. If the household water is high in radon it will be released to the indoor environment when the water flows as small drops (e.g., the shower) or when it is in contact for long periods (e.g., a filled bathtub). The contribution to indoor radon also depends on the amount of water consumed per day, water temperature, house volume and indoor air exchange rate during radon degassing. WHO (2011) estimates that 1000 Bq/L of radon dissolved in tap water can contribute around 100 Bq/m^3 to indoor air through degassing for a consumption rate of 1 m3/day, while the European Council Directive 2013/51/EURATOM recommends a dissolved radon concentration of 100 Bq/L.

4.1.3. Radon from building materials

Radon amounts emanating from building materials are typically low however they can be quite high in some areas where local building stones have elevated uranium and radium concentrations. This can include cement produced with some types of aggregates, but is particularly true in some areas where volcanic rocks like tuff are used to construct foundations or walls, such as in central Italy, or where rocks like granite are used for countertops and decorative aspects. As described by IAEA (2021), the contribution of radon from walls can be estimated as follows:

$$C_{bm} = \frac{1}{(\lambda+n).V} \cdot \sum_i E_i \cdot A_i$$

where: C_{bm} = radon contribution to indoor air concentration from construction material; λ = radon decay constant = 0.00755; n = air exchange rate (volumes/hour); V = room or buildings inner volume (m3); E_i = radon exhalation rate (Bq/m2h); and A_i = surface area of walls made using the construction material (m2). Assuming a room that is 3x4x2.5m in size, a ventilation rate of 0.5, and an exhalation rate of 13 Bq/m2h, the contribution of the construction material to the radon concentration in the room can be calculated as: C_{bm} = (1/((0.00755 + 0.5) * 30)) * (13 * 55.4) = 50 Bq/m3.

4.2. PREVENTION AND MITIGATION TECHNIQUES

When the main source of indoor radon comes from the soil or rock beneath the house the best remedial approach is to intercept the radon and prevent it from entering the building. Although there are various different approaches and configurations possible the final choice will depend on the construction characteristics of the house and soil permeability. In terms of construction types it is possible that the building is in direct contact with the soil (either with the ground floor or a basement) or there is a crawl space that separates the ground from the living areas. A crawl space typically underlies the entire building and is most often created to minimize problems with humidity; they can be 10-70 cm high, accessible or inaccessible, completely empty or filled with materials of different permeabilities, and can be beneath the ground surface, partially beneath or totally above ground. While the use of a crawl space can be quite effective (and less expensive) for remediation, the crawl space characteristics will greatly influence its utility.

When the radon source is from the tap water the best approach is to degas the water before it is used in the house. Instead, when the source is the material used to construct the building itself the options are limited to enhanced air ventilation to remove/dilute radon in the living areas or trying to make the walls and floors impermeable to gas flow.

Some common remedial techniques are discussed in more detail below:

4.2.1. Waterproof barriers

This technique is mainly applicable in new buildings but can also be adapted to existing buildings in some cases. It involves laying a waterproof membrane over the entire surface between the ground and the building to deflect soil radon laterally so that it will be dispersed into the atmosphere (Figure 9). Although such membranes are commonly used to reduce the entry of water and humidity, they are typically only placed under the walls to stop wicking. Instead for this approach to be effective for radon the membrane must be installed over the entire building footprint.

Although numerous “anti-radon” membranes are available on the market, even standard bituminous or PVC waterproof membranes provide a sufficient barrier to radon migration. It must be highlighted, however, that complete coverage and careful installation is critical for proper functioning. In particular, any damage to the membrane during construction will create a preferential pathway, allowing the radon to migrate through the tear and into the building. To minimise the risk of rupture it is recommended that a strip of the membrane is first laid beneath any load-bearing walls and then the larger, complete membrane is laid over the entire area prior to construction of the floors, making sure to overlap with the previously laid strips by at least 15cm and seal all overlapping edges.

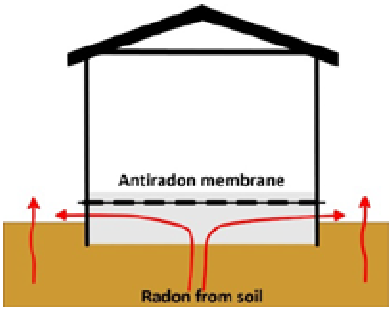

Figure 9. Impermeable membranes that separate the ground from the building are effective to prevent radon entry in homes.

4.2.2. Depressurization under the building

This method involves using an extraction fan to draw radon-rich air from below the structure, before it can find a path to enter the building, and venting it to the atmosphere at a point where it can’t re-enter the building (i.e., high and not near windows). Different configurations can be used depending on building characteristics and construction status (i.e., existing or to be built). Considering that depressurization is often effective over a 6-8 m radius, more than one depressurization point may be required to guarantee sufficient coverage.

In the case of existing buildings, the following options are available:

- depressurization of the ground below (Figure 10a) or around the perimeter of the building, in cases where living area floors are in direct contact with the ground. This requires that the sub-floor environment is sufficiently permeable for the fan to draw enough air from the entire building footprint. Multiple points can be used if permeability is poor. If permeability is good and the lowest floor has service rooms like a garage or laundry it may be possible to install a single extraction point in the centre of the building (Figure 10a).
- depressurization around the immediate perimeter of the building (Figure 10b) if the structure of the building does not allow sub-floor installation. This approach is less effective and would likely require multiple extraction points to be effective.
- depressurization of a pre-existing volume like a crawl space or a dis-used basement (Figure 10c). For this to be effective, also in terms of energy efficiency, any openings or doors that communicate with the living quarters above must be tightly sealed.

In the case of new buildings, the depressurization system can be designed and implemented from an early stage to guarantee effectiveness. There are two main options:

- a sump at the centre of the building which is connected to an evacuation fan and duct work that draws and transfers the radon-rich air outside (Figure 11a).;
- where water drainage pipes are planned, this infrastructure can be multi-purposed by connecting them together in series and again attaching an extraction fan for effective depressurization (Figure 11b).

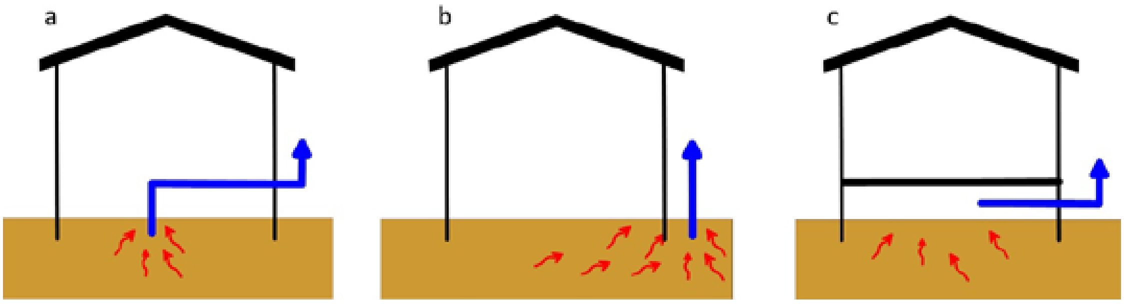

Figure 10. Depression of the subsoil under the building (a), the subsoil at the edge of the building (b), and a crawlspace beneath the building (c).

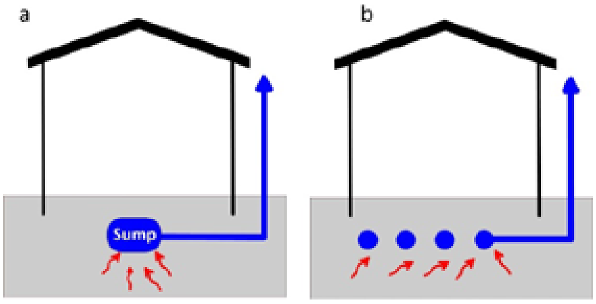

Figure 11. Depression of the subsoil for newly constructed buildings using (a) a sump or (b) drainage pipes.

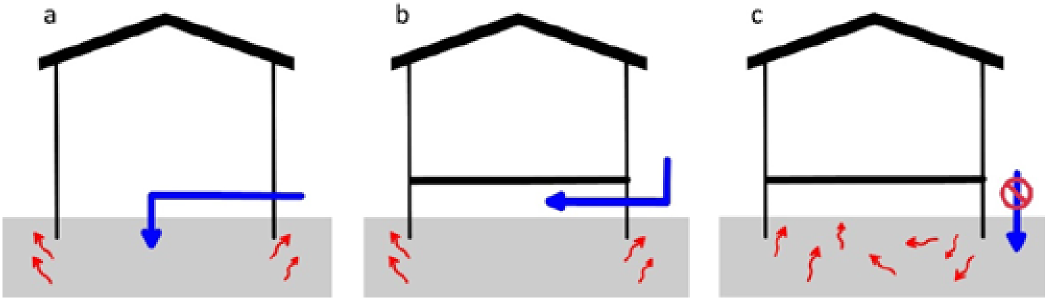

Figure 12. Pressurization of the ground (a); pressurization of the crawl (b); do not pressurize the soil around the building (c).

4.2.3. Pressurization under the building

The inverse of the previous technique involves blowing air under the building to over-pressurize the subsurface. This counteracts the suction effect created by the house itself (i.e., wind and stack effects) and pushes the gas outside the perimeter of the building where it disperses to the atmosphere. This technique is particularly suitable for existing buildings, whereas are less effective and more expensive for new constructions compared to the barrier and depressurization approaches described above.

Options include:

- Pressurization of the ground beneath the foundation floor (Figure 12a) or an crawl space beneath the building (Figure 12b);
- it is also possible to pressurize a room on the ground floor or basement. This could be a used or unused area, as the increase in pressure required to prevent radon entry would be small, however this volume would have to cover the lower level, this level would need to be well sealed from the upper levels to guarantee pressurization, and this approach would likely not be very energy efficient as outdoor air would need to be injected indoors;
- instead, pressurization of the ground around the perimeter of the building is not an option (Figure 12c) as the gas pushed away from the pressurized point could be channelled inwards to other points of the building. Furthermore, the type of fans required would be excessively noisy and high power consuming.

4.2.4. Water de-gassing

When radon entry is via release from tap water coming from a private well the best option is to degas the water to remove all dissolved radon prior to its use. A common approach is to use a large volume holding tank where the water can be aerated, either by fountaining the water or using air bubbles. Both approaches will transfer the radon to the gas phase, after which an extraction pump is used to release it outside at a location where it can’t re-enter the building. Aeration units that operate directly at the well head also exist and lower the risk of degassed radon remaining in the house. Finally, the groundwater can be flowed through activated carbon where the radon is absorbed; this approach, however, has the disadvantage that the activated carbon accumulates the radon rather than disposing of it, meaning that it would require periodic maintenance with associated risks.

4.2.5. Air exchange / ventilation

Ventilation can be a viable option when it is not possible to prevent the radon from entering the living area, thus necessitating its removal from the indoor air.

The simplest and least expensive option is obviously to open the windows for a period of time, preferably at both ends of the building to facilitate cross-flow and improved exchange, although even a single window can have a beneficial effect. Opening windows, however, has numerous limitations. To begin with it is not practical in cold climates, as it would make indoor temperature conditions highly uncomfortable. Even in moderately cold conditions, opening the windows will have a significant impact on heating-related energy consumption. Clearly this will be expensive for the occupant and may have an impact on greenhouse gas emissions if fossil fuels are used. Finally, once the windows are closed again the indoor radon values may once again rise quickly to relatively high values if radon accumulation rates are high.

Passive ventilation is another possibility, which involves the installation of wall vents or window trickle vents (Figure 13) to continuously bring fresh air into the building. This approach suffers a number of the same problems related to energy efficiency and comfort as opening the windows. It does, however, have the advantage of a slower, more constant air exchange rate that may be feasible for some sites if radon accumulation rates are not too high and outdoor temperatures not too cold. In addition, direct connection with the outdoors should reduce indoor pressure differentials that may draw radon from the soil. In this regard, these vents should only be installed at the base of the ground floor, as installation higher up may actually enhance the stack effect and result in an increase rate of radon entry from the subsoil.

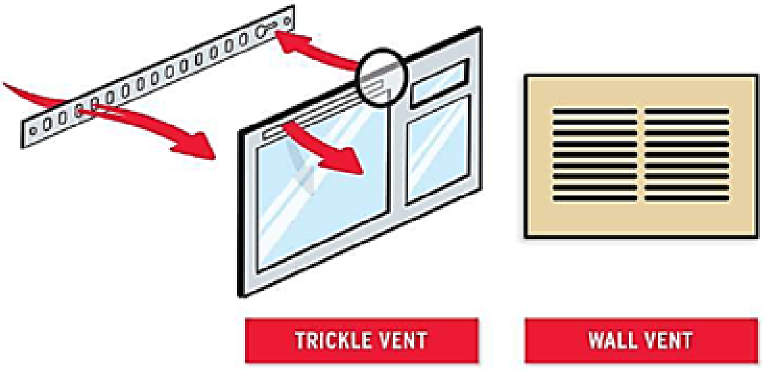

Figure 13. Examples of possible passive air exchange approaches (EPA-Ireland, 2019b).

Forced air ventilation has the potential to overcome problems related to comfort and energy efficiency if heat recovery (Figure 14a) or heat exchange (Figure 14b) units are used. Heat recovery fans are small, wall-mounted units that use an alternating bi-directional fan and porous ceramic cylinder to pass heat from expelled indoor air to incoming outdoor air. These units are less expensive, and easier and less expensive to install, however they move less air (up to 25 m3/h) and thus are only appropriate for smaller volumes. In terms of heat exchangers, although wall-mounted versions do exist, it is far more common that these are large centralized units that circulate air throughout a building using ductwork. In contrast to heat recovery fans, heat exchange units have two completely separate pathways and associated fans that transfer heat from indoor to outdoor air thanks to proximity and counter flow directions (Figure 14b). These units are more costly to buy and install, however they can be used for multiple rooms and can move very large volumes of air (typically 150-350 m3/h, but also >500 m3/h). Issues to consider when choosing such forced air systems include: total indoor volume to be remediated; fan flow rate; efficient air mixing; low energy consumption and high heat recovery efficiency; and fan noise level.

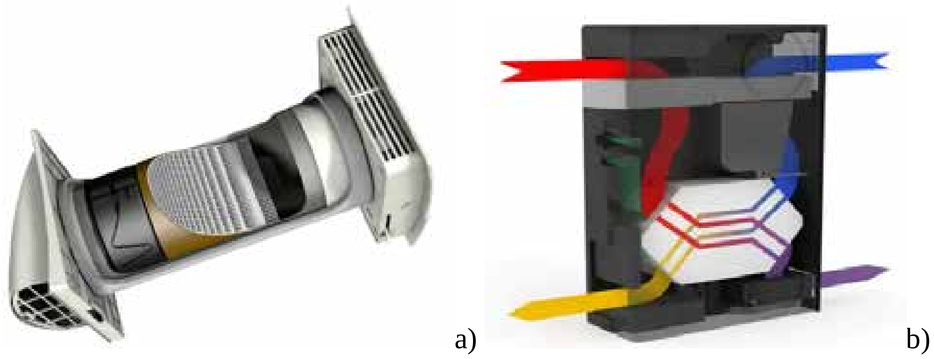

Figure 14. Examples of the inner workings of a small heat recovery fan (a) and a large heat exchange unit (b).

4.3. ADDITIONAL ISSUES TO CONSIDER

4.3.1. Depressurize or Pressurize?

While depressurization is the preferred method for new buildings, it is not possible to define, *a priori*, which of these two approaches may be best for an existing building site because it is difficult to know the exact construction techniques and present-day status of the foundation and surrounding soil.

Some general observations can, however, be made:

- The depressurization or pressurization systems are the same from a technical point of view, only the air flow direction is different. For this reason, it is convenient to use a fan that can be easily reversed or flow inverted, to allow for tests to assess the better configuration;
- Depressurization requires a pipe that transports the gas for dispersal in atmosphere. The exit point must be high to prevent radon from re-entering the windows, while the pipe must be relatively straight to ensure good flow. For pressurization, instead, an air intake point at the base of the building near the fan is sufficient, although it will require maintenance to prevent it from being partially obstructed;
- The pressurization technique generally requires a greater consumption of electricity, higher operating costs, and likely an increase in noise levels. In addition, it is more affected by losses due to the imperfect sealing of the pressurized volume;
- With depressurization the radon is drawn from, and evacuated to, known and planned points. With pressurization the path and eventual release points of the radon are unknown;
- It is advisable to pressurize a small-volume free crawl space, otherwise it is preferable to depressurize. In crawl spaces with closed compartments the efficacy of pressurization is limited, as different pressure gradients across the compartments may lead to radon migration into the building; in such cases it is preferable to use the depressurization technique.

While both solutions are valid, it can reasonably be argued that depressurization reduces radon gas concentrations more easily while pressurization needs greater experience to evaluate site conditions.

4.3.2. Natural ventilation or forced ventilation?

Rather than using fans to transfer air from an empty crawl space (or a disused area like an under-home garage) for building remediation, natural ventilation can sometimes be used if radon accumulation rates are not too high and building characteristics permit it. This typically involves making 10-12 cm wide holes at the base of the wall near the ground (Figure 15a). Where possible, it is preferable to place the holes on the north and south sides of the building, with the south holes higher for better ventilation. If the results are not satisfactory, natural ventilation can be improved by attaching a pipe on the north side hole and extending it beyond the roof line; thanks to the wind-induced Venturi effect the suction will be greater (Figure 15b). Finally, if even this configuration is insufficient, an extraction fan could eventually be installed in the pipe (Figure 15c). In the case of natural ventilation, it is essential to have openings on opposite walls for air inlet and outlet. In the case of forced ventilation, instead, it is better to seal air inlet holes to achieve greater depressurization / pressurization relative to the ground.

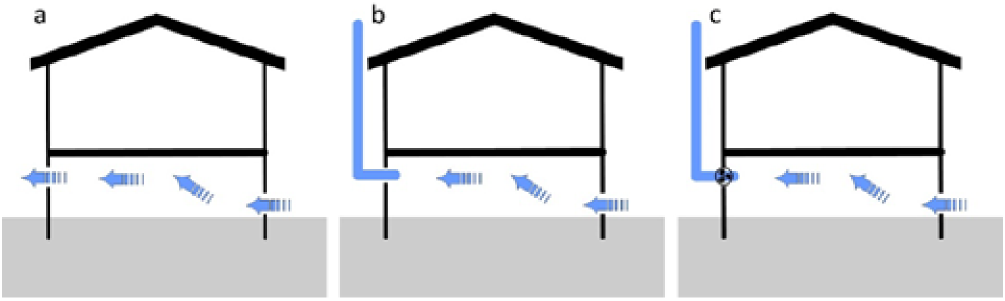

Figure 15. If the volume of the crawl space is free it is possible to consider natural ventilation of the volume (a,b). If insufficient an extraction fan can be added at a later date (c).

4.3.3. The noise problem

Ventilation systems can generate noise and vibration which can become annoying to the occupants. In addition to the possibility of system shutdown at night (where gas concentration and building use allows it), pipes and fans should be well fixed to reduce vibrations and sound-insulating materials should be installed to reduce noise transmission. While these solutions work well for fans installed in crawl spaces or utility spaces that are rarely occupied (e.g., laundry room), noise from ventilation units installed in living areas (like in-wall heat recovery fans) is more difficult to resolve.

4.3.4. System automation and timing

If active systems are used, such as sub-slab depressurizing or living area ventilation, it may be possible to reduce power consumption by timing fan activation to optimise the efficiency of the remediation system. The feasibility of this approach will depend on the concentration levels of indoor radon and, especially, the rate of descent of the radon concentration after switching on and its ascent rate after switching off the fan(s). This type of evaluation can only be done using continuous radon monitoring equipment, combined with a rigorous testing protocol, such as:

- off, at least 9-10 days, including a weekend
- turned on, at least 9-10 days, including a weekend
- off, at least two days (fixed time)
- turned on, at least two days (fixed time)
- off, at least two days (fixed time)
- turned on, at least two days (fixed time)

In this way it is possible to account for natural variability, linked to changing environmental conditions like wind and temperature, as well as different occupancy and occupant habits during the work week and on the weekends, and at night versus during the day. By assessing the impact of the ventilation system relative to the specific conditions and use of a site (e.g., a school, an office building, or a home), it is possible to understand if the fans have to be left on at all times or if they can be timed to maintain radon values below a threshold.

Instead, another option is to have a continuous radon sensor directly control the ventilation system in real time. In this way the system itself constantly optimizes its effectiveness as a function of changing conditions. This was the approach taken in the LIFE-RESPIRE project, as summarized below in Section 4.4.

4.4. THE LIFE-RESPIRE MONITORING AND REMEDIATION SYSTEM

As has been highlighted above, indoor radon concentrations and behaviour can be quite complex and variable due to unique building characteristics, individual occupant habits, and constantly changing environmental conditions. Because of this there is no simple, single solution for radon remediation, meaning that any approach must be flexible. In addition, considering the sometimes conflicting needs for comfort versus energy efficiency, it is highly desirable that systems take advantage of recent developments in automation, communication and smart technologies to strive towards a system that is active only when it is actually needed, without the need for constant human intervention.

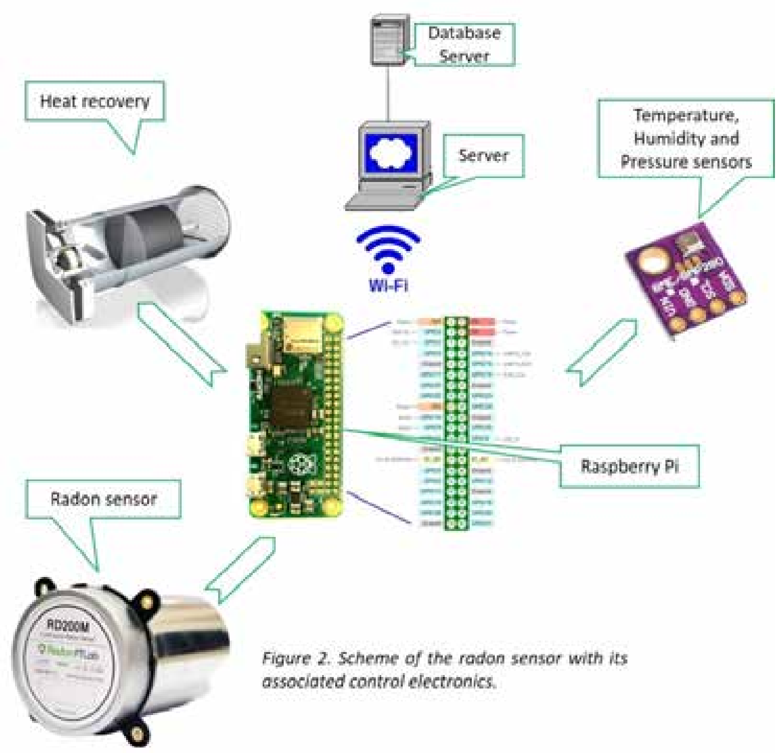

Figure 2. Scheme of the radon sensor with its associated control electronics.

Figure 16. Schematic drawing of the main components of the Respire Radon Remediation System (R3S).

This is the approach taken by the LIFE-RESPIRE project during the development of its Respire Radon Remediation System (R3S) (Figure 16). The R3S combines a small, dependable, commercial radon sensor (RD200M) with an inexpensive mini-computer with data logging and Wi-Fi / Bluetooth communication capabilities (Raspberry Pi Zero) to pilot any type of fan (e.g., sub-floor depressurization, in-wall heat recovery, or centralized heat exchange fans) that is able to reduce radon concentrations at a given site below the threshold value (300 Bq/m^3) indicated by the European Directive 2013/59/EURATOM. In addition, the R3S transmits the radon measurements, together with temperature, pressure and relative humidity data, to a web database where the occupant can plot trends and results to assess the effectiveness of the chosen remediation installation and to determine radon exposure levels.

Testing was conducted both in Italy and Belgium, which was highly advantageous given the many differences between these two European countries in terms of issues and parameters that can influence indoor radon and its remediation. For example, Belgium has a colder climate, soil is the primary source of indoor radon, and its buildings tend to be made of brick with crawlspace or utility areas below the main living areas, whereas central Italy has a warmer climate, radon comes from both the soil and the building materials, and many of its buildings tend to be built directly on the ground out of volcanic tuff with no crawlspace access. These factors have an important impact on what remedial approaches can be applied. In this regard, all R3S units in Belgium pilot depressurization fans installed in lower levels whereas most R3S units in Italy pilot heat recovery fans in the living areas to improve ventilation and air exchange. Many sites were tested in both countries however not all resulted in a long-term R3S installation, typically due to radon values that were too low or technical / logistical problems. At present there are 9 units functioning in Belgium and 18 in Italy. Problems related to COVID-19 (lock-downs, access rules and reduced willingness of people to give access to their homes) had a strong influence on how many units could be installed and how often they could be visited for updates and maintenance.

A detailed description of the R3S system, all deployments (including experimental test sites), and the obtained results are given in Deliverables B2.3 ("Report on evaluation of the remediation system") and B2.4 ("Report of the one-year monitoring after the application of the remediation system"). Some representative examples are shown in Figure 17, including using a bi-directional heat recovery fan in one room while monitoring it and an adjacent, non-ventilated room (Figure 17a), a heat exchange fan with multiple velocity settings (Figure 17b), and a crawlspace depressurization fan beneath a monitored living area (Figure 17c). This illustrates the flexibility of the R3S, as it can control whatever ventilation system is most appropriate for a given site. It must be remembered, however, that it is critical to scale and design the ventilation system properly to account for the total indoor volume to be remediated and the rate of radon ingress / accumulation. While also true for depressurization systems it is particularly critical for living area ventilation approaches (which are often needed if the radon originates from the building materials).

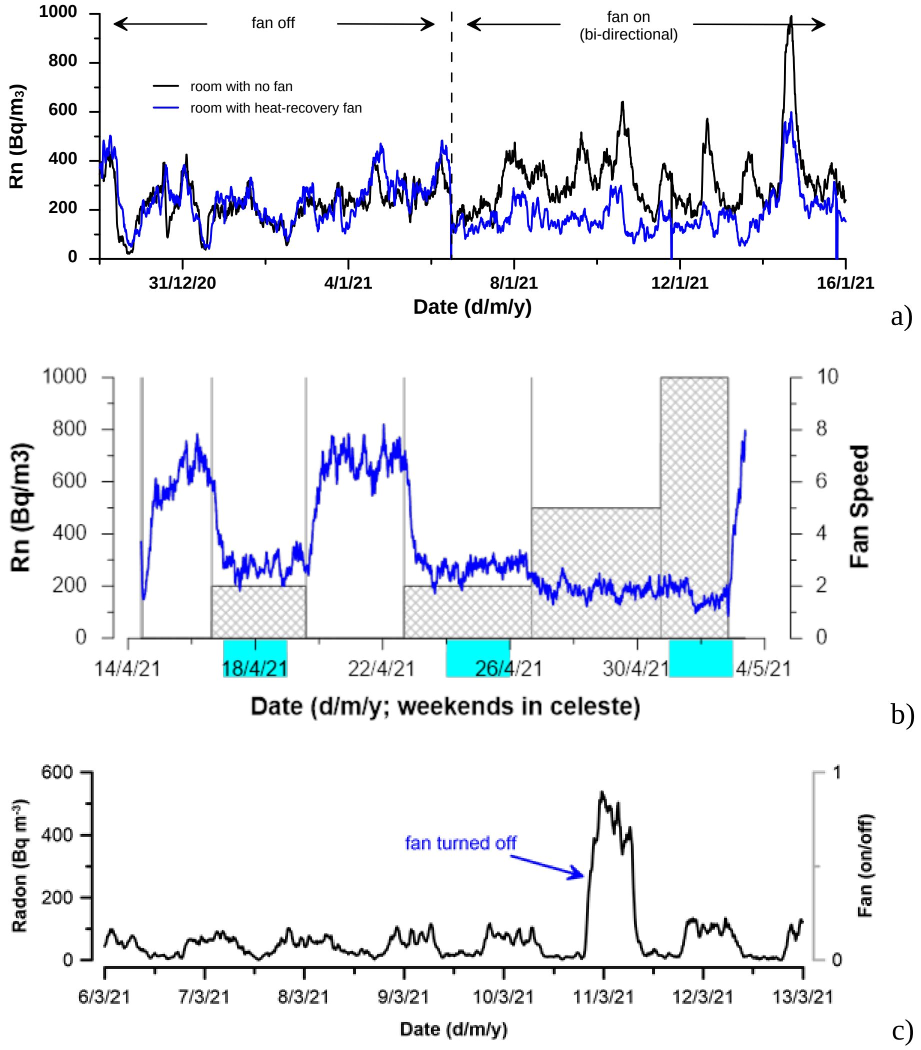

Figure 17. Examples of test results from using a bi-directional heat recovery fan (a), a heat exchange fan with different speed settings (b), and a depressurization fan (c). Note that while depressurization systems prevent radon entry and thus can potentially achieve very low values, living area ventilation fans are basically diluting the radon already present and thus final radon concentrations will depend on total volume, fan flow rate and radon exhalation rate.

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