IAEA TECDOC SERIES

IAEA-TECDOC-1951

Protection against Exposure Due to Radon Indoors and Gamma Radiation from Construction Materials — Methods of Prevention and Mitigation

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PROTECTION AGAINST EXPOSURE DUE TO RADON INDOORS AND GAMMA RADIATION FROM CONSTRUCTION MATERIALS — METHODS OF PREVENTION AND MITIGATION

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2021

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Printed by the IAEA in Austria
May 2021

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Protection against exposure due to radon indoors and gamma radiation from construction materials : methods of prevention and mitigation / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2021. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 1951 | Includes bibliographical references.
Identifiers: IAEAL 21-01397 | ISBN 978-92-0-105521-7 (paperback : alk. paper) |
ISBN 978-92-0-105621-4 (pdf)
Subjects: LCSH: Radiation sources — Safety measures. | Radon — Safety measures. | Radiation, Background. | Radon. | Gamma rays — Safety measures.

FOREWORD

Radon is a chemically inert, naturally occurring radioactive gas generated by the radioactive decay of ^{238}U and ^{226}Ra, which are present in rocks, soils and building and construction materials. It has no smell, colour or taste, and is detectable only with special measurement instruments. Some types of rock have higher than average uranium and radium contents. These include light-coloured volcanic rocks, granites and dark shales, as well as sedimentary rocks including karst limestone, sandstone, chalk and some clays that contain traces of these rocks.

Radon is transported from soil and rocks by convection and diffuses into the upper layers of soil and then into the atmosphere. Radon is drawn into buildings as a result of wind action and pressure differences induced by air densities (stack effect). Soil gas infiltration is recognized as the most important source of radon in dwellings and other buildings. Other sources of radon include building and construction materials and water extracted from wells, but they are of less importance. In some areas of the world, particularly in countries with certain geology and with long and cold winters, some houses can have very high levels of radon.

The United Nations Scientific Committee on the Effects of Atomic Radiation has observed that, for most people, radon is the largest source of radiation exposure throughout their lifetime. The World Health Organization has estimated that the proportion of lung cancers linked to radon lies between 3% and 14%, depending on the average radon concentration in the country and the method of calculation.

IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, establishes requirements for the protection of the public against exposure due to radon indoors. Where activity concentrations of radon in buildings are of concern for public health, governments are to establish an action plan of coordinated actions to reduce activity concentrations of radon in existing and future buildings. One element of the action plan would be to include in building codes appropriate preventive measures and corrective actions to prevent the entry of ^{222}Rn.

This publication describes methods for reducing the entry of radon into dwellings and other buildings (i.e. preventive measures for new buildings and corrective actions for existing buildings). The publication provides examples (with graphics) of methods for reducing radon in buildings that can be used with different types of building foundation. It also provides advice on the investigation of the entry of radon into buildings and on the design and technical parameters of measures and actions for reducing radon entry, as well as examples of some design features that may adversely impact the long term effectiveness of these measures. The publication contains practical information on the types of measurement that need to be considered to demonstrate compliance with established national reference levels for exposure to radionuclides in building and construction materials and other construction materials.

The IAEA officer responsible for this publication was O. German of the Division of Radiation, Transport and Waste Safety.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Radon-222, commonly called radon, is a radioactive gas generated by the radioactive decay of ^{238}U and ^{226}Ra, which are present in rocks, soils and construction materials. Radon is continuously released into outdoor air, where it is quickly reduced to harmless concentrations. However, when it enters an enclosed space, it can sometimes build up to potentially hazardous concentrations.

For many people, radon represents the major contributor to their lifetime exposure due to radiation. The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) in two comprehensive reports in 2000 and 2006 [1, 2] concluded that inhalation of radon and its decay products are established carcinogens for the lung (doses to other organs and tissues were at least an order of magnitude smaller than the doses to the lung).

The International Committee on Radiological Protection has reviewed the scientific evidence of health effects due to exposure due to radon in several publications and has made recommendation on the protective actions needed against indoor exposure to radon [3–7].

In 2009, the World Health Organization (WHO) published the its Handbook on Indoor Radon [8]. The WHO review of the recent studies on indoor radon and lung cancer in Europe, North America and Asia found that they provide strong evidence that radon causes a substantial number of lung cancers in the general population. The WHO estimates that the proportion of lung cancers attributable to radon range from 3 to 14%, depending on the average radon concentration in the country concerned and the calculation method used. The WHO finds that radon is the first cause of lung cancer after smoking.

IAEA Safety Standards Series No. GSR Part 3, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards [9], establishes requirements for protection of the public against exposure due to radon indoors. In particular, para. 5.20 of GSR Part 3 places the responsibility on national authorities to “ensure that an action plan is established comprising coordinated actions to reduce activity concentrations of radon in existing buildings and in future buildings” [9].

IAEA Safety Standards Series No. SSG-32, Protection of the Public against Exposure Indoors due to Radon and other Natural Sources of Radiation [10], provides guidance on the actions to be included in the radon action plan. These actions include the following:

(1) To establish an appropriate reference level for ^{222}Rn for dwellings and other buildings with high occupancy factors for members of the public;
(2) To decide what other types of building with high occupancy factors for members of the public, such as kindergartens, schools and hospitals are included in the scope of the action plan for radon;
(3) To facilitate the measurement of ^{222}Rn in dwellings and other buildings with high occupancy factors for members of the public;
(4) To identify ^{222}Rn prone areas;
(5) To give priority to actions to reduce activity concentrations of ^{222}Rn in those situations for which such action is likely to be most effective;
(6) To include in building codes appropriate preventive measures and corrective actions to prevent the ingress of ^{222}Rn and to facilitate further actions wherever necessary;
(7) To implement measures to control and reduce exposure due to ^{222}Rn, including determining the circumstance under which measures are to be mandatory or to be voluntary;

(8) To evaluate the success of the action plan.

This TECDOC provides examples of possible preventive measures and corrective actions that could be considered by national authorities for including in national building codes, i.e. relating to item (6) in this list of elements of a radon action plan.

Paragraph 5.7 of GSR Part 3 requires that the regulatory body or other national authority ensures that the “remedial actions or protective actions are expected to yield sufficient benefits to outweigh the detriments associated with taking them, including detriments in the form of radiation risks” [9], i.e. that the remedial actions and protective actions are justified. This TECDOC provides examples of preventive measures and corrective actions that have been used successfully in some States. It is up to the national authorities to ensure that such examples are justified for use in their State.

Recommendations on limiting exposure and implementing radon preventive and mitigation measures are also expressed in the WHO’s publication on radon [8].

Building practices have an impact on radon concentrations. In areas where higher radon concentrations are a known risk, preventive building practices may be adopted to lower radon ingress into new structures. In buildings and homes that have elevated radon concentrations corrective or remedial actions need to be taken to reduce those concentrations. These remedial actions have been shown to be effective in lowering radon concentrations.

Since publication of GSR Part 3 in 2014, the IAEA has received many requests for advice and assistance in providing a comprehensive overview of mitigation techniques for lowering radon concentrations in buildings as well as techniques for reducing exposure from construction materials. In addition, guidance related to including preventive measures in building codes, has been requested.

Requirement 51 of GSR Part 3 requires that the exposure due to radionuclides in commodities, such as construction materials, will not contribute to annual effective doses to the population higher than 1 mSv [9]. This requirement is used for the justification of remedial actions needed to reduce exposure of the population in existing as well as newly build buildings. SSG-32 [10] provides guidance on protection of the public against exposure to gamma rays from radionuclides in construction materials. This TECDOC provides practical advice on the measurements that can be performed to demonstrate compliance of the materials with the requirements of GSR Part 3 and practical advice on remedial actions against ionising radiation in construction materials.

1.2. OBJECTIVE

The main objective of this TECDOC is to provide a review of technical solutions for both corrective actions and preventive measures to reduce the ingress of radon indoors. This review includes the description of methods, design and implementation of measures and actions to reduce ingress of radon into buildings, and of the materials and equipment used in these solutions. The TECDOC also includes methods for measuring gamma radiation from radionuclides in building and construction materials and for reducing exposure due to gamma radiation from building and construction materials.

This TECDOC is aimed primarily at national authorities responsible for the development of national building codes; at national authorities responsible for the development and implementation of national radon action plans; and at building professionals responsible for the implementation of national building codes (e.g. architects, construction engineers). This TECDOC is also aimed at building and construction professionals designing and installing radon reducing measures, and measures for reducing exposure from building and construction materials, as well as educational establishments providing higher education, including practical training, in construction and architecture.

1.3. SCOPE

The publication covers both mitigation measures for existing buildings and protective measures for new buildings. Detailed discussion is given on diagnosing the problem for a range of common construction and ventilation types and their influence on radon ingress into a building. A comprehensive selection of mitigation methods and protective measures for new buildings are described. There is no single method that can be used in all cases. Some dwellings may need a combination of more than one method so that the radon levels are reduced to below the national reference level.

This TECDOC does not cover the following topics: the national system of regulatory control of indoor radon which is covered in SSG-32 [10] and in the Draft Safety Guide Protection of Workers against Exposure Due to Radon [11]; the regulatory control of building and construction materials which is described in Ref. [12]; the design and implementation of national and regional surveys of indoor radon or thoron which is covered in Ref. [13]; and the design and implementation of a national action plan to reduce public exposure due to radon indoors, which is covered in SSG-32 [10].

1.4. STRUCTURE

This TECDOC consists of seven Sections. Section 1 provides introduction to the publication. Section 2 gives overview of basic knowledge on radon and construction properties that are necessary to be considered for designing any radon corrective or preventive action. In Section 3 mitigation methods for existing buildings are described while Section 4 deals with mitigation of radon when the source of radon in the household water. Radon preventive methods for new constructions are provided in Section 5. General considerations of efficiency assessment of preventive and corrective measures are provided in Section 6. Section 7 deals with the protection against gamma radiation arising from building and construction materials. The Appendix provides advice on the selection and installation of fans as part of the measures to reduce radon levels in buildings.

2. BUILDING FOUNDATIONS, VENTILATION AND CONSTRUCTION MATERIALS THAT RELEASE RADON

2.1. TYPES OF FOUNDATION

A building is generally constructed with one of four foundation types: (1) slab-on-grade, (2) crawl space, (3) basement with footings, or (4) basement[1] with load bearing slab and wall construction [14]. Most buildings will use only one foundation type, while some, particularly where building extensions have been added over the years, may use several foundation types.

It is important to identify each foundation type to properly address radon prevention and mitigation issues in a building. All buildings will have some contact with the ground so they may potentially have a radon problem. Therefore, each foundation type can contribute to the radon concentration in the building. Radon reduction measures applied to a building may fail if the floors and walls forming the foundations are overlooked or ignored during the mitigation process.

The types of foundation are more or less the same around the world, although there may be some minor modifications.

Slab-on-grade is a type of foundation where the lowest floor of the building is a concrete slab poured directly on the ground at the existing grade level. Because the slab is in direct contact with the ground, a building built with this type of foundation may have a radon problem if the slab is cracked or it is punctured for the provision of services. A schematic drawing of a slab-on-grade type of foundation is shown in Fig. 1.

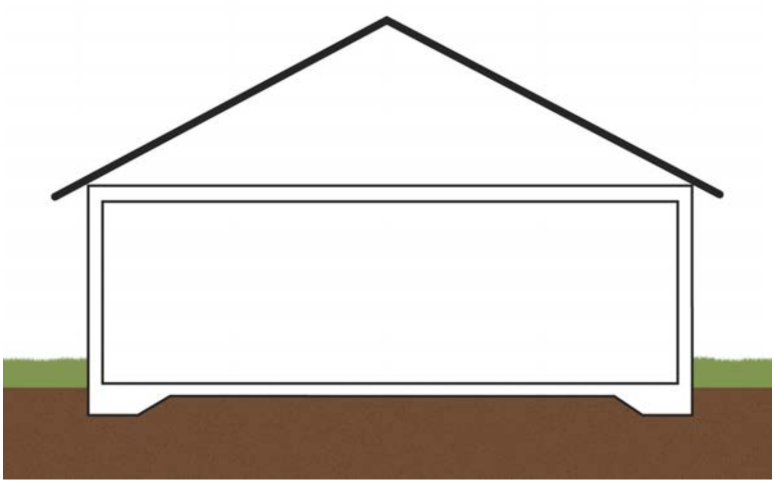

FIG. 1. Slab on grade type of foundation.

There are two sub-types of slab-on-grade foundation:

(a) The superstructure and/or walls built-off the floor slab;

(b) The superstructure and/or walls built-off strip or pad foundations, with the slab poured after the foundation walls have been installed.

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[1] Basements include occupied spaces fully or partially below ground level.

Basement is a type of floor construction where the lowest floor of the building is a slab that is below grade level and has all or some of its walls in contact with the adjacent ground or bedrock [15]. There are various types of basement, for example:

(a) Full basement – where the basement is located beneath the full footprint of the building, and all of the external walls below grade level are in contact with the adjacent ground;

(b) Partial basement – where the basement is only located beneath part of the building;

(c) Semi-basement – where the building is cut into the hillside and some external walls are partially or fully below grade level in contact with the adjacent ground; and

(d) Stepped construction – where a building is stepped up a sloping site.

Whilst basements are typically a single storey below ground level of a building, they can also be multi-storey below ground level. An occupied space below ground level is referred to as a basement, whereas an unoccupied space below ground is usually referred to as a cellar.

A schematic drawing of these four types of basement or cellar are shown in Fig. 2.

From a radon protection point of view, methods for reducing radon are implemented in basements rather than cellars, as basements are occupied by people. The radon mitigation expert may also need to understand if and how radon moves from a cellar into the occupied areas of the building. It may be necessary to seal the cellar to prevent movement of radon from cellar into the occupied areas of the building. Cellars may also prove useful for locating mitigation ventilation fans and routing pipe work out of sight.

Basements can be found in all climates, and ground conditions. As basements have a larger surface area in contact with the ground (both floors and walls), and proximity to preferential pathways for the movement of radon under and around the foundation (e.g. utilities, floor-wall joints, sump pits), buildings with basements are more likely to have significant radon entry than for buildings with other foundation types.

There are two types of foundation used for buildings with basements: basement with footings and basement with load bearing slabs.

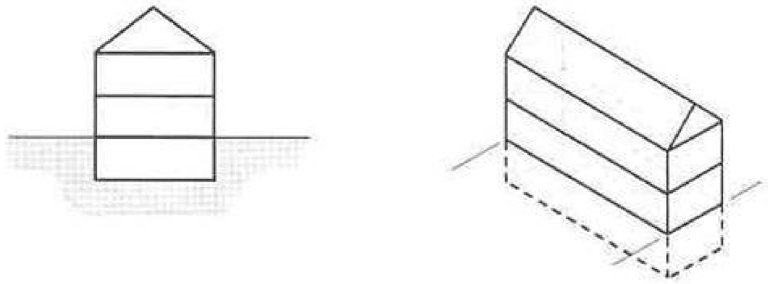
Basement with footings. In this construction type, the house is built on footings with the floors poured between the basement walls. The basement walls and floor are not created at the same time.

A schematic drawing of a basement with footings is presented in Fig. 3.

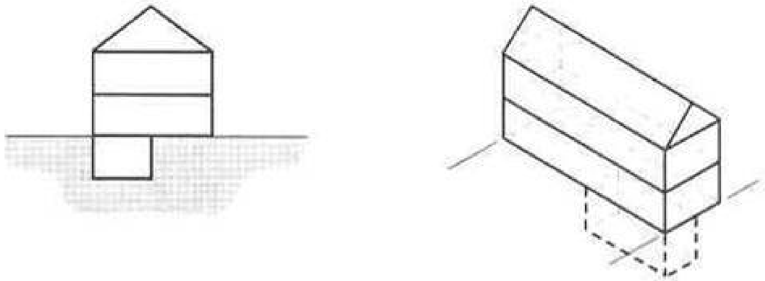
Basement with load bearing slab. In this construction type, the house is built on a solid load bearing slab. This allows for fewer radon entry points. The basement walls and floors are created at the same time.

A schematic drawing of a basement with load bearing slab is presented in Fig. 4.

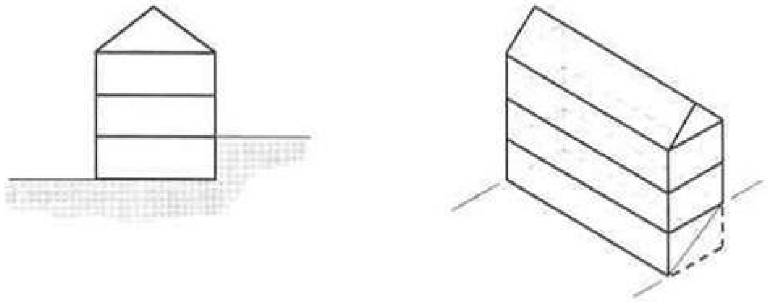
(a) Full cellar or basement, completely located below ground level



(b) Partial cellar or basement, completely located below ground level



(c) Semi-basement or cellar



(d) Stepped constructions

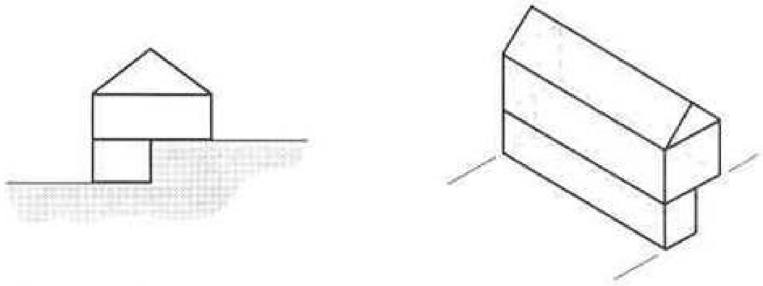


FIG. 2. Different kinds of cellars and basements (reproduced with permission of IHS Markit from Ref. [15]).

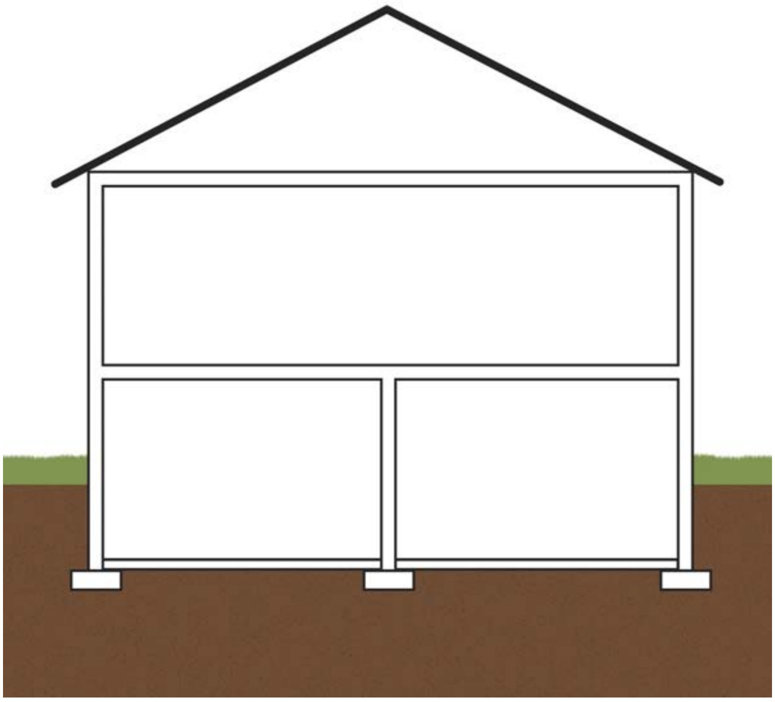


FIG. 3. Basement with footings.

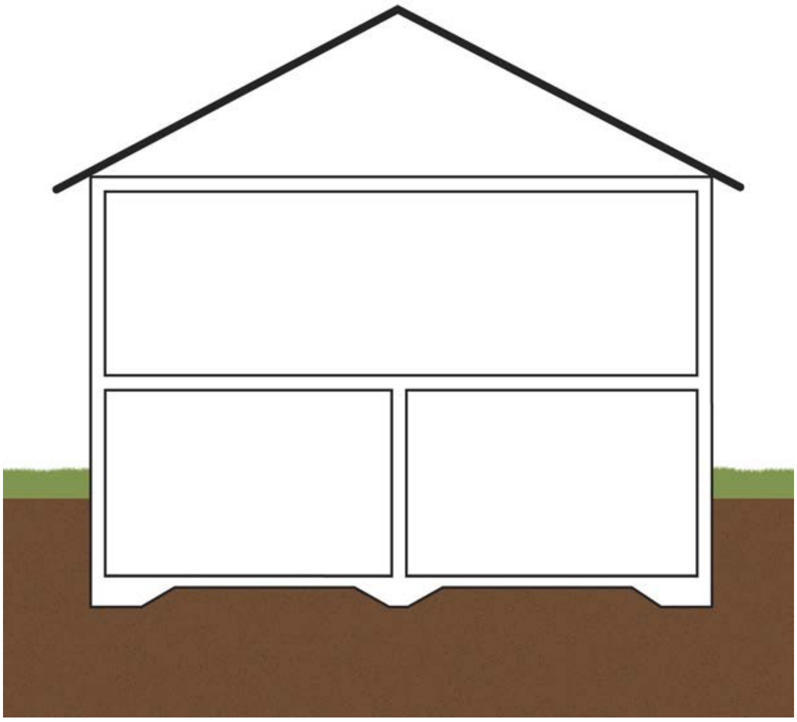


FIG. 4. Basement with load bearing slab.

Crawl space is a type of foundation with an open area beneath the lowest occupied space of the building. The lowest living or occupied level is built above the crawl space and is usually elevated 200 mm or so above grade. While crawl spaces are not habitable areas, they may contain utilities or mechanical ductwork that serves the rest of the building. Crawl spaces are often uncovered earthen material that can be a source of radon. If left untreated, they can contribute to elevated radon levels in the building. Some crawl spaces may have a poured concrete floor. When constructed, the crawl space needs to be provided with under floor vents to ensure ventilation under the floor to remove moisture that rises from the ground and to prevent timber rot in timber floors.

A schematic drawing of a crawl space type of foundation is presented in Fig. 5.

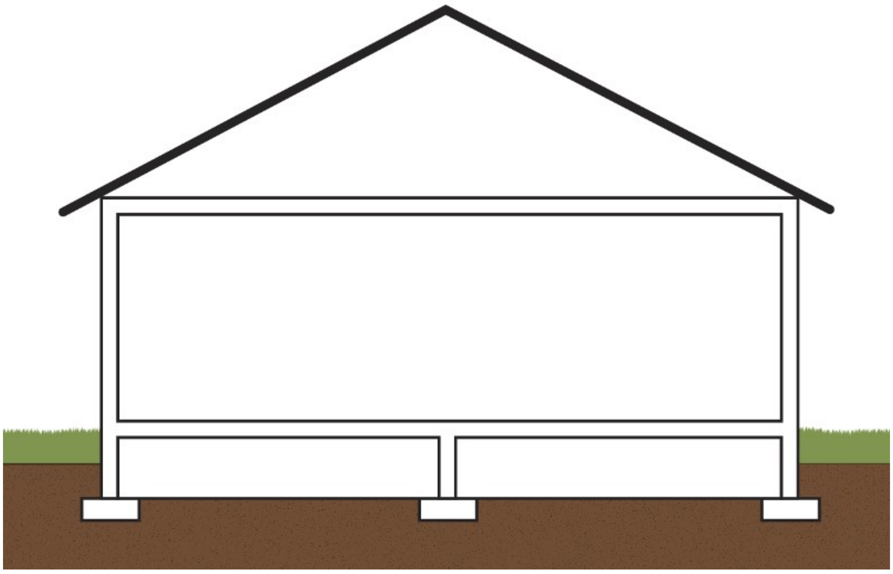


FIG. 5. Crawl space type of foundation.

2.2. TYPES OF VENTILATION

There are three common types of ventilation system used to ventilate dwellings: (a) natural draught ventilation; (b) mechanical exhaust air ventilation system; and (c) mechanical supply and exhaust air ventilation system having different influence on indoor radon accumulation or ventilation.

Natural draught ventilation.

Historically this is the method most commonly used across the world. It is based on pressure difference between the inside and the outside of the building which is induced by the difference in density between the indoor and outdoor air. The rate of air change is determined by the pressure flow (often referred to as the “stack or chimney effect” or “warm air rising effect”) induced by the pressure differences between the indoor and outdoor air, and the volume of the building.

A schematic drawing of a dwelling with natural draft ventilation is presented in Fig. 6.

The air exchange rate, also known as air change per hour (ACH), is defined as the ratio of airflow and the total volume of air given by Eq. (1):

$$\mathrm{ACH} = \Delta V/\Delta t \cdot 1/V \tag{1}$$

where

ΔV = Volume of air (in m^3) exhausted in one hour;

Δt = Time = 1 hour;

V = Volume of the building (in m^3).

The rate of air change is affected and determined by the number of indoor and outdoor air openings, e.g. passive ventilators, windows, doors, and their opening area. The rate of air change is also dependant on the airtightness of the building and is also influenced by the wind. The draught system can provide reasonably stable ventilation on a yearly basis but is prone to have high daily variations.

The natural draught ventilation system works better in cold climates than warmer ones due to higher temperature differences between the inside and the outside of the building.

If a building which relies on natural ventilation has an elevated level of radon, it is usually not possible to reduce the radon levels to a specified level (e.g. below reference level) by natural ventilation alone. Instead, a far higher air exchange rate would be needed to solve an existing radon problem in the building.

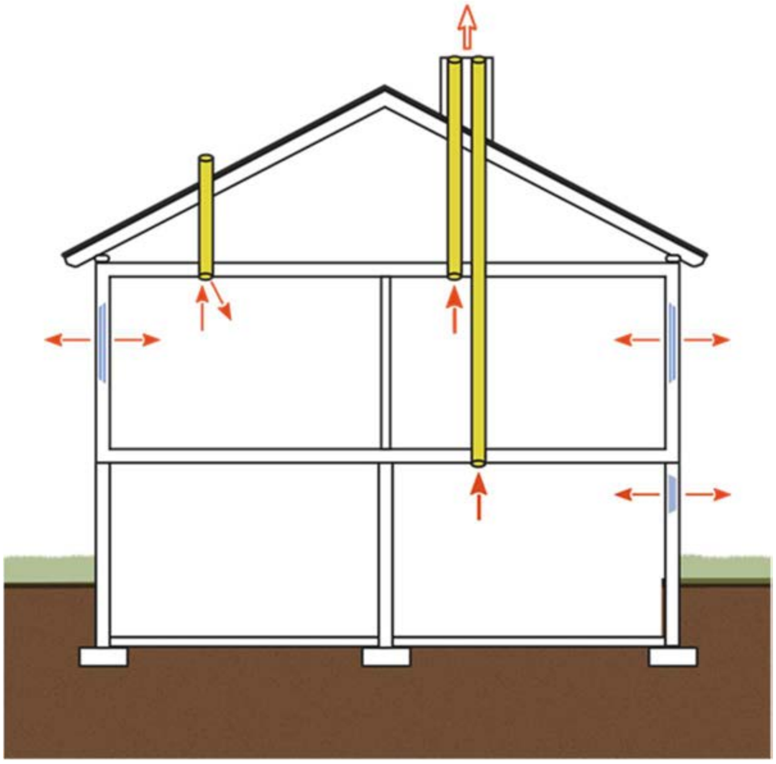


FIG. 6. Natural draft ventilation.

Mechanical exhaust air ventilation system

In this system the rate of air change is determined by the fan rating in the mechanical exhaust, the area of the ventilation opening to the outside, and the airtightness of the building. Compared to natural draught ventilation, this system is significantly less affected by the density difference between indoor and outdoor air and the influence of wind.

For dwellings with an installed mechanical exhaust air ventilation system, that have elevated radon levels originating from the soil, it is essential to find and seal all cracks and leaks in the floor construction and if needed also install a soil depressurization solution. Mechanical extraction of air from the building results in the air in the building being under pressurized compared to the external air, and also compared to the soil gases that contain radon. The pressure difference between the soil and the inside of the building draws the soil gases towards the inside of the building. The ventilation system will need to be carefully balanced to ensure that the system does not increase the radon problem from the ground.

If the elevated radon levels in the dwelling is caused by the exhalation of radon from the building and construction material, the solution can include installing a mechanical exhaust air ventilation system. However secondary effects need to be considered as well – increased ventilation without heat recovery may increase heat losses, which may be unacceptable in cold climates.

A schematic drawing of a dwelling with mechanical exhaust air ventilation system is presented in Fig. 7.

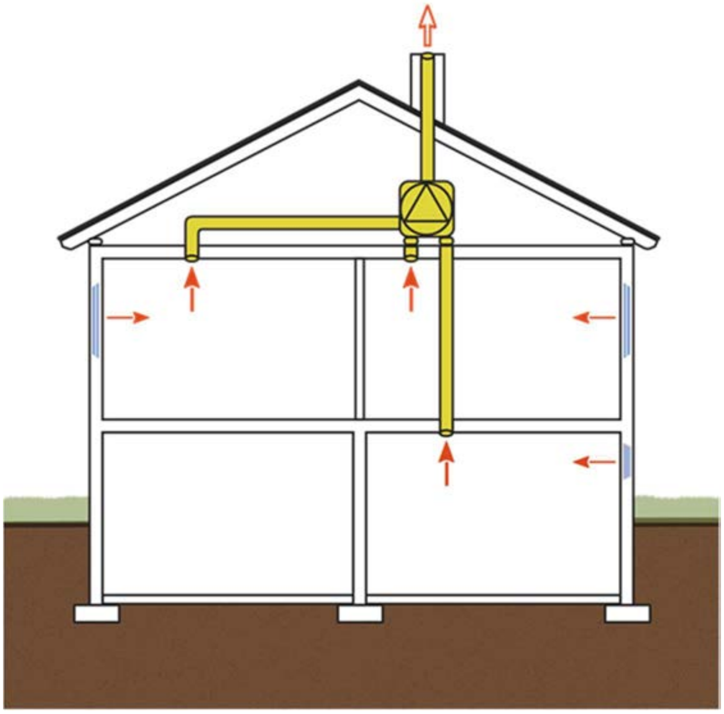


FIG. 7. Mechanical exhaust air ventilation system.

Mechanical supply and exhaust air ventilation system

In this system the rate of air change is determined by the balance between air supply and exhaust airflow rates. This is known in some areas of the world as an air-to-air exchanger or a heat recovery ventilator.

Compared to the natural draft ventilations and mechanical exhaust air ventilation systems, the mechanical supply and exhaust air ventilation system has a better ability to control and balance the movement of air through the building. Control can be applied to fans and ventilation grilles used for both incoming and exhaust air. A well-balanced system will result in far less influence on the ventilation of the building from the weather, such as external air temperature and wind. An unbalanced system may induce ingress of radon from the soil into the building and lead to elevated radon levels.

Mechanical supply and exhaust air ventilation would normally have enough capacity to solve an existing radon problem due to exhalation of radon from building and construction materials used in a building. However, systems that are designed for a high degree of energy efficiency may not have sufficient spare capacity to allow for increased airflows that may be necessary to reduce indoor radon levels.

A schematic drawing of a dwelling with a Mechanical supply and exhaust air ventilation system is presented in Fig. 8.

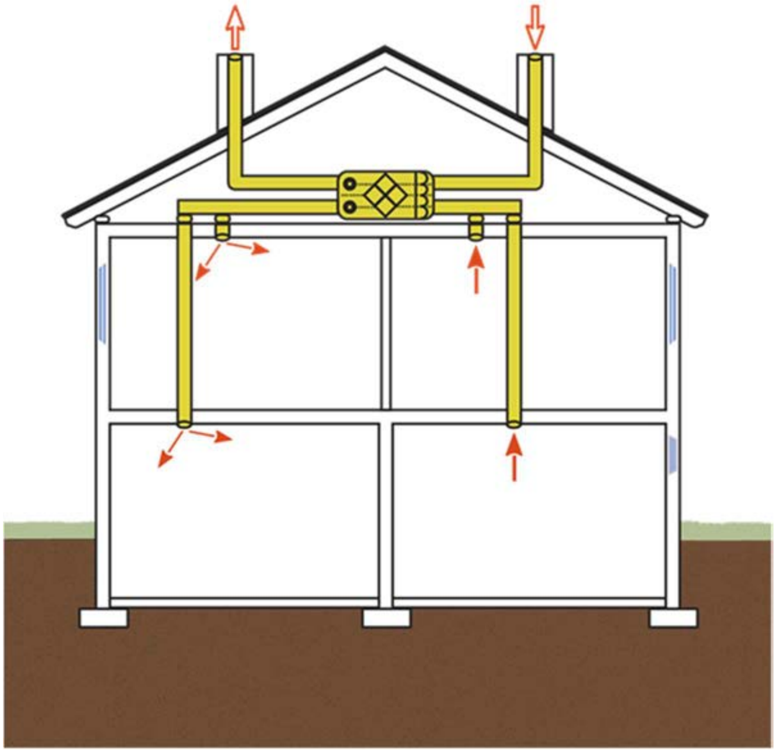


FIG. 8. Mechanical supply and exhaust air ventilation system.

With an existing mechanical supply and exhaust air ventilation system in a building and the elevated radon levels in the building coming from the soil air, it may be enough to adjust the system with a slight over pressure in the building to reduce the ingress of radon into the building and therefore lower the radon levels. However, in countries with very cold climates, care needs to be taken to prevent internal moist air entering into a layer in the interstitial structure of the building that is at dew point temperature, as it may condense and could freeze. As a consequence, it is important to consider the local building construction methods and the climate that they were built for when considering over-pressurizing a building. Furthermore, for larger multi-zone buildings, it may be difficult to control and balance airflows. It also involves greater cost with electrically controllable exhaust and inlet vents and the need for a sophisticated building management system. Therefore, such systems may be appropriate for individual houses but not for larger buildings.

Even with mechanical supply and exhaust air ventilation, it is still important to find and seal all significant cracks and leaks in the floor construction when implementing radon remedial measures. If changes are not to be made to the ventilation system, then an active soil depressurization system will need to be installed to solve an existing radon issue.

2.3. TYPES OF MATERIAL THAT MAY EXHALE RADON

For the purposes of this publication, and in accordance with SSG-32 [10], ‘building materials’ are construction materials that are used for the construction of buildings such as dwellings, and offices, industrial premises and other workplaces. To provide a constancy with the terminology of the GSR Part 3 [9], dealing with commodities such as construction materials, this TECDOC uses both “building and construction materials”. Given that all stone-based construction materials are naturally occurring and mined from the earth, they contain trace amounts of uranium and radium. Therefore, it is mainly concrete construction material used for floors, walls or ceilings of buildings, or crashed stones used for filling beneath the buildings, that may emanate radon that contributes to the indoor radon concentrations.

Generally, concrete is made of roughly 10% cement, 10% water and 80% of aggregates of different fractions [16].

Models have been developed for the dose assessment of gamma radiation emitted from construction materials. These models use a reference room that is assumed to have the dimensions 3 m x 4 m x 2.5 m and that is made from concrete [17].

The level of radon in the room can be calculated using Eq. (2) (see Ref. [18]):

$$C_{bm} = \frac{1}{(\lambda+n).V} . \sum_i E_i . A_i \tag{2}$$

where

C_{bm} = Radon contribution to indoor air concentration from construction material

λ = Radon decay constant = 0.00755

n = Air exchange rate = 0.5 volumes/hour

V = Room or buildings inner volume = 30 m^3

E_i = Radon exhalation rate = 13 Bq/m^2h

A_i = Surface area of walls made using the construction material in the room = 55.4 m^2

The radon exhalation from concrete is assumed to be 13 Bq/m^2h for this exercise, which is also typical for untreated concrete surfaces, for building and construction materials with an activity concentration of about 60 Bq/kg Ra in accordance with [18].

The contribution of the construction material to the radon concentration in the room can be calculated using Eq. (2) above:

$$C_{bm} = (1/((0.00755 + 0.5) * 30)) * (13 * 55.4) = 50 \text{ Bq/m}^3$$

i.e. the construction material contributes about 50 Bq/m^3 to the indoor radon concentration from the concrete alone, assuming the ventilation rate is 0.5 air change per hour, which is a typical exchange rate for some workplaces and dwellings.

For workplaces and municipal buildings, the airflow demands are typically higher, up to 1.0 air change per hour. This additional ventilation may reduce the above contribution from the construction material to the total indoor radon concentration to approximately 25 Bq/m^3 for the same volume facility.

Knowing the contribution of building and construction materials to indoor radon concentrations is important in areas of the world with more stringent building codes. Some sustainable building standards necessitate very low radon concentrations in newly constructed buildings. If radon concentrations from building and construction materials are not accounted for, the lowest achievable radon concentration in the building may be higher than what is stipulated in these building codes without taking drastic additional protection measures. In addition, it is important that the building designer has a knowledge of the radium content of the building and construction materials, and for the constructor and the concrete producers to be able to control the uranium and radium contents of the aggregate (ballast) used in the concrete for such buildings.

3. RADON MITIGATION STRATEGIES IN EXISTING BUILDINGS

Generally, there are three approaches to radon mitigation: depressurisation of the ground beneath the building, over-pressurisation inside the building or in the ground beneath the building, and isolation. The approaches are explained later in the Section.

The key point in successful mitigation is proper execution of the mitigation methods, that are implemented by experts who are trained and have expert knowledge on the methods to reduce radon levels in buildings. This TECDOC does not provide exact solutions for every possible case therefore understanding of the principles is equally important as the guidance itself.

Prior to designing and installing the measures to reduce ingress of radon into the building, the expert will need to review the measurements that have been made of the radon levels in the building, request or carry out diagnostic tests to determine entry points for radon into the building, and make an assessment of the type of foundation and the construction pf the building to determine the most appropriate mitigation methods to be installed in the building.

3.1. DIAGNOSTICS AND INVESTIGATION

The first step in mitigating a radon problem is to review the measurement results for existing indoor radon level for the building. The report containing measurement results will include the measured radon levels, the measurement technique which needs to have been a long-term measurement, and the time period for the measurements. The measured radon levels need to be compared with the national reference level. All of this is important as the radon level will help to determine the most appropriate mitigation method for the building. Some mitigation methods are best applied to lower radon levels, i.e. radon levels which are slightly above the reference level, whereas other methods, or a combination of methods, can deal with a range of radon levels. If the radon level exceeds the national reference level, mitigation works needs to be carried out, and on completion, the radon levels in the building need to be measured to demonstrate that the mitigation methods used were successful.

There are a range of different methods of radon measurements. The most commonly used method are etched track detectors (solid state nuclear track detectors) that allow for a measurement period up to one year. As radon levels in a building vary with weather conditions and occupant use of the building, longer duration monitoring is needed to give a more accurate average radon level for the building. The measurement period is preferably from two months to twelve months. Where shorter measurement periods are used, they need to cover the heating season. Active measurement using integral electronic devices can also be used but their cost is in principle higher compared to passive devices. Even in this case, it is recommended that the period of measurement is not shorter than two months during the heating season, to allow for averaging of prevailing conditions [10].

Radon concentrations in buildings vary over time. The concentration depends on numerous factors, such as the availability of radon gas in ground (or water), air pressure conditions, time dependent permeability for radon gas of topsoil layers, building construction foundations and ventilation, air pressure conditions inside the building and use of the building.

When designing the measures for radon mitigation in existing buildings, all aspects influencing the radon levels need to be addressed. At the start of the mitigation, detailed data on radon entry routes into the buildings needs to be determined. Also, data on the building itself (such as construction materials used, type of foundation, layers beneath the visible ground floor, shafts) is often not known or is not reliable. Understanding these data is very important since it strongly affects the selection and success of the mitigation strategy starting from the concept, design, and details of execution.

Valuable sources of the information are the technical drawings (so called ‘blueprints’) for the building, if available. However, information found on the blueprints need to be verified to a sufficient extent to be deemed as reliable. In particular, this is valid for old buildings that have been reconstructed after the building was erected and the blueprints fail to capture most recent renovations. The same warning applies in the cases where changes to the blueprint might have not been recorded properly during the construction phase and the construction logs are not available. In practice, often information obtained with interviewing local community members can reveal potential discrepancies between the blueprints and the final building, e.g. material used under the floor during construction.

3.1.1. Data about the building

Before designing the radon mitigation measures, data on the building need to be collected in a systematic manner. It is recommended that a general drawing of the building represents the basis for recording the data.

The data have to comprise the following (the list is not exhaustive):

(a) General information on location of the building, with details about temperature range and expected wind conditions throughout the year and local ground characteristics, for example general permeability of the ground (different components will have different permeability that may also depend on moisture content e.g. clay, loam soil, sand, gravel) and other materials under the building, and information on air pressure from the ground, if available and/or relevant.

(b) General description of the building: terrain (flat or slope), how the building is following the terrain (e.g. flat, cascading or semi-buried), the use of the building, general footprint shape (e.g. rectangular, “L” shaped, “H” shaped) and approximate height of the building.

(c) Description of floors in the building, number of underground floors, if any, total estimated footprint area. This data is important for the estimation of natural pressure conditions in the building.

(d) Description of the building’s load bearing structure (e.g. concrete, wood, masonry), description of depth of foundation walls in the ground, and a description of the material used for the foundation walls.

(e) Definition of internal floor footprint areas within foundation walls. Estimation of shape and size of such area. Description of the expected underlaying layers, in particular identification of the air permeable layer. The preferential pathways due to settling of fill material and utility installation that occur in or under the floor structure, play an important role in establishing the radon mitigation approach.

(f) Description of sealing of the floor structure to the internal and external walls. The gap width between floor and internal/external walls, and materials of the floor and walls need to be noted. These parameters are important to plan for sealing of the gaps with an appropriate sealing technique. This sealing is often not present when initially inspecting the building.

(g) Year (or period) of construction of building and possible renovations or extensions to the original building; this data can often provide insight of typical construction practice of a given period. Often certain events like earthquakes or major floods may cause significant changes in building codes or practices affecting the ingress of radon into buildings.

(h) Estimated or measured airtightness of the building and description of windows and external doors. If the building is planned to be retrofitted to meet a specific energy standard, the airtightness of the building might be significantly altered. This can drastically affect the radon activity concentrations in the building.

(i) Location of the tunnels for utilities beneath the building, if present, and whether tunnels are closed at their ends, and if the tunnels are made of continuous material or made of modular elements with joints between the elements. Sometimes the tunnels are open at the pipe entry point in the boiler room.

(j) Location of the sewage pipes, including identification of sinks, floor sinks and other elements intended to collect wastewater. Location of any piping from the ground penetrating through the floor to the inside of the building.

(k) Location of the air exhaust or air supply vents, if any, and identification of the ducting and the point where internal air is released to the outside.

3.1.2. Diagnostic measurement

To properly design radon mitigation measures, additional information and measurements might be needed to understand the entry points of radon into building, and the volume of soil air entering the building.

Radon Entry points

Since no building is totally sealed from the ground, the common weak spots are presented for each of the following types of foundation:

(a) Concrete slab foundation;

(b) Basement;

(c) Crawl space.

A schematic drawing showing possible radon entry points into a dwelling is presented in Fig. 9.

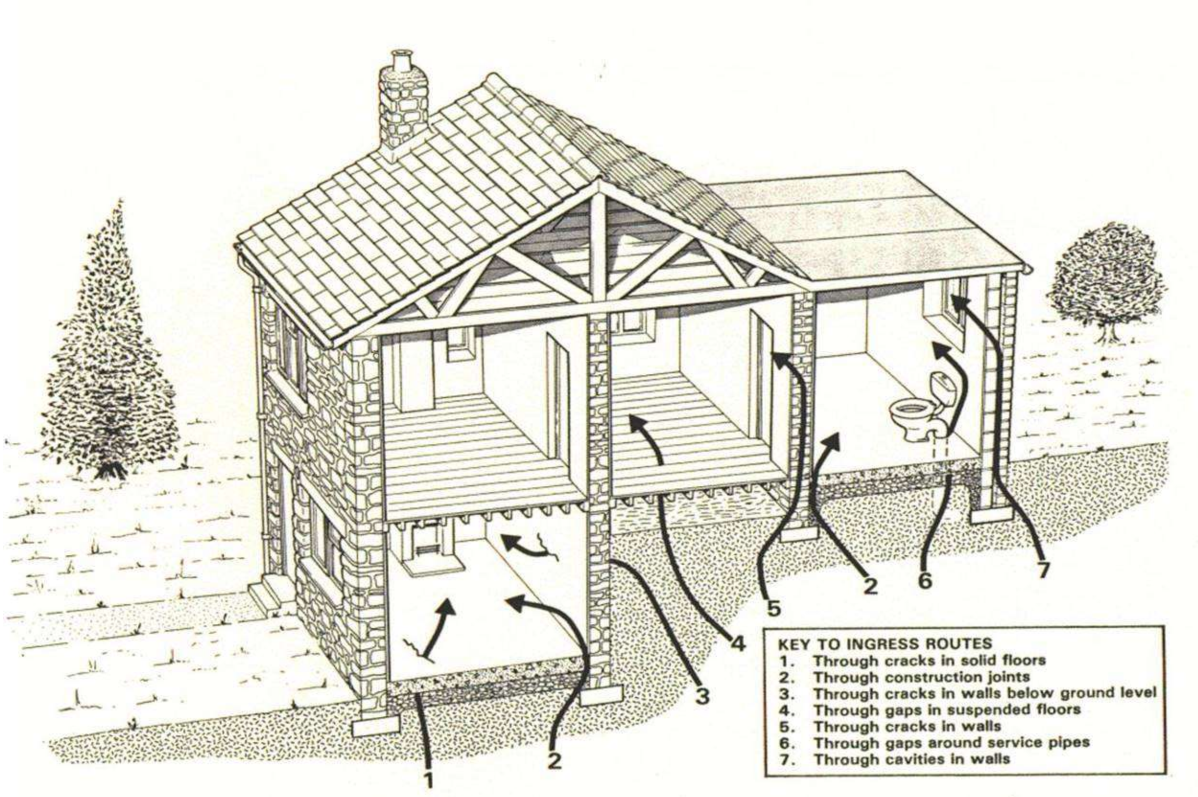


FIG. 9. Radon entry points (reproduced with permission of IHS Markit from Ref. [19]).

Concrete slab foundation

Most concrete shrinks when hardening, and the shrinkage creates gaps that become leakage points for soil air containing radon. The leakage points are:

(a) All floor connections against the wall construction when the slab is poured to the wall. This is also known as the floor-to-wall joint;

(b) All pipe and electrical installation penetrations through the concrete slab foundation;

(c) All floor slab against the pre-cast L-support. L-supports are mainly used as prebuilt die cast for the floating floor concrete and is a spot of radon leakage when the concrete hardens.

Basement

Basement with weight bearing footings and the concrete floor is cast afterwards are the weakest construction type against spots for soil radon entry. This is due to the concretes shrinking effect during its hardening. The house has many meters of this in each room of the basement:

(a) All floor connections against the wall construction when the slab is poured to the wall. This is also known as the floor to wall joint.

(b) All pipe and electrical installations through the concrete slab foundation.

(c) All floor slab against the pre-cast L-support.

Basement house with slab-on-grade construction

(a) All wall connections to the slab-on-grade floor;

(b) All pipe and electrical installation penetrations through the concrete slab foundation;

(c) All pipe and electrical installation penetrations through the concrete walls.

Crawl space

(a) All pipe and electrical installation penetrations through the floor construction.

Detection of radon entry points

The more important radon entry routes can normally be identified with a visual survey of the building. To help identify radon entry routes, an integrated radon measuring instrument with "sniffing" capability function can be used. However, the interpretation of results can prove difficult if individual areas of the building cannot be isolated. Radon measurements by *sniffer* detectors will be affected by the weather on the day of the survey and if the building has been or has not been closed over the previous 24 hours. The protocols in some countries necessitate that the building be closed for 24 hours prior to such measurements, while the protocols in other countries do not. Once a radon professional gains experience with visual surveys of buildings, and increase their understanding of building construction techniques, they need to rely less on the use of a radon sniffer detector.

Air intake, air exhaust, air pressure measurement

To measure the air intake rate and the air exhaust rate is essential to establish if the building is under-pressurized or over-pressurized. One way to determine the status is a measurement of airflows, done with an anemometer on the air exhaust and air intake diffusers. Most often a building is under-pressurized, which means that the building sucks in radon gas from soil air beneath the building through the leaking spots in addition to fresh outside air through its ventilation intake diffusers.

It may also be of interest to measure the radon concentration in the soil air beneath the floor of the building. This can be done by drilling a hole through the floor of about 8–10 mm size (the diameter depends on the probe, used) and measure the radon gas with an integrated radon measuring instrument. It is also an effective way to check the types of material underneath the building with an endoscope. This will also allow for the radon professional to determine whether the soil permeability is suitable for including a subfloor suction system in the mitigation solution.

Once the radon professional has enough data to compare the measured radon value in the building with the radon level in the ground under the building, together with the ventilation data, it will be possible to calculate how much soil air is entering the building from the ground every hour by using Eq. (3) (see Ref. [14]):

$$C_{house} = \frac{1}{(\lambda+n)*V} * C_{soil} * L \tag{3}$$

where

C_{house} = Measured radon concentration in the house (Bq/m^3)

C_{soil} = Measured radon concentration in the ground under the building (Bq/m^3)

λ = Radon decay constant

V = Volume of air in the house (m^3)

n = Air exchange rate (air exchange/h)

L = Volume of soil air entering the building per hour (m^3/h)

Two examples are provided to demonstrate the use of the equation to determine the volume of soil gas entering a house.

Example 1:

Assume the following parameters for the building:

Measured radon concentration in the house (C_{house})	500 Bq/m^3
Air volume of a house (V)	500 m^3
Air exchange rate ACH (n)	0.5/h
Measured radon concentration in soil under the building (C_{soil})	2 000 Bq/m^3
Radon decay constant λ	0.00755

The volume of soil air (L) entering the building per hour can be estimated by application of Eq. (4) (see Ref. [14]):

$$L = (C_{house} \cdot (\lambda + n) \cdot V)/C_{soil} \tag{4}$$

For the example, the calculated volume of soil air entering the building is

$$L = (500 * (0.00755 + 0.5) * 500) / 2\,000 = 63.4 \text{ m}^3\text{/h}$$

Once the soil air volume entering the building is known, one can start searching for entry points and understand what to do about the identified problem. In example 1, where 63.4 m^3/h of soil air enters the building, which is a lot of air, one can identify one major entry point is causing this large amount of soil air to entry to the building. That entry point can be, for example, an unsealed door to a crawl space or cellar.

In practice it is often lower airflow rates combined with higher radon concentrations in soil gas which are found entering a building, rather than those, demonstrated in example 1.

Example 2:

All parameter values are the same as in example 1, except for C_{soil}:

C_{soil} = 40 000 Bq/m^3.

In this case, the calculated volume of soil air entering the building is:

$$L = (500 * (0.00755 + 0.5) * 500) / 40\,000 = 3.2 \text{ m}^3\text{/h}$$

This calculation demonstrates that, for a given concentration inside the building, the higher the concentration of radon in soil, the lower the flow rate of air into the building, and less obvious leakage spots can be expected. The challenge of mitigation in example 2 is to find the leakage spot or spots where a flow of only 3.2 m^3/h enters the building. This is a very small amount of airflow, but due to the very high activity concentration of radon in the soil gas, it results in an activity concentration of 500 Bq/m^3 of radon in indoor air of the building.

Thermography

A thermographic camera can be a very useful tool in investigating leakage spots for ingress of radon into a building, especially in colder climate countries. The camera image shows the spots where cold ground air is entering the construction instantly and gives the radon professional a hint on where to perform the radon “sniffing”. This saves time and allows to avoid an unnecessary use of the radon instruments.

Blower door test equipment

This equipment can be used to establish the airtightness of a building. The test involves fitting a temporary fan and frame into the entrance door to the building, and either blowing air into (pressurizing) or drawing air out of (depressurizing) the closed building. In addition to calculating the airtightness of the building, by using tracer smoke when running the fan, the professional can visually see smoke passing through gaps in the structure. This gives an indication of the soil air entry points.

3.2. RADON MITIGATION SOLUTIONS

3.2.1. Depressurization of the soil

The basic principle employed in depressurization of the soil is to ensure that the pressure difference between the soil and the building is always negative. Specifically, the absolute pressure in the soil is lower than the absolute pressure in the building at all surfaces adjacent to the soil and also at all points where radon gas could enter the inside of the building (e.g. floor sinks, piping penetrations, cracks).

In general, the depressurization of the soil approach is deemed to be most robust and successful compared to other approaches. However, soil depressurization might increase heat losses from the building. Nonetheless, with proper system design (i.e. minimizing necessary airflow from the soil to the outside) this effect can be minor. Active soil depressurization also necessitates the use of a fan, consuming electrical power. With proper design, the consumed power can be kept well below 1 to 5 kWh/day[2] depending of the size of the fan used. Although the approach to mitigation using soil depressurization could be done using either as active or passive system, only active system is addressed here. Passive depressurization is prone to many different factors affecting its effectiveness. Passive systems always have to be designed in such a way that adaptation to an active system is possible and simple. In that sense the active system can be seen as a passive system, upgraded with active soil ventilation (depressurization). Currently there is much less data on the effectiveness of passive systems.

Active soil depressurization (ASD)

Active soil depressurization consists of the following elements:

- Permeable layer;
- Suction point(s);
- Exhaust;
- Sealing;
- Fan;
- Operation and monitoring system.

A sufficiently permeable layer is needed to allow the pressure field extension[3] and to allow the radon gas to flow from the point of higher pressure (soil) to the point of lower pressure (suction point). This layer could be a layer of permeable gravel, a layer of corrugated plastic, or a layer of air below an air-tight membrane. An understanding of the composition of the air permeable layer is an important input to the design of the configuration of the ASD system.

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[2] This electrical fan consumption value assumes good sub-slab/soil communication/pressure field extension.

[3] Pressure field extension refers to the effective area with lower soil gas pressure (i.e. effective area that has been depressurized).

One or more suction points may be needed. There are different techniques to collect radon (radon pit, drain tiles, sumps or air voids under a membrane) at the suction point. The section point is directly connected to the suction pipe, so that radon, collected from a certain area (size of pressure field extension) is drawn through the suction pipe to outside the building. The number of suction points necessary depends upon each individual building e.g. permeability of the layer, footprint area of the building. However, through careful planning and execution it is usually possible to reduce the number of suction points to a few or even only one. Experience in the UK has shown that a single suction point will typically have an influence over an area of 250 m^2 and a radius of 9 m [20].

The ASD system may have several different configurations:

(a) Sub-slab depressurization (SSD);
(b) Drain-tile depressurization (DTD).

The basic approach of the SSD and DTD systems is to create negative pressure under the existing ground concrete slab(s). A schematic representation of these two systems is presented in Figs 10 and 11.

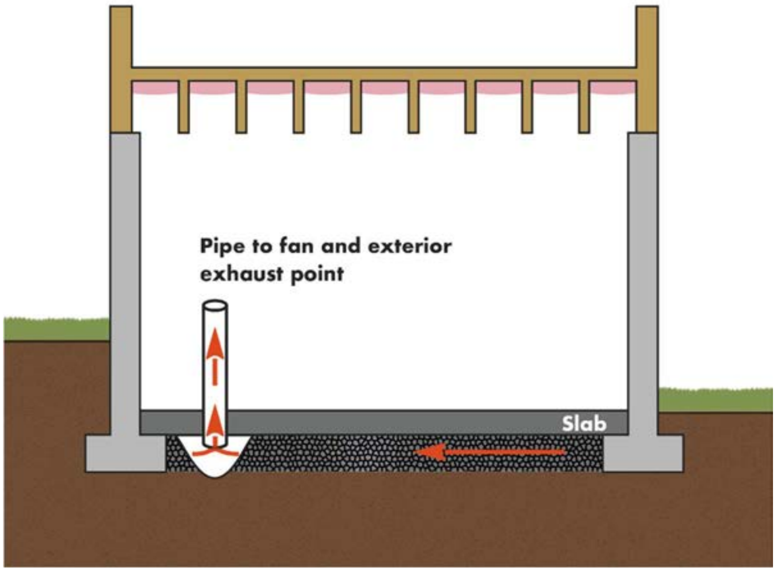

FIG. 10. Sub-slab depressurization system [21]. Copyright 2020 AARST.

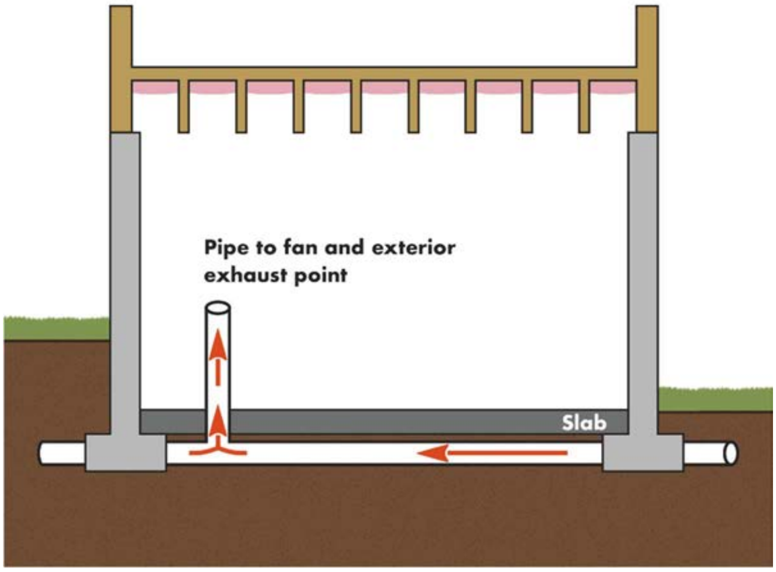

FIG. 11. Drain-tile system [21]. Copyright 2020 AARST.

These two configurations of the ASD system contain similar elements which are described in more detail below.

In order to ensure correct functioning of the SSD system, a sufficiently permeable layer needs to be available beneath the slab-on-grade. Prior diagnostics in the building will define the size of the negative pressure extension. Ideally, if a continuous layer of clean gravel a few centimetres thick is found beneath the slab, and if the layer extends across the whole area intended to be mitigated with a single suction point, it can be assumed the layer is sufficiently permeable.

If the DTD system is used, the drain tile is placed in a trench that is filled with permeable material. The function of the permeable layer is ensured through the drain-tile in direct contact with the soil air. It can be assumed that the negative pressure field extends over the whole surface of drain-tiles.

In the SSD system, soil gas containing radon migrates along the pressure difference towards the point of lowest pressure induced by the SSD system i.e. the suction point. To enhance radon gas collection, suction pits are constructed beneath the slab at the suction point(s). Suction pits are essentially voids of sufficient volume. A minimum size of 0.01 m^3 is necessary. However, larger pits are recommended, ranging from 0.03 m^3 to 0.05 m^3. These provide a larger wall area and enhance the effectiveness of radon-gas extraction.

Locating the suction pits along known preferential pathways is important. These pathways usually exist near utility tunnels and along footing lines. Regardless of where the suction pits are located, there needs to be a knowledge of localized air leaks (weaknesses) into the radon system. Any air leaks from the indoor air into the ADS need to be sealed. If the air leaks cannot be reasonably sealed, then the suction pits need to be relocated.

In the DTD system, there is no need for a special pit. The whole void of the drain-tile assumes the function of a pit.

The piping used in SSD and DTD systems need to be designed in a way that it does not introduce significant airflow resistance. A minimum diameter of 100 mm is recommended in the case of single-family houses and 150 mm in the case of larger buildings.

The material for piping is country dependent. PVC piping is commonly used. The piping has to be durable and impact resistant. The piping may be designed in a way that the material of the piping changes (e.g. PVC to iron).

The design of the piping needs to ensure a continuous downwards slope of approximately 1 cm fall per 1 m of length to prevent creating unintentional water traps in the piping system. If this is not possible appropriate methods for maintaining obstruction-less airflow through the piping need to be employed.

The openings around the SSD and DTD suction pipes need to be sealed in a durable and permanent manner. At the penetration point taking the suction pipe through the floor, the gap between the pipe and the floor structure needs to be sufficiently wide to permit the sealant to flow into the gap, but sufficiently narrow to enable efficient sealing. A gap width between 10 and 15 mm is recommended.

The sealing needs to be done using a durable sealant compatible with all materials it comes in contact (e.g. PVC, concrete, polyethylene)[4]. The sealant has to provide a durable, permanently elastic seal. If necessary, surfaces may need to be treated with primer, depending on selected sealant.

The surfaces need to be clean and sufficiently firm. The gap has to be first prefilled with backer rod or comparable material to ensure the correct shape of the seal. After the backer rod is inserted, the sealant is applied. After the sealant has cured, further work can be done on radon system piping.

The fan is intended to induce the pressure difference in the system. Issues that need to be considered in selection of the fan and positioning of the fan are described in the Appendix. Examples of different pipe routes and location of exhaust fans and roof level exhaust for building with sub-slab depressurization are presented in Figs 12, 13, 14 and 15.

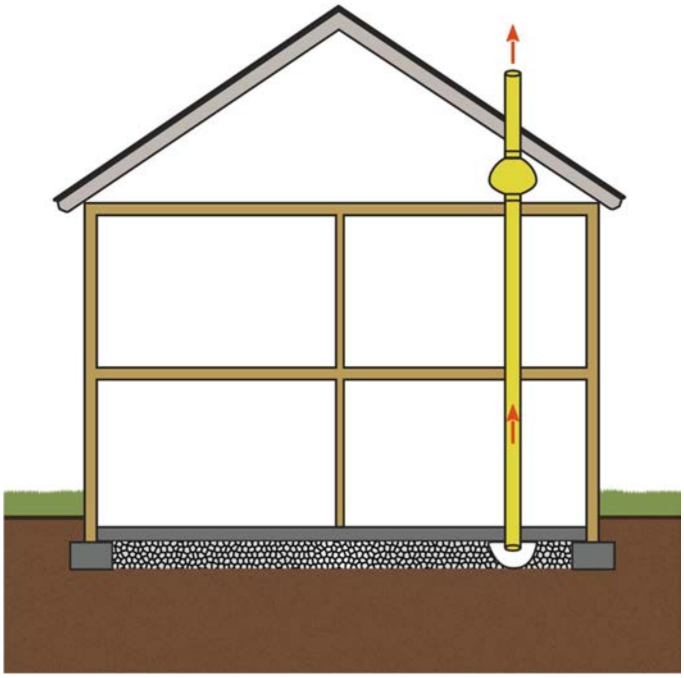

FIG. 12. Sub-slab depressurization with internal fan in ceiling and roof level exhaust.

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[4] Polyurethane based sealants may provide required properties.

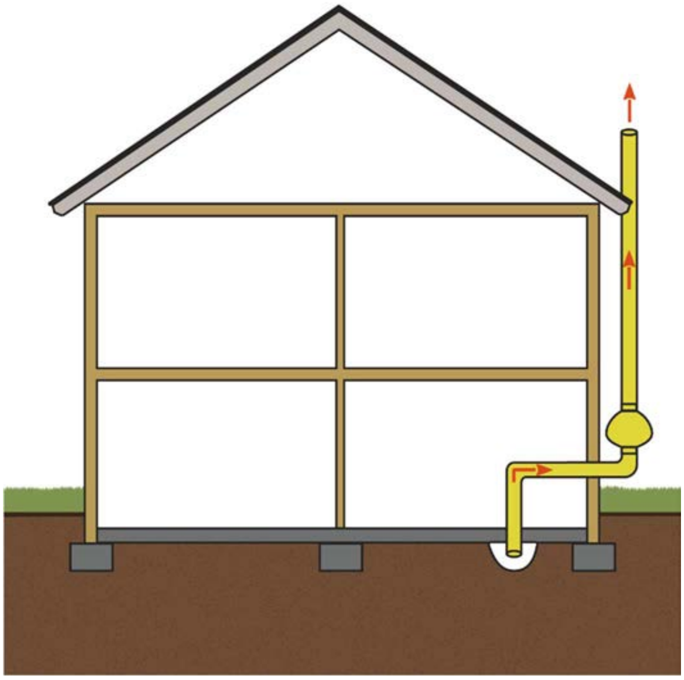

FIG. 13. Sub-slab depressurization with fan external to building and roof level exhaust.

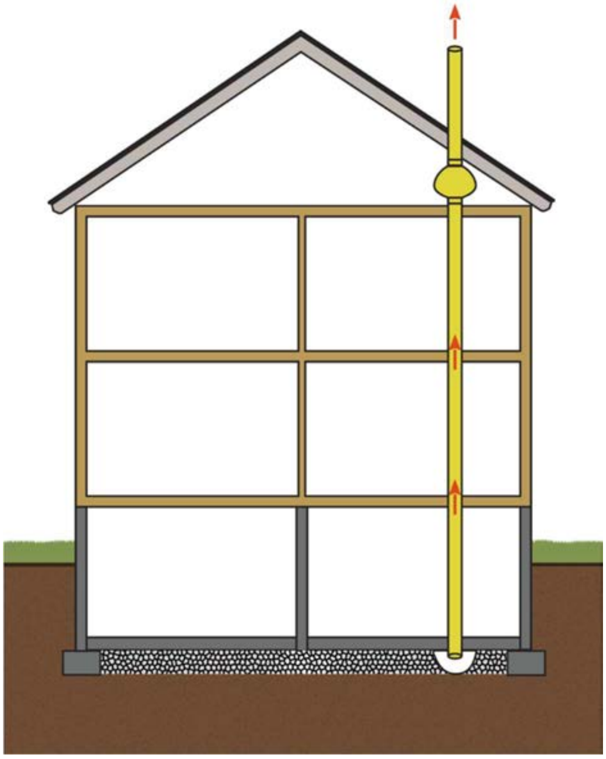

FIG. 14. Sub-slab depressurization with internal fan in ceiling and roof level exhaust from building with basement.

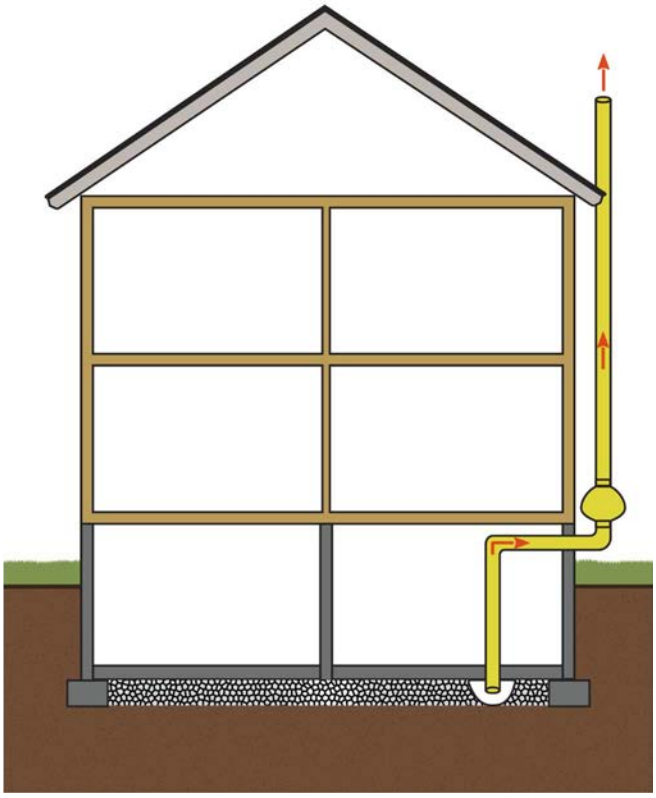

FIG. 15. Sub-slab depressurization with fan external to building and roof level exhaust from basement.

With smaller buildings, such as houses where there is a space around the building, it is possible to core drill through the foundation to form a suction point at the edge of the floor and connect it to a fan with a low level exhaust. The exhaust outlet has to be located where it will not be a nuisance. Whilst a measurement of the radon level at the outlet will be very high, within a few metres of the outlet the gas will be dispersed. A schematic drawing of such a system is presented in Fig. 16. A photograph of the exhaust outlet is presented in Fig. 17. This design may not be allowed in some countries. It is strongly advised to measure radon in the living areas adjacent to the exhaust location to determine if radon is re-entering the building.

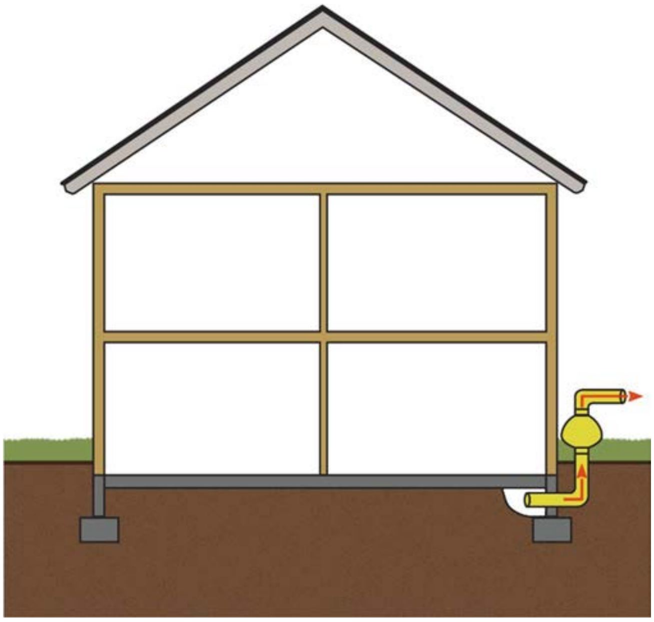

FIG. 16. External sub-slab depressurization low level exhaust.

FIG. 17. Example of a low level exhaust [20].

The operation of the system needs to be monitored continuously via an audible or visual pressure device. The owner of the building and/or building maintenance company representative needs to be provided with drawings of the system and a written operational manual.

Sub membrane depressurization (SMD)

The basic approach of the SMD system is to create negative pressure under a membrane. This design is used in cases where there is either no slab on the ground or the upper layer of the ground is permeable to an extent that prevents effective pressure field extension. It is also used in mitigating radon in buildings with crawl spaces. A schematic diagram of a sub-membrane depressurization system is shown in Fig. 18.

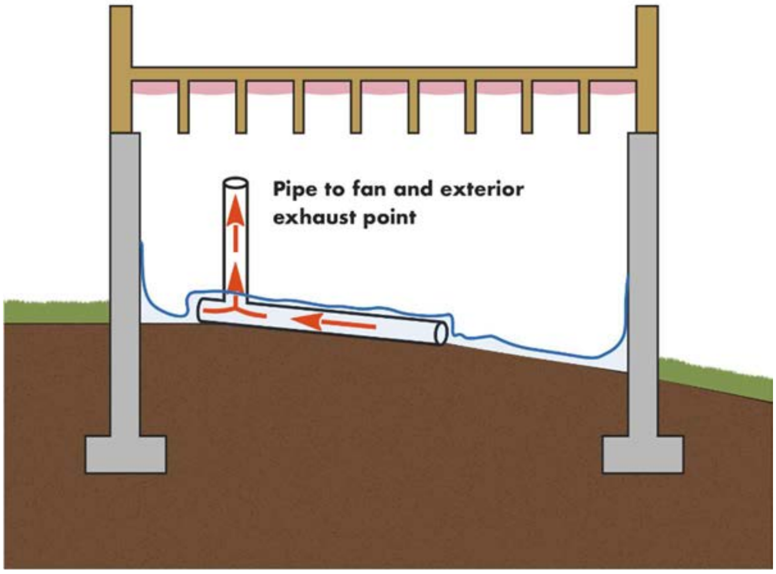

FIG. 18. Sub-membrane depressurization [21]. Copyright 2020 AARST.

The SMD system consists of the following elements:

- Membrane;
- Permeable layer;
- Suction point;
- Perforated pipe and suction pipe;
- Sealing;
- Exhaust;
- Fan;
- Operation and monitoring system.

Membranes used for sealing crawl spaces has to be durable and sealed airtight to stop any soil gas entry into the structure. Membrane pieces need to be overlapped by 300 mm and sealed to one another in a permanent airtight manner.

There are numerous membrane manufacturers providing a wide range of appropriate membrane products that can be used as insulating barriers for radon barriers [22]. Membrane strength and ease of installation are more important than thickness. The membrane has to be strong enough to take rough handling during the construction phase. Thicker materials can prove more difficult to use than thinner materials when it comes to folding, cutting and sealing.

A permeable layer is formed between the membrane and the ground. In order to enhance the pressure field extension a perforated drainpipe needs to be installed at the end of the suction pipe, penetrating the membrane. The perforated drainpipe needs to be connected to the suction pipe (e.g. using a “T” or “L” piece). It is recommended that the length of the perforated drainpipe is 3 m or more, and that the diameter of the perforated drainpipe is same as the diameter of the suction pipe.

The suction point is formed with the connection of the perforated drainpipe to the suction pipe (see Fig. 18).

The piping used in an SMD system is designed in a way that it does not introduce significant airflow resistance. A minimum diameter of 100 mm is recommended in the case of single-family houses and 150 mm in the case of larger buildings.

The material for piping is country dependent. PVC piping is commonly used. The piping needs to be durable and impact resistant. The piping may be designed in a way that the material of the piping changes (e.g. PVC to iron).

The piping has to be designed with a continuous downwards slope of approximately 1 cm fall per 1 m length to prevent building unintentional water traps in the piping system. If this is not possible appropriate methods for maintaining obstruction-less radon-gas flow through the piping has to be employed.

Penetration of the suction pipe through the membrane is durably sealed. The connection follows the principles of sealing the foils on roof for waterproofing. Membranes used for sealing crawl spaces has to be durable and sealed airtight to stop any soil gas entry into the structure. Membrane pieces need to be overlapped by 300 mm and sealed to one another in a permanent airtight manner. Crawl space membranes also need to be sealed in a permanent airtight manner to the building foundation walls, interior foundation supports, utility penetrations and any other penetrations through the membrane. The sealing material needs to be compatible with the surfaces it comes in contact. The sealing needs to be inspected upon completion to ensure high level of airtightness to ensure that any further radon reduction steps are successful.

The sealant has to provide a durable, permanently flexible seal. If necessary, rough surfaces has to be treated so that they are smooth, and then coated with appropriate primer, for the selected sealant.

The fan is intended to induce the pressure difference in the system. Issues that need to be considered in selection of the fan and positioning of the fan are described in the Appendix.

Examples of different pipe routes and location of exhaust fans and roof level exhaust for building with sub-slab depressurization are presented in Figs 19 and 20.

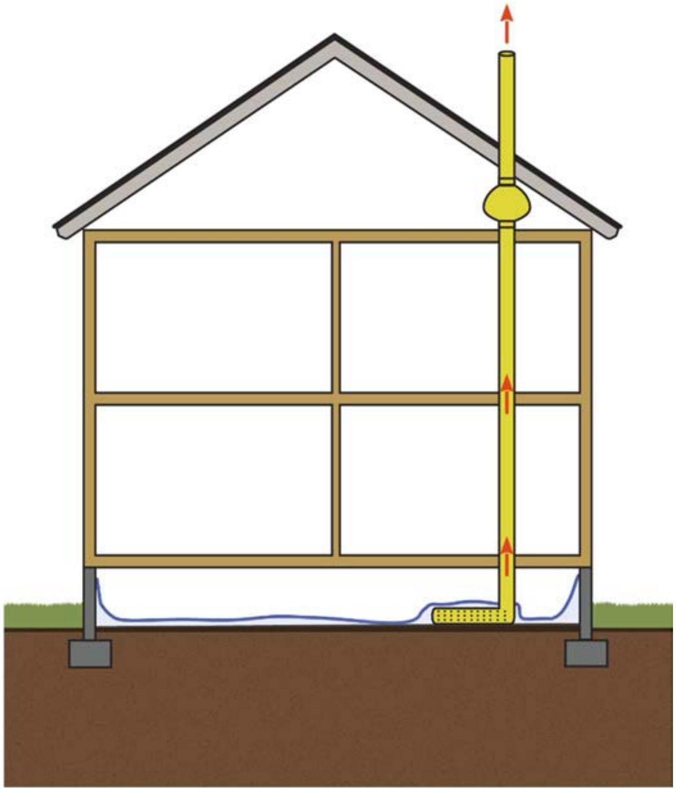

FIG. 19. Sub-membrane depressurization with internal fan and roof level exhaust.

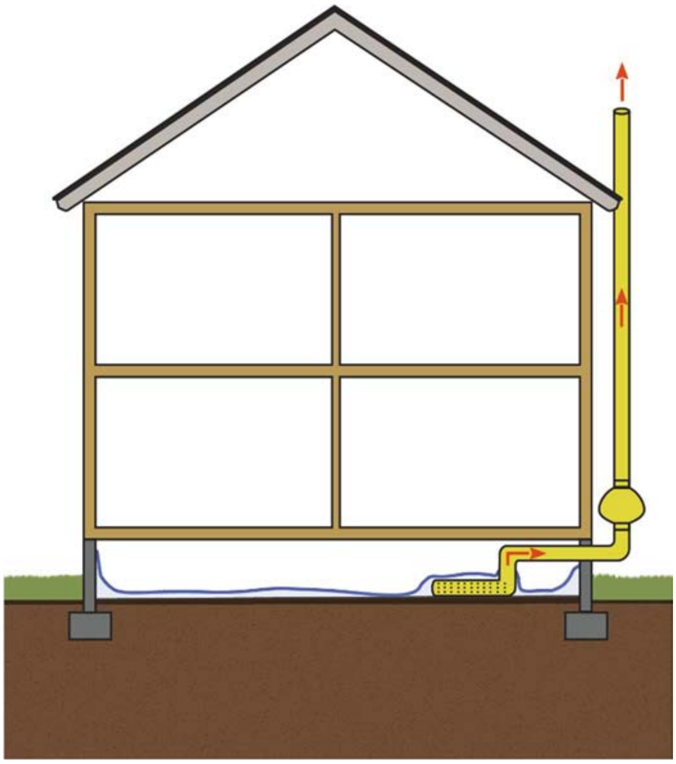

FIG. 20. Sub-membrane depressurization with external fan roof level exhaust.

Baseboard depressurization system (BBD)

The basic approach of the BBD system is creation of negative pressure in the cavity running along the inside perimeter of the concrete slab floor. A schematic drawing of a BBD system is shown in Fig. 21.

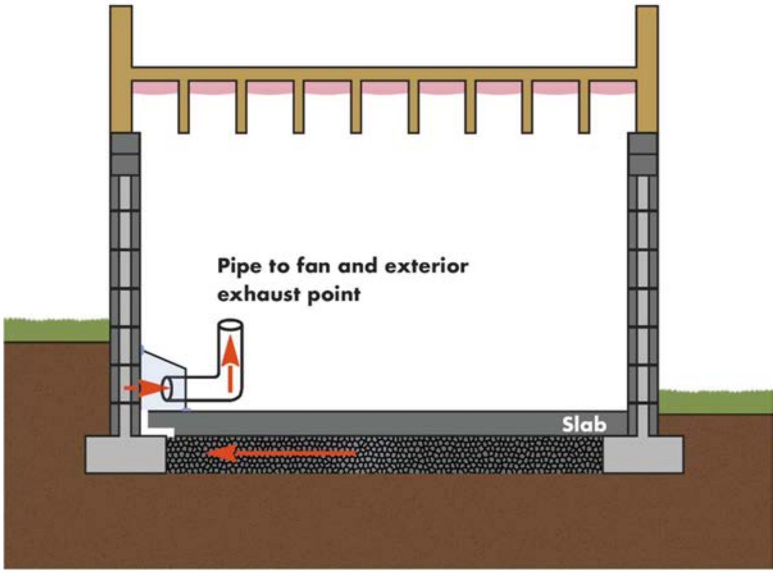

FIG. 21. Baseboard depressurization [21]. Copyright 2020 AARST.

The BBD system consists of the following elements:

- Radon collection;
- Suction point;
- Piping;
- Sealing;
- Fan;
- Exhaust;
- Operation and monitoring system.

In the BBD system, radon gas is collected at the block element running at the perimeter of the walls. The blocks are connected to the sump, usually via PVC drain. In the system radon is collected at the wall perimeter as well as in the sump.

The suction point is connected to the sump. The collection pipe penetrates the sump lid. Due to restricted access to the sump pump, once the lid is sealed and the suction pipe installed and sealed, the use of the sump may not be adequate solution. References [20, 21] provide further details on sealing sump lids and on the use of sump pumps.

The piping used in an BBD system needs to be designed in a way that it does not introduce significant air-flow resistance. A minimum diameter of 100 mm is recommended in the case of single family houses and 150 mm in the case of larger buildings.

The material for piping is country dependent. PVC piping is commonly used. The piping has to be durable and impact resistant. The piping may be designed in a way that the material of the piping changes (e.g. PVC to iron).

The piping has to be designed with a continuous downwards slope of approximately 1 cm fall per 1 m length to prevent building unintentional water traps in the piping system. If this is not possible appropriate methods for maintaining obstruction-less radon-gas flow through the piping has to be employed.

The openings around the BBD suction pipe need to be sealed in a durable and permanent manner. At the penetration point, the gap between the pipe and the wall structure has to be sufficiently wide to permit the sealant to flow in the gap, but sufficiently narrow to enable efficient sealing. Gap widths between 10 and 15 mm are recommended.

The sump lid has to be sealed at all locations that surround the hollow void network in order to maximize the suction effectiveness.

When fixing the pipe to the wall special care has to be taken not to introduce holes in the block wall that would penetrate to the voids. If this cannot be ensured, all fixing screws have to be sealed.

The fan is intended to induce the pressure difference in the system. Issues that need to be considered in selection of the fan and positioning of the fan are described in the Appendix.

Block Wall Depressurization (BWD)

The basic approach of the BWD system is the creation of negative pressure in the block walls installed as the basement foundation walls. A schematic drawing of the BWD system is shown in Fig. 22.

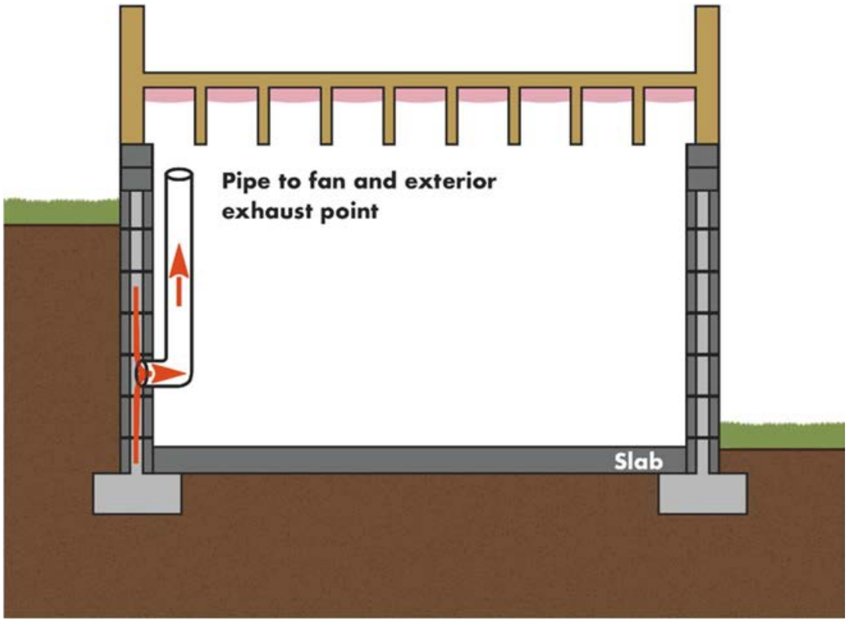

FIG. 22. Block wall depressurization [21]. Copyright 2020 AARST.

The BWD system consists of the following elements:

- Radon collection;
- Suction point;
- Piping;
- Sealing;
- Fan;
- Exhaust;
- Operation and monitoring system.

In BWD designs, radon gas is collected within the cores of the concrete blocks that comprise the foundation walls of the building. Although not a common mitigation technique, it has been shown to be a suitable radon reduction solution. Since many, or sometimes all of the hollow cores of the concrete blocks are connected to one another, drawing negative pressure from the block cores can reduce the radon in a building. This method is mostly used in conjunction with other mitigation techniques (SSD or SMD).

When BWD is used, it is important to seal the cores of all top blocks to avoid large air leaks of air from inside the building into the radon system. In addition, builders often fill some block cores for structural support so multiple suction points throughout the building may be necessary to achieve radon reduction. All these suction points can be properly sized to allow only the necessary amount of airflow. Pressure field diagnostics on the block walls would be needed to determine how much airflow each suction point would need to successfully apply the necessary pressures to lower the radon in the structure.

The suction points are connected to one or multiple collection pipes ultimately connected to a radon fan. The collection pipe(s) penetrate the concrete block and terminate in the hollow core of the block. Each suction point is sealed in an airtight and permanent manner like all radon suction points.

The piping used in a BWD system is designed in a way that it does not introduce significant air-flow resistance. Diagnostics determines how much airflow will be needed from each section of a BWD system to achieve adequate pressure field extension. This will aid in determining pipe size for each section of the system.

The material for piping is country dependent. PVC piping is commonly used. The piping has to be durable and impact resistant. The piping may be designed in a way that the material of the piping changes (e.g. PVC to iron).

The tops of all open block cores need to be sealed. The openings around the BWD suction pipe(s) need to be sealed in a durable and permanent manner. When fixing the pipe to the wall, special care has to be taken not to introduce holes in the block wall that would penetrate to the voids. If this cannot be ensured, all fixing screws have to be sealed.

The fan is intended to induce the pressure difference in the system. Issues that need to be considered in both selection and positioning of the fan are described in the Appendix.

3.2.2. Pressurization

Building pressurization

Building pressurization is closely connected to the functioning of the mechanical ventilation system, and this system for radon mitigation is only applicable in buildings with mechanical ventilation systems (see Section 2.3.3). The pressure inside the building is controlled by mechanical ventilation. It is essential that the pressure in all rooms is balanced.

Typically, pressurization is achieved with feeding excess fresh air into the building, while at the same time, balancing air supply and exhaust. There are many manufacturers who offer positive ventilation fan units to reduce problems caused by high humidity in buildings. The problems that might occur include mould, condensation and poor air quality. These units provide trickle ventilation into the house creating a very slight positive pressure and improved ventilation. They are widely used in areas of high humidity to both improve indoor environment and can also reduce indoor radon[5].

A schematic drawing of a positive building pressurization system is shown in Fig. 23.

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[5] Pressurizing large buildings may prove to be difficult to balance at all times. For this reason, the pressurization of buildings in practice has limited applicability. When considering pressurizing buildings, special care needs to be given to building envelope airtightness. Also, in large buildings with high user influence (opening the windows or doors, e.g. in schools) automatic adaptable air feed to individual rooms may be necessary. Furthermore, in pressurizing buildings special consideration needs to be given to the moisture flow from the internal air (it may have higher absolute humidity than the outside air) towards the building envelope.

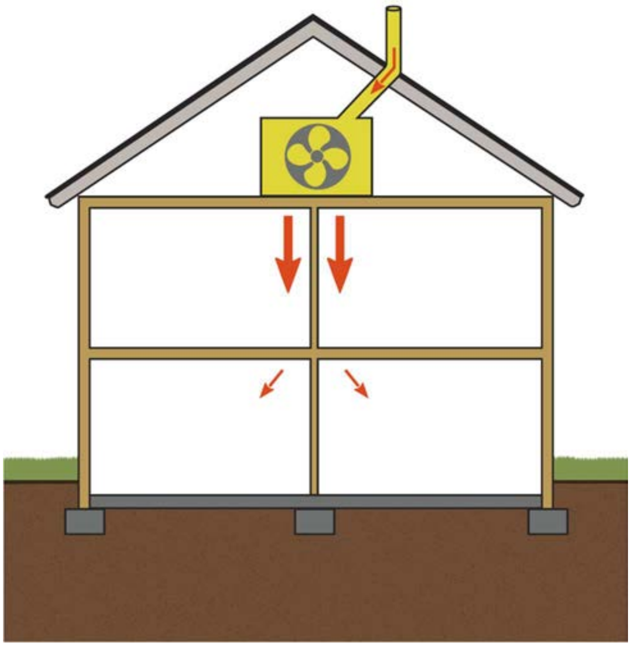

FIG. 23. Positive ventilation unit [23].

Sub-slab pressurization (SSP)

Sub-slab pressurization is essentially the same system as the SSD system, but the direction of the airflow is reversed. The important differences are described below.

The air supply is usually from the external outdoor air. If indoor air is used, care needs to be taken so as to not under pressurize some rooms in the building, as this could induce suction of radon rich air from under the building into these rooms.

When external outdoor air is used, care needs to be taken so as not to excessively cool the floor structures.

Instead of the suction point, a pressurization point is introduced. This point and the pit are technically the same as in an SSD system.

The fan of the system is located close to the pressurization pit in order to minimize the length of over pressurized pipes in the building.

The connections of the pipes to the fan and to the penetration (pressurization) point need to be carefully sealed. If there is a leakage of air at any of these connections, then the system will fail to over pressurize the sub-slab area.

All leakage points in the floor have to be carefully sealed, as any leak might allow radon rich soil air to enter into the building.

As the system will pressurize the sub-slab area, there is no need for an exhaust pipe.

The SSP systems work best where the sub-soil is highly permeable.

The downside of these systems is that, in extreme cold weather, they can freeze the foundations.

Block wall pressurization (BWP)

Block wall pressurization system is essentially the same as the BWD system, except the airflows are reversed.

The air supply is usually from the external outdoor air. If internal air is used, care needs to be taken so as not to under pressurize some rooms in the building, as this could cause suction of radon rich air from under the building into these rooms.

If external air is used, care needs to be taken so as not to excessively cool the concrete block wall.

Instead of the suction point, a pressurization point is introduced. The point and the pit are technically the same as in a BWD system.

The fan of the system needs to be close to the pressurization pit in order to minimize the length of over pressurized pipes in the building.

Special care needs to be taken to sealing the connections of all pipes between the fan and the penetration (pressurization) point.

The walls and core of the top block needs to be very carefully sealed as any leak might introduce radon rich soil air into the building.

Crawl space ventilation (CSV)

The basic approach for radon mitigation in buildings with crawl space foundations is either to ventilate the crawl space, or to install a sub-membrane depressurization (SMD) system. Where radon levels within the building are only just above the national radon reference level, the first step is to ensure that the crawl space is adequately ventilated. Original ventilation grilles may have become obstructed over time. The building may sometimes need additional ventilation grilles to adequately ventilate the crawl space to reduce the radon levels in the building. If the building has a timber floor, all significant gaps and cracks in the floor need to be sealed. An impermeable membrane is not be used, as it could result in some of the timber floor rotting.

A schematic drawing of crawl space ventilation is shown in Fig. 24.

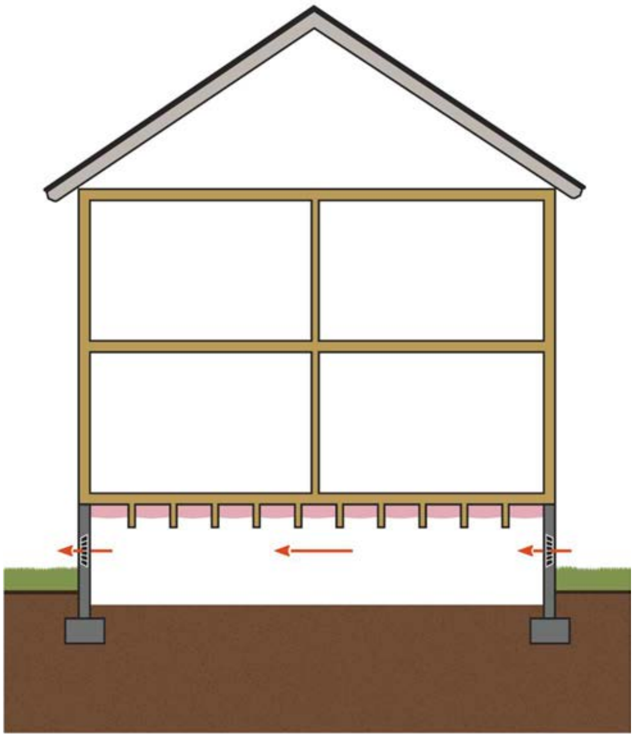

FIG. 24. Crawl space ventilation.

In buildings where the radon levels are significantly greater than the national reference level, and where there is no capping over the soil, the crawl space can be ventilated using a fan. However, using a fan, whether operating in positive or negative pressure, may have an adverse impact on indoor comfort, particularly during winter. Crawl space ventilation will alter temperatures in the crawl space. It is therefore necessary to consider whether there is sufficient thermal protection of the structure both with respect to heat losses and with respect to thermal bridges. It may be necessary to add thermal insulation of substantial thickness to the underside of the floor and to service pipes.

3.3 MITIGATION OF RADON EMITTING FROM CONSTRUCTION MATERIALS IN BUILDINGS

The options for mitigating an existing building with all or components of walls, structural framing or foundations made of construction materials that contain elevated levels of ^{226}Ra are limited to the following:

(a) Removal or replacement of the construction material containing elevated levels of ^{226}Ra. This would be a preferred option if it is possible to access the material (such as removal of internal decorative stone panels). However, if the material is embedded within the building structure (concrete foundation or structural framing), then this method is unlikely to be either a practical or an economical option;

(b) Ventilation of affected parts of the building;

(c) Ventilation between the layers of construction materials;

(d) Ventilation of the whole building.

Whilst ventilation has been used successfully to reduce indoor radon emanating from construction materials, it is essential when mitigating a building that the mitigation professional fully understands the building, its indoor radon level, how it was built, how it was originally ventilated and heated, and the way in which the building is used.

All these parameters are important to make a decision on the most appropriate solution, so that (a) the energy costs for heating are kept at an acceptable level, (b) the ventilation system is quiet, (c) the ventilation system does not adversely change the indoor humidity, and (d) the installation costs are economically acceptable.

Other approaches have been attempted over the last 30 years. These include trying to seal the radon emitting construction material with membranes, wall plaster/render, floor screed, liquid applied coatings, and radon wallpapers. Few of these solutions have proven successful in reducing radon levels, partly due to the difficulty of installing the sealing system, but also due to the disruption and excessive cost.

4. MITIGATION OF EXPOSURES FROM RADON RELEASED FROM THE WATER SUPPLY

If water containing dissolved radon is used in the household, it can be a source of elevated radon levels and sometimes very high concentrations of indoor radon. This is primarily an issue for buildings where the water supply is drawn from a private borehole in an area enriched with radium in the bedrock. Water from local water companies is usually sufficiently aerated in the storage, preparation and distribution process.

When water leaves a pressurized pipe, some of the dissolved radon gas in the water becomes airborne and contributes to the indoor radon concentrations. Dissolved radon in water can also become airborne during heating and splashing of water indoors (cleaning and cooking). The finer the water is divided, i.e. the smaller are the drops, and exposed to the air, the more of the dissolved radon gas can become airborne. Thus, radon concentration resulting from the household water will be highest in the kitchen, laundry room and in the bathroom.

As a rough indication of the household's water contribution to the radon concentration in a relatively small indoor space, it is a generally accepted that 1 000 Bq/l of radon in the water contributes to 100–200 Bq/m^3 of radon in indoor air, if the water consumption is 1 m^3/day [24].

The formula for the calculation of radon exhalation from the water into a building is given by Eq. (5):

$$C_v = \frac{C_W}{24\,.\,(\lambda+n)\,.\,V} \sum_i e_i\,.\,W_i \tag{5}$$

where

C_v = Radon contribution from household water usage to indoor air, Bq/m^3

C_w = Radon concentration in the water, Bq/m^3

λ = Radon decay constant, 0.00755 h^{-1}

n = Air exchange in the building, h^{-1}

V = Building volume, m^3

W_i = Volume of water used daily for purposes, m^3/day

e_i = Share of radon that merges into the indoor air, see Table 1.

TABLE 1. RADON EMANATION FROM HOUSEHOLD WATER USE TO INDOOR AIR [25]

Use (i)	Radon emanation to indoor air (e_i), %
Shower	60–70
Bath	30–50
WC	30
Laundry	90–95
Dishwashing	95
Drinking water	10–45

To solve a radon problem caused by the household water supply, the water can be aerated before it is used. The aeration system has to be of sufficient capacity to handle all the household daily water demand. Typically, the aeration system will need to have 200 litres of aerated water available for use.

Several technical solutions are currently available on the market that have been proven efficient. They are generally known under the category radon aeration system. The principle of the system is to agitate the radon laden water so that the radon gas is safely off gassed before the water is allowed entering the buildings water system.

However, caution is necessary where the system is placed. Radon released in process of aeration, has to be promptly removed from the space so it will not enter the indoor air of the building and cause an elevated level of radon. There are indications of new systems entering the market, which utilizes the aeration of radon gas at the well head, which, if proven functional, could also be a good solution.

5. RADON PREVENTION STRATEGIES IN NEW BUILDINGS

There are a several preventive measures that have been successfully used to prevent ingress of radon into new buildings. Preventive measures for new buildings are generally implemented through national building codes. Examples of such building codes are provided in Table III-1 of SSG-32 [10]. The national building authority may also specify whether the preventive measures are required in all new buildings, or whether they are only used in particular regions of the country that have elevated average levels of radon in buildings.

The main types of preventive measure are: (a) inclusion of a continuously impermeable membrane designed to isolate the building from the ground over the whole floor area of the building, and (b) the provision of soil depressurization or subfloor depressurization of the building. At the same time, it is important to seal all possible entry paths through a concrete slab floor into the building.

5.1. SEALING

Pipes and other utility penetrations through the slab need to be sealed in a permanent airtight manner. The sealing material has to be compatible with the surfaces to which it is applied. This sealing needs to be inspected upon completion to ensure the airtightness of the building, which is a precondition that any further radon mitigations steps to be taken will be successful.

All cracks, joints, and openings in the concrete slab need to be sealed in a permanent airtight manner. The sealing material needs to be compatible with the surfaces to which it is applied. Openings greater than 13 mm in width need to be pre-filled as needed with backer rod or comparable material prior to applying any sealant. This sealing needs to be inspected upon completion to ensure appropriate airtightness is achieved so as to ensure that any further radon mitigation steps to be taken will be successful.

5.2. MEMBRANES

There are many different types and thicknesses of membrane for use in radon mitigation in the construction of new buildings. These membranes are installed beneath poured concrete slabs for two reasons. First, the membrane holds the concrete in place while it cures so the concrete does not fill the permeable gravel layer. Secondly, the membrane can assist in bridging any future cracks that occur in the concrete after all the pertinent sealing has been done. It is not important for the membrane under a poured slab to be airtight nor does it need to be very thick as long as the slab cracks and penetrations above the slab are sealed. Having said that, some countries, like Ireland, do ensure that there is a fully sealed membrane beneath the slab across the full footprint of the building as additional protection.

Membranes used for sealing crawl spaces need to be durable and sealed airtight to stop any soil gas entry into the structure. Membrane pieces need to be overlapped by 300 mm and sealed to one another in a permanent airtight manner. Crawl space membranes also need to be sealed in a permanent airtight manner to the building foundation walls, interior foundation supports, utility penetrations and any other penetrations through the membrane. The sealing needs to be inspected upon completion to ensure high level of airtightness to ensure that any further radon reduction steps are successful.

5.3. ACTIVE AND PASSIVE DEPRESSURIZATION

The basic components needed to provide for passive depressurization, and provision for future active sub-slab depressurisation (if it proves necessary) in a new building are:

- Electric power outlets and sockets,
- Permeable layers,

- Vent pipes,
- Roof vent, vent hood and pipe connections,
- Sealing and membranes,
- Fan,
- Operation monitoring.

A schematic drawing of radon prevention strategies for a new building is shown in Fig. 25.

An additional electrical socket might need to be installed near the vent pipe where a future fan may be placed. This power supply will be in position to use if the passive depressurized system needs to be activated, by adding a radon fan, in the future. The preferred placement of a radon fan is outside the building so that all internal pipe work is kept in suction, to prevent leakage of radon inside the building.

A uniform layer of clean permeable aggregate, of a minimum 100 mm thickness needs to be spread under all areas within the building's foundation walls. For example, the aggregate might consist of material that will pass through a 50 mm sieve and be retained by a 6 mm sieve. Experience suggests that as long as there is some permeability, river pebble, crushed rock or recycled fill materials work equally well.

An alternative method using a uniform layer of sand, native or fill, with a minimum thickness of 100 mm, overlain by a layer or strips of geotextile drainage matting designed to allow the lateral flow of soil gases may also be used. Other materials, systems, or floor designs may be used if the material, system, or floor design is professionally engineered to provide depressurization under the entire membrane.

The vent pipe runs vertically through the building and the roof, directing the soil gases to the outdoors. The vent pipe is a minimum 75 mm to 100 mm diameter pipe that is connected to the "T" in the gas permeable layer. If the building has a sump pit or drain-tile system, the vent pipe can be inserted directly into the sump pit or connected to the drain-tile.

(1) Single vent pipe. The vent pipe is fully sealed at all joints to ensure that the pipe work is airtight and extends up from the radon collection point to a point terminating a minimum of 300 mm above the roof. The vent pipe needs to be located at least 3 metres away from any window or other opening into the heated spaces of the building. Vent pipes routed through unheated spaces need to be insulated so that the air temperature in the pipe does not change significantly. Vent pipes within the envelope of the building need not be insulated for temperature and condensation reasons but may need insulating for noise reduction.

(2) Multiple vent pipes. In buildings where interior footings or other barriers separate the gas-permeable material into two or more areas, each area needs to be fitted with an individual radon mitigation system in accordance with point (1) above or connected below the floor level to a single radon gas vent pipe terminating above the roof in accordance with point (1) above.

(3) Vent pipe drainage. All components of the radon vent pipe system need to be installed to provide drainage to the ground beneath the membrane.

(4) Vent pipe accessibility. Radon vent pipes need to be provided with space around the vent pipe for installation of a fan in the future, if needed. The space necessary for the future fan installation needs to be a minimum of 600 mm in diameter, centred on the axis of the vent pipe, and needs to extend a minimum distance of 900 mm vertically.

(5) Identification of radon vent pipes need to be clearly visible, with at least one label on each storey of the building, in attics and in crawl spaces. The label could read *Radon Gas Vent System* or similar.

(6) Combined basement/crawl space or slab-on-grade/crawl space foundations needs to have separate radon vent pipes installed in each type of foundation. Each radon vent pipe has to terminate above the roof or has to be connected to a single vent pipe that terminates above the roof.

Roof flashing or hood needs to be installed around the vent pipe where it exits the roof to prevent water leakage from precipitation and maintain the water tightness of the roof assembly.

All potential soil gas entry points into the building need to be sealed with caulk or other durable sealing material. All possible entry points need to be cleared of loose material prior to sealing. The sump pit needs to be covered and sealed. This sealing needs to be inspected upon completion to ensure airtightness. Special attention needs to be paid to the following spots in a construction:

(1) Floor openings around bathtubs, showers, water closets, pipes, wires, or other objects that penetrate the membrane and the concrete slab or other floor systems;

(2) Control joints, isolation joints, construction joints, or any other joints in the concrete slab, or the joint between the concrete slab and a foundation wall;

(3) Joints, cracks, or other openings around all penetrations of both exterior and interior surfaces of foundation walls.

Hollow block masonry foundation walls need to be constructed with either:

(1) A continuous course of solid masonry at or above the exterior ground surface;

(2) One course of masonry grouted solid at or above the exterior ground surface;

(3) A solid concrete beam at or above the finished exterior ground surface;

(4) When a brick veneer or other masonry ledge is installed, the masonry course immediately below the veneer or ledge needs to be solid or filled.

An appropriate membrane is placed over the gas permeable layer, as described in Section 5.2.

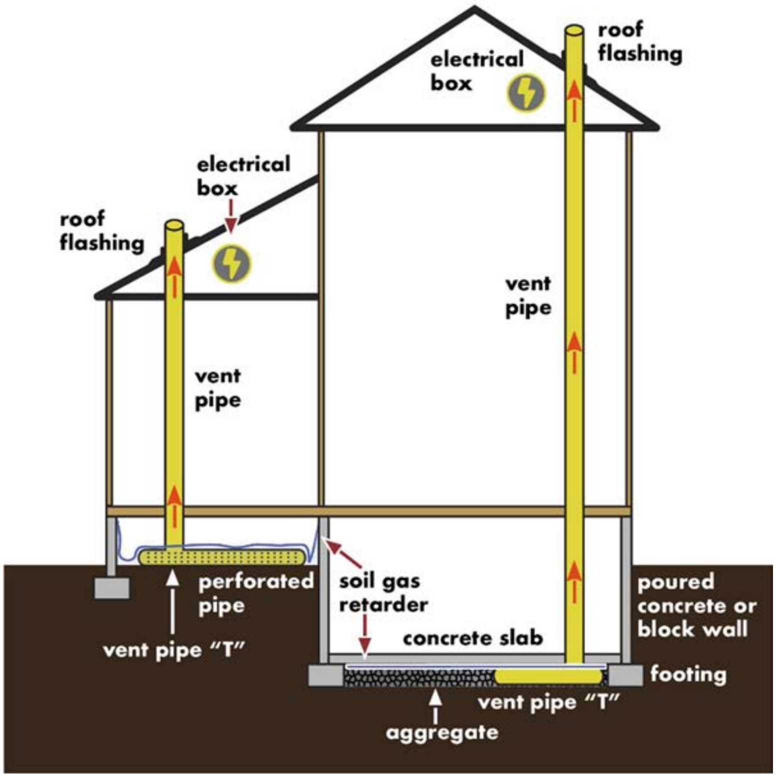

FIG. 25. Schematic drawing of preventive measures for a new building.

After the building is occupied, radon measurements are needed to evaluate the effectiveness of radon prevention membrane and to assess the need to activate the radon prevention system.

If the radon measurements show radon levels above the national reference level, then the passive system described above needs to be activated by installing a radon fan. The radon fan rated for continuous operation needs to be installed in the vertical vent pipe. The smallest energy consumption fan capable of producing the desired pressure field extension and airflow needs to be used. An example of a radon fan used in single family home system activation is one that provides a minimum of 85 m^3/h at 125 Pa. The fan needs to be installed inside the radon vent pipe. The fan provides upward airflow in the vent pipe, to draw the radon rich air from the soil below the membrane. The fan needs to be installed outdoors, in attics, or in garages. The fan is not be installed inside the building, basement, or crawl space. It is not to be located where it may create positive pressure in any portion of the vent pipe located inside the building.

An audible alarm, flashing light, a manometer, or other similar device may be installed to indicate when the fan is not operating.

6. EFFECTIVENESS ASSESSMENT

Any designed and installed radon mitigation system needs to be evaluated for its effectiveness immediately after the installation. This might be a part of the contract with the company carrying out the mitigation work, the basis for subsidiary payment, or for quality assurance.

The system has to be periodically re-evaluated by means of measurement.

For the same purposes any radon preventive measures need to be evaluated to assess its effectiveness or the need of activation. Also, this measurement might be used for claiming any potential construction company guarantee.

For any mitigation measures to be successful, it is important that the radon mitigation professional:

(1) Is appropriately trained, with an understanding of how radon flows and moves into and through a building;

(2) Has an understanding of relevant radon measurement and diagnostic techniques;

(3) Has a detailed understanding of construction techniques and indoor heating and ventilation;

(4) Possesses a sufficient knowledge and has experience of different kinds of mitigation techniques;

(5) Carries out the work in a professional manner;

(6) Provides appropriate operating and maintenance instructions to the building occupier, owner or building manager.

The role of radon professional associations is to support promotion of good practices and regulate the professional market. It is also important that the contract for radon mitigation or prevention work includes a set of guarantees for the effectiveness of the work and provides the customer with the opportunity to claim corrective actions at the builder's expense in case the mitigation work does not meet the agreed results.

Post-mitigation radon measurement

A post-mitigation measurement of radon levels in the building needs to be performed after the mitigation system is installed and operating. If the same method of radon measurement is used that was used in the pre-mitigation measurement, the monitors need to be placed in the same locations. This is particularly important when dealing with larger more complex buildings. The measurement of radon needs to be conducted using the same measurement protocols as the pre-mitigation measurement.

The radon levels in the building need to be remeasured after any alterations are made, such as changes to the building to make it weatherproof (for example by installing airtight windows or doors), extension to building, floor renovation, basement or foundation renovations or change, and change to the ventilation system.

Post-mitigation system checks

Every radon mitigation system needs to be inspected by an appropriately qualified radon mitigation professional to ensure proper installation. When finalising an active soil depressurization system, the suction in the system's main riser piping (e.g. fan monitor) needs to be measured and recorded. This pressure reading needs to be recorded on or near the system pressure gauge for future reference. A measurement of the airflow coming from each suction point needs to be made and recorded.

At least one pressure field extension measurement needs to be made at the furthest point away from the suction point(s) to ensure adequate negative pressure under the slab. In addition, the system effectiveness needs to be tested by creating worse-case conditions in the building – turning on all sources of air exhaust in the building and checking the pressure field extension to make sure there is adequate negative pressure at the furthest locations from the suction point(s). All of these pressure measurement readings are to be recorded.

Information for the occupier, owner, building manager

The radon mitigation professional needs to provide the following information to the building occupier, owner or building manager, as appropriate:

(1) A brief description of radon and health risks. This note could also contain clarification on why the mitigation has been carried out and why it needs to continue to work.

(2) Location of the pre-mitigation and post-mitigation radon measurement points for any future measurements.

(3) Description and drawings with demonstration of the installed mitigation system and description of how it works.

(4) Specification of the entire system, blueprints and equipment manufacturers details.

(5) Detailed description of what needs to be checked by the occupier, owner or building manager in order to know whether the system is working (i.e. fans are operating), and the frequency of the checks.

(6) Records of all measurement made of the system (e.g. pressure, electricity consumption), dates and readings.

(7) Recommended frequency of radon measurements to demonstrate that the system is continuing to adequately reduce radon levels in the building.

(8) Radon mitigation professional contact details.

(9) National radon guidance, and the contact details of national authority, if available.

7. BUILDING AND CONSTRUCTION MATERIALS

7.1. PROBLEM IDENTIFICATION

Building and construction materials can contribute significantly to gamma exposure of the occupants. In particular, the components of the concrete used for the inner walls of the building may contain high levels of naturally occurring radioactive materials (NORM). In order to prevent these situations, the regulatory body is required to establish specific reference levels for construction materials, based on an annual effective dose to the representative person that is not greater than 1 mSv (see para. 5.22 of GSR Part 3 [9]). The requirements of EU Directive 2013/59 Euratom [26] also stipulate a reference level for construction materials based on an annual effective dose of 1 mSv from construction materials. Guidance on the regulatory control of building and construction materials is provided in SSG-32 [10] and in Ref. [12].

In rare cases, building and construction materials may become a source of indoor radon. Methods to reduce radon levels in buildings due to release of radon from building and construction materials is provided in Section 3.3.

Concrete, aggregate (ballast) and sand are the three main stone-based construction materials of major interest when it comes to NORM content in construction material of buildings. To ensure compliance with the requirements of GSR Part 3 [9] on annual effective dose from construction materials [26], it is essential that all building and construction materials are tested before entering the market. For verification of compliance, there is a need to measure NORM in materials to be used for the new built.

SSG-32 [10] provides recommendations on a process to determine compliance of building and construction materials containing radionuclides of natural origin with the reference level. The process includes the determination of the activity concentrations of radionuclides of natural origin, followed by the determination of an activity index.

An example of an activity index *I* that could be considered by the national authority is given by Eq. (6) (based on para. 4.20 of SSG-32 [10]):

$$I = \frac{C_{Ra}}{300\,Bq/kg} + \frac{C_{Th}}{200\,Bq/kg} + \frac{C_K}{3\,000\,Bq/kg} \qquad (6)$$

where

C_{Ra} is the activity concentration of ^{226}Ra in the construction material in Bq/kg,

C_{Th} is the activity concentration of ^{232}Th in the construction material in Bq/kg,

C_K is the activity concentration of ^{40}K in the construction material in Bq/kg.

Guidance on the application of the activity index is provided in paras 4.21–4.27 of SSG-32 [10].

In situ dose rate measurement of gamma radiation of a 10-minute duration can be made in the middle of the room. This measurement includes gamma rays from radon daughter decay, so radon measurement is also necessary because the reference level of 1 mSv/a is related to the construction material only. If a calibrated integrated radon measuring instrument cannot be used, then a certified radon track detector can be used for a short time measuring phase of at least seven days [27, 28].

If the resulting dose exceeds 1 mSv/a, a further measurement is advised. This needs to include a radon concentration measurement with a calibrated integrated (instant) radon instrument.

The method for determining the NORM content for each individual section of the room in a concrete building includes a handheld gamma spectrometer applied on the middle of each wall, floor and ceiling [27].

An assay measurement is performed twice with a 300 second sample at the same position to obtain an average value. The spectrometer needs to be shielded from the background radiation during this measurement by applying a shield, provided by the instrument manufacturer, on the other side of the measured wall, floor or ceiling. Then a mathematical factor, that depends on the thickness of the tested material, is applied to the results. This factor is provided by the instrument manufacturer.

For determining NORM content in an existing building, measurements in the middle of the room with in-situ gamma-spectrometric instruments are utilized. The first screening measurement is expected to provide the results of gamma dose rate, indicating the need of further investigation or verification of compliance with 1 mSv/a [28].

In case the measurement results in doses over 1 mSv/a, testing has to be performed again with an integrated radon measurement so the deduction of gamma rays due to radon daughter decay on the total measured dose rate can be performed.

The measurement instruments have to be calibrated with traceability, in case of gamma spectrometer, for NORM (K, U, Th). The measurement service provider is to be accredited or approved by the national authority for the type of measurements.

For the determination of construction materials' activity index or content of NORM radionuclides, the measurement is to be performed with a gamma spectrometer on a representative sample of appropriate size [29].

A good starting point for deciding on the frequency and amount of construction material measurements can be gained from the EU directive on construction materials [30]. An important aspect for testing building and construction materials is that it has to be tested in the form intended to be used [29, 30]. This is due to physical properties of the materials that can be influenced by their form (solid, liquid, crashed). To avoid uncertainties in the result of the measurement caused by the physical state of the construction materials, it is a good practice to perform testing of the material in the intended form of use. In European countries, for instance, for test concrete a sample size cube of 150 mm x 150 mm x 150 mm is stipulated in EN 206 [16].

Several industrial standards are provided for determining the frequency of material testing, for example:

- Concrete 1/400 m^3 produced [16];
- Unbound fractions 1/week or 2/2 000 tons produced [31];
- Concrete components 1/week or 1/2 000 tons produced [32];
- Asphalt material 1/week or 1/2 000 tons produced [33].

The production process in combination of frequent testing of the components or final product of the construction material industry will allow the prevention of non-confirming material entering the market and its utilization in the construction. However, there are many buildings that have been constructed before the requirements of the IAEA were implemented and these need special attention.

7.2. MITIGATION OF EXPOSURES FROM RADIONUCLIDES IN BUILDING AND CONSTRUCTION MATERIALS

There are only three radionuclides normally occurring in stone-based construction materials: K, U and Th (also called NORM), which are more or less present in varying quantities in all stone-based construction materials.

To avoid a contribution of NORM to annual effective doses over 1 mSv, from construction material in the future, the producers need to start testing the raw materials before or at least during production of stone-based construction materials (i.e. concrete).

Remedial actions for buildings with elevated gamma dose rate can be very difficult or expensive to implement.

If the radiation levels in a building exceed the reference level, it needs to be thoroughly surveyed following the guidance provided in Section 7.1. Once the building has been fully investigated and the cause of the problem been identified, the following options can be considered to reduce the radiation levels in the room:

(a) Shielding of the source with elevated NORM with high-density materials (for example bricks, concrete or lead), if it is practicable for the building

    For example, if only two walls are identified to be the source of the elevated gamma radiation levels, a functional solution is to shield these two walls. This is done with high density material, such as concrete or bricks made of material containing very low levels of NORM. If concrete is chosen as shielding material, the dose rate can be reduced by about 50% for each 10 cm of concrete that is constructed in front of the wall with elevated levels of NORM (see Table 2). If bricks with very low levels of NORM are used as shielding material, about 15 cm thickness of bricks is needed to obtain the same reduction of dose (see Table 2).

(b) Removal or replacement of the construction material that contains elevated levels of NORM

    Removal of the material containing elevated levels of NORM is also possible if the area of inhabitant space is not adversely affected. This option may be more expensive than option (a).

(c) Demolition of the building

    If the building in question is a workplace, then an alternative can be to calculate the dose based on worktime the personnel spends in the building, and to compare it with national regulations. In case options (a) and (b) above are not realistic, demolition of the building can ultimately be the last resort. This option carries, however, serious economic and social penalties and should not be taken without careful consideration (see para. 4.30 of SSG-32 [10]).

TABLE 2. THICKNESS OF SHIELDING MATERIAL NEEDED FOR ATTENUATION FACTORS IN THE RANGE 0.9 TO 0.1 [34]

Shielding material	Thickness of shielding material (mm) necessary for given attenuation factors in the range 0.9–0.1								
	Attenuation factor								
	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1
Lead (p = 11 300 kg/m^3)	0.9	2.3	4.0	6.3	9.3	13	18	26	38
Iron (p = 7 800 kg/m^3)	6.1	11	17	23	29	37	46	59	81
Barite (p = 3 300 kg/m^3)	12	24	37	50	65	83	100	130	180
Barite (p = 2 800 kg/m^3)	18	34	50	66	84	100	130	160	220
Concrete (p = 2 300 kg/m^3)	30	50	69	89	110	130	160	200	270
Solid brick (p = 1 800 kg/m^3)	46	72	100	130	160	190	230	280	370

APPENDIX.
PROPERTIES AND POSITIONING OF THE FAN

The fan is intended to induce the pressure difference in the system. The following aspects need to be considered in fan selection:

(1) Position. If possible, the fan needs to be positioned outside of the conditioned volume of the building. If this is not the case, special care needs to be taken to ensure that the piping at the exhaust side of the fan is airtight.

(2) External use. If the fan is to be installed exposed to the elements, it needs to withstand rainwater, snow, and condensation as well as be protected from harm and manipulation.

(3) Safe electrical connection needs to be considered when designing the fan installation. It is often needed to install the power socket in the vicinity of the fan.

(4) Lifetime. The fan is intended for continuous, uninterrupted operation.

(5) Sizing of the fan has to be in line with the findings in building inspection and pressure field extension estimation and be based on: (i) necessary negative pressure to overcome suction due to the stack effect and possible mechanical air extraction from the building; (ii) characteristic of the soil, derived from flow and/or pressure measurements; and (iii) calculated or estimated air-flow resistance of the piping.

For longer lifespan, it is recommended that the fan does not operate at its maximum capacity, but rather at lower loads. The fan needs to allow for adjustable speed control, either in steps or step-less. Consideration has to be given to ensuring that the fan is operating quietly, and where the fan is to be located (indoors, outdoors, close to quiet rooms, neighbouring properties).

The exhaust of the radon gas from the system needs to be as vertical as reasonable. In wet climates, the exhaust needs to be protected from excess precipitation. In addition, the exhaust point needs to be protected from animals and debris from entering the system. Examples on the exhaust point location are provided in Figs 12–20 (see Section 3.2.1).

It is recommended that the operation of the system is documented in writing and supported with drawings as needed, and that it is monitored continuously via an audible or visual pressure device.

REFERENCES

[1] UNITED NATIONS, Sources and Effects of Ionizing Radiation, Volume II: Effects (Report to the General Assembly), Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UN, New York (2000).

[2] UNITED NATIONS, Effects of Ionizing Radiation. Vol. I: Report to the General Assembly, Scientific Annexes A and B; Vol. II: Scientific Annexes C, D and E, United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), UNSCEAR 2006 Report, E.08.IX.6 (2008) and E.09.IX.5 (2009), UN, New York.

[3] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, 1990 Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, Pergamon Press (1991).

[4] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Protection Against Radon-222 at Home and at Work, ICRP Publication 65, Pergamon Press (1993).

[5] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, The 2007 Recommendations of the International Commission on Radiological Protection, ICRP Publication 103, Elsevier (2007).

[6] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Lung Cancer Risk from Radon and Progeny and Statement on Radon, ICRP Publication 115, Elsevier (2010).

[7] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Radiological protection against radon exposure, ICRP Publication 126, Elsevier (2014).

[8] WORLD HEALTH ORGANIZATION, WHO Handbook on Indoor Radon: A Public Health Perspective, WHO, Geneva (2009).

[9] EUROPEAN COMMISSION, FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, UNITED NATIONS ENVIRONMENT PROGRAMME, WORLD HEALTH ORGANIZATION, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards, IAEA Safety Standards Series No. GSR Part 3, IAEA, Vienna (2014).

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Protection of the public against exposure indoors due to radon and other natural sources of radiation, IAEA Safety Standards Series No. SSG-32, IAEA, Vienna (2015).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, Protection of Workers Against Exposure due to Radon, Draft Safety Guide DS519 (in preparation).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Regulatory control of exposure due to radionuclides in building materials and construction materials, Safety Reports Series (in preparation).

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, WORLD HEALTH ORGANIZATION, Design and Conduct of Indoor Radon Surveys, Safety Reports Series No. 98, IAEA, Vienna (2019).

[14] CLAVENSJÖ, B., ÅKERBLOM, G., Radonboken befintliga byggnader, Stockholm: Svensk byggtjänst (2014).

[15] SCIVYER, C.R., JAGGS, M.P.R., A BRE guide to radon remedial measures in existing dwellings: Dwellings with cellars and basements, Report No. BR 343, IHS BRE Press, Garston, Watford (1998).

[16] EUROPEAN COMMITTEE FOR STANDARDIZATION, Concrete Specification, Performance, Production and Conformity, EN 206, Brussels (2013).

[17] EUROPEAN COMMITTEE FOR STANDARDIZATION, Construction Products - Assessment of Release of Dangerous Substances - Radiation from Construction Products - Dose Assessment of Emitted Gamma Radiation, CEN, TR 17113, Stockholm (2017).

[18] PETTERSSON, H., HILDINGSON, O., SAMUELSSON, C., HEDVALL, R., Radonexhalation Fran Byggnadsmaterial, Statens Provingsanstatt Technik Rapport SP-RAPP, 1982:32, ISN 0280-2503, Boras (1982).

[19] SCIVYER, C.R., Radon: Guidance on Protective Measures for New Buildings, 2015 Edition, Report No. BR 211, IHS BRE Press, Garston, Watford (2015).

[20] SCIVYER, C.R., Radon solutions in homes: Radon sump systems, BRE Good Repair Guide GRG 37 Part 3, IHS BRE Press, Garston, Watford (2013).

[21] AMERICAN NATIONAL STANDARDS INSTITUTE/AMERICAN ASSOCIATION OF RADON SCIENTISTS AND TECHNOLOGISTS, Radon mitigation standards for schools and large buildings, ANSI/AARST RMS-LB 2018, Hendersonville (2018).

[22] JIRANEK, M., HULKA, J., Applicability of various insulating materials for radon barriers, Sci. Total Environ. **272** (2001) 79–84.

[23] SCIVYER, C.R., Radon solutions in homes: Positive house ventilation, BRE Good Repair Guide, GRG 37 Part 2, IHS BRE Press, Garston, Watford (2013).

[24] CLAVENSJÖ, B., ÅKERBLOM, G., Radonboken – Förebyggande åtgärder i nya byggnader. Formas, Stockholm. ISBN 978-91-540-5926-7 (2004).

[25] NAZAROFF, W.W., et al., Potable water as a source of airborne ^{222}Rn in US dwellings: a review and assessment, Health Physics **52** (1987) 281–295.

[26] EUROPEAN COMMISSION, Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom, Official Journal of the European Union, L13; 57: 1–73 (2014).

[27] LÖFQVIST, T., LÖFQVIST, G., GERMAN, O., In-situ method for determination of Activity Index (AI) of construction materials indoors of existing buildings, MMK A2 606, Stockholm (2016).

[28] LÖFQVIST, T., LÖFQVIST, G., In-situ method for determination of gamma exposure indoors inside buildings, MMK 608, Stockholm (2020).

[29] LÖFQVIST, T., LÖFQVIST, G., GERMAN O., Testing of rock-based building material, MMK A2 605, Stockholm (2016).

[30] EUROPEAN COMMISSION, Regulation (EU) No 305/2011 of the European Parliament and of the Council of 9 March 2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC, Official Journal of the European Union, L88; p. 5–43 (2011).

[31] EUROPEAN COMMITTEE FOR STANDARDIZATION, Aggregates for unbound and hydraulically bound materials for use in civil engineering work and road construction, EN 13242, Brussels (2002).

[32] EUROPEAN COMMITTEE FOR STANDARDIZATION, Aggregates for concrete, EN 12620, Brussels (2002).

[33] EUROPEAN COMMITTEE FOR STANDARDIZATION, Aggregates for bituminous mixtures and surface treatments for roads, airfields and other trafficked areas, EN 13043, Brussels (2013).

[34] CZECH OFFICE FOR STANDARDS, Protection of Buildings against Radon and Gamma Radiation from Building Materials, CSN 730602, Czech Office for Standards, Metrology and Testing, Prague (2006).

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