Communication

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Techniques to mitigate the admission of radon inside buildings

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Abstract: In this work, the factors that influence indoor radon (Rn) level and most usual methods to prevent or mitigate Rn are presented and discussed, according to their way of action. The findings show that it is possible to select the most appropriate and effective solutions for each situation, even in cases where there is a high risk of Rn concentration, by combining these methods to increase overall efficiency. Finally, most relevant strategic recommendations are presented to guarantee the success of Rn protection measures, to reduce problems associated with Rn.

Keywords: radon, buildings, remediation, prevention, ventilation, depressurization, sealing

1. Introduction

Radon (Rn) is a radioactive gas that has no color, smell, or taste, which can be found in soil due to radioactive decay of naturally present elements such as uranium and radium. Rn is the greatest natural source of ionizing radiation and exposure of population to high levels of Rn for prolonged periods can become a public health problem. According to the World Health Organization, Rn is the second cause of lung cancer after smoking [1].

Rn can also be present in building materials and water, although at much lower concentrations.

Rn can enter and accumulate in buildings causing lung cancer when people are exposed to high levels of Rn for prolonged periods.

However, a large part of the population ignore this and the ways to prevent it. It is therefore important to raise awareness of the problem by disseminating knowledge, particularly about the most appropriate solutions for preventing and mitigating Rn in buildings, which is the main objective of this work.

The most usual methods to prevent or mitigate Rn infiltration in buildings use protection barriers and ventilation.

The problem of Rn has been the subject of many research studies and interventions around the world [2]. There are publications dedicated to several mitigation systems, like barriers [3], underfloor ventilation [4], positive house ventilation [5], and sump systems [6], among other solutions. The scientific literature also contains research studies on construction materials used in buildings where exposure to ionising radiation is not negligible [7–9]. The presence of Rn in water is also the subject of several studies [10–12].

The Rn problem has been around forever (past, present, and future) and can probably never be completely solved. However, awareness-raising campaigns for the general population, education in schools, and the development of specialized courses for construction professionals, companies, public and municipal institutions, raise awareness of the problem and help promote programs to prevent and mitigate Rn emissions in buildings.

Within this scope, this work presents an overview of the main prevention and remediation methods to prevent or mitigate Rn in buildings, giving useful information for both technical and non-technical readers and for anyone interested in Rn issues and solutions.

2. Overview of the main prevention and remediation solutions in buildings

Rn protection solutions aim to limit people's exposure to indoor Rn, reducing Rn concentration, particularly in spaces where people spend longer periods, such as habitable rooms. The objective of limiting Rn exposure can be achieved,

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directly, by protecting these habitable rooms, or indirectly, by protecting non-habitable rooms located underneath to those habitable rooms.

There are solutions that may be used alone or in combination, depending on the Rn potential risk or the measured concentration, either in new or existing buildings, to allow the minimizing of the concentration of Rn inside buildings.

Rn protection solutions can be classified according to the way of action [13]:

- Insulation of habitable rooms from the soil;
- Reduction in Rn concentration before it enters the building;
- Reducing Rn concentration within the areas to be protected.

The solutions leading to the insulation of buildings are as follows [13–15]:

- Application of Rn proof barriers (membranes) on the building envelope (building elements in contact with the ground [slab or wall] or a non Rn protected building area that enclose habitable rooms and isolate them from Rn).
- Sealing of the building envelope;
- Positive pressurization of habitable rooms;
- Airtight doors in openings in the building envelope.

The solutions leading to the reduction in Rn concentration before it enters the building are as follows [13–15]:

- Installation of a ventilation system in a containment space (crawl space* or non-habitable room such a garage, placed between the soil and the room to be protected);
- Installation of a sub-slab depressurization system;
- Use of drainage systems.

The solutions leading to the reduction in Rn concentration within the areas to be protected consist mainly in the use of natural or mechanical ventilation of habitable rooms, which can also be always considered as an additional or complementary way to improve indoor air quality.

In existing buildings, protection solutions are similar to those mentioned above, but with the limitations associated with the presence of existing building elements, the scope of the intervention, the available budget, etc. In addition to these solutions, other solutions can be used to reinforce their effectivity or to replace them when they cannot be used [13,14].

* The crawl space is a space between the floor and the natural ground, where various services (plumbing, drainage and cables for electrical circuits and telecommunications) or other equipment can be installed.

3. Factors influencing Rn potential

Indoor Rn concentration can fluctuate depending on many factors, soil type being the main driving factor. Climatic conditions (e.g., annual temperature differences, wind speed, and direction) can also be very relevant, as inducing changes in Rn concentration in the same building, as well as building characteristics given the building exposure to Rn [13]. In this section, the possible influence of the soil, the building characteristics, and the importance of ventilation are described.

3.1 Soil

The main variable associated with indoor Rn concentration is the geogenic Rn content in the soil, where granite rocks are usually more prone to have large contents of Rn. The exhalation of Rn from soil is also determined by the gas mobility through the soil, which is governed by its permeability: in fractured soils, the gas moves faster, reaching the outside or surroundings more easily. Gas mobility is also influenced by soil water content because Rn diffusion coefficient in water is lower than that in air. Therefore, the greater the compaction and saturation of the soil, the less easy the gas may propagate. This way, if the soil under the building is dry and the surrounding soil is saturated, the gas tends to take the easiest route and enters the building instead of flowing outwards.

3.2. Building characteristics

3.2.1. Ground floors

The concentration of Rn is usually higher in spaces located close to the soil, ground floors, and basements and semi-basements generally used as cellars, utility rooms, storerooms, and garages, i.e., non-habitable spaces with little occupancy.

For the purposes of assessing the risk of exposure to Rn, buildings are generally classified according to the type of construction, with emphasis on the type of building envelope (basements, semi-basements, ground floor concrete – slab on grade), or floors with a crawl space [14]. The larger the surface of the envelope in contact with the soil, the higher exhalation area, so the higher risk of Rn infiltration. When there is a gap between the building and the soil, the risk is lower, such as in the case of floors with a crawl space.

Some types of ground floor "pavements" in existing buildings are more prone to the inflow of Rn gas from the ground into the respective space, namely

- compacted terrain or smoothed rocky materials;
- a layer of poor concrete laid directly on the ground or over a rockfill;
- a layer of stone (which may be granite) laid directly on the ground or over a screed, with or without underlying rockfill.

In such cases, particularly in places with increased Rn in soil, it may be necessary to replace the existing "pavement" by another one in which permeability to Rn gas may be substantially lower, thus being a barrier to the passage of Rn from the ground.

3.3 Basement walls

The construction techniques and materials used for walls may be related to higher or lesser existence of cracks or increased risk of indoor Rn concentration. In terms of construction materials, the worst-case scenarios include walls made of the rock itself where the cellars of the buildings were excavated, with no barrier to Rn entry [14]. In the intermediate scenario, wall in basements may have stone or brick walls, built without barriers to protect against the passage of Rn, even if plastered with cement/lime and sand mortars (painted or not). Due to the permeability of these walls, which is increased in the existence of cracks in the wall itself and/or in the respective coatings, Rn may easily infiltrate through them [14].

Also, the presence of moisture on the walls may accelerate the ageing process of materials, leading to anomalies, such as cracking, and, thus Rn infiltration into buildings.

3.3.1 Intermediate floors

The floor that separates the cellar or basement from the immediately overlying floor is important as well as the possibility of high concentration of Rn in them is large.

Wooden floors, or their derivatives, are usually supported on beams of the same material. The joints between the planks or wooden planks are the most critical points for the passage of Rn from the lower space to the upper ones [14].

When floors are made of stone (granite, limestone, or other) or ceramic elements, generally forming arches with different configurations (e.g., vaults), they offer greater resistance to the infiltration of Rn from the lower floor, but Rn exhalation emissions from the materials themselves must also be considered (e.g., granite) [14].

Finally, in more recent constructions, the most common intermediate flooring solution consists of solid or lightened reinforced concrete slabs, or lightened slabs with prefabricated elements (e.g., joists and vaults). With these solutions, the permeability for Rn infiltration is reduced. It should be noted that, in these cases, the most critical points are the joints resulting from the crossing of the slab by various pipes, the openings, and the level of cracking of the floor constituent materials [14].

False ceilings give a low contribution to reduce the flow of Rn, if they are not completely watertight (as is the case with plasterboard sheets, applied continuously, creating an overlying airtight air box).

3.4 Ventilation

Natural ventilation in dwellings is traditionally performed through the openings in the interior bathrooms, the kitchen fume traps, or infiltration through the gaps around the blind boxes or the opening joints within the window and exterior door frames. Although window opening is not a permanent solution, it can be considered to contribute to the reduction in indoor Rn concentration [13,14]. Hybrid ventilation system, combining natural and mechanical ventilation, are becoming very common in dwellings, where fresh air enters through air inlets placed in windows or façade walls of dry rooms (bedrooms and living-dining rooms) and stale air is exhausted through ventilation shafts in wet rooms (bathrooms and kitchens) equipped with hybrid fans. While contributing to improving air quality, it may allow Rn concentration to decrease to lower levels, particularly if natural ventilation is coupled with mechanical ventilation.

Furthermore, mechanical ventilation systems are spreading among dwellings in low and nearly zero energy buildings, with the aim of controlling energy losses due to ventilation.

The obstruction of cooker hoods, or bathroom ventilation shafts substantially reduces the amount of air drawn from the interior of the dwellings [14]. In the same way, the obstruction of air inlets causes a reduction in the fresh air drawn to the interior. All these actions reduce the efficiency of natural ventilation [13].

However, it is important to remark that increasing ventilation should not be conducted without a previous detailed assessment of each case, because in some situations of exposure to the wind it can be counterproductive, causing a depressurization that draws Rn indoors through cracks and deficiently sealed joints in the envelope [13].

In addition to this, increasing ventilation usually results in a rise in energy demand (unless mechanical ventilation with a heat recovery system is used), so this aspect must also be assessed [13].

With the objective of improving air quality, ventilation rates, namely, air renovation requirements, may be important to understand to what level Rn concentrations can be managed, even if needed to be coupled with other Rn mitigation and remediation solutions.

3.5 Openings between spaces

The openings between spaces (e.g., the basement and the upper floor) can be doors to basements such as garages, which are generally communicated via interior staircases [14] or hatches to crawl spaces.

When openings are insufficiently airtight [14], low air permeability doors can be used that will also act as protective barriers against drafts, to avoid the infiltration of Rn into the building.

4. Specificity of different solutions

Aiming at reducing Rn infiltration and accumulation in buildings, multidisciplinary approaches may need to be applied. Firstly, a preliminary analysis of the geogenic characteristics of the building on site should be carried out in order to understand the potential for exhaling Rn from the ground. Secondly, in order to assess the potential for Rn infiltration, the characteristics of the building should be assessed, including its use (e.g. housing, workplaces), the type of occupation (permanent or temporary), the type of building materials used, the type of floors, walls, ceilings and the construction processes adopted, as well as the level of deterioration of the building. This should be coupled with ventilation design and requirements, in addition to building usage, to study Rn accumulation potentials. Finally, the implementation of prevention and remediation solutions will need to cope with the architectural aspects, as well as comply with building codes and regulations.

4.1 Rn barrier

Rn barrier (Figure 1) is any continuous element that is placed between the space that needs to be protected and the soil, which constitutes a protective barrier for the passage of Rn from the ground and which effectiveness can be demonstrated previously (by determining its properties) and, after installation, by measuring the reduction in radon concentration obtained.

Most common Rn barriers are membranes. A membrane is a laminar element in flexible plastic material or composite. The membranes for Rn protection can also act as a barrier against the capillary rise of ground water [14,15].

The membranes used as a barrier for the passage of Rn into buildings must allow a limited exhalation of Rn, function of both Rn diffusion coefficient and thickness. Some regulations estimate that exhalation of Rn is adequate when the Rn diffusion coefficient is lower than 10×10^{-11} m^2/s and the thickness is larger than 2 mm [16]. In addition to this main characteristic of Rn barriers, they must be sufficiently resistant to the actions they will be subjected to, namely, the mechanical actions of puncturing sharp elements. This solution, by itself, is generally sufficient to guarantee significant obstruction to the passage of Rn when the concentration of Rn in soil is lower than 600 Bq/m^3, provided that the continuity of the membrane is guaranteed on the entire surface to be insulated, especially in the joints between the floor and internal walls. Encounters of the envelope with construction elements (pillar, façade, or pipe crossing) and the existence of expansion joints facilitate the Rn entry into the interior of buildings, so they must be adequately sealed (Figures 2 and 3).

Rn protection membranes, solely, provide protection only against Rn infiltration up to levels of 600 Bq/m^3 [13,16],

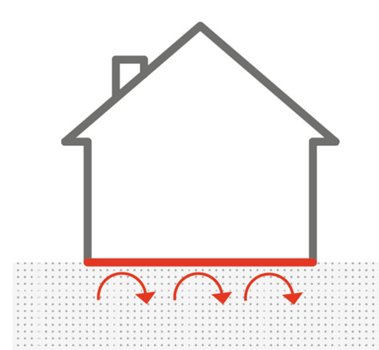

Figure 1: Rn barrier, [13].

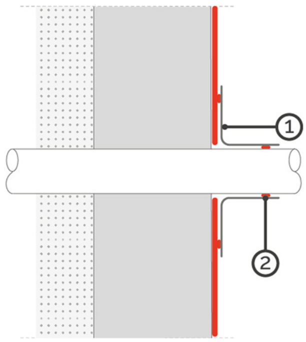

Figure 2: Sealing of encounter with drainage pipe. (1) Prefabricated piece (2) Rn proof sealant, [13].

and are used more in existing buildings when it is necessary to replace the floor. The effectiveness of this solution depends on the Rn permeability of the membranes [13,14]. In areas with average annual concentrations of more than 600 Bq/m^3, this measure must be complemented with other solutions such as sub-slab depressurization [16], which can be activated with a fan if the Rn level is high [14,15], or a ventilated containment space [13,16].

4.2 Sealing

In the rehabilitation of existing buildings, if it is not possible to place a Rn protection membrane and the envelope does not show widespread cracking or is porous such as a wooden floor, an effort should be made for floors and walls conforming the envelope to function themselves as Rn protection barriers. For this purpose, sealing fissures, cracks, and joints are a way to reduce inflow of Rn into buildings (Figure 4). This solution has effectiveness levels up to 600 Bq/m^3, but may require complementary measures such as the improvement of the ventilation of habitable spaces [14], sub-slab depressurization, or a ventilated containment space [13].

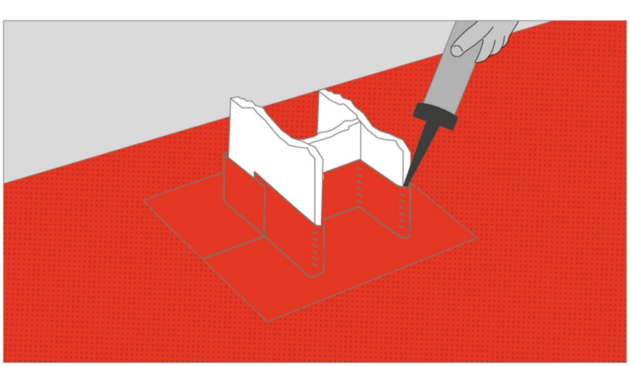

Figure 3: Sealing of encounter with pillar, [13].

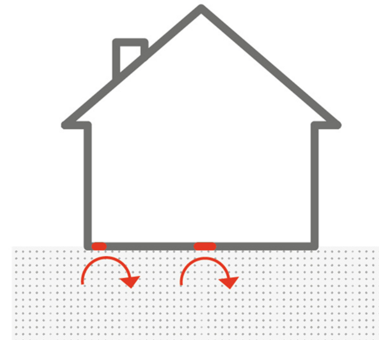

Figure 4: Sealing, [13].

4.3 Positive pressurization

A positive pressurization system consists of creating a difference in pressure between the air inside the building and the underlying ground, so the natural pressure difference is reversed. This is usually produced by a ventilation unit located in the attic, which is used to blow filtered fresh air into the main rooms (bedrooms and living rooms) of the house. The increase in pressure throughout the building reduces the possibility of Rn admission and causes the Rn to be diluted and leaked out, which nevertheless enters the building [5,14].

In dwellings, the use of this solution must be carefully assessed because it has been observed that in some cases condensations were caused.

This solution can also be used to protect small habitable areas located in large areas that are not protected, such as, e.g., surveillance cabins in garages [13,16] (Figure 5).

The effectivity of this solution greatly depends on the airtightness of the building envelope or, at least, of the space to be protected, which must be high.

Positive pressurization systems (air insufflation) present a degree of effectiveness up to Rn concentrations of 700 Bq/m^3, allowing, in some cases, success up to 1,000 Bq/m^3 [14]. For higher concentrations, it is recommended to use it in combination with other solutions such as Rn barrier or sealing [13]. When installing this solution in dwellings, a careful assessment must be conducted to prevent the occurrence of condensations [13].

4.4 Airtight access doors and hatches

It is important to create mechanisms that allow reduction in air infiltration from the containment space to the upper floor, thereby reducing air permeability of the access doors between them (Figure 6).

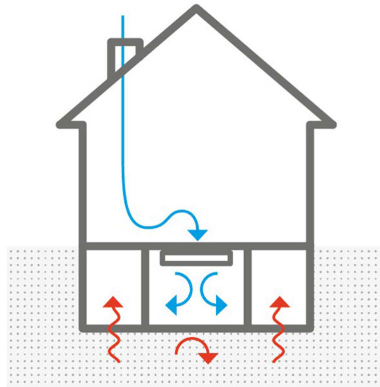

Figure 5: Positive pressure, [13].

In more recent buildings, or in old ones that have been subjected to retrofit, air tightness of the access doors between floors can be sufficiently guaranteed if the provisions regarding fire safety have already been adopted. This is an important contribution to especially prevent the passage of Rn from cellars, basements, or ground floors to the upper floors, which would have already been reduced if the walls and floors of these basements or ground floors are made up of elements of reinforced concrete [14].

Doors with air permeability class C or D according to EN 12207 are adequate from the point of view of airtightness [13].

In the case of improving an existing door, limiting air permeability can be achieved by [13]:
- Placing a self-closing door mechanism;
- Placing an elastic joint in the whole perimeter;
- Blocking existing ventilation grills.

In the case of hatches, the solution depends on the frequency of its use. When it is seldom used, it is better to seal it completely. When it is used regularly, the solution will be similar to those of doors.

In all cases, such a solution is not effective enough on its own and should be complemented with other mitigation methods such as Rn barrier, sealing, or ventilated containment space [13].

4.5 Installation of a ventilated containment space

Ventilated spaces such as a crawl space (Figure 7), a cavity wall, an underfloor space, or a basement or cellar, acting as containment spaces, may be used to dilute Rn, making difficult the diffusion of Rn towards habitable rooms of the building.

In new buildings, it is always recommended to install a ventilated crawl space or at least an aerated floor wherever possible [15].

In building renovations, an aerated floor can replace completely an existing floor or can be placed over existing slabs if a higher finished floor elevation can be accommodated (Figure 8).

In new buildings with basements, cavity walls ventilated with outdoor air can be constructed. During building renovations, such cavities can be added to the outside (Figure 9) or the inside of an existing basement wall when there is enough room for it and it is possible to connect it to the exterior.

Improvement of ventilation below the ground floor is effective up to Rn concentrations of 700 Bq/m^3 (passive) or 850 Bq/m^3 (active), in some cases making it possible to achieve success up to 1,200 Bq/m^3 [14]. Some regulations allow the use of this system on its own only up to 600 Bq/m^3. From this level of Rn up, this system must be combined with a Rn barrier [16].

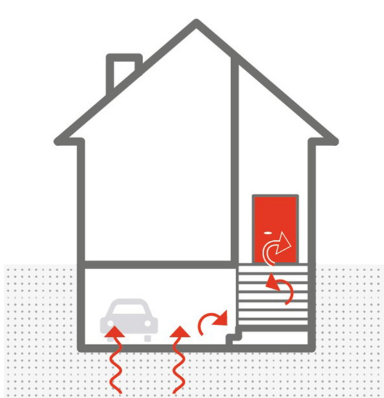

Figure 6: Access door to basement, [13].

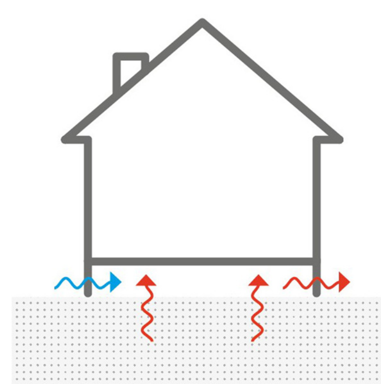

Figure 7: Ventilated containment space, [13].

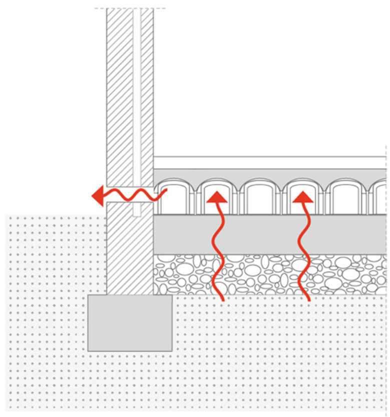

Figure 8: Aerated cavity floor placed over an existing floor slab. (1) Prefabricated pieces, [13].

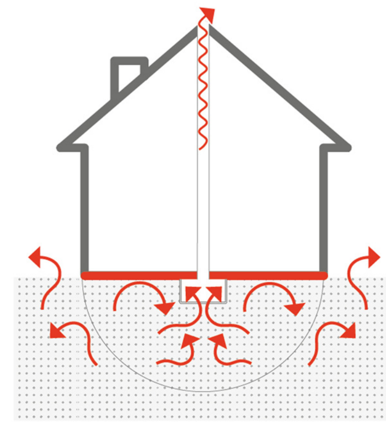

Figure 10: Sub-slab depressurization, [13].

4.6 Installation of a sub-slab depressurization system

One of the most widespread and successful protection techniques used to reduce Rn infiltration into buildings is soil depressurization (Figure 10) (for Rn levels up to 2,000 Bq/m^3 or higher), provided the soil is sufficiently permeable [14,15,17].

It consists of a single underground sump, multiple sumps, or perforated pipes, into which exhaust pipes are inserted aiming to suck out the Rn-laden air existing in the land, immediately below the ground floor of a building, discharging it harmlessly into the atmosphere [6,14,15].

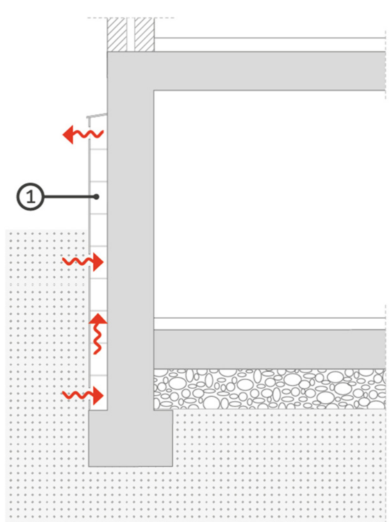

Figure 9: Ventilated cavity added outside an existing basement wall. (1) Prefabricated pieces, [13].

A sump is an underfloor space or cavity. Extraction can be passive, relying on natural stack effect and wind action, or active, with the use of an electric fan, which is a more effective system (Figure 11).

The effectiveness of this solution depends to a large extent on the permeability of the substrate in contact with the building (fill layer) and the tightness of the enclosure in contact with the ground.

For optimal effectiveness, the permeability of the substrate and the tightness of the enclosure must be high. This way, the presence of negative pressure fields is favored by high permeable backfill material, such as gravel, but is hindered using compact natural soil. Sub-slab obstacles, such as the presence of foundations within the substrate, will affect the level of efficacy of this solution. When the floor slab is not sufficiently airtight, pressure field restrictions also occur.

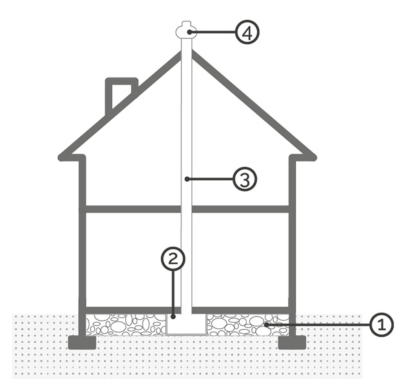

Figure 11: Components of a depressurization system. (1) Gravel layer, (2) sump, (3) exhaust pipe, and (4) electric fan, [13].

Sumps can be prefabricated or constructed on-site. Instead of sumps, perforated pipe networks can be used as well. Increasing the number of sumps or suction points in perforated pipes is more effective than increasing the power of the extraction fan.

The pipes that pass through the façade connecting sub-slab pipework with external vertical ducts have no perforations. Pipes' diameter can vary from 60 to110 mm.

The best location for the exhaust outlet for dissipating Rn away from the building is on the roof. Other low-level location is possible when there is no possibility of re-entry of Rn into the building.

The centrifugal fan must have an adequate power (usually 70 W) and must be located at an intermediate point of the vertical duct. In the case of an internal duct, the fan must be placed close to the exhaust outlet to ensure all internal pipework is under pressure. This way, in case of leakage, the chance of Rn-laden air entering the building is limited. In the case of a duct placed outside the building, the fan can be placed at a low level (for facilitating maintenance) because the risk of Rn-laden air entering the building from the duct is low, and it must contain a by-pass to prevent condensation or seepage water from coming in contact with it.

For the design of this solution, the number of fans needed and their location must be considered, and the reduction in problems associated with the installation, such as noise, aesthetic effects, efficiency, maintenance, etc., must be taken into account [13–15].

4.7 Use of drainage systems

In complement, drainage systems can be used to reduce Rn intake in new or in existing buildings, according to one of the following methodologies, [14,15]:

- Placement of a ventilation duct connected to a fan inserted in a tank for collecting and pumping rainwater from the ground, installed in the basement, exhausting it to an outlet located above the roof of the building, ensuring that the water tank cover can be removed, when necessary, to allow maintenance of the water pump installed in the tank.
- Connection of perforated drain pipes, installed under the ground floors, for water drainage, to a ventilation system consisting of ventilation ducts (including exhaust ducts) and mechanical fans, ensuring that any emergency points of this duct on the ground surface, installed for inspection, are closed by valves so as to allow the fan to build up a low pressure while allowing the water to drain.
- Rn aspiration system through the depressurization of the lower area of buried walls formed by perforated bricks or blocks.

Active systems are more effective than passive systems. The degree of effectiveness of this solution may be like that of underground depressurization systems.

4.8 Ventilation of habitable spaces

The installation of ventilation systems in the building should be foreseen to guarantee ventilation and indoor air quality in common spaces and basements of the building [14,15], to reduce Rn concentration.

Ventilation will have to be proportional to the level of occupancy; that is, it should be duly proportional to the number of occupants considering the volume of the space to be ventilated. Thus, adequate ventilation rates should be established after an assessment that takes into account indoor air quality (IAQ) and energy saving requirements, as well as possible depressurization that could draw Rn-laden air from soil to the building [13].

In new buildings, ventilation rates must comply with indoor air quality regulations, which usually specify minimum ventilation rates depending on the use of the space or building. Additionally, ventilation rates should be in accordance with energy saving regulations, so energy loss due to ventilation is within an adequate threshold. A balance must be found between both requirements [13].

In existing buildings, this solution can be used when ventilation is poor and does not comply with the minimum requirements specified in the IAQ regulations.

In existing buildings, when ventilation is adequate and complies with the minimum requirements specified in the IAQ regulations, an assessment in relation to energy saving and IAQ must be carried out to determine the viability of increasing ventilation rates [13].

In the case of mechanical ventilation, a depression could be produced favoring the entry of Rn from the ground through gaps and cracks. To avoid this effect, it is recommended to implement ventilation of double-flow (balancing the extraction flow and supply of air) or increase the air intake openings [14].

In general, ventilation of habitable spaces, on the upper floors, is effective for Rn concentrations lower than 600 Bq/m^3, particularly when it is close to 300 Bq/m^3. It is recommended to complement it with other mitigation methods such as Rn barrier, sealing, or ventilated containment space [13].

Although active systems (mechanical ventilation) are more effective in the buried floors than passive systems

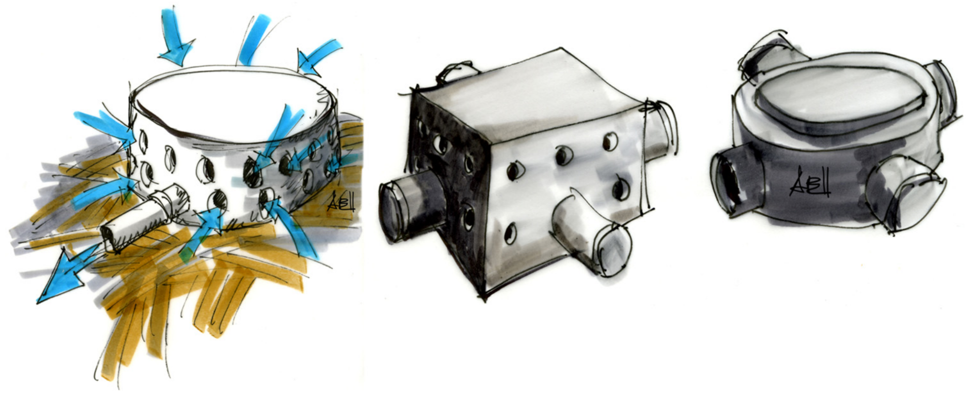

Figure 12: Prefabricated sumps [15] (courtesy of architect António Batista Coelho).

(natural ventilation), in new buildings, it is always recommended to install a passive system and later, if necessary, convert it into an active system by installing a fan in the exhaust conduit [15].

4.9 Combined solutions

When the concentration of Rn in soil is high, the protective solutions may need to be combined [13,16].

When there are several types of foundation in the same building, it may be also necessary to apply a combination of Rn mitigation techniques to levels converging with the reference level.

5. Materials and products

5.1 Sumps

There are several types of underground sumps, namely, prefabricated solutions, which can be easily and quickly installed under the ground floor of new buildings [15]. Prefabricated sumps are generally made up of plastic material or composites (Figure 12).

Sumps can also be built on site using, e.g., perforated bricks (or not) arranged in a honeycomb pattern, so as to build a box around the end of the exhaust pipe, leaving the vertical joints open and applying mortar only in the horizontal ones (Figure 13).

5.2 Fans

There are three main types of fans used for moving air, axial, centrifugal (also called radial), and cross flow (also called tangential).

Centrifugal fans are considered the most efficient and versatile to move air. The scroll housing in a centrifugal fan accelerates the air and changes the flow direction twice, a total of 90°, before exiting the housing.

Exhaust fans can be made of plastic, composite, or metal.

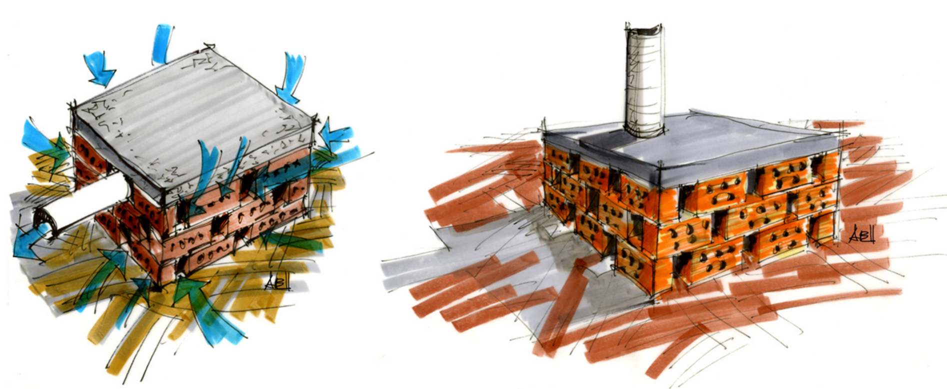

Figure 13: Built on site sump [15] (courtesy of architect António Batista Coelho).

Plastic fans are better than metal ones as they have lighter blades and smooth edges, which ensure safety during installation and also do not overload the motor. In addition to this they are more energy efficient, and corrosion and weather resistant.

PVC fans (with polypropylene blades) provide good protection for many applications in corrosive environments. However, they are more brittle and their strength decreases with the increase in temperature. PVC/polypropylene fans normally do not have metallic parts in contact with the air stream and are suitable up to temperatures of 60°C. Both polymers can withstand slightly higher temperatures when formulated with flame retardants. These plastics are resistant to many acids, caustic, and inorganic saline products used in labs.

Fans made up of fiber reinforced plastic (FRP) are highly durable, have a higher strength-to-weight ratio, and are lighter than metal fans. However, they are generally used in corrosive environments and at extremely low temperatures or reasonably higher than the ambient temperature (up to 120°C).

In contrast with FRP fans, PVC/polypropylene fans often are a more economical option. Thus, for Rn extraction, and not necessary to work in extremely corrosive environments, with hot fumes, or aggressive vapors, PVC or PP fans are better.

5.3 Exhaust pipes

The exhaust system is usually made up of plastic, usually polyvinylchloride, polyethylene or polypropylene, or composite pipes, because these materials are suitable for Rn exhaust as well as for humid environments where metals perform worse.

Plastic and composite materials are also an excellent choice for caps.

Likewise, plastic and composite materials can be used successfully in noise attenuators for air streams containing condensation products.

All joints within the pipework, with sumps and other elements shall be fully sealed.

5.4 Drainage systems

The perforated drainage pipes are commonly made up of plastic materials. Underground water reservoirs, which can also be used to extract Rn, are also preferably made up of plastic and composite materials, which are more resistant to corrosion in humid environments.

5.5 Barriers

Most common Rn barrier membranes are made up of plastic, bitumen, and composite materials that are also suitable as methane gas and water vapor barrier: thermoplastic polyolefins (high or low-density polyethylene) with smooth or textured surfaces, consisting of single layer or multilayer low-density polyethylene that can include metal (generally aluminum) or plastic layers, bituminous membranes modified with atactic polypropylene, or styrene butadiene styrene, with internal or external reinforced layers.

There are also strips or membrane profiles specifically suitable for sealing construction elements with angular areas or those whose geometry is difficult to circumvent.

Another possible solution consists of liquid gasproofing membranes.

5.6 Sealants

In order to guarantee a high level of sealing efficiency, the most suitable solution must be chosen for the type of cracks or joints to be sealed, guaranteeing adequate adhesion of the sealant to the contact surfaces [14].

The sealing of small cracks or fissures in concrete floors can generally be done using mastics or other polymeric sealants like epoxy or polyester.

In the case of small holes, sealing elements based on polyurethane foam (possibly expandable) can be applied [14].

On walls and in the joints of wooden floors in underground walls, special filling mortars are currently used [14].

To guarantee the continuity of membranes on joints and overlapping zones, double-sided tape based on acrylic adhesive is mostly used.

Around pipes, pillars, or columns that pass through the membranes, a sealing sleeve with a self-adhesive ring (based on butyl rubber or an adequate polymeric sealant) must be used.

6. Main remarks and conclusion

Many of the Rn protection measures listed can be routinely installed in new buildings during construction but are more difficult to implement in existing buildings [14,15], alike in other retrofit implementation measures.

In addition, these solutions are not suitable for all types of buildings, nor for all levels of Rn concentration, and in specific cases, it may be necessary to adopt more than one solution to solve the problem of high indoor Rn concentration.

Therefore, in each protection action, a prior study must be carried out to evaluate the location of the building and the surrounding area, taking into account the exhalation of Rn from the ground, groundwater, or free surface water, to ensure that the most appropriate protection techniques are implemented, which may need to be combined to increase the overall efficiency in cases where there is increased risk of Rn concentration.

Finally, the study may be complemented with a cost-effectiveness of mitigation techniques.

7. Future challenges and recommendations

The management of Rn in buildings needs multidisciplinary approaches, from risk perception to technical measures to be implemented. At a strategic level, there can be economic incentives, regulation and legislation, research and technological development, new materials and techniques, training, and knowledge production through publications, to contribute to decision making and to be effective for Rn prevention and remediation.

The most relevant strategic measures, to reduce Rn problems, may be classified at various levels, and are summarized below:

a) Economic incentives:

- To create financial assistance programs for Rn measuring, testing and mitigation;
- To create favorable financing conditions for the construction of Rn resistant buildings;
- To stimulate continuous investment in innovation for Rn protection technologies;
- To promote and reward pioneering innovation on Rn technologies;
- To reduce VAT for Rn products and technologies.

b) Regulation and legislation:

- To develop regulations that allow new buildings to use Rn resistant construction practices, particularly in Rn prone areas;
- To support Rn policy activities;
- To support the development of indicators of protection efficiency and performance in the construction sector.

c) Research and technological development

- To encourage research and technological development in the area of Rn technologies, particularly in the field of depressurization, range of action of sumps, design and sizing of the system, etc.;
- To compile environmental product declaration data for selected building construction materials and Rn protection products.
- To develop barriers or outdoor coatings made of nanomaterials to reduce Rn diffusion.
- To develop solutions based on reverse osmosis, due to the fact that exterior paints must prevent Rn from entering while interior paints should allow the escape of gas and vapors which in the meantime are concentrated in the interior environment, in particular, in the case of double walls with an air gap.
- To develop prefabricated composite sumps with higher resistance
- To minimize radioactive components in construction materials, through new compositions.
- To develop more energy efficient solutions, including the use of lighter and more efficient construction materials, either used in fans or in energy recovery systems.
- To increase the use of recycled and more environmentally friendly materials in protection systems.

d) Training and knowledge production through publications

- To promote training and training actions, providing workers with knowledge on Rn protection systems and how to install them;
- To promote multifaceted communications and public awareness campaigns to improve awareness of Rn;
- To implement or increase Rn education at schools.

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