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SOLUTIONS FOR RADON PREVENTION AND MITIGATION IN BUILDINGS

Luís Pimentel Real
Laboratório Nacional de Engenharia Civi (LNEC), Lisboa, Portugal

João Viegas
Laboratório Nacional de Engenharia Civi (LNEC), Lisboa, Portugal

Jorge Patrício
Laboratório Nacional de Engenharia Civi (LNEC), Lisboa, Portugal

Alcides Pereira
Univ Coimbra, IDL, Department of Earth Sciences, Coimbra, Portugal

José Costa
Univ Coimbra, ADAI, Department of Mechanical Engineering, Coimbra, Portugal

Pilar Linares- Alemparte
Instituto de las Ciencias de la Construcción Eduardo Torroja (CSIC), Madrid, Spain

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Abstract: Radon (Rn) is the largest natural source of ionizing radiation and exposure to high levels of this gas and its short-lived offspring over prolonged periods can become a public health problem. Radon exists in soils and building materials and can enter buildings by convection through cracks in the envelope or by diffusion through the envelope itself when it is porous, reaching concentrations above the recommended reference levels. The aim of this article is to present the factors that most influence the potential of radon gas in buildings and to indicate the main technological solutions for controlling, reducing and mitigating its effects. Calculations are presented showing that the proper sizing of membranes and ventilation systems ensures indoor air quality, whatever the level of radon in buildings. The conclusions highlight the importance of ventilation technologies in radon reduction systems, as well as their effectiveness in both preventing radon gas from entering and reducing its concentration once it has entered the building. Also noteworthy is the ability of protective barriers to insulate the building envelope, provided they are properly sized with the appropriate mechanical characteristics, with a special focus on installation requirements. Finally, the main future developments are outlined, with a view to ensuring greater sustainability of the materials, products and protection systems used.
Keywords: Buildings, Radon, Prevention, Mitigation, Indoor air

INTRODUCTION

The problem of radon has been the subject of many research studies and interventions around the world (Khan *et al.* 2019). In order to minimize this problem, there are publications dedicated to various mitigation systems, such as barriers from protection (Jiránek n/d), ventilation under the first floor (Scivyer 2012), positive pressurization and depressurization systems (Scivyer 2013ab), among other solutions. Similarly, research studies on construction materials used in buildings where exposure to ionizing radiation is not negligible are also available in the scientific literature (Aladeniyi *et al.* 2021), (Baeza *et al.* 2018), (Domingos *et al.* 2021), (Madruga *et al.* 2019), (Mustonen *et al.* 1999), (Pereira *et al.* 2012), (Pereira *et al.* 2013), (Ramadan and Ubeid 2018), (Siegesmund *al.* 2022). The presence of radon in water has also been the subject of several studies (Di Carlo *et al.* 2019), (EPA 2012), (Martins *et al.* 2019).

Radon (Rn) emanates from soil rocks as a result of the radioactive decay of natural elements such as uranium and radium, which causes the release of energy. The migration of radon in the soil, resulting from the mechanisms of diffusion (transport, dragging through the porous volume of the soil), emanation (escape through interstitial spaces) and exhalation (release into the atmosphere through the soil surface), is influenced by the permeability of the soil, taking into account various factors, including porosity, the degree of cracking, its composition, granulometry, temperature and pressure gradients and moisture content, among others (Thu, Thang and Hao 2020).

Although radon can also exist in building materials, the radon flux from the ground is about two orders of magnitude higher than that from building materials, with the contribution of the ground to the radon concentration inside buildings being about 80% and building materials only the remainder (Swiss Radon handbook, 2000). It should be noted, however, that the results of radon concentration in building materials also show great variability (Nuccetelli, Leonardi, Trevisi 2020).

The scope of this article is to list the factors that influence the level of radon in buildings and to present some technological solutions that make it possible to control, reduce and mitigate the effects of radon gas in buildings, highlighting the importance of protective barriers and ventilation in fulfilling this objective, with a focus on compliance with good construction rules during the installation of these solutions, in order to guarantee the protection of people from radon.

FACTORS INFLUENCING RADON CONCENTRATION

The concentration of radon inside buildings can vary depending on a number of factors, the most important of which is the type of soil and its permeability, where the concentration can be 1000 times higher than inside. However, climatic conditions, the characteristics of the building and the permeability of the surroundings can also be very relevant to changes in radon concentration in the same building and its variability between different buildings on the same site, respectively (Linares and Ortega 2020).

Soils derived from granitic rocks are generally associated with greater radon production capacity. On the other hand, the permeability of soil determines how easy it is for the gas to migrate, controlled in particular by porosity and its type, cracking and water content.

Given the higher density relative to air, the concentration of radon is usually higher in spaces located close to the ground (ground floor, basements and semi-basements). However, other factors, such as exhalation from existing building materials, unsealed interior communications (such as a continuous staircase between the basement or ground floor and the top of the building, without landings or fire doors at landings, and elevator shafts), which allow the gas to rise by chimney effect (when the temperature inside is higher than outside) and can lead to its accumulation if there is inadequate ventilation.

The location of the building and the direction of the prevailing winds also influence the level of radon in buildings. There are cases in which the pressures generated by the wind can either promote the transport of the gas through the soil (if it is permeable) to the inside of basements, or, on the other hand, and in most cases, dilute and drain the radon to the outside (due to the increased ventilation caused by the association of positive pressures on the windward façades and lower pressures on the other façades).

The type of foundations is also a relevant factor, as ventilated air vents reduce the amount of radon entering the building's living area.

The air permeability of building floors, particularly near the ground, has a major influence on the flow of radon gas from the ground into the interior of built spaces.

The type of partially or fully buried basement walls and their permeability also influence the entry of radon.

Transfer to the inside of buildings is obviously greater in the absence of protective barriers, with cracking (in conjunction with humidity) and the porosity of the constituent materials (site rock, brick, stone, mortar) of floors and ceilings.

The type of intermediate flooring that separates basements from the floor immediately above and below is as important as the greater the concentration of radon on the lower floors, with the most unfavorable case being wooden floors (or their derivatives), which have joints between the boards, or false ceilings that are not completely watertight (Real *et al.* 2020a). On the other hand, monolithic or lightened reinforced concrete slabs, or lightened slabs with prefabricated elements (e.g. beams and vaults) are the least permeable to radon, provided that there are properly sealed joints, resulting from the slab being crossed by several pipes, and that there is no cracking in the floor's constituent materials (Real *et al.* 2020a).

Openings between basements and upper floors also play an important role in radon transport if they are insufficiently airtight (Real *et al.* 2020a). Doors with air permeability class C or D, according to EN 12207, are suitable from the point of view of airtightness (Linares and Ortega 2020), contributing to the reduction of radon concentration.

In any case, whether it's foundations, walls or floors, you should opt for building materials that exude less radon and are more sustainable, meeting the appropriate mechanical and structural strength requirements.

MAIN MITIGATION SOLUTIONS

MEMBRANES

A protective barrier or membrane consists of a continuous laminar element made of flexible plastic or composite material, placed between the space to be protected and the ground, and whose effectiveness can be demonstrated. These membranes can also act as a barrier against the capillary rise of groundwater (Real *et al.* 2020ab).

The most important requirements to guarantee the effectiveness and durability of the membranes are as follows:

- Quality installation in continuity, without cracks, with sealed joints and abutments, using pre-formed components or compatible products, particularly in situations where pipes, columns and pillars cross (Real *et al.* 2020ab), (Linares and Ortega 2020).

- Application with guaranteed resistance appropriate to its use.

- With a technical specification that includes a set of performance characteristics, supported by documentation issued by qualified entities, including essential test results (radon diffusion coefficient, dimensional characteristics, reaction to fire classification, water vapor transmission, tensile properties, tear resistance and content, emission and/or release of hazardous substances), among other characteristics specific to the type of materials that make up the membranes.

- Adequate durability for the useful life of the building, not less than 25 years.

Below are typical illustrations of the installation of membranes below and above the floor slab, figures 1 and 2 respectively. The installation shown in figure 1 is typical of installation in new buildings, while figure 2 is more representative of installation in existing buildings, above buried basements (with a periscopic opening for ventilation). Other examples would be possible, such as installations over an air gap, over suspended floors, complemented or not by the installation of membranes on exterior or interior walls.

Methodology for sizing the radon protection membrane

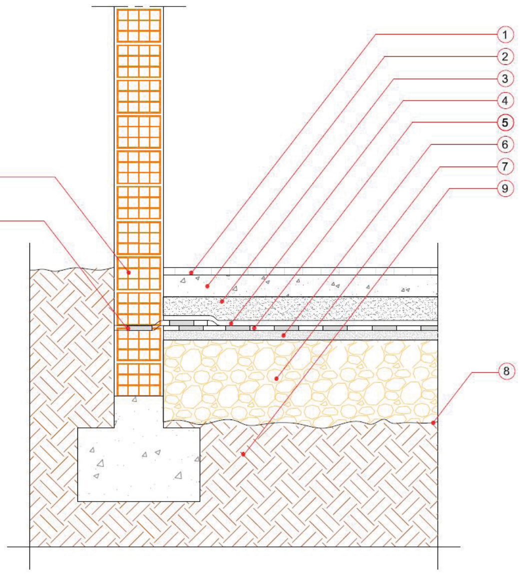
The membrane must have a thickness and diffusion coefficient such that the radon flux on its surface (E) is less than a given threshold value (E_{lim}). This is expressed in Bq/m^2.h and is determined by the following expression (DBHS6 2019):

$$E_{lim} = C_d \cdot \frac{Q}{A} \qquad (1)$$

in which:

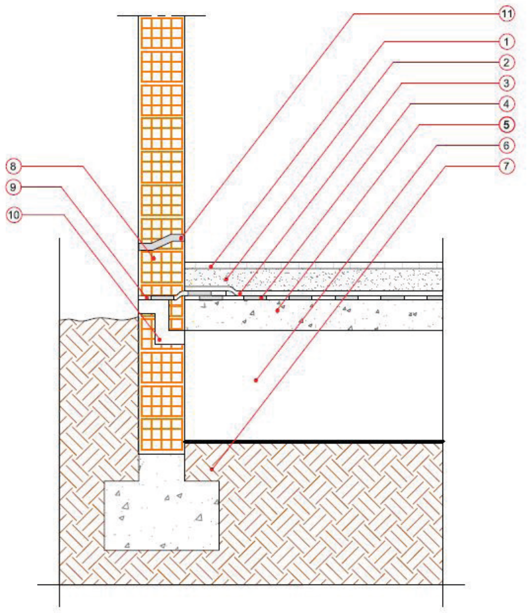
C_d is the design concentration, which corresponds to 10% of the reference level ([Rn]=300 Bq/m^3);

Q is the ventilation flow rate of the premises to be protected (m^3/h), which depends on the volume of the space and the air renewal rate. If the value of the ventilation rate is not defined according to the type of room (bedrooms, kitchen, bathroom) or is unknown, a minimalist flow calculation corresponding to 0.1 renovations/hour can be considered;



1. New floor covering
2. Concrete floor
3. Regularized screed
4. Desolidarization layer
5. Radon barrier membrane
6. Cleaning concrete layer (if any)
7. Rockfill
8. Geotextile
9. Ground
10. Radon protection band (if possible)
11. Brick mansonry (or dressed stone)

Figure 1 - Membrane under the slab applied to the ground (new buildings)



1. New floor covering
2. Regularized screed
3. Desolidarization layer
4. Radon protection membrane
5. Concrete floor
6. Buried basement
7. Ground
8. Brick mansonry (or dressed stone)
9. Radon protection strip (if possible)
10. Periscopic ventilation opening
11. Cavity tray (with damp-proof course DPC)

Figure 2 - Membrane on the slab applied over a buried or semi-buried cellar

$A = V/h$, is the surface area of the membrane (m^2), equivalent to the area of the compartment to be protected, V the volume and h the height.

In the absence of specific studies, the predicted radon flow rate through the barrier (E) can be estimated from the following expression (DBHS6 2019):

$$E = \frac{3 \cdot 10^5 \cdot \lambda \cdot l}{\sinh\frac{d}{l}} \quad (2)$$

in which:

λ is the decay/disintegration constant of radon (7.56 x 10^3 h^{-1});

sinh is the hyperbolic sine;

d is the thickness of the barrier, in m;

l is the linear dimension of the radon penetration into the barrier, in m, calculated according to equation (3) (DBHS6 2019):

$$l = \sqrt{\frac{3600 \cdot D}{\lambda}} \quad (3)$$

where *D* is the diffusion coefficient of the radon barrier (in m^2/s).

When the value of radon exhalation from the ground (C_s) is known, eq. 2 is replaced by eq. 4 (ČSN, 2019):

$$E = \frac{\alpha \cdot C_S \cdot \lambda \cdot l}{\sinh\frac{d}{l}} \quad (Bq/m^2 \cdot h) \quad (4)$$

in which:

α is the safety coefficient, which can take the following values:

a. For basement walls in contact with permeable soil or backfill: α=1;

b. In other cases: α can be obtained from Table 1, depending on the air permeability of the soil and whether or not there is an additional ventilation system.

Air permeability of the soil	No additional ventilation system	With additional ventilation system	
		Natural	Mechanic
Low	2,1	1,5	1,0
Average	3,0	2,0	1,0
High	7,0	4,0	1,0

Table1 - Coefficient of safety α

Results of the radon protection barrier sizing

Table 1 shows typical results for membrane sizing calculations in cases where the radon flux from the soil is unknown, determining the thickness *d as* a function of the membrane's diffusion coefficient *D* in order to meet the condition ($E < E_{lim}$). As can be seen from Table 1, as the radon diffusion coefficient (*D*) of the membranes increases, the thickness must also be increased to guarantee a satisfactory result. Thus, for a maximum value of D=1x10^{-11} m^2/s a minimum thickness of 1.3 mm must be guaranteed, while for a maximum value of D=1x10^{-12} m^2/s a membrane with a thickness of 140 μm is sufficient.

In Table 3, a similar analysis is carried out to assess radon exhalation from a very permeable soil, which allows the same results to be obtained with the same membranes considered in Table 2, therefore maintaining the values of the variables C_d, Q and E_{lim}.

VENTILATION

With the exception of membranes, all radon prevention and mitigation systems in buildings use passive (natural) or active (mechanical) ventilation technologies, particularly in containment spaces, in basement depressurization systems and with ventilation of living spaces. All of these systems can, however, be complemented with the installation of membranes in order to increase the overall effectiveness of radon protection, particularly when the gas level is high.

Ventilated containment space

Ventilated containment spaces, such as an air gap under the floor (sanitary basement) or inside double walls, or a rarely used basement, can be used to dilute the radon that fills this space by means of ventilation, making it difficult for this gas to flow into the habitable rooms of the building, thus acting as a radon containment space. These solutions are appli-

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C_d	30						
Q	27						
E_{lim}	8,1						
D	1×10^{-10}	1×10^{-11}	1×10^{-11}	1×10^{-12}	1×10^{-12}	1×10^{-13}	1×10^{-13}
l	0,00690	0,00218	0,00218	0,00069	0,00069	0,00022	0,00022
d	9×10^{-3}	$1,3 \times 10^{-3}$	$1,2 \times 10^{-3}$	$1,4 \times 10^{-4}$	$1,3 \times 10^{-4}$	$1,4 \times 10^{-5}$	$1,3 \times 10^{-5}$
E	9,2	7,8	8,6	7,7	8,3	7,7	8,3
$E < E_{lim}$	Non-compliant	Compliant	Non-compliant	Compliant	Non-compliant	Compliant	Non-compliant

Table 2 - Results obtained for a room with a surface area of 100 m^2 and a height of 2.7 m, without knowing the radon exhalation in the soil

E_{lim}	8,1						
C_S	40000	80000	150000	150000	80000	200000	80000
D	1×10^{-10}	1×10^{-11}	1×10^{-11}	1×10^{-12}	1×10^{-12}	1×10^{-13}	1×10^{-13}
α	7	7	7	7	7	7	7
l	$6,90 \times 10^{-3}$	$2,15 \times 10^{-3}$	$2,18 \times 10^{-3}$	$6,90 \times 10^{-4}$	$6,90 \times 10^{-4}$	$2,18 \times 10^{-4}$	$2,18 \times 10^{-4}$
d	$9,3 \times 10^{-3}$	$1,1 \times 10^{-3}$	$3,2 \times 10^{-3}$	$4,5 \times 10^{-4}$	$2,4 \times 10^{-4}$	$6,2 \times 10^{-5}$	$2,4 \times 10^{-5}$
E	8,1	7,5	8,4	7,8	8,2	8,0	8,4
$E < E_{lim}$	Non-compliant	Compliant	Non-compliant	Compliant	Non-compliant	Compliant	Non-compliant

Table 3 - Results obtained for a space with a surface area of 100 m^2 and a height of 2.7 m, knowing the exhalation of radon in a highly permeable, unventilated soil

cable to both new and existing buildings (Linares and Ortega 2020), (Real *et al.* 2023).

Underground depressurization system

One of the most effective protection techniques for reducing the radon flux in buildings is underground depressurization, which consists of a single underground reservoir or several reservoirs in which exhaust pipes are inserted to suck up the radon-contaminated air in the ground and discharge it harmlessly into the atmosphere (Real *et al.* 2020ab), (Scivyer 2013b). Extraction can be passive, based on the chimney effect and the action of the wind, or active, using an electric fan.

For optimum efficiency, the permeability of the substrate in contact with the building (infill layer) should be high and the air permeability of the space in relation to the ground should be low, so the system should ideally be supplemented with membranes.

Water drainage systems can be used in a similar way and with practically the same level of efficiency (Real *et al.* 2020ab), either by placing a ventilation duct inserted in a tank for collecting and pumping rainwater from the ground, installed in the basement, or by using perforated drainage ducts, installed under the first floors, to drain water; in both cases using a ventilation system consisting of ventilation and exhaust ducts.

Ventilation in living spaces

Ventilation is necessary to ensure the quality of indoor air in living spaces and reduces the concentration of radon. It should be greater the higher the degree of occupancy, i.e. it should be duly proportional to the number of occupants, taking into account the volume of the space to be ventilated.

In new buildings, ventilation rates must comply with IAQ (Indoor Air Quality) regulations, which usually specify minimum ventilation rates depending on the use of the space or building, and a balance must be ensured with energy conservation regulations (Linares and Ortega 2020). For new residential buildings, Portuguese regulations stipulate a minimum value for natural ventilation corresponding to 0.5 air changes per hour (RPH) (Ordinance n.º 138-I/2021).

Figure 3 illustrates the effect of ventilation to ensure that the radon concentration in the indoor air of an inhabited space in a building, located in a risk zone and with the ground floor in direct contact with the ground, does not exceed a reference limit considered safe ($[Rn]_{ref}$=300 Bq/m^3). The simulation is based on the transient differential equation for radon concentration, whose solution translates its temporal evolution $C(t)$ in a control volume, in Bq/m^3:

$$C(t) = C_{equil} + (C_0 - C_{equil}) \cdot e^{-(\lambda+n)t} \quad (4)$$

where C_{equil} is the equilibrium concentration at steady state (*i.e.*, when $t \rightarrow \infty$), in Bq/m^3, given by:

$$C_{equil} = \frac{E \cdot A}{(\lambda+n)V} \quad (5)$$

C_0 is the initial concentration ($t=0$) of radon in the indoor air, V (m^3) is the effective volume of the space under study, n (h^{-1} or RPH) is the air renewal rate, which corresponds to a ventilation flow rate $Q= n \cdot V$ (m^3/h), and the other parameters are defined in the figure. The flow rate E [Bq/(m^2.h)] is commonly referred to as the exhalation rate and the product $G=E \cdot A$ (Bq/h) as the radon generation rate. It should be borne in mind that the deduction of the basic differential equation and its solution (Eqs. (4) and (5)) are based on the following simplifying assumptions: (*i*) the ventilation flow rate and the radon generation rate are constant in time; (*ii*) the dilution of the pollutant is perfect, *i.e.*, the concentration of radon in indoor air is uniform throughout the space at any time *t*; and (*iii*) the concentration of radon in outdoor air is considered negligible, which is plausible for this pollutant, given the values in indoor air in the cases under study.

The graph in Figure 3 represents the effect of ventilation in a case of decontamination (*e.g.* of a house located in a risk zone that had been unoccupied and without significant ventilation). On the other hand, Eq. (5) is useful for determining the design value of the required ventilation flow rate; in fact, by making it explicit in n, in h^{-1}, it can be written:

$$n_{min} = \frac{G}{C_{equil} \cdot V} - \lambda \quad (6)$$

In the case shown in Figure 3, the objective was to guarantee C_{equil}=250 Bq/m^3, a radon concentration value lower than the reference limit ($[Rn]_{ref}$=300 Bq/m^3), represented in the graph by the horizontal line with a red interrupted line. On the one hand, this option makes it possible to better illustrate the decontamination effect; on the other hand, it constitutes an additional safety margin, which is advisable at the design stage, given the great real variability of the radon flux coming from the ground. Thus, Eq. (6) shows that in this case, with a radon flux of $E=60$ Bq/(h.m^2), the minimum ventilation rate required is $n \approx 0.1$ h^{-1} (RPH), which is equivalent to a ventilation flow rate of 7.7 m^3/h.

Using Eq. (4), and looking at the graph in Figure 3, it can be concluded that, in this decontamination process with that minimum level of ventilation, the reference limit would only be reached after 32 hours. However, if the regulatory requirement for natural ventilation (VN) for new residential buildings is taken into account, $n=0.5$ RPH, the decontamination period would be reduced to just 3.85 hours. It can also be concluded that, even in a very high risk situation, *i.e.* considering a radon flux 5 times higher, $E=300$ Bq/(h.m^2), the natural ventilation requirement mentioned above would be sufficient to guarantee good IAQ in this living space, in terms of radon

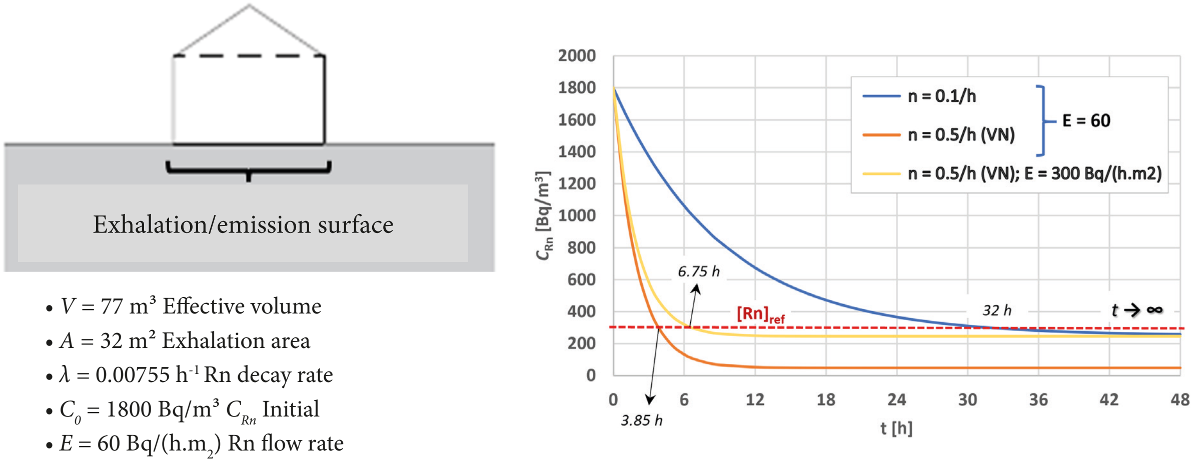
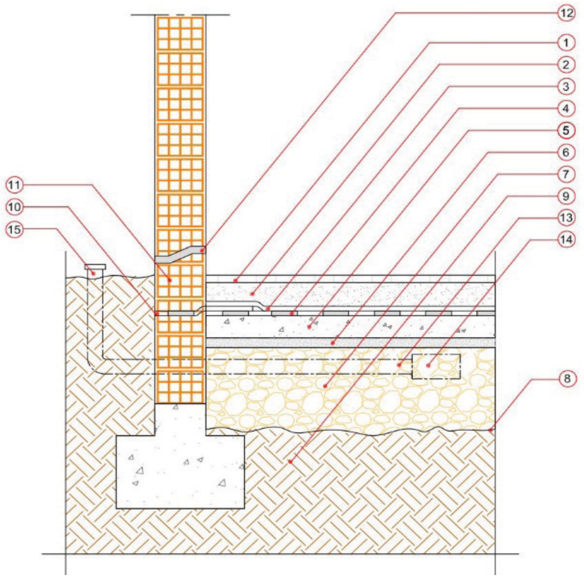
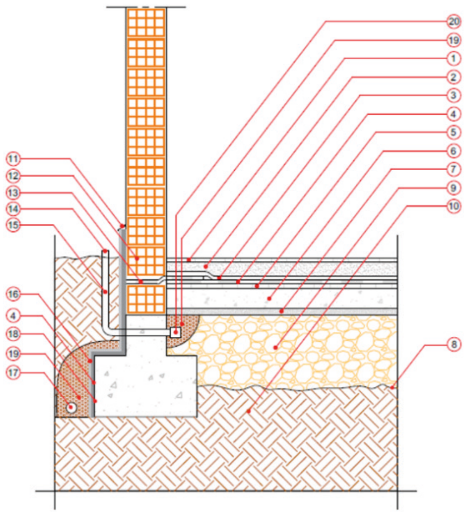


Figure 3 - Example of the effect of permanent natural ventilation (NPV) in a living space initially contaminated with radon



1. New floor covering
2. Regularized screed
3. Desolidarization layer
4. Radon barrier membrane (below the slab)
5. Concrete sab
6. Cleaning concrete layer (if any)
7. Rockfill
8. Geotextile
9. Ground
10. Radon barrier band (if possible)
11. Brick masonry (or dressed stone)
12. Damp-proof membrane (DPC with cavity-tray)
13. Pipeline of depressurization system
14. Sump
15. Capped-off sump pipe

Figure 4 - Depressurization system underground with a membrane applied on the slab



1. New floor covering (tiles, stone, etc.)
2. Regularized screed
3. Desolidarization layer
4. Radon protection barrier
5. Existing floor covering (or primer, if there is none)
6. Concrete floor (sill slab)
7. Concrete cleaning layer (if any)
8. Geotextile
9. Rockfill
10. Ground
11. Finishing profile
12. Brick mansonry (or dressed stone)
13. Radon protection barrier (if possible)
14. Chimney - for vapor dissipation (including radon)
15. Ventilation - vapour dissipation
16. Drainage and vapor dissipation membrane (piton plate that makes an air gap)
17. Perforated drain pipe
18. Primer (eventual)
19. Separating layer, with gravel or rolled stone, wrapped in geotextile
20. Vapor dissipation box

Figure 5 - Drainage system that can be adapted for radon aspiration with a mechanical fan

concentrations. The graph in the figure also suggests that a ventilation process, passive or active, for radon prevention in residential buildings should be permanent, to guarantee the safety of occupants in terms of human health.

In the case of mechanical ventilation, a depression can be produced that favors the entry of radon from the ground through cracks and fissures, so it is recommended to install complementary membranes and implement double-flow ventilation (balancing the extraction flow and the air supply) or increase the air intake openings in order to reduce their pressure drop and thus reduce the depression inside the house (Real *et al.* 2020a).

In certain situations, particularly in single-family homes, a positive pressurization system can be installed (in multi-family homes, the pressurization of one room can allow odors generated in one room to flow to another adjacent room with a lower pressure), which consists of creating a pressure difference between the air inside the building and the underlying ground, in order to reverse the natural pressure difference. This difference is usually produced by a ventilation unit located in the attic, which is used to blow fresh filtered air into the main compartments (bedrooms and living rooms) of the living space. The increase in pressure throughout the building reduces the possibility of radon ingress and causes dilution and expulsion of radon gas, which nevertheless enters the building, so it can also be considered an insulation method (Real *et al.* 2020a), (Scivyer 2013b). The effectiveness of this solution depends to a large extent on the air permeability of the building envelope or the room to be protected, which must be low, so it is recommended to use it in combination with other solutions, such as waterproofing with a radon barrier (Linares and Ortega 2020).

Figures 4 and 5 show typical examples of the installation of ventilation systems complemented by membranes.

CONCLUSIONS

The use of membranes, provided they are properly sized in terms of thickness (taking into account the respective diffusion coefficient for radon), makes it possible to limit the flow of radon coming from the ground or from materials that make up the building's construction solutions (walls or floors).

It is important to note the possible existence of areas of discontinuity in the membrane (rupture of the membrane, joints between membrane elements, joints with building elements, etc.), which could condition this means of limiting the radon source.

The example of implementing ventilation in inhabited spaces shows that the regulatory minimum ventilation rate is sufficient to maintain the concentration of radon in indoor air, considering current values of the radon exhalation rate from a floor of the dwelling in direct contact with the ground, below the reference limit ($[Rn]_{ref}$=300 Bq/m^3). The duration of the transient period that occurs after the ventilation is activated, until the reference limit is reached, indicates that the ventilation should be permanent.

This analysis suggests that, in cases where the concentration of radon in indoor air exceeds the reference limit, there may be a more general health problem due to low ventilation rates. It is recommended that when selecting a solution to mitigate indoor air contamination with radon, the entire health problem of the dwelling should be taken into account, and that a technique should be adopted that also mitigates the health problem, namely the implementation of a ventilation system.

From the above, it is clear that the complementarity of solutions consisting of protective membranes and ventilation systems allows for greater effectiveness in radon protection, guaranteeing adequate indoor air quality.

FUTURE DEVELOPMENTS

In terms of the materials that make up radon protection systems, future technological developments should be promoted with a view to:

- Inclusion of nanomaterials in external barriers or coatings, which also make it possible to retain contaminants.
- Minimizing radioactive components in building materials through new compositions.
- Development of liquid coatings for waterproofing building materials that are sustainable, effective, with adequate resistance and good durability
- Study of more energy-efficient solutions, including the use of lighter and more efficient materials, whether used in fans or in energy recovery systems.
- Use of recycled (and more environmentally friendly) materials in radon protection systems.

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