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MITIGATION TECHNIQUES FOR INTERIOR RADON IN REFURBISHMENT WORK IN HIGH RADIATION AREAS OF GALICIA: AN EXPERIMENTAL MODEL TO TEST BUILDING SOLUTIONS

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Abstract

Radon is a naturally occurring radioactive gas, which tends to accumulate inside built structures. It is therefore necessary to include techniques to mitigate radon concentration during refurbishing work. The aim of this study is to assess the effectiveness of a number of mitigation techniques, under real conditions, to determine which is most suitable, in each case, for use in rebuilding solutions. The methodology consisted in performing four experimental tests on mitigation strategies recommended by the Código Técnico de la Edificación (Technical Building Code) (CTE-DB-HS6) and by the Government of the Autonomous Community of Galicia, (Xunta de Galicia, 2018). The concentration was measured with three different systems: radon in soil at 80 cm, passive detectors to confirm mean concentration, and continuous monitoring by devices calibrated at the LaRUC Laboratory of the University of Cantabria, in order to compare the results of the tests. The experiments were carried out in premises located in a high radiation area in Arteixo (La Coruña, Spain). Four experimental models were designed, corresponding to each of the building solutions under study, and tested over a period of 16 days in two repeated series of trials. The results obtained show that, of the different strategies tested, pressurising the living space achieves an efficient reduction of the radon concentration with a significant simplicity of construction. This solution, compatible with the minimal intervention and reversibility principles stablished in the charters of Venice, Krakovia and Nara, is shown to be especially useful when work is carried out on structures considered to be part of protected heritage.

Keywords:

Radon;
Heritage;
Mitigation;
Refurbishment;
Air quality

1 Introduction

Radon gas build-up inside buildings is one of the leading causes of death from lung cancer in non-smokers. Concentrations of 200 Bq/m^3 may be a risk factor for this disease [1-4]. It is estimated that between 15 % and 25 % of cases of this disease stem from this specific building pathology. This value is below the limit of 300 Bq/m^3 set out in the Directive 2013/59/EURATOM [5] and doubles the 100 Bq/m^3 given as the reference level for minimising health risks from indoor exposure to radon [6, 7].

Recommendations published by national and international public bodies for radon mitigation include a selection of solutions based on different strategies [8, 9]: ventilation of premises, positive pressurisation of premises and soil, depressurisation of the soil beneath the structure, and impermeable barriers, see Fig. 1.

Floor type	Solid		Suspended	
Radon level* (Bq m^{-3})	Under 500	Over 500	Under 500	Over 500
Recommended solutions, best first	Radon sump or Positive ventilation	Radon sump	Natural under-floor ventilation or Positive ventilation	Mechanical under-floor ventialtion or Natural under-floor ventilation

Fig. 1: Recommendation chart for mitigation solutions [9].

The legal framework which sets out the Basic Requirements for mitigation with respect to radon gas in Spanish law is CTE-BD-HS6. This document includes the obligation to undertake mitigation measures in situations where there is a risk of build-up, and recommends, depending on the area at risk, three mitigation strategies, although it allows the use of equivalent alternative solutions. These requirements are not applicable during refurbishment or in areas occupied by existing buildings. The Consejería de Ordenación del Territorio y Medioambiente de la Xunta de Galicia (Environmental Department of the Galician Autonomous Government) has published manuals and technical instructions with mitigation measures to be taken in areas of special risk of radon gas build-up. These recommendations also fail to take into account the problems with implementation in existing buildings [10].

Putting these mitigation techniques into effect in existing buildings runs into many difficulties inherent in actions undertaken in an already existing structure. These difficulties derive from the interaction with other pre-existing elements, such as old facilities and services in the building, and even with issues of heritage, which must be accounted for when considering the aesthetics, health and comfort of the living space.

The question of energy efficiency must also be included. In the case of refurbishment intended to improve energy efficiency, ensuring less energy loss, the problem of the quality of the air inside the building needs to be considered, since at times the work done may lead to an increase in concentrations of interior radon [11].

2 Research question

The aim of this study is to analyse the efficiency of several mitigation methods for refurbishment, given the many variables to be accounted for in real conditions. In other words, cost of the activity, aesthetic issues, energy efficiency, comfort in terms of heat and noise, and heritage values, while also addressing questions of efficiency, economy and the minimal intervention and reversibility principles stablished in the Charter for the Conservation and Restoration of Monuments and Sites [12].

This means that a balance must be struck between the varied needs to be met and the activities to be carried out. For new buildings designed from scratch, it is more feasible to achieve compatibility between them. However, with pre-existing structures, the constraints may lead to the rejection of certain solutions, either because they cannot be carried out in a way that is compatible with other requirements, or due to the high costs involved, and therefore the result is less than ideal.

This paper seeks to show the complexity of the circumstances to be considered for different mitigation solutions. This will, in turn, allow reflection on the difficulty of balancing these solutions, and other matters that need to be addressed in any refurbishment work.

3 Materials and methods

The site chosen for the experiment is a partially buried structure in an area of high radiation [13] (Latitude: 43.29758, Longitude: -8.435155), in Arteixo, province of A Coruña, Autonomous Community of Galicia, Spain, EU.

The terrain below the construction area is made up mainly of granite, with a high degree of weathering and little consistency. The land is high in mica.

After a radon in soil test had been carried out, five measuring points around the house were determined, distributed over the plot, see Fig. 2. The measurements taken are shown in Table 1.

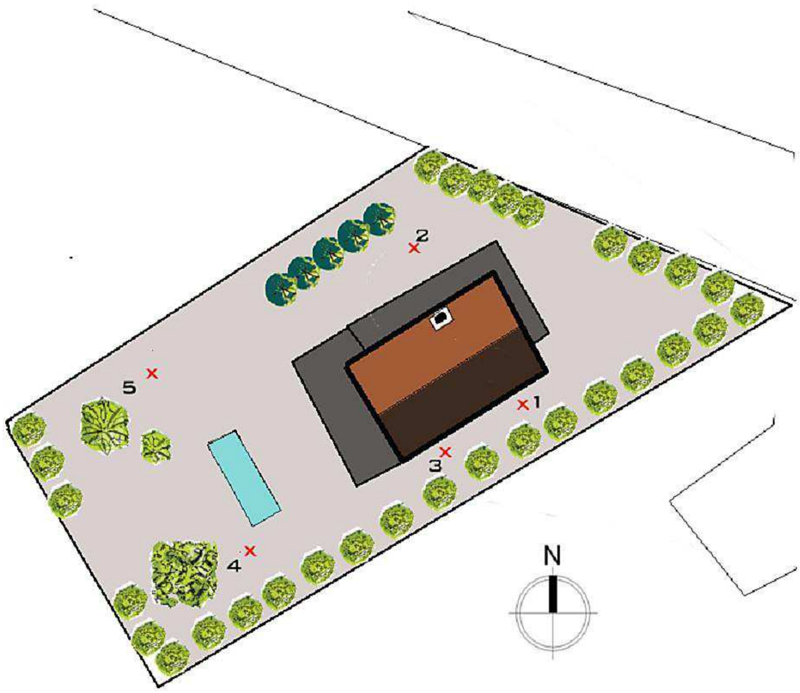


Fig. 2: Location of soil measurements around the premises.

Table 1: Results of radon in soil measurements around the premises.

Place	**Date**	**Time**	**Depth**	***C_A* [kBq/m^3]**	***RP***
1	09/07/2020	11:27	80	275	224,3
2	09/07/2020	11:34	80	95,8	77,6
3	09/07/2020	11:49	80	167	135,9
4	09/07/2020	11:57	80	120	97,4
5	09/07/2020	12:04	80	50	40,10

The highest values found are 275 kBq/m^3 measured at a depth of 80 cm in the ground immediately outside the wall of the premises. The permeability test on the soil carried out with a portable permeameter gave these results:

With $k = 0.6{\cdot}10^{-11}$ m^2. Using the classification criteria for radon potential in construction, according to the methodology given in Neznal and Barnet [14]

$$RP = \frac{c_A - 1}{-\log k - 10}\,, \tag{1}$$

where c_A is the radon activity concentration [kBq/m^3] in the soil at a given depth, and k the permeability in m^2 measured at the same depth.

The radon in soil test gave, for all points, the value of *RP* > 35, and thus, according to the Czech approach, the *RI* (risk of radon emitted from soil) would be HIGH as shown in Fig. 3.

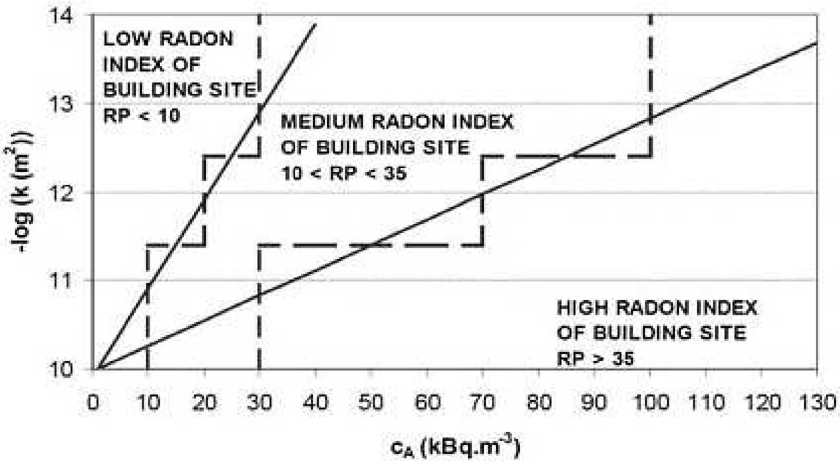


Fig. 3: Classification criteria for areas susceptible to radon [13].

The spatial characteristics of the premises are as follows: volume of air 316.46 m^3 and surface 100.42 m^2.

The building system is based on 25 cm thick reinforced concrete containing walls, a 15 cm thick reinforced concrete deck grounded on a 15 cm thick gravel layer, which is in turn placed on a 5 cm layer of blinding concrete. The southern façade consists of a 30 cm thick double layer of brick dressed in granite and local Schist.

All the openings are on this south wall, giving a total ventilation surface of 4.08 m^2.

Measurements were taken at the premises with passive radon detectors, by the LaRUC Laboratory, accredited by the Nuclear Safety Council in September 2017, and the resulting annualised concentrations were over 800 Bq/m^3.

4 Identification of sources

The data in Table 2 show that the main source is to be found in the plot bordering the building to the East, Place 1. To confirm this, a new set of radon-in-soil concentration measurements was taken by technicians from the LaRUC Laboratory, at a depth of 80 cm, with a properly calibrated ionisation chamber, giving values of 332, 269, 312, 456, and 295 kBq/m^3.

Radon enters the premises by a convective (advective) process. The convective flow is established by a difference in pressure between the substrate, where the radon is, and the atmosphere or the inside of the building. This process depends on the permeability of the medium and the pressure gradient and is modelled via Darcy's Law. [15].

The main entry points for radon were identified by continuous radon measurement, using a scintillation cell from Radon sniffer. The results show a specific concentration of 1826 Bq/m^3 at the southern wall, near the venting points and the door to the premises. The measurements in the rest of the building were between 600 Bq/m^3 and 1200 Bq/m^3. These cases arise from diffusion sources such as the cracks and fissures in the building through which the radon exhaled by the soil in contact with the outside walls on the North-eastern and South-eastern faces. Radon-in-soil concentration measures were also taken in these areas (Points 1 and 3) giving results of 275 and 167 kBq/m^3 respectively.

5 Measuring equipment

In order to quantify the effectiveness of the mitigation methods tested, continuous measurements were taken which, although less accurate, allowed differences stemming from the activation of the devices to be identified beyond doubt. Two Radon Scout devices were used in parallel, calibrated to improve the accuracy of the measurement. This simultaneous use is justified in order to check for and eliminate possible errors in the measuring equipment. Radon concentrations undergo constant, random variations, depending on multiple factors, over the period of measurement, and so measurements taken over a very short period are open to distorted interpretations. It was therefore decided to carry out two sets of measurements, repeated twice, over a period of two consecutive weeks, for each of the solutions tested.

6 Testing sequence

In order to perform the experiment, a sequence was established of 24 hours with the systems to be tested activated, followed by 24 hours with the equipment switched off, to allow the concentration to return to the initial conditions between tests for the different mitigation solutions, as shown in Figure 4. The building was closed while the measurements were taken. Monitoring was continuous, with a measurement taken every hour, over a period of 24 hours.

Forced ventilation	A2.1								A2.2						
Positive ventilation			P3.1								P3.2				
Negative radon sump					D4.1								D4.2		
Positive radon sump							E2.1								E2.2
Day	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

Fig. 4: Graph of testing sequence.

7 Preliminary actions to prepare the conditions for the experiment, sealing cracks and fissures

Radon issuing from the subsoil filters into the building through fissures and apertures because of the pressure difference. This takes place both through the parts in contact with the ground, and via the fronts and roofing. This means that one technique for preventing its entry is to seal the places where it can happen, with special attention paid to bulkheads, cable sleeving, electrical and water conduits, pipes, and in general any open passage to the outside.

After a detailed visual inspection of the premises, five kinds of entry point were identified: holes at anchor points for recoverable formwork, pipes and ducts that pass through the walls, carpentry joints, the joints of the three drains in the base of the structure, and joints where the waste pipes from sanitary facilities leave the structure.

The outlets from the casing were sealed with high density epoxy mortar. The joints and meeting points of the sanitary waste pipes were covered with PVC adhesive to ensure they were airtight. The points where the channels and pipes meet other elements of the building were injected, firstly with expanding polyurethane foam when the difference between the elements was greater than 2 cm, and then a perfect seal was ensured with a final layer of permanently elastic mono-component adhesive polymer. An acrylic sealant was used for the drains. For the woodwork joints, however, a quick-drying mono-component acidic silicon was applied which, in contact with the ambient humidity, vulcanised, forming an elastic joint.

Another entry point for radon is the tubing which protects the electric cables when they reach junction boxes and mechanisms. The decision was made to apply a bicomponent insulating silicone gel. The traps of the wastewater pipes were checked and found to be in good condition and working properly, although since radon is soluble in water, they do not guarantee that it is completely sealed. The premises were closed for the two days prior to the start of the experiment, in order to allow the concentration to rise, reaching levels of 3600 Bq/m^3 as shown in Fig. 5.

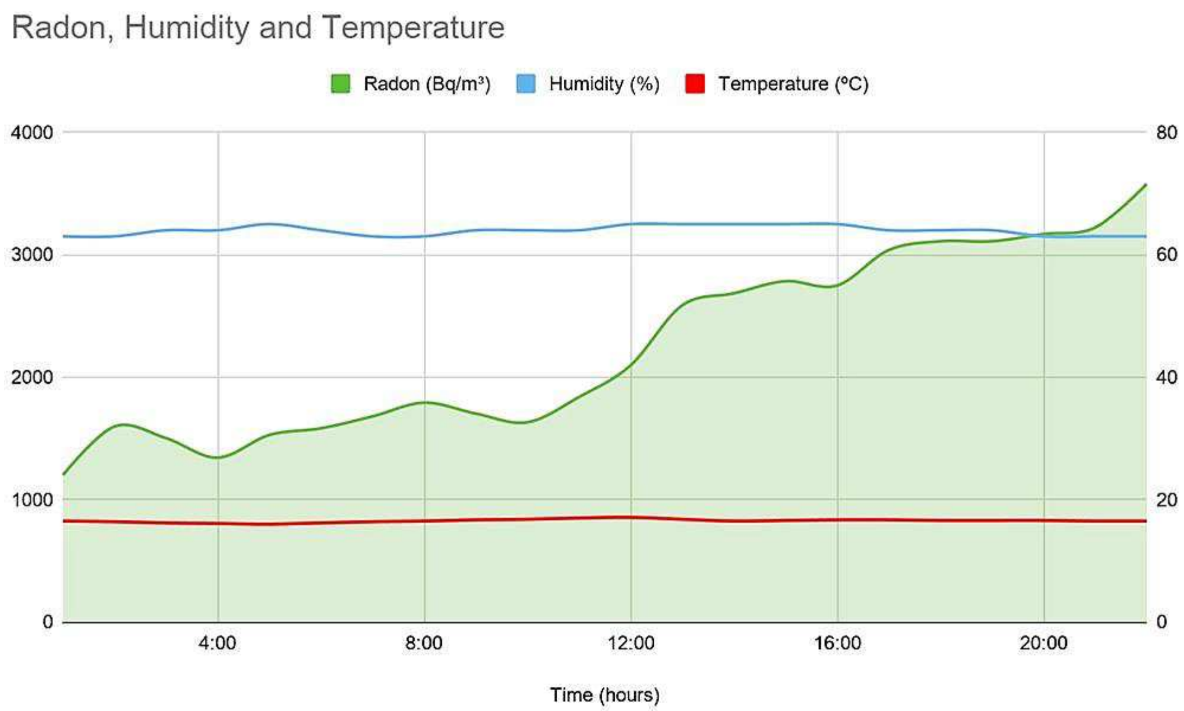


Fig. 5: Graph of radon concentration in the days before the start of the experiment.

8 Techniques tested

The methodology used was to perform four experimental trials for the active mitigation strategies recommended in the Technical Building Code [16] and in the Technical Supplement of the manual published by the Galician Institute for Housing & Land [10], specifically A2 Forced ventilation, P3 Pressurisation of premises, D4 Depressurisation of soil, and E2 Positive pressurisation of soil. In order to obtain comparable results for the dependent variable (efficiency of the strategy), the same model of fan was used for all the systems tested; the consumption, the nominal flow and the sound power are fixed, to eliminate confounding variables which could distort the results of the experiment. With respect to the other confounding variables, such as temperature, meteorological conditions, conditions of use, and variations in soil permeability, the trials were repeated sequentially to check the similarity of the results in the dependent variable.

8.1 Forced ventilation A2

Ventilation is based on replacing contaminated air from inside with air from the outside, see Fig. 6. Inside air is contaminated by harmful particles from human consumption such as CO_2, formaldehyde and others, among them radon gas. Transport is favoured by the pressure gradient between the outside and inside. The main triggering factors for this air flow are convection by temperature gradient, and the action of the wind.

1) Intake pipe 120 mm in diameter.
2) Intake fan S&P TD-350 230 V-50 HZ, 26.94 W (0.0456 m^3/s).
3) Intake diffusor.
4) Sealed chimney (cassette).
5) Sealed pipes and fissures.
6) Extraction diffusor.
7) Extraction fan S&P TD-350 230 V-50 HZ, 26.94 W (0.0456 m^3/s).
8) Extraction pipe 110mm in diameter.

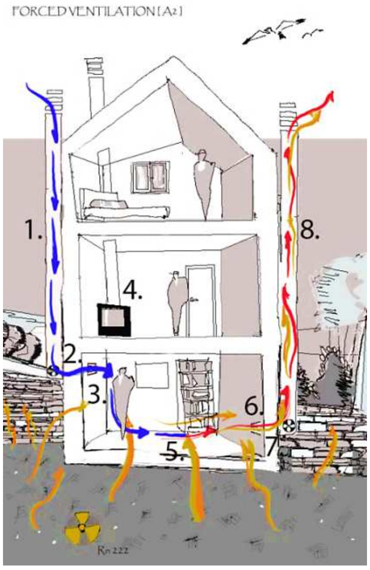


Fig. 6: Section plan of the setup.

The A group of ventilation strategies in the manual includes the following: A.1. Natural inside the premises, A.2 forced inside the premises, A.3 and A.4 natural and forced in the underground clearing space.

To set up a test of efficient natural ventilation, A.1, it would be necessary to create new strategically placed apertures in such a way as to ensure proper renewal of the air inside. This possibility was rejected, since the characteristics of the building (partially buried and clad in reinforced concrete) make it unfeasible, on grounds both of planning and cost. Thus, the ventilation strategy was only tested with the technique of forced ventilation.

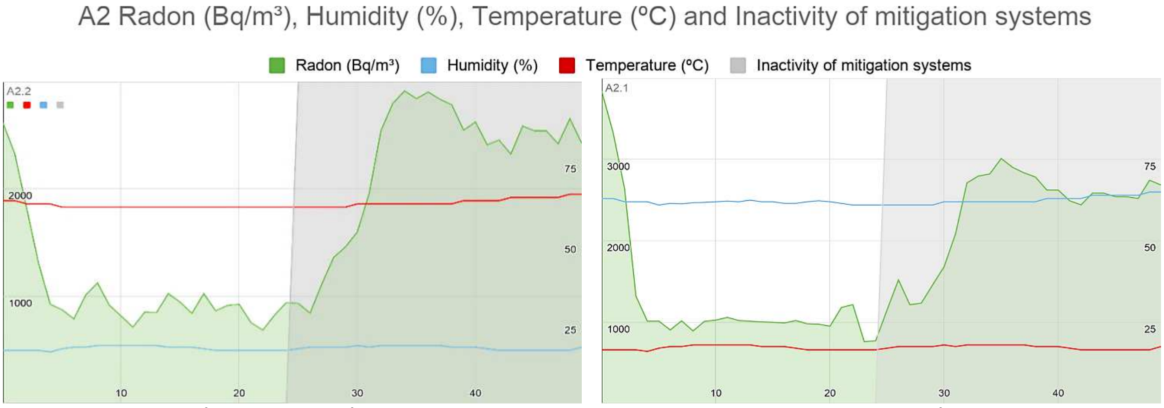
A.3 & A.4. Forced ventilation in clearing spaces were also rejected, as impossible to put into practice, since the building in question has no clearing space under the formwork.

The experiment consisted of installing a series of ventilation ducts in 120 mm diameter PVC tubes to give a renewal flow of 220.57 m^3/h, measured with a TESTO 440 thermal anemometer, across the axis of the straight section of the pipe at a distance of 1 diameter. Two in-line mixed-flow duct fans (each 230V-50HZ, 26.94W) were used, with balanced entry and exit flow, a reference flow of 0.0456 m^3/s and a reference pressure difference of 45.21 Pa. The ducts are uniformly distributed through the ceiling vault so that the flow is constant, with no dead areas, giving a ventilation flow of 61.27 l/s, 6 times greater than that required by Standard DB-HS 3 for the premises tested. Special attention was given in the experimental design to intake point for outside air since, as radon is a naturally occurring environmental pollutant, it exists in higher concentrations in lower band which is in contact with the surface of the surrounding land. It was also guaranteed that there was no exchange of pollutants between the discharged flow and the air taken in, by placing the intake and venting points on opposite walls, bearing in mind the pressure gradient produced by the prevailing winds, as high pressures reduce emission of radon from the ground [17,18]. Given all the above, the decision was taken to place the intake point at a height of +5.80 m on the East-facing wall, open to the prevailing winds.

The results for this method of mitigation were obtained by taking continuous measurements.

Once the building had been closed for 24 hours, on the 18th of January at 12:00 hrs, the ventilation system was turned on by simultaneously activating fans 1 and 2, to guarantee a continuous flow of 220 m^3/h, ensuring a renewal rate of 0.70/hour. The first measurement was taken at 12:26 hr, giving a concentration of 3841Bq/m^3.

As can be seen in Fig. 7, 5 hours after turning on the system, the concentration of radon was reduced by 3000 Bq/m^3. The concentration remained stable, with values around 1000 Bq/m^3 for the next 24 hours, during which the system continued to operate. The concentration value began to increase immediately the system was switched off, reaching levels of 3000 Bq/m^3 12 hours later. Similar results were obtained on the second sequence of tests done one week later.



First sequence, day 1 Last sequence, day 7

Fig. 7: Graph of radon concentration with the fan system operating.

This method of mitigation leads to a reduction in radon concentration although it does not allow the values recommended by the legal guidelines to be reached and is some way from the 300 Bq/m^3 set as the maximum value by EURATOM. The negative effects for comfort inside the building should be noted, such as the noise level of the system, above 25 dB, the air currents, and consequently the thermal comfort. On the other hand, the renewal rate per hour (0.70) is designed not to exceed the calculation values for ventilation set out in the Energy Efficiency Indicator, so as not to have a negative effect on the energy classification of the dwelling [19].

The great advantage of this system, for use in buildings undergoing refurbishment, is that one single action addresses a number of problems, thanks to its compatibility with highly energy efficient air-heating systems. Although it also has drawbacks that require complementary measures to be taken with heat exchangers, diffusers and silencers, to counteract the effects on comfort.

8.2 Positive ventilation P3

The technique is grounded in the idea of making entry of radon into the premises more difficult by the effect of the positive pressure difference inside, as "radon flow into the building, due to convective processes, occurs when the pressure gradient is positive PB > PA".

This is achieved by introducing clean air from the outside. This has two consequences; on the one hand it increases the pressure inside the building, leading to air flow from the inside outward, through the permeability of the surrounding material, which makes it difficult for radon to enter from the outside. The unpolluted air introduced also assists in diluting the concentration of radon inside Fig. 8.

1) Intake pipe 120 mm in diameter.
2) Intake fan S&P TD-350 230 V-50 HZ, 26.94 W (0.0456 m^3/s).
3) Intake diffusor with air filtering.
4) Sealed chimney (cassette).
5) Sealed pipes and fissures.

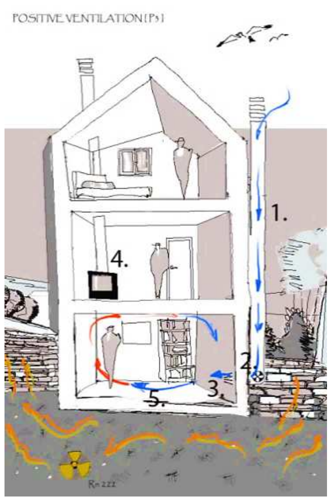


Fig. 8: Section plan of the setup.

This technique was implemented by placing a series of 120 mm diameter PVC tubes, the joints of which were sealed with adhesive for PVC. For the reasons already set out in the forced ventilation experiment, special attention was given to the intake point for outside air, which was placed at a height of +5.80 m on the East-facing wall, open to the prevailing winds.

The nozzles were placed outside the occupied area, understood to be 30 cm from the walls below head height, in order to distribute the air supplied at a speed and in conditions appropriate to welfare and ventilation in the living space. The speed of the air supplied as measured by a TESTO 440 thermal anemometer, 30 cm from the grille, is less than 0.10 m/s, and is therefore compatible with environmental comfort.

The grilles were placed on the vertical surfaces 30 cm from the highest point of the flooring. They were positioned at this height to maximise their efficiency, as radon is heavier than air and tends to accumulate at the lower levels [18]. Their placement at this height makes it easier for the concentration of radon to be diluted, and it also increases the pressure at the point closest to the localised entry source, as well as maximising thermal efficiency over the winter period by preheating the air introduced, assisting convective flow.

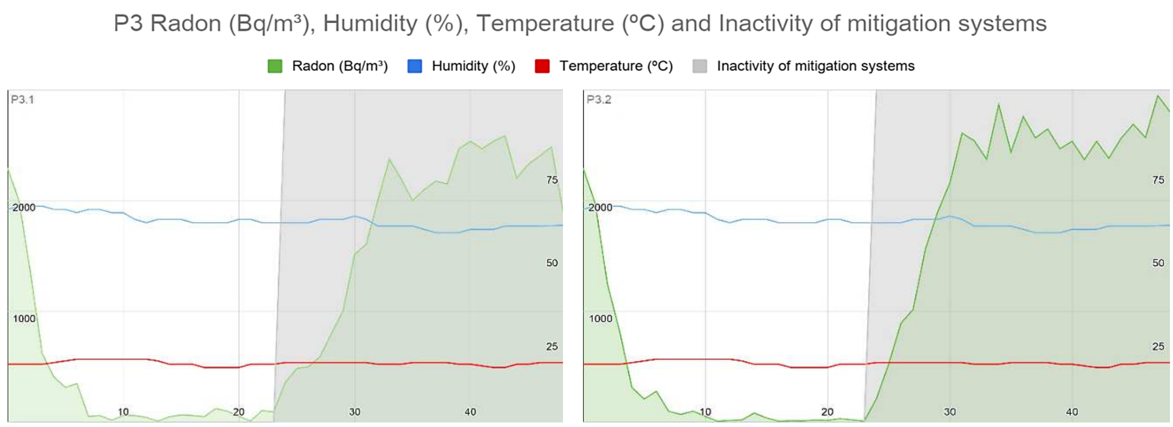
It should be noted that the location of the pressure grilles goes against what is set out in point 3.1.1.e) of DB HS-3 of the CTE, which requires them to be place at a height greater than 1.8 m above the height of the floor, although the following points should be mentioned:

1) The building has natural ventilation which meets the Standard, and so the hybrid system need not necessarily be considered a ventilation system, but rather a system of radon concentration mitigation which happens to improve the flow of clean air.

2) The requirement of the Standard to place the grilles higher than 1.8 m should be understood as requiring that they be placed outside the occupation area, to afford greater environmental comfort. In our case, as the premises are located in C thermal area of Spain (CTE), where the increase in air temperature is more important, as most of the time the outside temperature is below the comfortable temperature, placing the pressure grilles out of the occupation area on the side walls improves convective flow and energy efficiency.

A 230V-50HZ, 26.94 W in-line mixed flow duct fan was placed in the conduit leading from the intake to the nozzles with a reference entry flow of 0.0456 m^3/s a reference pressure difference of 45.21 Pa. The grilles were placed on the East wall, as the nearest point to the main entry source, giving a flow of clean air from the outside of 61.27 l/s which, for the 316.46 m^3 building being tested, meant and extra 0.19 l/s per cubic meter.

A measurement taken prior to setting the designed solution in motion, taken on 21/01/2020 at 01:26 the radon concentration was 3000 Bq/m^3 ±10 %. The turbine was started at 12:00 and switched off 24 hours later. After 1 hour 26 minutes, a measurement was taken of 2200 Bq/m^3, decreasing 7 hours later to 57 Bq/m^3 ± 45 %. These concentration levels, below 100 Bq/m^3, remained stable until the fan was switched off at 12:00 the next day, see Fig. 9. These measurements have higher uncertainty, around 50 %, given the detection limit of the apparatus.



First sequence, day 3 Last sequence, day 11

Fig. 9: Graph of radon concentration with the pressurisation system.

The fan was switched off until 12:00, that is, for 24 hours. Over this period, the concentration rose slowly to a value of 2560 Bq/m^3 ± 10 %. These results show that the system is efficient at containing concentration levels below those required by European Standards, and even below the 100 Bq/m^3 proposed by the WHO.

The use of this system in an existing building also has important advantages. Firstly, it is simple to introduce, the materials are cheap and easily available, and it can be done quickly. Secondly this solution, is shown to be compatible with the minimal intervention and reversibility principles stablished in the charters of Venice, Krakovia and Nara, especially on buildings considered to be part of protected heritage.

One disadvantage systems from adding air flow from the outside, whose effects on the comfort of those living inside involve thermal variation, noise, air currents and the entry of external pollutants, especially allergens such as pollen or airborne dust particles. For these reasons it is advisable to include filters and heating elements to these systems, to correct these problems, which in turn leads to an increase in operating costs.

Improvements to this design with respect to noise pollution might include the possibility of placing the fan on the outside, in a sealed mounting, although this would also increase the cost of installation, or include noise suppressors.

8.3 Negative radon sump D4

This technique is grounded in the idea of transporting the radon rising from the lower ground layers to the intake point at a level below that of the building floor, and then expelling it naturally, in the case of D.1 and D.2, or mechanically in the case of D.3 and D.4. It was decided only to test depressurisation by mechanical means D.4, as it is based on the same principle as the natural process, but is more efficient, and so a competitive comparison can be made with the other solutions tested, see Fig. 10. It was also considered that efficient natural ventilation would normally require a very specific design, which would be much more difficult to achieve in the case of a refurbishment, because of the constraints of the existing structure.

1) Concrete prefabricated drain.
2) 25 mm thick gravel layer.
3) Extraction pipe 90mm in diameter.
4) Extraction fan S&P TD-350 230 V-50 HZ, 26.94 W (0.0456 m^3/s).
5) Sealed pipes and fissures.

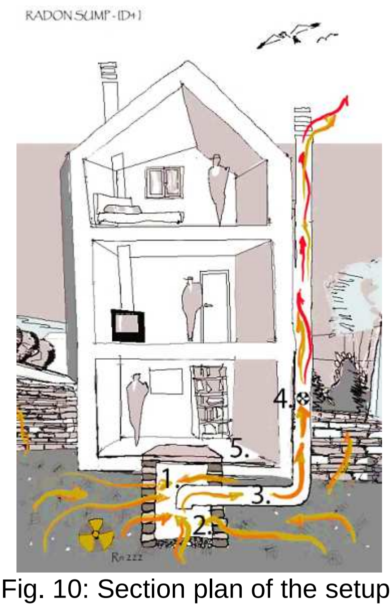


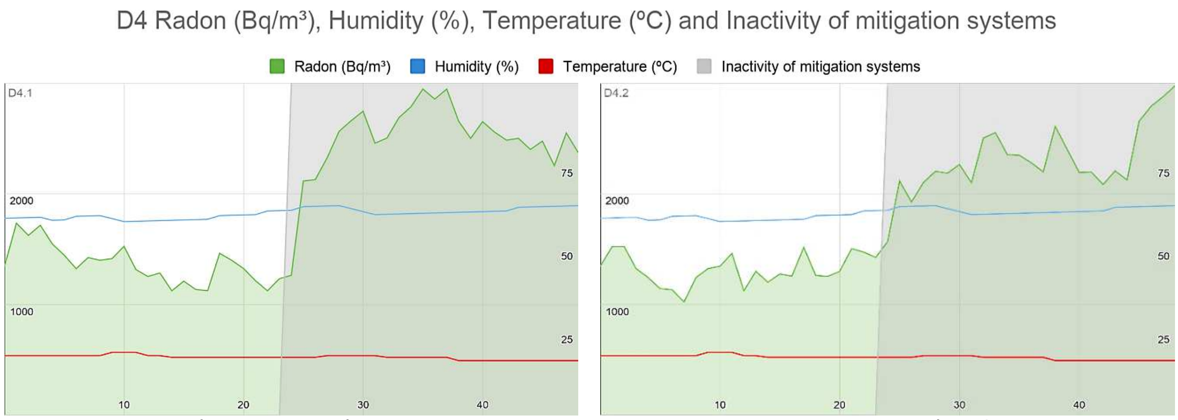
Fig. 10: Section plan of the setup.

The technique D.3 Forced depressuring at one side of the building, was rejected as a subject of testing, as it was understood to be similar to but less suitable than D.4 for the building in question, although it is useful when applied to existing structures, requiring less intervention as the pit can be dug outside the perimeter of the building.

To reduce the pressure in the ground, using the existing characteristics of the building, a set of three drains, now unused, from the old waste disposal system, were reused; these were joined together by a channel 220 mm in diameter. These drains were chosen due to their ideal location with respect to the building surface and the sources of radon. To ensure the suction effect, and given that the drains were connected to other waste pipes from the building, they were sealed with polyurethane foam and epoxy mortar, turning the three chosen drains into an isolated suction system. A new pipe was used to connect the last drain to the outside, and the system was depressurised using an in-line mixed flow duct fan placed outside the building, carrying the radon outside. An S&P TD-350 230 V-50 HZ, 26.94 W fan was installed, with a reference flow of 0.0456 m^3/s and a reference pressure difference 45.21 Pa.

To increase the rate of entry of ^{222}Rn to the drains, a platform was dug out and finished with a 25 mm thick gravel layer to increase permeability.

A prior measurement was taken after the building had been closed for 24 hours, and the measurement was started at 00:00 on the 23rd. 24 hours later the extraction system was set in motion, by activating the extractor fan connected to the drains. Immediately the fan was switched on, a drop in the concentration level of 1000 Bq/m^3 to 1500 Bq/m^3 was observed, but no further reduction was achieved over the rest of the time during which measurements were taken. From 0:00 a.m. on the 25th, the system shuts down, and gradually returned to the previous concentration levels of around 2800 Bq/m^3, see Fig. 11.



First sequence, day 5 Last sequence, day 13

Fig. 11: Graph of radon concentration with ground depressurisation.

This solution proved not to be very effective in comparison with the previously tested solutions, although the limitations imposed on the method must be considered, since in order to minimize the degree of intervention it was decided to repurpose an existing manhole system.

Although the location of the catchment wells was deemed appropriate to cover most of the area of the premises, the location of the manholes did not correspond to an ideal model, neither in number nor in precise positioning. These variables undoubtedly influenced the result.

Various studies [20, 21] show this to be an effective solution, but in the case of refurbishment aimed purely at reducing interior concentration levels of radon gas, this system is not well-suited due to the high cost arising from the building elements to be altered, such as flooring, conduits and foundations, as well as the difficulties in installation. It may, however, be appropriate if combined with a radon barrier in a general refurbishment which already involves working on the ground beneath the structure.

8.4 Positive radon sump E2

The basis of the technique consists in hindering the convective (advective) process which carries the radon into the building, by forming positive pressure bulbs to divert the gas flow [14], transporting it via the porosity of the soil towards areas of lower pressure away from the structure, see Fig. 12.

1) Concrete prefabricated drain.
2) 25 mm thick gravel layer.
3) Intake pipe 90mm in diameter.
4) Intake fan S&P TD-350 230 V-50 HZ, 26.94 W (0.0456 m^3/s).
5) Sealed pipes and fissures.

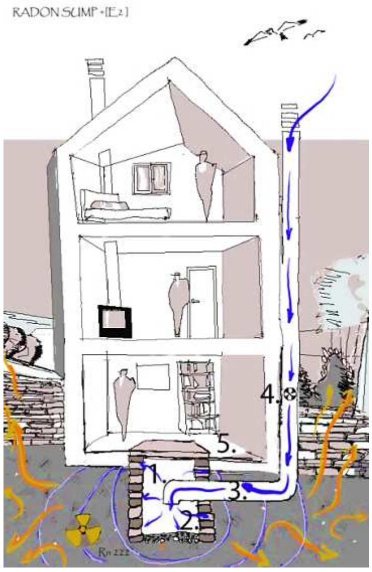
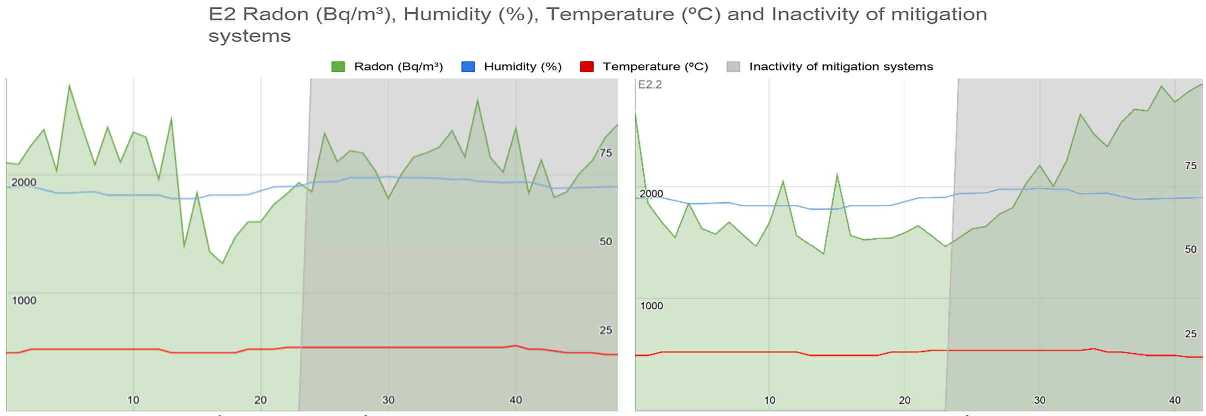


Fig. 12: Section plan of the setup.

With the same set of drains as in the previous experiment, the flow of the in-line mixed flow duct fan was reversed, and it was placed to drive the outside air towards the drains, increasing the pressure inside and beneath them, to create a barrier in the ground under the building formed by a pressure bulb.

A prior measurement was taken after the premises had been closed for 24 hours, starting at 00:00 on the 25th, yielding concentration levels that reached 2973 Bq/m^3. 24 hours later the pressurisation system was started by introducing air from the outside, driven by the reversed flow of the exterior fan. Six hours after the fan was switched on, a drop in radon concentration of some 1200 Bq/m^3 was observed, which rose again over the following hours to 2400 Bq/m^3, and then began to drop once more over the rest of the measurement period, to 1800 Bq/m^3.



First sequence, day 7 Last sequence, day 15

Fig. 13: Graph of radon concentration with the ground pressurisation.

When the fan was turned off, at 00:00 on the 27th, the concentration reached a level of 2630 Bq/m^3, although it should be noted that once the system was turned off, there was a further decrease in concentration in the following 12 hours to 1800 Bq/m^3, so it is not very clear if the variations in concentration were produced exclusively by the effect of overpressure or if they influenced by other variables related to soil permeability, such as saturation of the ground pores due to the abundant rainfall that occurred throughout the trial.

Similar results were obtained on the second sequence of tests done one week later in different weather conditions, although in the second instance the concentration drop was more stable keeping its value between 1400 and 2000 Bq/m^3, and after the shutdown of the mitigation systems there was a gradual increment on the radon concentration from 1542 to 2915 Bq/m^3, see Fig. 13.

While it is the case that some other studies [22, 23] highlight the effectiveness of this system, in the current case the solution was not seen to be effective.

The same consideration applies to refurbishment work as for depressurization of the soil, that the use of this method is not suitable unless it is carried out in combination with the installation of a radon barrier, and in comprehensive refurbishments requiring actions in the subsoil, which collides with the minimal intervention and reversibility principles stablished in the Charter for the Conservation and Restoration of Monuments and Sites.

9 Conclusions

The experiment described shows that not all the techniques are suitable, and that issues such as the following should be borne in mind in making a choice:

1) The radon solution system should consider the level of intervention to be addressed.

2) The design of the solutions should take place only after all the characteristics of the buildings and its surroundings have been examined.

3) The combination of various systems is what gives the assurance of greater efficiency in radon reduction.

4) The passive solutions are not seen to be effective at reducing the concentration, but they do contribute to ensuring the building is properly sealed, and they undoubtedly assist the action of active measures, both those that involve pressurisation and the opposite.

Below, in the graph of the series of test carried out, which allows us to appreciate the effectiveness of the different solutions, see Fig. 14. The system of forced ventilation A2 is especially interesting in refurbishments requiring air-conditioning systems, as, combined with air-sourced heating, it may be suitable for places where the concentration does not exceed 2000 Bq/m^3. This demands that special attention be given to the layout of the intake and outlet conduits of the systems, to ensure the intake of air that is not polluted with radon.

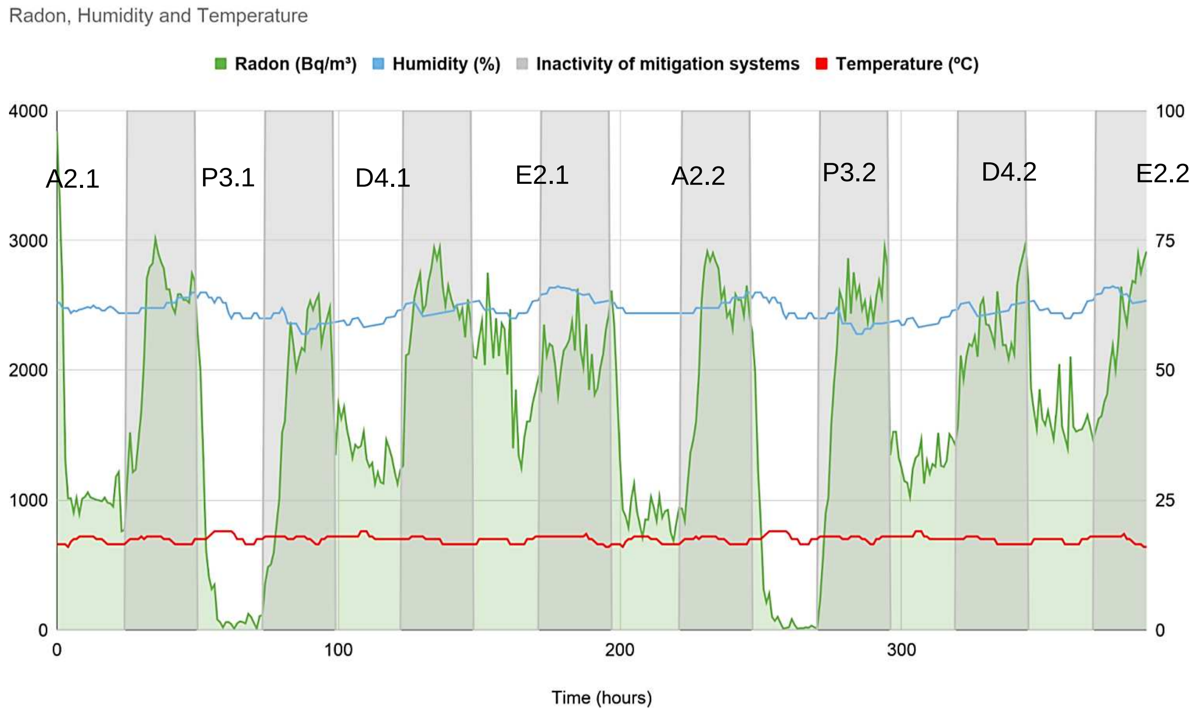


Fig. 14: Graph of radon concentration over the entire length of the experiment, showing the effect of sequential activating the various measures.

A positive ventilation P3 in the building calls for less invasive action and lower cost, compared with other systems, and is highly effective, meaning that it can cover a range of possibilities within the scope of refurbishment. This is especially true for actions aimed at mitigating the problem of radon in buildings where the concentration is above 1000 Bq/m^3 and is compatible with the minimal intervention and reversibility principles stablished in the charters of Venice, Krakovia and Nara when it is the case of interventions over heritage.

For actions on the ground D4, E2, there are two main difficulties. Firstly, the need for more preliminary studies, specifically of the permeability of the ground, composition and homogeneity of the soil beneath the building. Furthermore, the modelling of the pressure bulb is only at the development stage, and so there are no reliable tools to calculate it. All of this requires the action of specialists in the field, who are not always available.

Secondly, they are more invasive and more costly systems, little suited to cases where the only purpose of the action is the mitigation of radon. Their use may, however, be appropriate in general refurbishment work with permeable soils, since offer the advantage of not affecting the habitability of the interior of the structure.

In any case, its use is always recommended in combination with the radon barrier, as established in the CTE DB-HS6 instruction. However, the interaction between the different systems must be taken into account, since in most cases the result will be additive, but it may happen that in some cases the systems neutralize each other, this can fundamentally happen when the combination of two active systems is used, such as pressurization of the building and simultaneous depressurization of the soil, in this case, it would be advisable to carry out a detailed study of the interaction of both systems.

References

[1] BARROS-DIOS, J. M. - BARREIRO, M. A. - RUANO-RAVINA, A. - FIGUEIRAS, A.: Exposure to residential radon and lung cancer in Spain: a population-based case-control study. American Journal of Epidemiology, Vol. 156(6), 2002, pp. 548-555.

[2] SAMET, J. M.: Radon and lung cancer. J. Natl. Cancer Inst, 81, 1989, pp. 745–757.

[3] DARBY, S. - HILL, D. - AUVINEN, A. - BARROS-DIOS, J. M. - BAYSSON, H. - BOCHICCHIO, F. - DEO, H. - FALK, R. - FORASTIERE, F. - HAKAMA, M.: Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. B.M.J., doi: 10.1136/bmj.38308.477650.63.

[4] BRANION-CALLES, M. C. - NELSON, T. A. - HENDERSON, S. B.: Evaluation of different radon guideline values based on characterization of ecological risk and visualization of lung cancer mortality trends in British Columbia, Canada. BMC Public Health, 2015, https://doi.org/10.1186/s12889-015-2438-2.

[5] EUROPEAN COUNCIL DIRECTIVE 2013/59/Euratom on 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. Off. J. Eur. Union 2014, L13, 1–73. Available online: http://data.europa.eu/eli/dir/2013/59/oj (accessed on 26 September 2018).

[6] WHO Handbook on indoor radon. A public health perspective. Ed. Hayo Zeeb & Frend Shannoun, 2009.

[7] PIEDRECAISA-GARCIA, B. - FRUTOS, B.: Radon concentrations in cave houses of Crevillente. Journal of Construction, Vol. 17, No. 1, 2018, https://doi.org/10.7764/RDLC.17.1.60.

[8] FRUTOS, B. - OLAYA, M. - ESTEBAN, J. L.: Sistemas de extracción como técnicas constructivas para evitar la entrada de gas radón en las viviendas. Informes de la Construcción, Vol. 63(521), 2011, pp. 23-36.

[9] PUBLIC HEALTH EMGLAND, 2020. https://www .ukradon.org/information/reducelevels.

[10] Instituto Galego da vivienda e solo. https://igvs.xunta.gal/web/actuamos/921.2019.

[11] SYMONDS, P. - REES, D. - DARAKTCHIEVA, Z. - MCCOLL, N. - BRADLEY, J. - HAMILTON, I. - DAVIES, M.: Home energy efficiency and radon: An observational study. Indoor Air. 29, 2019. https://doi.org/10.1111/ina.12575.

[12] MOHAMMADIAN, Z. - SHAHBAZIS, M.: Study of the Effect of Sustainable Architecture on the Design of Residential Buildings (Case Study: Qazvin Pardis Complex). Civil and Environmental Engineering, Vol. 14, Iss. 2, 2018, pp. 91-98, https://doi.org/10.2478/cee-2018-0012.

[13] RUANO-RAVIÑA, A. - QUINDÓS-PONCELA, L. - SAINZ FERNÁNDEZ, C. - BARROS-DIOS, J. M.: Radón interior y salud pública en España: tiempo para la acción. Gaceta Sanitaria, Vol. 28(6), 2014, pp. 439-441, https://dx.doi.org/10.1016/j.gaceta.2014.09.003.

[14] NEZNAL, M. - MATOLIN, M. - BARNET, I. - MIKŠOVÁ, J.: The new method for assessing the radon risk of building sites. Prace Ceskeho Geologickeho Ustavu, 2004, pp.7-47.

[15] FRUTOS VÁZQUEZ, B. - OLAYA ADÁN, M.: Las prestaciones en construcción de las barreras antiradón. II Congreso Nacional de Investigación en Edificación. IETcc-CSIC.2010.

[16] REAL DECRETO 732/2019 de 20 diciembre 2019 (BOE 27/12/2019).

[17] SCHUBERT, M. - SCHULZ, H.: Diurnal radon variations in the upper soil layers and at the soil-air interface related to meteorological parameters. Health Physics, Vol. 83(1), 2002, pp. 91-96.
[18] JELLE, B. P.: Development of a model for radon concentration in indoor air. Science of the Total Environment, 416, 2012, pp.343-350.
[19] ÁLVAREZ DOMÍNGUEZ, S. - SÁNCHEZ DE LA FLOR, F. J. - DE LUXÁN GARCÍA DE DIEGO, M. - GOMEZ MUÑOZ, G. - ROMÁN LÓPEZ, E. - TENORIO RÍOS, J.: A Procedimiento simplificado para certificación de eficiencia energética de edificios de vivienda. ANDIMAT, 2007.
[20] COLLINSON, A. J. L. - HAQUE, A. K. M. M.: A scintillation counter for the measurement of radon concentration in air. Journal of Scientific Instruments, Vol. 40(11), 1963, p. 521.
[21] VÁZQUEZ, B. F. - ADÁN, M. O. - PONCELA, L. S. Q - FERNANDEZ, C. S. – MERINO, I. F.: Experimental study of effectiveness of four radon mitigation solutions, based on underground depressurization, tested in prototype housing built in a high radon area in Spain. Journal of environmental radioactivity, Vol. 102(4), 2011, pp. 378-385.
[22] ABDELOUHAB, M. - COLLIGNAN, B. - ALLARD, F.: Experimental study on passive Soil Depressurisation System to prevent soil gaseous pollutants into building. Building and Environment, Vol. 45(11), 2010, pp. 2400-2406.
[23] GADGIL, A. J. - BONNEFOUS, Y. C. - FISK, W. J.: Relative Effectiveness of Sub-slab Pressurization and Depressurization Systems for Indoor Radon Mitigation: Studies with an Experimentally Verified Numerical Model. Indoor Air, Vol. 4(4), 1994, pp. 265-275.