Testing positive pressurization technique against radon indoor accumulation.

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ABSTRACT

Radon is one of the common contaminants inside buildings, with maximum presence in high potential areas classified as radon prone areas. This radioactive gas, which comes from the spontaneous disintegration of radium present in the earth's crust, can penetrate buildings and accumulate inside them. The spaces closest to the ground (basement and first floors) are the most affected. Its inhalation in high doses is associated with an increased risk of lung cancer. Several techniques are commonly used to mitigate its presence. One of them consists of blowing air from the outside to internal spaces, generating a double effect of interior pressurization and dilution of the gas. The effectiveness of this technique, and the implications on energy efficiency, depend on the constructive characteristics of the building, the volume, and the initial state of concentration.
This paper presents the preliminary results of a study to characterize the effectiveness of the technique for three different types of buildings located in an area of high radon potential. The system applied consist in a commercial fan that blow air from outside to the indoor living spaces. Two types of fans have been used function of flow rate according to indoor volume of the three types of buildings. Several test have been carried out: envelope airtightness, indoor/outdoor and indoor/underground differential pressure measurements, flow rates, and continuous monitoring of radon levels for set ups analysis. The data show radon reductions between 47 and 96% for the different test sets. By adjusting the design variables, radon levels have been reduced to below 300 Bq/m^3 (European Directive) for all three buildings.

KEYWORDS

Radon, Mitigation technique, Pressurization, Ventilation

1 INTRODUCTION

Radon gas (isotope Rn-222) originates from the spontaneous decay of radium (isotope Ra-226) present in the earth's crust. It enters and accumulates inside buildings mainly through transport phenomena from the ground (Garbesi et al., 1993; Muñoz et al., 2017; Nazaroff et al., 1988; Sherman, 1992). Materials used in construction may have radium content in their raw materials (aggregates, ceramics, plasters, mortars, etc.) and also constitute a source of radon. However, their contribution to indoor concentration, compared to ground, is in most cases of little relevance (Frutos et al., 2021; Sabbarese et al., 2020).

Considering radon from the ground as the main source, its transport into buildings can be explained by the two mechanisms of gas movement: advection and diffusion. (Vasilyev and Zhukovsky, 2013). Advection refers to the gas movement driven by pressure difference between the soil pores and the interior space. It is the one with the greater contribution to concentration, but it requires communication between both spaces. It occurs through cracks or open joints in the building envelope in contact with the soil (walls, floors and slabs). The diffusive mechanism appears due to the difference in concentrations between the two environments (soil pores and indoor air). Its flow is produced through the structure of the building envelope materials. It is a slow movement and in most cases less relevant than the advective one.

Radon accumulated in high concentrations inside buildings increases health risk to inhabitants. WHO warns of lung cancer risks from inhaling the gas (WHO, 2009). The European Directive (Directive 59/2013 EURATOM) requires corrective measures to be taken when levels exceed 300 Bq/m^3.

To reduce the presence of this gas inside buildings, several mitigation techniques are applied: a) soil depressurization; b) radon barriers placed on envelopes in contact with the soil; c) ventilation systems. Of those mentioned, soil depressurization is considered of most effective technique (Frutos et al., 2020, 2011; Hung et al., 2018). But its application requires advanced knowledge in fluid mechanics and the control of parameters such as substrate permeability (Fuente et al., 2019). The radon barrier option is an attractive technique as it does not require active systems or electricity supply for its operation. However, in existing houses, its application implies works in building floor slabs, which are not always feasible (Jiranek, 2004). Finally, the ventilation technique may be suitable for the treatment of indoor contaminants without requiring excessive intervention. It is based on dilution of the indoor gas by air exchange with the outside. It can work in several ways (Figure 1): a) in a balanced air exchange between the inlet and outlet flow; b) extracting air from the interior and allowing the outside air to filter through grids in the enclosure and c) blowing air from the outside into the interior.

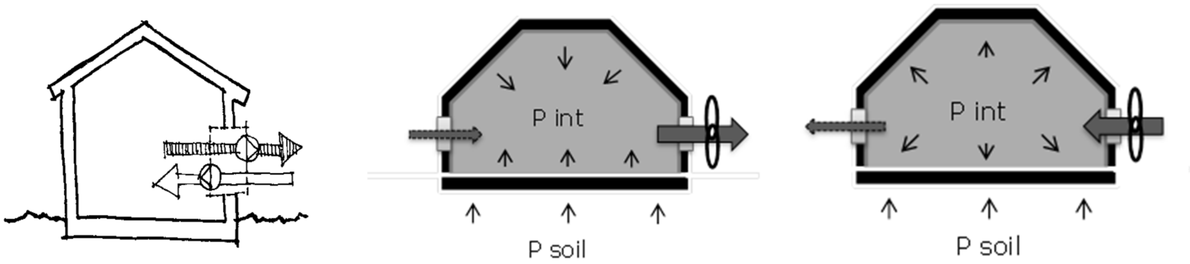

Figure 1: a) balanced flow ventilation; b) exhaust ventilation; c) supply ventilation

In all three variants, the calculation of ventilation rates must satisfy the reduction of pollutants by dilution. However, there are differences in effectiveness between the 3 techniques. While the balanced flow solution maintains a neutral state of pressures inside, in the extraction and impulsion solutions, the state of pressures inside is slightly modified. The extraction solution causes a depressurization in indoor air that can be negative by suctioning radon from the ground. The supply solution would act in the opposite way, slightly pressurizing the interior space and attenuating the radon flux from the ground (Figure 1c). This effect has been studied by several authors who confirm the increased effectiveness of pressurization (Collignan et al., 2012; Collignan and Powaga, 2019; Diallo et al., 2013).

This paper presents the studies carried out with this technique to characterize its effectiveness in three different types of buildings in terms of indoor radon concentrations and volumes to be treated.

2 FUNDAMENTALS OF TECHNIQUE

The pressurization ventilation technique is based on a double effect:

- Dilution. The mixing of the outside fresh air with the inside air causes a dilution of the gas. The rates are calculated according to the indoor concentration, the gas exhalation rate, and the natural infiltration rate of the building (also called airtightness).
- Pressurization. The air that is pushed inward causes a slight pressurization inside the space that attenuates the advective mechanism of gas ingress. The degree of pressurization will depend on the flow rate of the fan, the degree of airtightness of the building and its interior volume.

3 METHODS AND MATERIALS

The following tests and studies have been carried out to analyse these aspects:

- Airtightness of the envelope. It is performed according to UNE-EN ISO 9972:2019 (Thermal performance of buildings. Determination of air permeability of buildings. Fan pressurization method). A blower door equipment (The Energy Conservatory, Minneapolis model) has been used. The parameter n50 (h^{-1}) is obtained as an indicator of infiltration renewal rates at 50 Pa.
- Pressurization capacity provided by the fan installed in the building. Differential pressure between the interior space and the subsoil, and between the interior space and the exterior, at different flow rates, are measured (PCE-VA 20 anemometer equipment).
- Radon concentration monitoring during the study phases. The air flow of the fan is programmed with different discharge powers and the evolution of the radon concentration is monitored. Radon Eye+2 (FTLab) with ionization chamber and recording at 1h intervals is used.

Figure 2: a) Airtightness test with blower door equipment; b) Differential pressure measurements between the internal environment and the ground; c) Continuous radon monitoring equipment

3.1 Buildings analyzed

For the selection of the buildings, the following characteristics were proposed: radon concentrations above 300 Bq/m^3 and different volume and airtightness characteristics. All of them were located in the municipality of Torrelodones, Madrid, Spain.

- Building A. Security guardhouse (Figure 3a).
  Floor area: 27 m^2; interior volume: 69 m^3; envelope area: 109 m^2.
- Building B. Public school (Figure 3b).
  Floor area: 160 m^2; interior volume: 528 m^3; envelope area: 493 m^2.
- Building C. Coworking space in historic palace (Figure 3c).
  Floor area: 58 m^2; interior volume: 205 m^3; envelope area: 244 m^2.

Figure 3: a) Building A. Security guardhouse; b) Building B. Public school; c) Building C. Coworking space in historic palace

3.2 Ventilation fans

For the studies in the buildings, air supply fans were installed. These take air from the outside and blow it into the inside. They have an electrical resistance that enables the air to be preheated. For buildings A and C, the machine was installed directly on the facade wall with the following characteristics: Model (CTA1502365); Maximum fan power (47 W); Maximum flow rate (150 m^3/h); Maximum pressure (31 Pa).
For building C, the machine was installed in the ceiling with an intake duct on the facade and 3 discharge ducts distributed in different rooms. The system has the following characteristics: Model (500 V1); Maximum fan power (61 W); Maximum flow: (500 m^3/h); Maximum pressure (580 Pa).

Figure 4: a) Model CTA1502365 installed in buildings A and C; b) Equipment 500 V1 installed in Building B.

4 RESULTS

4.1 Airtightness of the buildings

Airtightness tests were performed on the 3 buildings. Air exchange rate by natural infiltration was obtained. The test is performed according to method B of the UNE-EN ISO 9972:2019 standard, with the building's grids and openings closed. The blower door is fitted to the frame of the access door and the fan is activated in the depressurization position. Table 1, below, shows the results obtained for building A.

Table 1: Results of the airtightness test performed in building A

Parámetro y unidad	Indicador	Valor
n50 (h^{-1})	Air exchange rate (50 Pa)	20.50
n0 (h^{-1})	Air exchange rate (0 Pa)	1.03
V50 (m^3/h)	Flow rate (50 Pa)	1414 (+/- 0.4 %)
W50 ($m^3/h.m^2$)	Air leakage rate at 50 Pa (floor surface)	52.38
q50 ($m^3/h.m^2$)	Air leakage rate at 50 Pa (envelope surface)	12.98
CL	Air leakage coefficient $m^3/(h·Pa^n)$	144.1 (+/- 2.4 %)
n	Exponent (n)	0.584
EqLA 10Pa (cm^2)	Effective leakage area at 10 Pa	616.6 cm^2 (+/- 0.9 %)
LBL ELA 4Pa (cm^2)	Effective leakage area at 4 Pa	348.8 cm^2 (+/- 1.5 %)

The n50 value represents the airtightness level of the building at 50 Pa pressure. It is a parameter that allows intercomparing different buildings regardless of the specific climatic conditions of the test, especially with regard to wind. However, for the purposes of this study, the level of airtightness (air exchange by natural infiltration) under normal conditions of pressure n0 (close to 0Pa between inside and outside) is of interest. For this purpose, the simplified method has been used, dividing by 20 the parameter n50 to obtain n0 (Prignon and Van Moeseke, 2017). The results obtained for the 3 buildings are shown in table 2.

Table 2: Results of parameters n50 and n0 for the 3 buildings

Building	**Volume (m^3)**	**Parameter n50 (h^{-1})**	**Parameter n0 (h^{-1})**
Building A	69	20.50	1.03
Building B	528	4.55	0.23
Building C	205	10.09	0.50

It can be seen that the building with the highest airtightness is building B, while building A has the lowest. According to the ISO 13790 classification, building A has a low level of airtightness, building B a high level, and building C a medium level.

4.2 Capacity of pressurization of spaces by activation of the air supply fan

The pressure level inside the building, at different activation powers, were measured (table 3).

Table 3: Indoor pressurization results achieved with supply air equipment at different powers

Power scale	Flow rate (m^3/h)	Dif. pressure Indoor-Outdoor (Pa)	Dif. pressure Indoor-soil (Pa)
Building A			
Initial 0%	0	- 0.3	0.0
25%	42	0.6	0.0
50%	54	0.8	0.0
75%	66	1.1	0.0
100%	114	1.5	0.5
Building B			
Initial 0%	0	- 0.6	0.0
25%	156	0.4	0.0
50%	210	0.7	0.0
75%	306	0.7	0.0
100%	324	0.8	0.0
Building C			
Initial 0%	0	- 0.5	0.0
25%	60	0.6	0.0
50%	78	0.8	0.0
75%	96	1.1	1.0
100%	120	1.4	1.0

The maximum indoor pressurization level in building A is 1.5 Pa at maximum machine power, 0.8 Pa in building B, and 1.4 Pa in building C. Results for pressure difference between indoor and soil under the building are lower, possibly due to connection through cracks in floor slabs.

4.3 Indoor radon concentration monitoring at different supply air power levels

The indoor radon concentration curves are analysed as a function of the different flow rates programmed in the fans. In building A and C, outlet air grids were installed in the facades. For buildings A and C, the analysed phases contemplate different flow rates, and the condition of open or closed grids. Figure 5 shows an example of the evolution of radon concentration in building A.

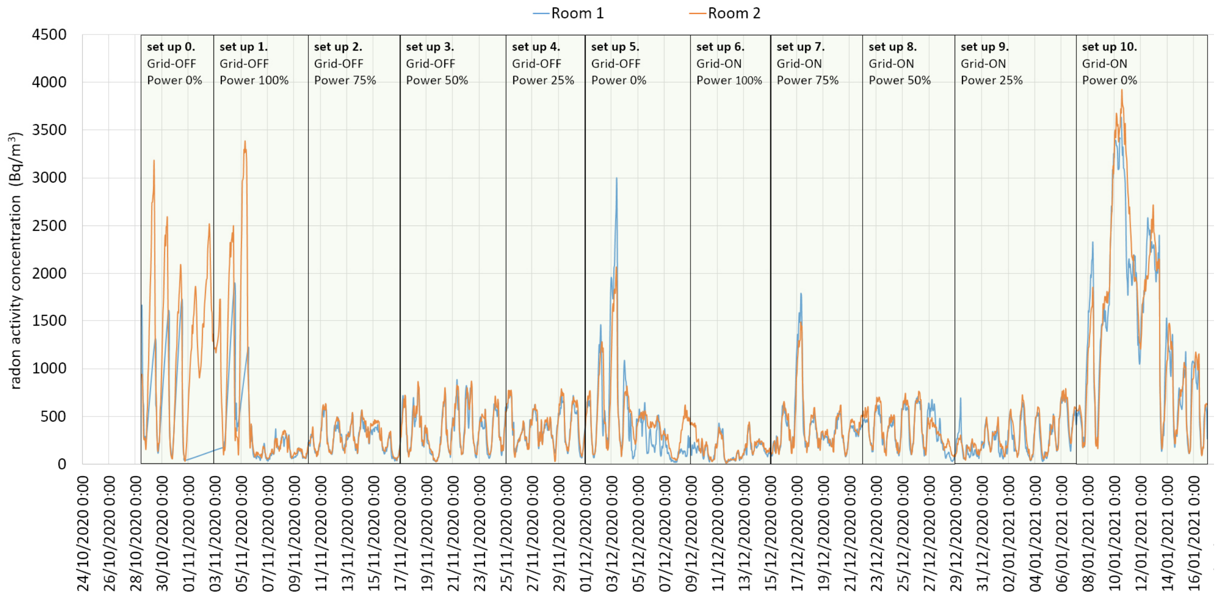

Figure 5: Radon monitoring in building A. Set ups as a function of the supply flow rate and the open or closed exhaust grid condition

Effectiveness is obtained by comparing the levels at each set up with the radon levels in the initial state without the machine operating. Table 4 shows the effectiveness data achieved in building A.

Table 4: Effectiveness achieved at each set up

Building A. (Vol: 69 m^3) Fan power: 47 W – max flow:150 m^3/h – max pressure: 31 Pa						
Grid (ON/OFF)	Power (%)	Fan flow rate (m^3/h)	Fan flow rate (h^{-1})	Total ACH (natural infiltration + fan flow) (h^{-1})	Rn (Bq/m^3)	Efect. (%)
	INITIAL (0%)	-	-	1.03 (natural infiltration)	1423	0%
OFF ON	25	42	0.61	1.64	400 323	72% 77%
OFF ON	50	54	0.78	1.81	384 360	73% 75%
OFF ON	75	66	0.96	1.99	307 -	78% -
OFF ON	100	114	1.65	2.68	162 152	89% 89%

5 DISCUSION

The reduction of pollutant concentration can be studied according to the expression (1):

$$C_{Rn} = \frac{\Phi}{(\lambda_{Rn}+\lambda_{ACH})\times V} \quad (1)$$

Where: C_{Rn} = radon activity concentration (Bq/m^3); Φ = total radon surfaces exhalation rate (Bq/h); λ_{Rn} =radon decay constant (0,00756 h^{-1}); λ_{ACH} = ACH due to fan + ACH natural infiltration (h^{-1}); V = Building volume (m^3). For the 3 buildings, the simulated dilution curves are shown compared to the real radon reduction curves achieved by the flow rates (figure 6).

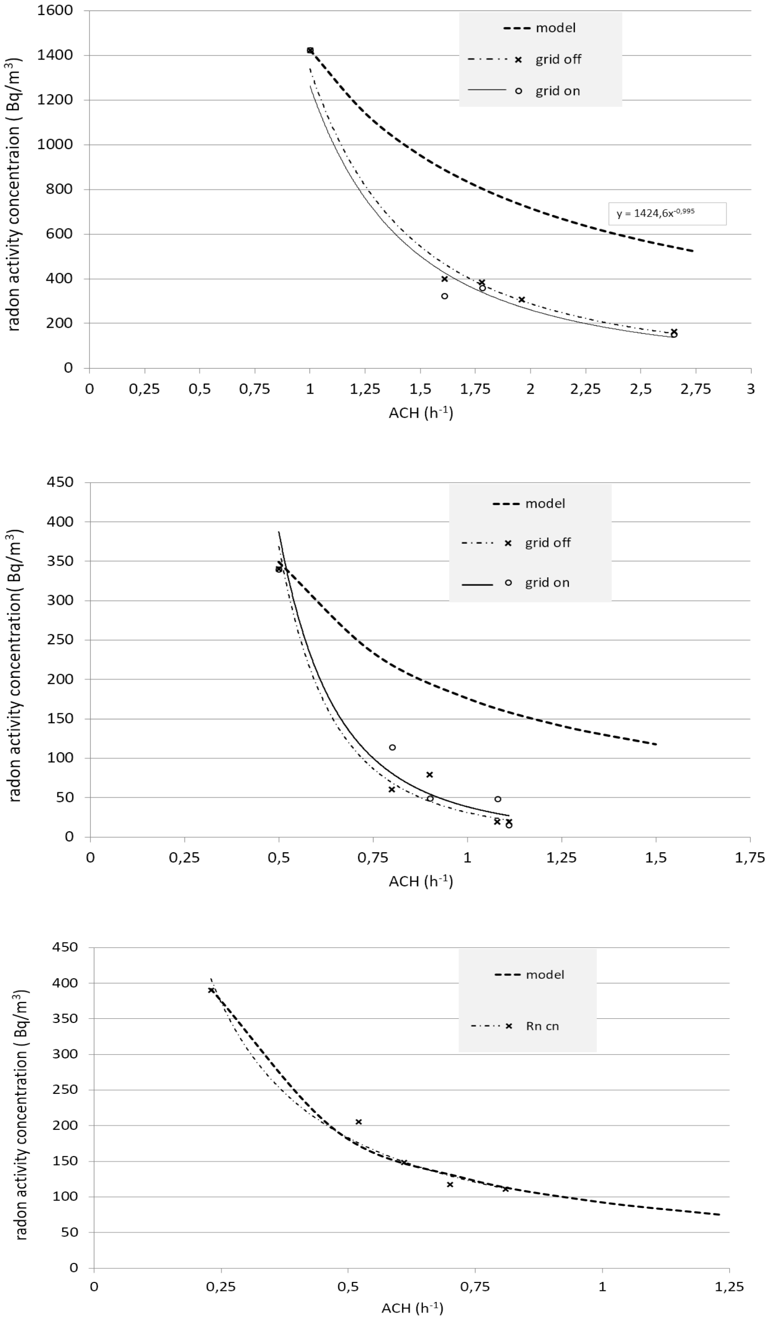

Figure 6: Radon evolution curves function of ACH rates vs. simulated dilution model. Building A, B and C

For buildings A and B, it is observed that simulated curves, obtained from the theoretical expression of pollutant reduction, shows slightly lower reduction than those achieved in the real field tests. This could be due to the effect of the pressurization achieved by the fan, which would be an improvement compared to a balanced ventilation by blocking the radon flow by positive pressure of the space. In building C, this phenomenon is not observed and both the model and the monitored data show the same behaviour.

As a summary, the following table 5 shows the effectiveness achieved by the supply air ventilation technique in the 3 buildings analysed.

Table 5: Effectiveness achieved by the possitive pressurization ventilation technique in the 3 buildings and building parameters asscociated.

Building	Volume	Initial Rn concentration	Natural infiltration	Fan flow rate	Pressurization	Effectiveness
	(m^3)	Bq/m^3	h^{-1}	h^{-1}	(Pa)	(%)
Building A	69	1423	1.03	0.61-1.65	0.6-1.5	72%-89%
Building B	528	340	0.5	0.30-0.61	0.4-0.8	66%-96%
Building C	205	390	0.23	0.29-0.58	0.6-1.4	47%-72%

6 CONCLUSION

This paper presents a study on the positive pressurization ventilation technique as a radon mitigation solution. This technique constitutes a possible solution with a relatively low initial investment. Its effectiveness has been analyzed and its dependence on parameters such as the volume to be treated, the airtightness of the building or the initial radon concentration in its effectiveness has been proved. These would be the aspects to be taken into account in the dimensioning in terms of power and flow rate needed. For the specific cases studied, the results have shown an effectiveness range from 47% to 96%.

It has been observed that the radon reduction achieved improves the predictions of the dilution decontamination models. This behaviour may be related to the effect of pressurization as a mechanism to block radon exhalation from the sources. However, it has not yet been possible to determine the degree of influence of both effects and will be studied in future work with more controlled laboratory models. It will also be necessary to test the technique on a larger sample of buildings with different characteristics.

Regarding the feasibility of the technique, it should be taken into account that, in severe climates, the flow rate introduced may cause a decrease in comfort conditions, temperature and humidity, and energy efficiency. Its application should be evaluated on a case-by-case basis so as not to compromise other building requirements. The inclusion of air pre-treatment systems, in terms of temperature and humidity, may be necessary in certain climates.

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8 REFERENCES

Collignan, B., Lorkowski, C., Améon, R., 2012. Development of a methodology to characterize radon entry in dwellings 57, 176–183. https://doi.org/10.1016/j.buildenv.2012.05.002
Collignan, B., Powaga, E., 2019. Impact of ventilation systems and energy savings in a building on the mechanisms governing the indoor radon activity concentration. J. Environ. Radioact. 196, 268–273. https://doi.org/10.1016/j.jenvrad.2017.11.023
Diallo, T.M.O., Collignan, B., Allard, F., 2013. Analytical quantification of airflows from soil through building substructures. Build. Simul. 6, 81–94. https://doi.org/10.1007/s12273-

012-0095-2
Frutos, B., Martín-Consuegra, F., Alonso, C., Perez, G., Peón, J., Ruano-Ravina, A., Barros, J.M., Santorun, A.M., 2021. Inner wall filler as a singular and significant source of indoor radon pollution in heritage buildings: An exhalation method-based approach. Build. Environ. J. 201, 108005. https://doi.org/10.1016/j.buildenv.2021.108005
Frutos, B., Olaya, M., Esteban, J.L., 2011. Extraction systems as construction techniques to prevent radon entry in homes. Inf. la Constr. 63, 22–36. https://doi.org/10.3989/ic.09.056
Frutos, B., Sicilia, I., Campo, O., Aparicio, S., Gonz, M., Daniel, R., 2020. A full-scale experimental study of sub-slab pressure fields induced by underground perforated pipes as a soil depressurisation technique in radon mitigation 225. https://doi.org/10.1016/j.jenvrad.2020.106420
Fuente, M., Muñoz, E., Sicilia, I., Goggins, J., Hung, L.C., Frutos, B., Foley, M., 2019. Investigation of gas flow through soils and granular fill materials for the optimisation of radon soil depressurisation systems. J. Environ. Radioact. https://doi.org/10.1016/j.jenvrad.2018.12.024
Garbesi, K., Sextro, R., Fisk, W.J., Modera, M.P., Revzan, K.L., 1993. Soil-Gas Entry into an Experimental Basement : Model Measurement Comparisons and Seasonal Effects. Environ. Sci. Technol. 27, 466–473. https://doi.org/10.1021/es00040a003
Hung, L.C., Goggins, J., Fuente, M., Foley, M., 2018. Investigation of sub-slab pressure field extension in specified granular fill materials incorporating a sump-based soil depressurisation system for radon mitigation. Sci. Total Environ. 637–638, 1081–1097. https://doi.org/10.1016/j.scitotenv.2018.04.401
Jiranek, M., 2004. Testing and Design of Radon Resisting Membranes Based on the Experience from the Czech Republic, in: Roceedings of the 4th European Conference on Protection against Radon at Home and at Work Conference Programme and Session Presentations. p. 377.
Muñoz, E., Frutos, B., Olaya, M., Sánchez, J., 2017. A finite element model development for simulation of the impact of slab thickness, joints, and membranes on indoor radon concentration. J. Environ. Radioact. 177. https://doi.org/10.1016/j.jenvrad.2017.07.006
Nazaroff, W.W., Moed, B.A., Sextro, R.G., 1988. Soil as a Source of Indoor Radon, Generation, Migration, and Entry, in: Radon and Its Decay Products in Indoor W.W. Nazaroff, A.V. Nero Jr. New York, pp. 57–112.
Prignon, M., Van Moeseke, G., 2017. Factors influencing airtightness and airtightness predictive models: A literature review. Energy Build. 146, 87–97. https://doi.org/10.1016/J.ENBUILD.2017.04.062
Sabbarese, C., Ambrosino, F., D'Onofrio, A., Roca, V., 2020. Radiological characterization of natural building materials from the Campania region (Southern Italy). Constr. Build. Mater. 121087. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2020.121087
Sherman, M., 1992. Simplified Modeling for Infiltration and Radon Entry.
Vasilyev, A. V., Zhukovsky, M. V., 2013. Determination of mechanisms and parameters which affect radon entry into a room. J. Environ. Radioact. 124, 185–190. https://doi.org/10.1016/j.jenvrad.2013.04.014
WHO, 2009. Who Handbook on Indoor Radon - A Public Health Perspective. World Heal. Organ. 110 p. https://doi.org/10.1080/00207230903556771