Radon concentrations in cave houses of Crevillente. A study about typological factors and proposals for remedial actions based on ventilation techniques

Concentraciones de radón en casas-cueva de Crevillente. Estudio de factores tipológicos y propuestas de remedio en base a técnicas de ventilación

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Abstract
The present paper analyses the influence of typological factors on radon gas concentration in the cave houses of Crevillente (Alicante province, Spain). Despite their location in an area included in the lowest category of potential exposure to radon (according to the Marna Project), a radon accumulation exceeding the recommended values is obtained; room depth emerges as a parameter which increases the concentration found; small differences are also detected between interior and exterior temperatures (3°C), thus moving away from the usual comfort parameters and making it necessary to use additional air-conditioning systems so that these rooms can be habitable. Furthermore, the study of infiltrations reveals that the number of renovations/hour needed to reduce the existing radon concentration to 300 Bq/m^3 is feasible even starting from very high initial conditions; however, the most restrictive recommendations (100 Bq/m^3) are unlikely to be reached, since they imply over 13 renovations/hour of the whole dwelling volume even starting from relatively low concentrations.

Key words: Cave houses, indoor radon, ventilation, Crevillente, electret.

Resumen
El presente trabajo analiza la influencia de factores tipológicos en la concentración de gas radón existente en las casas cueva de Crevillente (provincia de Alicante, España). A pesar de la ubicación de estas viviendas, en un área incluida en la categoría más baja de exposición potencial al radón (de acuerdo con el Proyecto Marna), se obtiene una acumulación de radón que sobrepasa los valores recomendados; la profundidad de la estancia se identifica como un parámetro que incrementa la concentración obtenida; también se detectan diferencias bajas entre temperaturas interiores/exteriores (3°C), alejándose así de los parámetros habituales de confort y haciendo imprescindible el uso de climatización añadida para acondicionar estas estancias. Además, el estudio de infiltraciones constata que el número de renovaciones/hora necesario para reducir a 300 Bq/m^3 la concentración de radón existente es asumible incluso partiendo desde condiciones iniciales muy elevadas; sin embargo, las recomendaciones más restrictivas (100 Bq/m^3) son poco viables de alcanzarse ya que suponen más de 13 renovaciones/hora del volumen total de la vivienda, incluso partiendo de concentraciones relativamente bajas.

Palabras clave: Casas cueva, radón interior, ventilación, Crevillente, electret.

Introduction

Radon gas

Radon is an odourless, colourless, invisible and insipid noble gas which consists of three radioactive isotopes (^{219}Rn, ^{220}Rn and ^{222}Rn) coming from three natural disintegration chains (^{235}U, ^{232}Th and ^{238}U). ^{222}Rn (hereinafter radon) tends to be the isotope which acquires the most radiological importance due to its longer disintegration period (3.8 days), which allows it to cover greater distances and easily enter indoor areas before disintegrating.

Its short-lived descendants (less than 30 minutes), such as ^{218}Po, ^{214}Pb, ^{214}Bi y ^{214}Po, are highly chemically active metals which, either free or adhered to atmospheric aerosols of various sizes and composition, have a high likelihood of disintegrating in the lungs before being eliminated, thus increasing the risk of contracting carcinogenic diseases.

Despite the importance of this fact and the existence of numerous international regulations –more or less far-reaching depending on each specific country– on radon gas, Spain has developed a greater volume of legislation with regard to workplaces than to actual dwellings. Nevertheless, various European regulations suggest recommended limits for radon concentration inside existing dwellings on the basis of several acceptable maximum values; amongst them stands out the 90/143/EURATOM standard (Council of the European Union, 1990) (considered during more than 20 years), in which the European Union recommends an indoor radon concentration level of 400 Bq/m^3 as the threshold to initiate remedial actions in already-built dwellings. The recommendation has currently been turned into obligation through the Directive 2013/59/Euratom (Council of the European Union, 2013), which repeals previous regulations in ionising radiations and establishes the action level at 300 Bq/m^3 for any type of indoor area –a value which had already been collected by the World Health Organisation in 2009 (WHO, 2009).

State of the art. Previous studies about dwellings affected by radon in Spain

Taking into account that the most important contribution to the radiological impact caused by natural radiation received by the population is due to radon gas emanations, it comes as a surprise to check that the concern about the problems derived from its accumulation in dwellings did not start until the late 1970s. With the passing of time, both the airtightness of constructions and the increased social permanence in closed environments have aroused a growing interest in the study of those indoor environmental conditions which are likely to cause harmful effects on health.

In the Spanish context, the danger that high radon concentrations inside inhabited spaces can mean for health has called the attention both of the scientific community and of the general public through global research initiatives focused on conventional dwellings (Quindos, Fernandez, & Soto, 1995), in-depth reports about specific areas of Madrid (Sainz et al., 2009), Galicia (Barros-Dios, Ruano-Ravina, Gastelu-Iturri, & Figueiras, 2007) or Salamanca (Frutos, 2009), and studies referring to excavated dwellings in the *Levante* [Eastern Spain] area which are used as first residences (Piedecausa García, 2012).

It is thus worth highlighting that the existence of permanently inhabited cave houses is a significant peculiarity of Spain as opposed to other European countries, where such architecture seldom appears. Preliminary studies (Piedecausa & Chinchón, 2015) suggest that the excavated typologies might have an exposure to radon concentration exceeding those identified by the zoning in the Marna Project (Suárez Mahou, 2001), with indoor concentration levels similar to those found in other caves or mines where a few Bq/m^3 of radon on the floor (resulting from low ^{226}Ra levels) may generate indoor results at a kBq/m^3 level. Therefore, it becomes clear that a very low potential radon risk will be found in cave houses if only gamma radiation and soil permeability values are considered, which does not tally with the reality measured on-site in such spaces.

Description of the problem

The Valencian Autonomous Region is not considered a *radon prone area* (ICRP, 1993) on a global scale (areas prone to radon accumulation where over 1% of dwellings have concentrations 10 times above the national average value); nevertheless, certain excavated typologies do exist where the maximum recommended values are exceeded. Thus, it was verified that the indoor concentrations measured in excavated dwellings located in Crevillente (Alicante) largely exceed the recommended reference values, this result being an indicator which makes it advisable to carry out a more in-depth study.

In the light of all the above, the present paper analyses the influence exerted by a variety of characteristic typological factors (concentration distribution, shape, room depth, hygrothermal conditions, ventilation levels, flows, etc.) on the potential reduction of the existing radon concentration for two standard-type excavated dwellings in Crevillente (Alicante) which have values clearly above those recommended on a European scale.

Methodology

The proposed methodology can be structured around three blocks: examination of two case studies in Crevillente cave houses (selection, identification and building description); study about the influence of specific typological factors (radon concentration, depth and hygrothermal conditions); and analysis of the ventilation required (remedial actions) to reduce the initial radon concentration (infiltration levels and added renovations).

Case studies

The previous study about dwellings excavated in the northern quarter of caves corresponding to the municipality of Crevillente (Alicante) identifies three excavated typologies:
Typology 1. Cave: it has spaces fully excavated in the ground where no elements added to the exterior exist.
Typology 2. Cave + Attached constructions: in addition to having excavated rooms, it includes other conventionally built constructions on its front part, with access from outside and inside the dwelling.
Typology 3. House + cave: it apparently looks like a conventional dwelling in the exterior, its excavated nature going unnoticed.

The present paper focuses on the specific analysis of two dwellings belonging to the *House + Cave* typology because the fact that it resembles the most a conventional construction provides a higher degree of representativeness and makes it possible to establish parallelisms with other national and international studies.

Dwelling 1 (No. 29 Llorens Street)

It is in a good state of repair and shows good qualities in its coating material because of a previous refurbishment carried out in 2003. It has a usual occupation status all year round, since it serves as the first residence for a young couple with two children.

The dwelling has 7 excavated rooms (main dining room, 3 bedrooms, kitchen, storage room and living room with a *lumbrera* –skylight–); 4 non-excavated rooms (bathroom, bedroom, storage room and laundry room); and an inner access patio. It deserves to be highlighted that there are rooms without direct ventilation (spaces 2, 4, 5, 6 and 8 in Figure 1) and with direct ventilation (spaces 1, 3, 7, 9, 10 and 11 in Figure 1); the dining room and the kitchen have no separation elements between them.

The maximum inside height is 2.80 m (room 9) and the minimum one, 2.10 m (room 6). An average dwelling height of 2.50m will be considered for the present study.

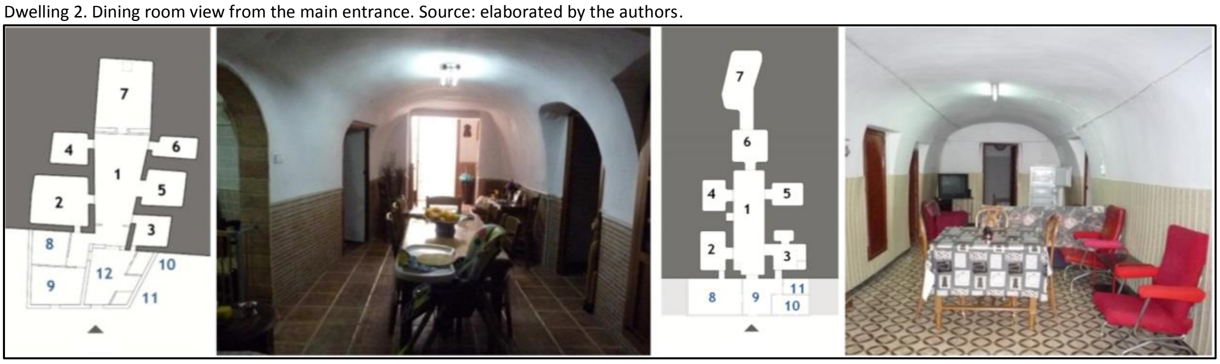
Dwelling 2 (No. 12 Sendra Street)

It is in an acceptable condition despite having been excavated more than 50 years ago and being currently unoccupied.

The dwelling has 7 excavated rooms (5 bedrooms, kitchen and living room); 3 non-excavated rooms (bathroom, storage room and exterior kitchen-laundry room); and an inner access patio. It is worth highlighting the existence of rooms without direct ventilation (spaces 4, 5, 6 and 7 in Figure 1) and with direct ventilation (spaces 1, 2, 3, 10 and 11 in Figure 1); the dining room and the kitchen have no separation elements between them.

The maximum inside height is 2.65 m (room 3) and the minimum one, 2.05 m (room 5). An average dwelling height of 2.35m will be considered for the present study.

Figure 1. First image. Dwelling 1. Floor plan of the excavated spaces (in black) and the attached constructions (in blue). Second image. Dwelling 1. Dining room view from the deepest bedroom. Third image. Dwelling 2. Floor plan of the excavated spaces (in black) and the attached constructions (in blue). Fourth image. Dwelling 2. Dining room view from the main entrance. Source: elaborated by the authors.



Research development

The environmental concentration measurements were implemented by means of LLT-type E-PERM devices formed by an L-type chamber plus an L-type electret (in rooms 2, 3, 6, 7 and 10) for a four-week exposure period under habitual use conditions in dwelling 1 (ventilated on an everyday basis before and during the measurements from July 13 to August 9, 2011). Furthermore, SST-type E-PERM devices made up of an S-type chamber plus an electret were utilized (in rooms 1, 2, 3, 4, 5, 6, 7, 10 and 11) during a three days' exposure in closed conditions in dwelling 2 (without being ventilated, neither during the previous 12 hours nor during the measurements between April 17 and April 20, 2011). The study has been limited to a specific period and, although during the realization of this type of measures there may be certain seasonal oscillations (European Commission, 1995, Denman et al., 2006, Groves-Kirkby et al., 2015), the main objective of the study is not to perform an analysis of possible fluctuations in the annual concentration, but is based on using the concentration data obtained in a specific period to propose a mitigation trend by means of certain ventilation measures.

Following the measurements, an examination was performed of possible turning points in radon distribution according to the depth of each room, additionally analysing the hygrothermal conditions in the course of the data collection process. The theoretical determination of the watertightness rate for each dwelling with the aim of checking the initial ventilation conditions, as well as the way in which they influence the existing concentration, gives way to the identification of the minimum ventilation needed to reduce radon concentration to values below 300 Bq/m^3 (established in the European reference standard (Council of the European Union, 2013)) and the implications derived from reducing it even more to 100 Bq/m^3 (recommended by the World Health Organisation (WHO, 2009)).

Results

Radon concentration distribution (Bq/m^3)

The radon concentration obtained for the excavated rooms in both dwellings (the first one in normal use conditions and the second in closed conditions) exceeds the values mentioned in various reference standards (Council of the European Union, 1990, 2013; WHO, 2009) as action levels to initiate remedial actions in existing constructions. The main field data obtained are shown in Table 1 and Figure 2.

Table 1. Data on radon concentration and room depth. Source: elaborated by the authors.

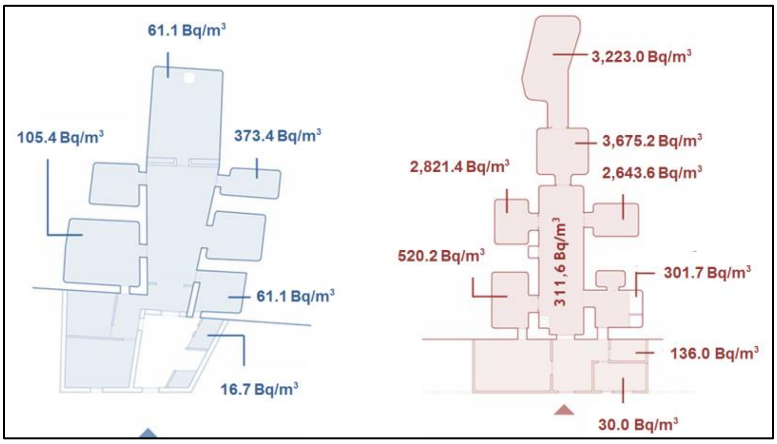
Room	Radon concentrat. (Bq/m^3)	Depth Initial (m)	Depth Final (m)	Depth Middle (m)
Dwelling 1				
2.Bedroom	105.4	0.0	-4.8	-2.40
3.Bedroom	61.1	0.0	-3.2	-1.60
6.Storage room	373.4	-8.3	-10.2	-9.25
7.Living room	61.1	0.0	-10.0	-5.00
10.Storage room	16.7	0.0	+2.2	+1.10
Dwelling 2				
1.Dining room	311.6	0.0	-10.3	-5.15
2.Bedroom	520.2	0.0	-4.5	-2.25
3.Kitchen	301.7	0.0	-3.3	-1.65
4.Bedroom	2,993.1	-6.4	-9.4	-7.90
5.Bedroom	2,695.6	-6.9	-9.1	-8.00
6.Bedroom	3,994.5	-10.3	-14.2	-12.25
7.Spinning machine room	3,235.3	-14.2	-21.7	-17.95
10.Ext. kitchen	30.0	+1.5	+3.5	+2.50
11.Bathroom	136.0	0.0	+1.5	+0.75

The maximum radon concentration value obtained in excavated rooms (long-term normal use conditions) for dwelling 1 is 373.4 Bq/m^3 (space 6), whereas the maximum value in excavated rooms (short-term closed conditions without use or ventilation) for dwelling 2 is 3,994.5 Bq/m^3 (space 6). Table 2 shows the main global data (maximum, minimum and mean values) of the excavated part (brown colour) and of the part built externally to the ground (orange colour); it deserves to be stressed amongst them that the arithmetic mean of the results obtained is 123.5 Bq/m^3 and 1,579.8 Bq/m^3 respectively for each dwelling.

Table 2. Summary of the radon concentration obtained in excavated and exterior rooms. Source: elaborated by the authors.

Radon Concentration (Bq/m^3)	Dwell. 1	Dwell. 2
Global maximum	373.4	3,994.5
Global minimum	16.7	30.0
Arithmetic mean	123.5	1,579.8
Geometric mean	75.5	650.3
Excavated maximum	373.4	3,994.5
Excavated minimum	61.1	301.7
Exterior maximum	16.7	136.0
Interior minimum	16.7	30.0

Figure 2. Left image. Average radon results per room in dwelling 1 (long term): 2. Bedroom (105.4 Bq/m^3); 3. Bedroom (61.1 Bq/m^3); 6. Storage room (373.4 Bq/m^3); 7. Living room with skylight (61.1 Bq/m^3); 10. Storage room (16.7 Bq/m^3). Right image. Average radon results per room in dwelling 2 (short term): 1. Dining room (311.6 Bq/m^3); 2. Bedroom (520.2 Bq/m^3); 3. Kitchen (301.7 Bq/m^3); 4. Bedroom (2,821.4 Bq/m^3); 5. Bedroom (2,643.6 Bq/m^3); 6. Bedroom (3,675.2 Bq/m^3); 7. Spinning machine room (3,226.0 Bq/m^3); 10. Exterior kitchen (30.0 Bq/m^3); 11. Bathroom (136.0 Bq/m^3). Source: elaborated by the authors.



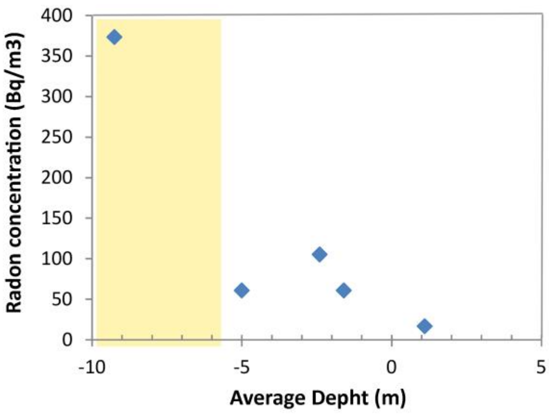
It is also worthy of mention that, apart from the installation of radon detectors, environmental gamma radiation levels were measured in all the aforementioned spaces using a portable Dosimeter PM 1203M device –with an average result of 0.07 µSv/h.

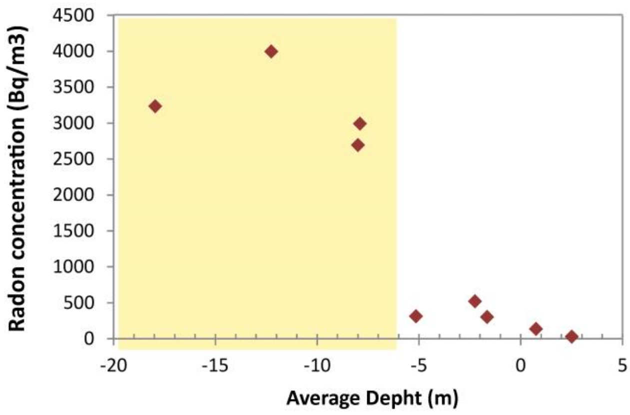
Concentration (Bq/m^3) according to average room depth (a)

The average value (a) of the initial wall and the final wall (the closest and the furthest ones, respectively, with regard to the exterior wall) identified in Table 1 was considered to perform the comparative analysis between indoor radon concentration (Bq/m^3) in excavated spaces depending on the depth of each room (Figure 3); the excavation line (façade) was taken as value 0, the results obtained being negative if the room is excavated and positive if it is built outside the ground.

An increase in radon concentration can be inferred from this ratio as the excavation depth of the studied room grows, that concentration becoming lower as the built rooms are further from the ground (Figure 3). It is additionally worth noting that a considerable quantitative leap appears in the concentration obtained at a depth above -5m, increasing by more than six times the radon value reached in other areas (Figure 3 shaded band).

Figure 3. **Left image.** Radon concentration according to room depth for dwelling 1. **Right image.** Radon concentration according to room depth for dwelling 2. Source: elaborated by the authors.





Hygrothermal conditions

The climate of Crevillente is placed within a range of annual temperatures between 0.6°C and 36.5°C (Meteorología, 2016); nevertheless, and despite the outdoor oscillations, it can be verified that the humidity and temperature conditions in the excavated dwellings of the area remain within a constant bracket all year round.

Two different seasonal periods have thus been studied: summer (dwelling 1); and spring (dwelling 2). The measurements carried out on-site during the radon concentration assessment were completed with various climate-related data; some of the results obtained appear in Table 3.

Table 3. Summary of interior and exterior hygrothermal conditions on the first and the last measurement days. Source: elaborated by the authors.

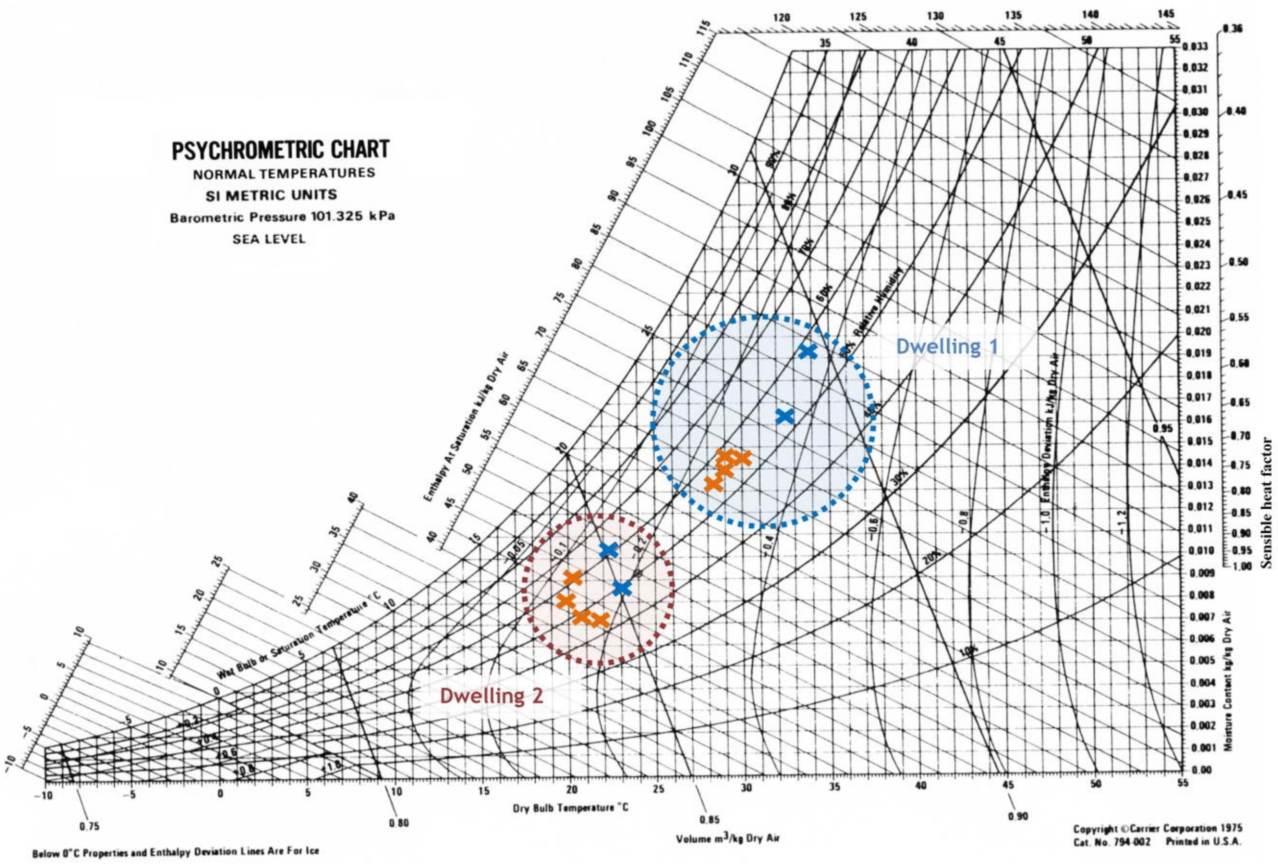
Date	Max. interior temp. (°C)	Min. interior temp (°C)	Exterior temp (°C)	Max. interior relative humidity (%)	Min. interior relative humidity (%)	Exterior relative humidity (%)
Dwelling 1						
13/07/11	28.3	27.9	32.1	56.8	56.3	53.6
09/08/11	29.2	28.7	33.7	54.7	53.3	58.1
Dwelling 2						
17/04/11	21.9	21.5	23.0	46.2	44.1	48.1
20/04/11	20.2	19.7	22.4	61.4	55.3	62.3

After identifying the aforementioned data on a psychrometric chart, it becomes visible that both the measurements for dwelling 1 (blue circle-summer) and for dwelling 2 (red circle-spring) lie within a range of stable values for both times of year (Figure 4). However, even though the town examined has a mild climate, differences of nearly 10°C between both periods arise in exterior temperatures (values in blue), temporarily separated by few months; this disparity similarly affects the interior temperatures obtained (values in orange). Both seasons show a difference of about 3°C between the exterior and interior temperature for each dwelling.

Infiltration levels

Even though the typology of Crevillente cave houses has few contact points with the outside (being characterised by an in-depth excavated development), the carpentry utilized on the façade becomes essential for the infiltration of air towards the inner spaces; that infiltration will depend on factors such as the material, the opening system and the adjustment of the frame, as well as on the existence of small clearances through which air can pass as a result of the differences in pressure inside and outside the dwelling. The property for an element (window or door) to let the air come through it is known as permeability.

Figure 4. Psychrometric chart specifying the temperatures and humidities obtained. Source: elaborated by the authors.



A number of basic parameters need to be established (Hatt, Saelzer, Hempel, & Gerber, 2012) for the calculation of initial infiltration levels during radon measurements. Each one of the doors and windows (Fig. 5) is graphically identified for this purpose, their characteristics being also collected, namely: type of excavated (brown surface) or non-excavated (blue surface) space; type of element, door (D) or window (W); exterior (e) or interior (i) location; material, wood (brown line) or metal (blue line) and type of continuous element (continuous line) or mixed with glass (mixed).

Finally, it deserves to be highlighted that the numbers of rooms for the room where they are located will be maintained for the characterisation of doors and windows, thus facilitating their identification; due to this fact, there are rooms the numbers of which do not appear on the corresponding graphs or tables, since those elements do not exist. Once all the elements have been graphically located, a quantitative identification (Table 4) is performed of the specific characteristics for each element and room, namely: room area (m^2), volume (m^3), as well as width/height/surface/material/type for each door and window.

Figure 5. Left image. Identification and characterisation of doors and windows for dwelling 1. Central image. Identification and characterisation of doors and windows for dwelling 2. Right image. Key to identify types of spaces, utilized materials, and their relationship with the exterior. Source: elaborated by the authors.

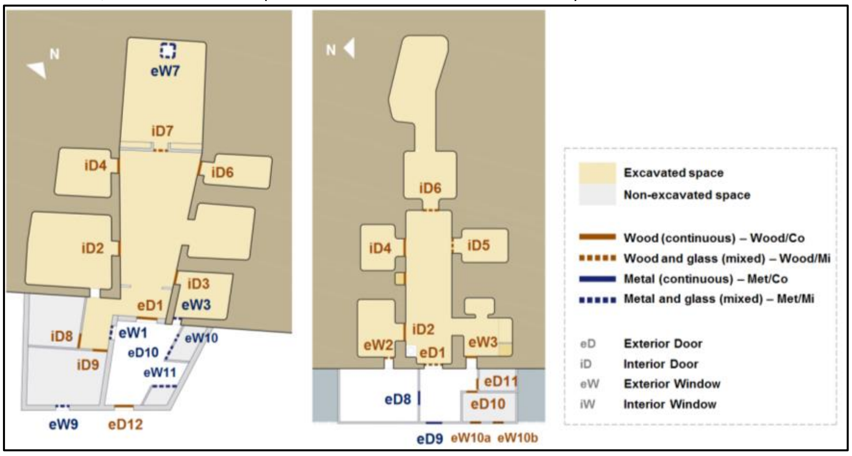


Table 4. Specific characteristics of rooms, doors and windows in the two dwellings. Source: elaborated by the authors.

Space	Area (m^2)	Volume (m^3)	Relation-ship with the exterior	Door						Window					
				Name	Width (m)	Height (m)	Area (m^2)	Material	Type	Name	Width (m)	Height (m)	Area (m^2)	Material	Type
Dwelling 1	h = 2.50m														
1.Dining room	36.0	90.0	Yes	eD1	1.2	2.2	2.64	Wood	Co	eW1	0.8	0.8	0.64	Met	Mi
2.Bedroom	21.5	53.8	No	iD2	0.8	2.1	1.68	Wood	Co	-	-	-	-	-	-
3.Bedroom	8.4	21.0	Yes	iD3	0.8	2.1	1.68	Wood	Co	eW3	0.5	0.5	0.25	Met	Mi
4.Bedroom	9.3	23.3	No	iD4	0.8	2.1	1.68	Wood	Co	-	-	-	-	-	-
5.Kitchen	11.2	28.0	No	-	-	-	-	-	-	-	-	-	-	-	-
6.Storage room	7.0	17.5	No	iD6	0.8	2.1	1.68	Wood	Co	-	-	-	-	-	-
7.Living room	28.3	70.8	Yes	iD7	0.8	2.1	1,68	Wood	Mi	eW7	0.7	0.7	0.49	Met	Mi
8. Bathroom	9.0	22.5	No	iD8	0.8	2.1	1.68	Wood	Co	-	-	-	-	-	-
9.Bedroom	14.0	35.0	Yes	iD9	0.8	2.1	1.68	Wood	Co	eW9	1.0	1.0	1.00	Met	Mi
10.Storage room	3.3	8.3	Yes	eD10	0.7	2.1	1.47	Wood	Mi	eW10	0.3	0.3	0.09	Met	Mi
11.Laundry room	2.0	5.0	Yes	eD11	1.4	2.1	2.94	Wood	Mi	-	-	-	-	-	-
12. Patio	16.3	40.8	Exterior	eD12	0.8	2.1	1.68	Wood	Co	-	-	-	-	-	-
TOTAL	166.3	415.8													
Dwelling 2	h= 2.35m														
1.Dining room	29.0	68.2	Yes	eW1	1.2	2.2	2.64	Wood	Mi	-	-	-	-	-	-
2.Bedroom	9.5	22.3	Yes	iD2	0.7	2.0	1.40	Wood	Co	eW2	0.6	0.6	0.36	Wood	Mi
3.Kitchen	8.5	20.0	Yes	-	-	-	-	-	-	eW3	0.6	0.6	0.36	Wood	Co
4.Bedroom	6.0	14.1	No	iD4	0.7	2.0	1.40	Wood	Co	-	-	-	-	-	-
5.Bedroom	5.0	11.8	No	iD5	0.7	2.0	1.40	Wood	Mi	-	-	-	-	-	-
6.Bedroom	11.0	25.9	No	iD6	0.7	2.0	1.40	Wood	Mi	-	-	-	-	-	-
7. Spinning mach. room	23.0	54.1	No	-	-	-	-	-	-	-	-	-	-	-	-
8. Stable	21.0	49.4	Exterior	eD8	1.20	2.1	2.52	Met	Co	-	-	-	-	-	-
9. Patio	12.0	28.2	Exterior	eD9	1.20	2.1	2.52	Met	Co	-	-	-	-	-	-
10.Exterior kitchen	6.5	15.3	Yes	eD10	0.7	2.0	1.40	Wood	Co	eW10a Ve10b	1.0 0,6	1.0 0,6	1.00 0,36	Wood Mad	Co Co
11.Bathroom	3.0	7.1	Yes	eD11	0.7	2.0	1.40	Wood	Co	-	-	-	-	-	-
TOTAL	134.5	316.1													

On the whole, infiltrations make it possible to renovate the building's interior air and become more relevant in proportion with the impact of the wind or the difference between inner and outer temperatures (very cold winters and very hot summers). Therefore, some initial infiltration conditions will exist for each dwelling as a consequence of the permeability in exterior carpentry during concentration measurements (doors and windows). Seeking to identify such values, an identification is made of the main characteristics associated with each elements that is in contact with the exterior, namely: size (m), total area (m^2) and infiltration surface (m^2) (Table 5).

Table 5. Infiltration surfaces for exterior elements (doors and windows). Source: elaborated by the authors.

Space	Door							Window						
					Infiltration surface							Infiltration surface		
	Name	Width (m)	Height(m)	Area (m^2)	Opening (m^2)	Clearance (m^2)	Total (m^2)	Name	Width (m)	Height (m)	Area (m^2)	Opening (m^2)	Clearance (m^2)	Total (m^2)
Dwelling 1														
1. Dining room	eD1	1.2	2.2	2.64	$^2/_3$ 2.64	0.0136	1.7736	eW1	0.8	0.8	0.64	$^2/_3$ 0.64	0.0064	0.4331
3.Bedroom	-	-	-	-	-	-	-	eW3	0.5	0.5	0.25	$^2/_3$ 0.25	0.004	0.1707
7.Living room	-	-	-	-	-	-	-	eW7	0.7	0.7	0.49	0.49	0.0056	0.4956
9.Bedroom	-	-	-	-	-	-	-	eW9	1.0	1.0	1.00	$^2/_3$ 1.00	0.008	0.6747
EXCHANGE AREA							1.7736							1.774
Dwell. 1 TOTAL EXCHANGE AREA = 3.5476 m^2 (35,476 cm^2)														
Dwelling 2														
1.Dining room	eD1	1.2	2.2	2.64	0.00	0.0136	0.0136	-	-	-	-	-	-	-
2.Bedroom	-	-	-	-	-	-	-	eW2	0.6	0.6	0.36	0.00	0.0048	0.0048
3.Kitchen	-	-	-	-	-	-	-	eW3	0.6	0.6	0.36	0.00	0.0048	0.0048
EXCHANGE AREA							0.0136							0.0096
Dwell. 2 TOTAL EXCHANGE AREA = 0.0232 m^2 (232 cm^2)														

It is worthy of mention that, on one side, 2 mm are considered in all the perimeters of doors and windows for surface calculation in perimeter clearances (m^2) to obtain the total infiltration surface (m^2). On another, an added exchange percentage that has to do with the exterior contact surface of the construction element is also included because measurements in dwelling 1 take place in normal use conditions (and not in closed conditions like in dwelling 2). Thus, a 100% opening arc is assumed in the door to the patio and in all the exterior swing windows for dwelling 1, insofar as measurements take place in summer, thus generating a larger exchange surface; it is considered that this situation lasts during two thirds of the day (the rest corresponds to the work period).

With these premises in mind, the total infiltration area (A) in contact with the exterior turns out to be 3.5476 m^2 for dwelling 1 and 0.0232 m^2 for dwelling 2. It was verified that Table 4.1 about the effective area of the mixed ventilation openings at premises specified in the Technical Building Code (Vivienda, 2006) cannot be applied to the present case, since the former only refers to the use of small ventilation surfaces (grilles in carpentry) and not to completely open windows or doors. Thus, considering the aforementioned exchange area (A), the value of the initial flow (Q) in each dwelling (m^3/s) during the radon concentration measurements is obtained using the following expression:
$Q = r \cdot Spe \cdot A_i \cdot \sin \alpha$ (Olgyay & Olgyay, 1963, cited by Fuentes Freixanet, 2012)

Where:

- Q is the ventilation rate or amount of air (m^3/s)
- r is the ratio between the inlet and the outlet opening area
  $r = 0.6 ((Rv / (1 + Rv^2)^{0.5}) / \sin 45°)$
  Rv is the ratio between air outlet opening (m^2) and inlet opening area (m^2): $Rv = A_o / A_i$.
- Spe is the wind speed (m/s)
- A_i is the air inlet opening area
- α is the angle formed by the wind direction and the opening plane (45° are considered)

A calculation is subsequently made for the equivalence of that flow in renovations per hour taking into account the total volume of each dwelling (V) and assuming that $Q_{renov} = Q \cdot 3.600 / V$

Where:

- Q_{renov} is the total flow (renovations/hour)
- Q is the flow (l/sec)
- V is the dwelling volume (m^3)

The renovations/hour are finally obtained in a quantitative way at the moment when radon measurements are taken for each one of the dwellings studied; in other words, the watertightness rate of the building (Table 6).

Table 6. Air renovation rate (No. of times per hour) in each dwelling at the time of radon measurements. Source: elaborated by the authors.

Dwelling	$R_v = A_o / A_i$	r (ratio between inlet and outlet opening)	Speed (m/s)	Q (l/s)	Dwelling volume (m^3)	Q_{renov} (renov/hour)
1	R_v = 0.4956/3.0520 = 0.1624	0.1130	1.42	0.4168	415.8	3.609
2	R_v = 0.0232/0.0232= 1.0	0.4986	1.75	0.0172	316.1	0.196

Ventilation needed to reduce radon concentration in the dwelling

Bearing in mind that the strategies to reduce radon levels in an existing dwelling by means of ventilation systems can be based on two different mechanisms (gas dilution through exchange of exterior air with less concentration or modification in pressure states in a natural or forced way), the present paper will develop the first of them.

Therefore, a reduction in the radon concentration of the dwellings under study requires establishing the necessary ventilation rate to achieve the aim of reducing the presence of that gas through an exchange of air with the exterior. This phenomenon was simulated by means of the following differential expression for environmental conditions, taking into account only dilution through the exchange of air with the exterior:

$$C=R/V. \lambda t$$ (Frutos & Olaya, 2014)

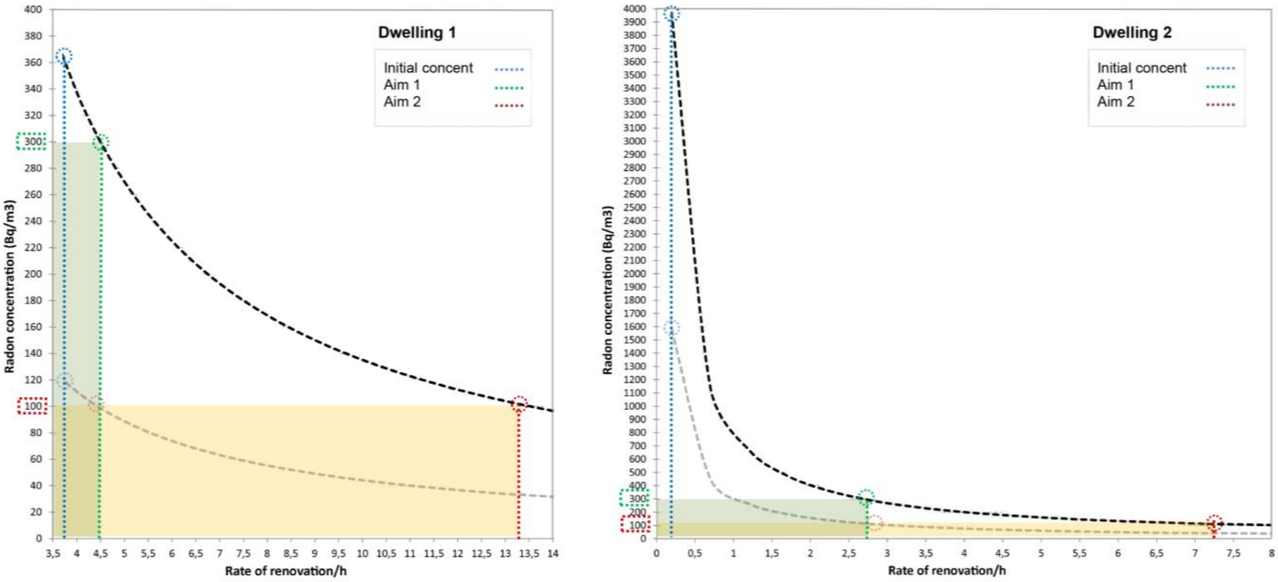
Where:

- C is the radon concentration in Bq/m^3
- R is the radon entry rate through the floor (Bq/s)
- V is the accumulation volume in the inhabited space (m^3)
- λt (h^{-1}) is the sum of: λ_d radon disintegration constant + λ_h airtightness rate + λ_r rate of renovations/h

Seeking to identify the most unfavourable case, attention was paid to the data corresponding to maximum initial radon concentration measured on-site for each dwelling (Table 2) and the airtightness rates obtained (Table 6); this makes it possible to infer the ratio existing between the air renovation rate (No. of times per hour) and the final radon concentration (Bq/m^3), thus allowing us to determine the number of extra renovations needed to reduce the initial radon concentration to the main standard values (Figure 6). It is consequently concluded that a reduction in radon concentration to 300 Bq/m^3 (Council of the European Union, 2013) (Aim 1) requires 4.5 renovations per hour of the whole air volume for dwelling 1 and 2.70 renovations per hour for dwelling 2. In turn, 13.25 renovations per hour for dwelling 1 and 7.35 renovations per hour for dwelling 2 are respectively needed to bring that maximum concentration to 100 Bq/m^3 (WHO, 2009)(Aim 2).

In short, dwelling 1 would need 1 extra renovation (with regard to the already existing airtightness rate) to fulfil the first aim and practically 10 extra renovations to achieve the second one. As for dwelling 2, more than 2 renovations would have to be added to achieve Aim 1 and more than 7 to reach Aim 2.

Figure 6. Air renovation rate (No. of times per hour) with regard to the existing radon concentration (Bq/m^3). The evolution of the maximum concentration obtained is shown in black; the evolution of the average concentration obtained for each dwelling is shown in grey. Source: elaborated by the authors.



Finally, it is worth stressing the importance of considering maximum radon concentration values, since the use of mean values implies results for renovations per hour well below the most unfavourable ones (4.45 renovations per hour as opposed to the more than 13 renovations needed in dwelling 1, as well as 2.8 renovations per hour compared to the more than 7.35 renovations required in dwelling 2).

Conclusions

Firstly, as regards the distribution of radon gas concentration, it was verified that the excavated dwelling typology, despite being located in areas not excessively prone to generate radon (because they are not granitic but formed by limestone and sandstone) show a remarkable accumulation of this gas in their interior spaces due to their permanent contact with the ground where they are inserted and to the ventilation habits of its occupants. It is verified that the concentrations obtained largely exceed the internationally recommended limits, the problem becoming even worse if the rooms are not properly ventilated (dwelling 2 as opposed to dwelling 1). This situation highlights some unknown factors referring to the nature of radon exhalations insofar as, even though Crevillente is placed within the lowest category of potential exposure according to the Marna Project (Suárez Mahou, 2001), the present research shows the opposite and emphasises the need to carry out more specific studies at a local and national level in areas which, in principle, do not imply an initial danger because they are included in category 0. Likewise, room depth clearly arises as a parameter to be valued in future concentration studies because an increase in the values obtained has been checked as the spaces are further from the exterior façade.

Secondly, and although these cave houses have been internationally recognized as sustainable constructions which do not need any energy or air-conditioning input (since they are considered to maintain stable temperatures both in winter and in summer), significant differences were found (around 8°C) between summer and spring hygrometric data.

Furthermore, small differences appeared between interior and exterior temperatures (approximately 3ºC), with spaces that nearly reach 30°C in summer, these being values which are far from the usual comfort parameters in spaces used as dwellings and thus make necessary the utilization of additional air-conditioning systems to cool the inhabited rooms.

It must additionally be highlighted that, even though many of these excavated dwellings were rehabilitated in recent years so that they could adapt to the new directives on energy efficiency, the use of more advanced and watertight construction elements (which generated a lower level of air exchange with the exterior) does not directly imply a higher radon concentration in inner spaces –since the ventilation in each room plays an essential role in this respect. Thus, dwelling 1 shows a low interior radon concentration (despite having a recent –and consequently more watertight– metal carpentry) because of the ventilation that characterises a habitual dwelling use. In turn, dwelling 2 shows very high radon concentrations despite having rudimentary and not properly maintained wood carpentry, with visible clearances and a low level of watertightness that permit a constant air exchange with the exterior. This consequently underlines the importance of a correct ventilation in spaces prone to have radon, the utilisation of highly watertight elements not constituting the main reason for possible concentration increases.

Finally, with respect to the ventilation needed to reduce radon concentration in exposed cave houses, it was checked that the number of renovations per hour required to comply with the recommendation of 300 Bq/m3 (Council of the European Union, 2013) can be assumed even starting from very high initial concentrations (dwelling 2); nevertheless, the most restrictive recommendations (WHO, 2009) seem hardly viable because reducing the concentration to 100 Bq/m3 means more than 13 renovations per hour of the whole dwelling volume even with relatively low initial concentrations (dwelling 1). Such requirements are excessive, especially taking into account that only dilution, and no other complementary effects such as changes in pressure states, are considered; those rates of renovations per hour can only be reached through the use of additional forced ventilation systems, which entail losses of the thermal control that is so characteristic of these dwellings, along with a higher energy consumption and increased maintenance expenses in the aforementioned buildings.

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