NUKLEONIKA 2016;61(3):327–332
doi: 10.1515/nuka-2016-0054

ORIGINAL PAPER

DE GRUYTER OPEN

Factors underlying persistently high radon levels in a house located in a karst limestone region of Ireland – lessons learned about remediation

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Abstract. The remediation of buildings with elevated radon concentrations is generally straightforward. However, in some cases a number of attempts may be needed to reduce concentrations to below the reference level and, occasionally, it may be impossible to reduce concentrations to below the reference level in a cost effective way. This paper details the work carried out between 2004 and 2012 to reduce radon concentrations in a house with initial radon concentrations of almost 1500 Bq/m^3. Over this period, high radon levels were consistently recorded despite the introduction of various radon remedial measures. Remedial work was carried out on ten occasions with 29 radon tests carried out to measure the effect of this work. The paper describes the structure of the house and the karst geology that it is built on and the likely contribution of these factors to the difficulties encountered reducing concentrations. Ultimately, radon concentrations were reduced to about 450 Bq/m^3 but no further reductions were considered practicable without substantial and costly renovation to the house. Nonetheless, the remedial work carried out to date has resulted in a significant reduction in the risk to the homeowner of developing lung cancer. This work has also added to the understanding of radon remediation techniques in Ireland, particularly for houses built on karst limestone.

Key words: karst geology • lessons learned • radon • remediation methods

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Received: 11 December 2015
Accepted: 31 March 2016

Introduction

Radon is a naturally occurring radioactive gas that originates from the decay of uranium in rocks and soils and is linked to some 13% of lung cancer cases in Ireland. Between 1992 and 1999, the Radiological Protection Institute of Ireland (RPII)[1] carried out a National Radon Survey (NRS) of Ireland to identify the areas of the country most at risk from high indoor radon levels. Those areas where it was predicted that more than 10% of homes will have radon concentrations above the reference level of 200 Bq/m^3 were designated High Radon Areas [1]. During 1999, in response to public awareness work related to the NRS, a homeowner living in a high radon area near Lisdoonvarna in County Clare (Fig. 1) in the southwest of Ireland used the RPII's radon measurement service to carry out a radon test in her house. A radon concentration of almost 1500 Bq/m^3 was identified, compared to the Irish reference level of 200 Bq/m^3. In 2004, the householder engaged a radon remediation contractor to reduce radon concentrations. The contractor installed mechanical ventilation to extract radon

[1] The Radiological Protection Institute of Ireland merged with the Environmental Protection Agency in 2014.

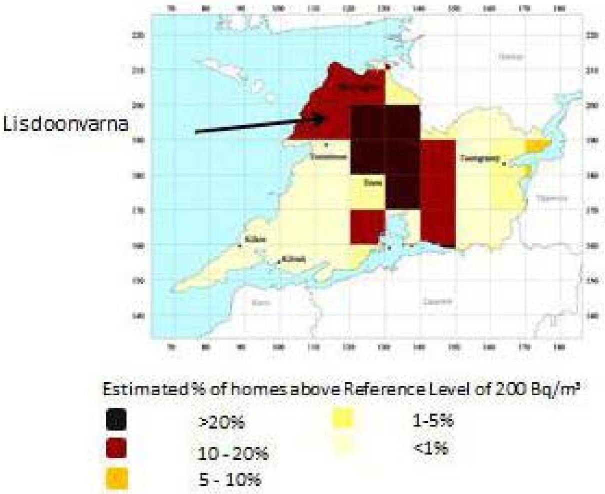

Fig. 1. The radon map of the southwest of Ireland showing the location of the house in Lisdoonvarna, County Clare.

from the sub-floor area. This work was unsuccessful and marked the beginning of a series of attempts to reduce the radon concentration to below the Irish reference level. This paper describes the structure of the house in question, the local geology and its contribution to the problem and the work carried out between 2004 and 2012 to reduce the radon concentration in this house.

The geology of the 'Burren'

Lisdoonvarna in County Clare is located in an area known as the 'Burren' which is an area of special interest in terms of its geology and ecology. The word 'Burren' comes from an Irish word 'boíreann' meaning a rocky place. The geology consists of granite overlain with carboniferous limestone, which in turn is overlain by younger shale. In many parts of the 'Burren', the limestone pavements are exposed showing classical clints (blocks of limestone) and grykes (fissures in the limestone). These clints and grykes make up the limestone pavements (Fig. 2). This shaping of the landscape has largely been carried out by the relatively recent glaciations which scoured the surface soil from the base rock. This has resulted in what is known as a karst landscape which includes features such as sinkholes, vertical shafts, disappearing streams and complex underground drainage systems and caves [2, 3]. Karst limestone areas are often associated with elevated radon concentrations in the houses built there [4, 5].

The house in question is located in an area of limestone interdigitation, a finger-shaped piece of land, covered in a thin layer of soil, from which the shale has been removed. The three different geological layers are all likely to have an impact on radon movement through the ground and ultimately on indoor radon concentrations. Radon-222 is part of the uranium-238 decay series and, since granite is relatively rich in uranium, it is often associated with elevated indoor radon concentrations [3]. Both shale and limestone can act as a conduit for radon as it can easily pass through cracks and fissures in

Fig. 2. Exposed limestone pavements separated by grykes.

both rock types, particularly limestone. The land surrounding this area of interdigitation is overlain with shale, and it has been postulated that radon can travel more freely to the surface in the area of interdigitation, as there is one less layer of rock for the radon to move through. In this way, the area of interdigitation may be acting as a 'release valve' for radon in much of the surrounding area.

In addition, the movement of water as part of the system of underground streams that often form in limestone areas can transport radon dissolved in the water over large distances. There is known to be an underground river, which emerges following heavy rainfall, flowing directly below the house in question. This may also be a contributing factor to both the elevated radon concentrations measured and the significant variation observed.

The property

The house is a single storey building facing north and consisting of ten rooms and a hallway leading to two corridors (Fig. 3). The house was first built prior to1841 and over the years, it has been converted and extended. The original house was made up of the present day living room, dining room, bathroom and small bedroom, the flooring in this part of the house is made of chipboard slabs laid over bare earth on dwarf walls. Some of the walls in this part of the house are up to 75 cm thick. In 1965, the home was extended to include the kitchen and the big bed-

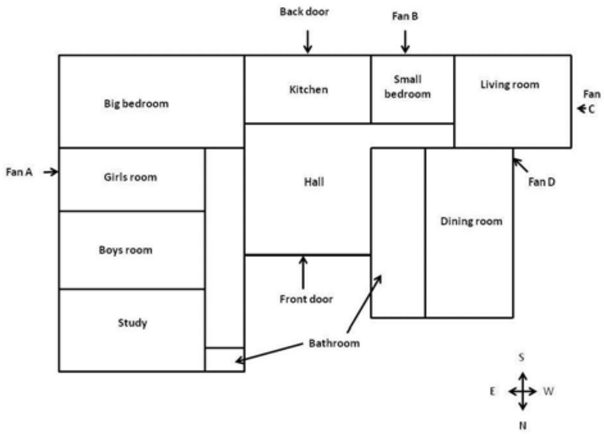

Fig. 3. Schematic diagram of the layout of the house.

room. In 1974, the girl's room, boy's room, the study and small bathroom were added with suspended timber floors laid in this part of the house. At this time, the courtyard area was enclosed to form the hall and concrete floors were laid in this area and the short corridor between the small bedroom and the bathroom. It is likely that a damp proof course was laid in this part of the home. Under floor ventilation was installed via louvered vents at regular intervals around the perimeter of the building, however, it is likely there was little through ventilation between the different underfloors.

Radon concentrations measured and remedial work carried out

The radon concentrations detailed below were measured with a two-part polypropylene holder and a CR-39 detecting element. The holder acts as a simple radon diffusion chamber, excluding radon decay products and dust, limiting access of moisture but allowing the entry of radon gas. The composition of the detectors is poly(allyl diglycol carbonate). The alpha particles emitted following the decay of radon in the detector chamber leave tracks on the detector. The detectors are then chemically etched in 6.25 M sodium hydroxide at 98°C for 1 hour and the track density counted and converted to radon concentration.

As described above, the first radon test was carried out in 1999 and resulted in a seasonally adjusted annual average [6] of 1467 Bq/m^3. During 2004, a further test was carried out in the house as part of a study by University College Dublin confirming the initial high test results for the house [7]. Between the first test in 1999 and the most recent one carried out in 2013, a total of 29 sets of 10-day and 3-month tests were carried out by both the RPII and a private radon measurement service. Remedial work to reduce the radon levels was carried out on the house on 10 separate occasions during this period. The principal test results and associated work have been compiled from records held by the RPII and the homeowner. The RPII carried out many of the tests on the home and provided advice to the homeowner on the health significance of these results. These results and others provided by the homeowner are summarized in Table 1 and further details given below. Note the uncertainties in the measurements quoted in Table 1 are typically 27% at the 95% confidence level [8].

In 2004, the homeowner engaged a radon remediation contractor who installed mechanical ventilation via an electric fan attached to a pipeline to extract air from under the suspended floor so

Table 1. Summary of remedial work radon test results carried out between 1999 and 2013

Test date	Test laboratory	Test length	Measured radon concentration [Bq/m^3]
May 1999	RPII	3 months	1467[1]
May 2004	UCD	3 months	1856; 3294[2]
November 2004	Mechanical ventilation system installed – fan B		
March 2005	RPII	3 months	1330[1]
March 2005	Fan B removed to position A and fan C installed		
August 2005	RPII	3 months	1138[1]
December 2005	RPII	3 months	1210[1]
December 2005	All 12 external vents sealed. One fan set to extract the other to introduce air		
January 2006	Private service	10 days	990; 3220[2]
February 2006	Some vents re-opened and both fans set to extract		
March 2006	RPII	10 days	1344; 1595[2]
April 2006	Positive pressurization unit installed		
May 2006	RPII	3 months	3096[1]
May 2006	All vents opened and extraction fans A and C switched off		
September 2006	RPII	3 months	754[1]
May 2007	RPII	3 months	1852[1]
August 2007	Fan speeds in positive pressurization unit increased		
January 2008	Private service	3 months	390; 590[2]
November 2008	Fan speeds in positive pressurization unit increased further		
November 2008	RPII	3 months	1242[1]
May 2009	RPII	1 week live monitoring	50 to 6000
May 2009	RPII	3 months	899[1]
February 2010	New fans installed (fan B + D) and original fans turned on		
August 2010	Private service	3 months	319; 907[2]
August 2011	RPII	3 months	803[1]
December 2011	Remediation expert from BRE inspects house		
July 2012	Direction of fans reversed and vents sealed		
October 2012	RPII	3 months	480[1]
September 2013	RPII	3 months	454[1]

[1] Seasonally adjusted average result. [2] Individual results not seasonally adjusted.

preventing the gas from entering the occupied indoor space. This system was installed at the location marked 'fan B' in Fig. 3. Follow up tests showed that this work had not resulted in any reduction in radon concentration (Table 1). The contractor then moved the fan that had been installed to the east of the building (to the position marked 'fan A') and an additional fan was installed on the west side (in the position marked 'fan C'). Follow up tests carried out that year demonstrated that, while this work had largely been unsuccessful, a reduction from the initial result of 1467 Bq/m^3 to 1138 Bq/m^3 had been achieved; this was confirmed by a repeat test that December. Later in December, the contractor decided to seal up the 12 external vents and changed the fans such that one extracted and one introduced air. A subsequent 10-day test showed that this work seemed to have exacerbated the levels of radon in the house, so some of the vents were re-opened and both fans set to extract radon. Further, 10-day tests showed that this did not result in any reduction in concentrations.

In April 2006, a positive pressurization unit was installed. This system blows air into the house from a fan unit installed in the attic, thus achieving a very slight positive pressure (typically between 0.5 and 5 pascals) in relation to outside air. This increased indoor air pressure reduces radon entry through the floor. Positive pressurization can also have the effect of increasing ventilation and thereby reducing the radon concentration by dilution. Follow-up tests did not show any reduction in radon concentration, in fact the problem became even worse with radon concentrations increasing to 3096 Bq/m^3. Following this, all vents were opened, and the extraction fans turned off to assess the effectiveness of the positive pressurization unit in isolation. Follow up tests carried out during the summer of 2006, showed an apparent drop in concentrations to a seasonally adjusted 754 Bq/m^3. This was attributed to the effectiveness of the positive pressurization unit working in isolation, although the particularly good summer of 2006 may have contributed to this reduction as the warm weather meant that windows and doors were open significantly more than usual and pressure-driven flow of radon into the house is likely to have been reduced. The following test was carried out during a particularly bad winter, and these results showed that the elevated radon levels persisted with a seasonally adjusted average result of 1852 Bq/m^3.

During 2006, the possibility that water was a pathway for the transport of radon into the house was also considered, and radon tests were carried out on samples of drinking water from the home. The results of these were 0.5 Bq/l, ruling out the water supply as the source of radon. This result was not unexpected as the water is sourced from a surface water supply and so would be highly unlikely to have elevated radon concentrations. However, it was important to eliminate the water supply as a potential source of radon in the home.

In August 2007, the speed of the fans in the positive pressurization unit was increased, and this resulted in a reduction in concentration between 390 and 590 Bq/m^3. The power of the fans was further increased during 2008, however, this resulted in an unexpected increase in concentrations to 1242 Bq/m^3.

In May 2009, two active radon monitors were left running in the house for a one week period. The results of this monitoring showed that radon concentrations in the house varied substantially over the course of the week, from 50 Bq/m^3 to about 6000 Bq/m^3.

In February 2010, two additional fans were installed (at the locations 'fan B' and 'fan D') and the two existing fans were re-started. Tests to measure the effectiveness of all four fans running simultaneously showed that radon concentrations continued to be elevated. By August 2011, radon concentrations were still high at 803 Bq/m^3. No substantial reduction had been achieved in the radon levels despite multiple attempts to reduce concentrations. At this time, the homeowner offered her home to the RPII as a case study to better understand why remediation had proved so difficult and to learn more about the behaviour of radon in homes built on this geology type.

Case study conclusions and recommendations

This case study was carried out in collaboration with the UK Building Research Establishment (BRE) to identify the remediation technique most likely to succeed in reducing the radon levels to below 200 Bq/m^3 and to identify lessons which may be relevant to other houses in the locality or houses in areas with similar geology.

Following inspection of the house in December 2011, it was concluded that due to the fact that the house had been extended several times it was likely that there was little through ventilation between the different under floor voids. For example, it seemed likely that vents in the former external wall to the small bedroom and bathroom would have been blocked by the concrete floor in the hall. For this reason, the use of multiple extraction systems for the house was considered appropriate. However, it was recommended that the direction of the four fans installed should be reversed to pressurize the under floor space with fresh air rather than extracting air (Fig. 4). This is because extracting the air may have been increasing the radon concentration below the floor by drawing up more radon laden air from the ground. By reversing the direction of the fans the floor void would be pressurized to minimize the entry of radon laden air from the ground and the fresh air introduced would also dilute the radon laden air. In addition, by positively pressurizing the under floor air space, the system of fans would be working in conjunction with the positive pressurization system installed in the roof space. Overall, this means that the air pressure and dilution of radon laden air should counter the natural stack effect of the property [3, 9].

In July 2012, the direction of the fans was reversed to blow air into the under floor space. In addition, the piping was used to connect the space under the floor of the big bedroom to 'fan A' to ensure that

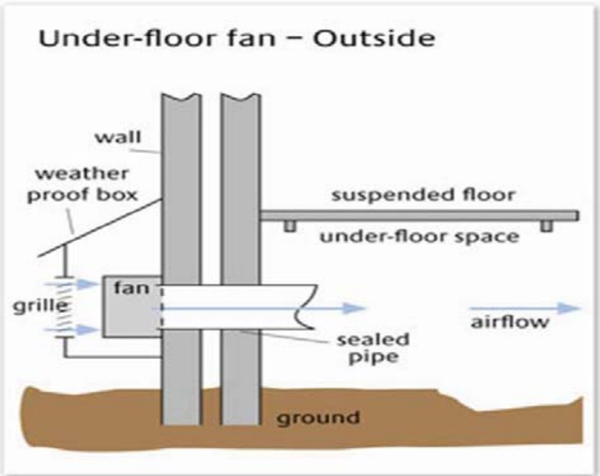

Fig. 4. Schematic of ventilation of under floor space.

this space was pressurized as it was unlikely that the space under this room had been vented to any of the other rooms. The vents under the floors of the girl's room, the boy's room and the study were also sealed to maximize the positive pressurization of the under floor space.

The house was retested, and the seasonally adjusted average had reduced to 480 Bq/m^3. It was considered that this was likely to be the minimum radon concentration that could be achieved without either replacing the floor with a concrete slab or increasing the fan speed further. The advantages and disadvantages of these options were discussed with the householder. Clearly, the first option would be expensive and very disruptive and difficult to justify to achieve a further reduction in the radon concentration. Increasing the fan speed would mean further increasing the already significant ventilation of the house and would be likely to cause it to be quite cold. It was felt that the benefit of either of these measures would be outweighed by the disadvantages associated with them and therefore further remedial work was not recommended. A follow-up test 12 months later showed that concentrations had remained stable at 454 Bq/m^3.

Discussion

Difficult to remediate buildings and implications for training of remediation contractors

The remediation of most buildings with elevated radon concentrations is very straightforward. However, it is inevitable that some properties will be difficult to remediate and require work to be carried out on more than one occasion before a reduction in radon levels is achieved. A Public Health England (PHE) study of the remediation of 2700 houses found 12% of houses had work carried out between two and four times [10]. For a minority of houses, it will be impossible to reduce concentrations below the reference level. The PHE survey found that the percentage of remediated houses whose radon concentrations were reduced to below 200 Bq/m^3 ranged from 35 to 74%, depending on the remedial method used. In addition, surveys by the RPII of Irish homeowners that have carried out remedial work on their houses found that in some 70% of cases the remedial work had reduced the radon concentration below 200 Bq/m^3 [11, 12].

It is not unusual for buildings with suspended timber floors built on bare earth to be difficult to remediate as, regardless of whether the space is to be ventilated or pressurized, it is difficult to create a seal between the ground and the floor to ensure this is carried out effectively [3]. In the UK, many of the houses that have been difficult to remediate have been located on geology that is more permeable than average including limestone, gravels and sandstone. In many of these cases, the solution has been to reverse the fans to pressurize instead of extracting air [3]. The fan power required to pressurize the under floor space is considerably less than that often used to extract air. For example, in this house the power used to run the fans was 14 W, compared to a typical wattage of 70 W used to extract air.

It is clearly important that the training provided for remediation contractors addresses the fact that remediation of houses with suspended floors, particularly those built on permeable rock or soil, can be difficult and often the appropriate remedial method is different than would normally be recommended.

Estimation of the annual radon concentration in a building

The results presented in this paper underline the importance of carrying out a radon measurement for at least 3 months to ensure a reasonable estimate of the average annual radon concentration in a home. This minimum length of measurement is recommended to take account of seasonal variations in radon concentrations [6]. A comparison of some of the 10-day and 3-month test results presented in this paper illustrates this point well. For example, during 2007, 10-day test results ranged from 730 to 890 Bq/m^3, while 3-month tests carried out at about the same time resulted in a seasonally adjusted average of 1852 Bq/m^3. Likewise, 10-day test results carried out in 2011 ranged from 80 to 156 Bq/m^3, while the 3-month seasonally adjusted average was 803 Bq/m^3.

It has been reported that the seasonal variation in radon concentrations in houses built on karst limestone can be reversed, i.e., that higher concentrations are measured in summer than in winter months [4, 5]. It is not possible to tell whether this is the case for the house in question as most tests followed some form of remedial work on the house making it difficult to directly compare the results of tests carried out at different times of the year.

It is also the case that dramatic short-term and seasonal variations in radon concentrations, up to factors of 10, have been observed both within karst bedrock and the overlying houses [4, 5]. The driving force for this is the pressure difference created by the difference in temperature between the underground and outdoor temperatures, which drives radon-

-bearing soil gas through the underground network of fissures and caves. This variation is illustrated by the significant variation in radon concentrations measured during the live monitoring in this house of between 50 and over 6000 Bq/m^3 over a 7-day period during 2009.

For all of these reasons, it is important that radon tests are carried out for a minimum period of three months in all buildings, but particularly those built on karst limestone where it is likely that the variation in radon concentration will be greater than normal. In fact, it has been suggested that it may be useful to carry out year-long tests in houses built on karst limestone bedrock [5].

Conclusions

The lessons learned from this case study support findings that:

- Most buildings can be remediated easily, however, there is no certainty that radon concentrations will be reduced to below the reference level even following a number of attempts.
- For buildings that have suspended floors, pressurization of the under floor space may be a more appropriate remedial technique than extraction, which can increase the indoor radon concentration, particularly if it is built on permeable soil or rock. Often a fan of lower power is sufficient for pressurization relative to that needed to extract the air. In this house, fans of 14 W were considered to be suitable. The use of fans of lower power can result in significant savings in energy over the long term.
- The significant variation in radon concentration that is known to occur in all buildings may be even greater in those built on karst limestone. For this reason, only the result of a radon test carried out over a minimum of 3 months can be compared to the reference level. This is recommended for all buildings in Ireland, but is critical for buildings of this geology type.

It is important that training of remediation contractors addresses the points outlined above to ensure that the most appropriate remediation solution is applied to homes of this construction type built on this geology.

In this case, it was considered that further reduction in the radon concentration could only be achieved by either replacing the floor with a concrete slab or increasing the fan speed further. Both of these options must be weighed against their significant disadvantages which include the expense and disruption for the first option and further increasing the already significant ventilation of the house, resulting in a very cold house, for the second option. However, a significant reduction in the exposure of the homeowner to radon from 1467 to 480 Bq/m^3 has been achieved. The fact that the homeowner is a never smoker means that the additional risk due to exposure to radon concentrations of 480 Bq/m^3 is about 1 in 280 and comparable to other everyday risks.

Acknowledgments. We would like to acknowledge the contribution of Mrs Mary Angela Keane for her endless patience and good humour during the years of work carried out on her house. Equally her generosity in allowing the details of this work to be published in order to add to the understanding of the behaviour of radon is much appreciated. We are also grateful to Ms Sue Hodgson (PHE) for supplying Fig. 4.

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