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Passive Remediation of Radon in UK Homes

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Public Health England
133–155 Waterloo Road
Wellington House
London SE1 8UG
T: 020 7654 8000

www.gov.uk/phe

Twitter: [@PHE_uk](https://twitter.com/PHE_uk)

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Any enquiries regarding this publication should be sent to

Centre for Radiation, Chemical and Environmental Hazards
Public Health England
Chilton, Didcot, Oxfordshire OX11 0RQ
E: Radon@phe.gov.uk

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Passive Remediation for Radon in UK Homes

S A Hodgson and V Pudner*

*No longer at PHE

Abstract

The effectiveness of passive remedial systems to reduce radon levels in homes has been analysed using data from the UK National Radon Database to establish whether passive remedial systems are effective compared to 'fan powered' systems. Passive remedial systems are environmentally friendly, sustainable and generally have a lower installation and maintenance costs. Increasing under-floor ventilation is the most frequently used passive method with typical reduction factors (RF) of around 1.8. Installing a passive sump (sub-slab depressurisation using a passive stack) reduces radon levels by a factor of around 1.6. Sealing floors and introducing permanent ventilation into the home have a RF of around 1.3. There is no real difference in reduction factor when the passive sump stack pipe is installed inside or outside of the property. Rotating cowls on stack pipes are found to increase effectiveness (RF~2.1). By using a passive system, there are savings in energy costs because fans are not required and householders may be more likely to use passive systems because of lower installation and running costs and quieter operation. Passive systems are generally not as effective as 'fan powered' systems but could be used as a viable alternative when radon levels in homes require reduction when the annual average is around 300 Bq m⁻³.

The information will be used to update guidance for householders and other radon stakeholders.

Centre for Radiation, Chemical and Environmental Hazards
Public Health England
Chilton, Didcot
Oxfordshire OX11 0RQ

This report from the PHE Centre for Radiation, Chemical and Environmental Hazards reflects understanding and evaluation of the current scientific evidence as presented and referenced in this document.

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1 Introduction

Radon is a radioactive gas originating from uranium that occurs in trace amounts in rocks and soils. Radon mixed with air in the soil enters buildings through gaps in the floor due to pressure differences inside buildings compared with outside. The lower pressure inside buildings is caused by warm air rising and winds blowing over the buildings; this may be increased by chimneys and flues.

Radon in the home is the largest source of exposure to ionising radiation for the UK population and accounts for 48% of the total exposure on average (Oatway et al, 2016). Data from epidemiological studies have shown a correlation between exposure to radon in the home and increased risk of lung cancer (Darby et al, 2005). In the UK, radon in homes is linked with over 1000 deaths per year (HPA, 2009). In July 2010 the Health Protection Agency (HPA) (now Public Health England, PHE) issued advice (HPA, 2010), recommending that radon exposure should be reduced where the annual average radon concentration exceeds the Action Level (AL) of 200 Bq m^{-3} and ideally to below the Target Level (TL) of 100 Bq m^{-3} .

Indoor radon gas concentrations can be reduced in buildings by installing remedial measures that are designed to divert or dilute the radon gas before it enters the building. These systems work best when they are fan assisted, especially when higher concentrations of radon are encountered (Hodgson et al, 2011). However, passive remedial measures have been used effectively to reduce radon levels in homes in the UK. Advantages of passive systems are that they require little maintenance, are environmentally friendly and there are no running costs. The reduction of radon in buildings using passive methods is less effective than powered systems (Hodgson et al, 2011) but in some situations the reduction may be sufficient to reduce radon levels to below reference levels. Householders may be persuaded to invest in a lower cost passive method that would provide adequate radon reduction in contrast to a more expensive powered system.

In the UK, new buildings in radon Affected Areas with a greater than 10% probability of the homes being above the Action Level are built with 'full' radon preventive measures. Sumps are installed 'ready to go' but are capped, without an electrically powered fan and hence not working. Potentially, these sumps could be installed in new buildings with an open pipe so they are potentially working to reduce radon levels in the building from the outset.

1.1 Passive remedial systems

Remedial methods are designed to reduce radon levels as far as is practical and to remain durable over many years. These are described in more detail elsewhere (Hodgson et al, 2011, Scivyer, 2015). Passive remedial methods are briefly described here:

a Passive sumps

A passive sump is a small space or void under a concrete capping or a membrane. The void is connected to an exit pipe, normally routed to exhaust above the roofline. A combination of both the stack effect of the pipe and wind action blowing over pipe exit results in depressurisation of the void. Radon in air is extracted from under the building.

b Passive or natural under-floor ventilation

Under-floor ventilation can be improved by increasing airflow to the under-floor space by clearing and/or adding more air bricks. The concentration of radon gas entering the building from the void is diluted by increased ventilation.

c Natural ventilation of living spaces

Ventilation of the living spaces can be improved using fresh air vents, such as trickle ventilators in windows or vents through walls. Radon concentration in the building is diluted.

d Sealing radon entry routes

Radon enters the building through gaps in floors, joins between walls and floors caused by shrinkage of concrete slabs and gaps where service pipes penetrate the floor. Sealing these entry points could reduce radon gas in the building.

Other factors considered in this study:

a The position of the stack pipe for passive sumps – inside or external to the building. Theoretically, an internal stack will be warmed by the internal heat of the building. Warm air within the stack will be thermally buoyant creating a negative pressure within the sump. This draws radon laden air from the sump. This effect is increased when the temperature difference inside to outside is greater. The external pipe relies on warming from outside air or from the sun which in turn warms the air within the stack.

b The type of stack pipe terminal - rotating cowls, fixed cowls and the ridge vents.

The terminal of a stack pipe will influence the movement of air in the pipe. There are many types of terminals (cowls) used. They have been categorised and generalised for this study as rotating cowls, fixed cowls and the ridge vents (located in the ridge of the roof). Fixed cowls are those that provide the basic requirement to protect against rain water and animal entry. Cowls types are described in more detail elsewhere (Welsh, 1995).

1.2 Aims of the study

Information about these remediation projects has been extracted from the UK national radon database maintained by Public Health England. It contains data on standard 3 month duration measurements of radon in the house before and after remediation, the type of remediation deployed and characteristics of the property. Information from the analysis of these data can be used to improve advice given to householders and other stakeholders, by updating the PHE radon website at www.ukradon.org.

The main objective of this work is to assess the effectiveness of the different passive remediation methods and associated fixtures to improve guidance for householders and professionals on the type of radon remediation methods. Factors studied were:

- the effectiveness of passive remedial methods and their approximate installation costs; specifically passive sumps, under-floor ventilation, passive ventilation of the home and sealing
- the effectiveness of internal and external stack pipes and different types of cowls on passive sumps

Other factors that may affect the effectiveness of passive sumps such as the location of the stack on the roof, wind direction and speed, have not been considered here.

2 Methods

Information on PHE's radon measurements in homes, property characteristics, location and remedial works is routinely collected on the UK National Radon Database (NRD). This analysis uses information collected between the years 2000 to 2013 and covers approximately 7000 remediation projects, of which around 1200 used passive methods. Specifically, data was used for properties that met the following criteria: a pre-remediation radon measurement; details about the passive remediation technique and a post remediation measurement. This data was first collected and stored in the NRD from the year 2000. The effectiveness of each remedy in homes is assessed by comparing a radon measurement before and after remediation. The annual average radon concentration is estimated by using integrating etched-track detectors (Daraktchieva et al, 2018): one detector placed in the main living area and one in a used bedroom for a 3 month period.

Two criteria were used to quantify and compare the effectiveness of the passive remedy used. The first, the Reduction Factor (RF) is the proportionate reduction in the radon concentration: a value greater than one implies a reduction in radon level. The RF is calculated using the geometric mean because the distribution of concentrations is approximately log-normal (Hodgson et al, 2011). Such distributions are often found when a number of independent variables interact multiplicatively. The second criterion quantified the percentage of properties that were reduced below the Action Level or the Target Level (Success Rate). The elements of the analysis included:

- a** The effectiveness of passive methods
- b** The performance of passive methods depending upon the initial radon concentration
- c** The effectiveness of passive sumps considering the stack pipe position and the type of cowls used at the pipe exits
- d** The cost of installation of passive methods

A 5% statistical significance level was used: the analyses were performed using Minitab 15 Statistical Software (2007). State College, PA: Minitab, Inc. (www.minitab.com).

3 Results

3.1 The effectiveness of passive remedial methods

A summary of the reduction factors and the success rates for the passive methods is given in Table 1. The most frequently used and the most effective passive method in this study was 'increasing under-floor ventilation': with a reduction factor of ~1.8 and over 50% and 25% of homes were reduced below the AL and TL respectively. Passive sumps were almost as effective, followed by natural ventilation and sealing.

Table 1: Summary of radon reductions achieved by passive remediation methods

Remediation	Number	Geometric mean (Bq m ⁻³)				% reduced below		
		Before	After	Reduction	Action	Target		
		Remediation	Factor	95% CI	Level	Level		
Natural under-floor ventilation	630	301	169	1.8	1.7	1.9	57	26
Passive sumps	159	331	217	1.5	1.3	1.7	47	12
Natural indoor ventilation	216	275	218	1.3	1.2	1.4	50	13
Sealing	188	328	260	1.3	1.1	1.4	35	11

3.2 Performance of passive methods depending on the initial radon concentration

The aim of radon remediation is to obtain a reduction in radon level to below the AL and if practicable to below the TL. Table 2 shows that as the initial radon level increases, there are marginal increases in the reduction factors and the success of reducing radon levels below the AL and TL is decreased. The sample size is small in some groups where higher radon levels were measured. Therefore, the viability of the data may not be representative and the uncertainties will be large. A great majority of passive remedial methods are in the range 100 – 600 Bq m⁻³.

Table 2: Reduction factors and success rates depending on the initial radon concentration

Remedy	Initial radon concentration range Bq m ⁻³			
	100 - 300	301 - 600	601 - 1000	Over 1000
	Reduction factor (total number of houses)			
Total number in each range	707	370	83	33
Natural under-floor ventilation	1.7 (375)	2.0 (192)	1.9 (47)	2.1 (16)
Passive sump	1.3 (80)	1.2 (64)	1.9 (8)	4.2 (7)
Passive indoor ventilation	1.2 (152)	1.6 (49)	1.7 (13)	2.4 (2)
Sealing	1.1 (100)	1.2 (65)	2.2 (15)	2.8 (8)
	% reduced below AL 200 Bq m⁻³, (total number of houses)			
Natural under-floor ventilation	70.4 (375)	42.2 (192)	19.1 (47)	18.8 (16)
Passive sump	58.8 (80)	37.5 (64)	12.5 (8)	28.6 (7)

Passive indoor ventilation	59.2 (152)	26.5 (49)	23.1 (13)	50.0 (2)
Sealing	49.0 (100)	20.0 (65)	20.0 (15)	12.5 (8)
% reduced below TL 100 Bq m⁻³, (total number of houses)				
Natural under-floor ventilation	31.2 (375)	22.4 (192)	6.4 (47)	12.5 (16)
Passive sump	16.3 (80)	7.8 (64)	0 (8)	14.3 (7)
Passive indoor ventilation	14.5 (152)	10.2 (49)	0 (13)	0 (2)
Sealing	16.0 (100)	4.6 (65)	6.7 (15)	0 (8)

3.3 Effect of stack pipe position and cowl types on passive sumps

Table 3 shows that the radon reduction is marginally greater when the stack pipe for a passive sump is positioned inside the building. Around 50% of passive sumps reduce the initial radon concentration to below the AL, regardless of whether the pipe is positioned inside or outside. The average radon concentration in homes before remediation was around 350 Bq m⁻³.

Data was limited for different cowl types; the fixed cowl type was most frequently used. The rotating cowl achieved the greatest radon reduction, although the sample number was small, followed by the ridge vent and then the fixed cowl type.

It was not always stated whether the pipe was inside or outside of the building and what type of cowl was used, therefore the total number of properties studied is less than the total number of passive sumps analysed.

Table 3: Effect of stack pipe position and different cowls on passive sumps

Remediation	Number	Geometric mean (Bq m ⁻³)			% reduced below		
		Before Remediation	After Remediation	Reduction Factor	95% CI	Action Level	Target Level
All passive sumps	159	331	218	1.5	1.3 1.7	47	12
Pipe inside	44	362	220	1.6	1.2 2.2	50	18
Pipe outside	102	333	224	1.5	1.3 1.7	46	8
Fixed cowl	105	327	229	1.4	1.3 1.6	43	10
Rotating cowl	8	342	161	2.1	0.8 5.8	63	38
Ridge vent	10	344	208	1.7	1.1 2.4	70	0

3.4 Costs of passive remedial methods

Information on cost to the householder was collected. This sub-dataset included 342 entries; unknown costs were excluded. Costs are given as the arithmetic and geometric means and the median since the distribution of cost does not follow either a normal or log-normal distribution. The data in Table 4 reflect a distribution of 'paid for' work. The cost of the remedial work may be combined with other costs such as costs, double glazed windows with 'trickle vents', replacing floors etc.

Table 4 Costs of passive remedial methods employed

	Frequency (n)	Cost £			Range	
		Arithmetic mean	Geometric mean	median	min	Max*
Passive sump	64	682	292	350	20	8500
Natural under-floor ventilation	200	265	133	164	8	4236
Permanent ventilation	43	958	154	90	10	8728
Sealing	35	686	95	66	5	10000

*Very high costs may be combined with costs of other building work carried out at the same time.

4 Discussion

The aim of radon remediation is to obtain a reduction in the radon level in a building, below the Action Level (200 Bq m⁻³) and if practicable below the Target Level (100 Bq m⁻³) and hence reduce the exposure to the occupants and their risk of developing lung cancer. The aim of the analysis is to determine the effectiveness of passive remedial systems to reduce radon levels and to provide guidance for householders.

4.1 The performance of passive remediation methods

Hodgson et al (2011) reported analysis of passive systems between 2000 and 2007. This report analyses data from that time period and is extended to 2013 inclusive.

Results are reported as reduction factors in radon concentration and as the success rate at reducing radon levels below the Action Level or Target Level. Reduction factors for passive methods range from 1.3 to 1.8 with a success rate of 35 to 57% for reducing radon levels

below the AL and 11 to 26% for reducing radon levels below the TL (Table 1). Generally, the success rate decreases as the original radon level increases and reduction factors increase marginally with increased original radon levels (Table 2).

Radon was reduced by almost 50% and 33% for natural under-floor ventilation and passive sumps respectively and 23% for both natural ventilation of the living space and sealing floors.

4.2 Other passive remediation studies

There is limited data published on the effectiveness of passive radon remedial methods. An EU project 'Radon prevention and remediation' (RADPAR) collected information on the analysis and assessment of current radon remediation techniques in EU countries describing the efficiency and the potential impact on energy consumption (Holmgren and Arvela, 2012). The most common passive remediation methods used in European countries are summarised in Table 5 (Holmgren and Arvela, 2012). The reduction factors may vary according to the reporting country and differences due to climate, geology and construction methods. Results from this study are comparable with the ranges of results found in that study.

Table 5 Reduction factors for passive methods in EU countries.

Remediation method	Reduction factor (%) Typical range
Improving crawl space ventilation	40 - 60
Passive sumps	30 - 50
Improving natural ventilation of living spaces	10 - 50
Sealing entry routes in floors	10 - 60

This analysis and those carried out by others support a suggestion that when initial radon levels are about 2 times higher than the Action Level (200 Bq m^{-3}), passive under-floor ventilation and passive sumps should be considered as a method that could sufficiently reduce radon levels. Some property owners are reluctant to use fans because of concern about cost, noise and draught. Any reduction in radon levels achieved by using passive methods will result in reduced radon exposure and risk. The option to add a fan to the system can be used at a later date to achieve further reductions if required.

4.2.1 Natural under-floor ventilation

Improving under-floor ventilation is the most frequently used passive method and is relatively low cost. It can be achieved simply by cleaning blocked vents, changing vents to a type allowing a greater flow of air or by adding extra vents to the under-floor space. In this study, typical reductions are around 50%; this is comparable to typical reduction factors of around 50% reported in EU countries (Holmgren and Arvela, 2012).

4.2.2 Passive sumps

Depressurisation of a sump constructed under an impermeable or solid floor is usually achieved by using a fan. This is one of the most effective remedial systems (Hodgson et al, 2011). Passive sump depressurisation is achieved by thermal buoyancy of warm air rising in stacks coupled with the effect of wind blowing over the exit terminal of the stack. Passive sumps reduce radon levels by a factor of about 1.5 (~33% reduction) with around 50% and 12% achieving a reduction below the Action Level and Target Level respectively (Table 1).

The Building Research Establishment (BRE) (Scivyer, 2012) used existing homes to develop methods to reduce radon levels. Sixteen properties were fitted with passive stack systems and around 50% were reduced below the AL and almost 90% of them showed radon reduction factors of 1.0 to 8.2. This is comparable to a typical range of reduction factors of 30% (RF 1.4) – 50% (RF 2) reported by EU countries (Norway 0 – 20%) (Holmgren and Arvela, 2012).

The effect of a passive sump in an occupied home in the US showed 30% reductions in radon concentrations. The effect was most pronounced during the winter and spring (Holford and Freeman, 1996; Abdelouhab et al, 2010).

Irish data based on work done by a contractor on 7 homes 'retrofitted' with passive sumps and rotating cowls demonstrated an average reduction of around 58% (personal communication, EPA Ireland). This is similar to reductions reported in other countries.

Although the performance of passive sumps is limited, the reduction may be sufficient to reduce radon levels to below the Action Level. If not, a fan can be added to reduce radon levels further. The advantage of the passive sump is that there is no ongoing cost (no fan) and negligible maintenance costs.

4.2.3 Natural ventilation of living spaces

Passive ventilation of living spaces can be achieved simply by opening existing trickle vents in windows or vents through walls. Theoretically, radon in air is diluted by outside air.

Radon levels in this study are shown to be reduced by a factor of 1.3 (~23% reduction). A typical reduction reported for EU countries was between 10% and 50% (Holmgren and Arvela, 2012). A substantial radon reduction can be achieved by opening a sufficient number of doors and windows but this is not reliable or enduring because security is compromised and openings would be closed during inclement weather.

The marginal reduction in radon levels achieved by natural ventilation of living spaces generally does not warrant the high cost of installation, for example, installing new windows with trickle vents. It is doubtful that the use of trickle vents is sustainable as householders may choose to close them during cold weather conditions.

4.2.4 Sealing floors

Sealing radon entry routes such as cracks, gaps, pipe penetrations and around the edges of floors is not as effective as some other passive methods; a reduction factor of 1.3 (~23%) was observed. Typical reduction reported for EU countries was around 10 – 60%, (Holmgren and Arvela, 2012). It is difficult to seal floors effectively and when used alone this method is unlikely to gain appreciable reductions. However, it has been shown that it would be

advantageous to seal very large holes or cover large expanses of exposed earth with suitable membranes (Naismith, 1994, Pye, 1993). The benefit of sealing may be expensive for little gain in radon reduction.

4.3 Factors affecting effectiveness of passive sump systems

4.3.1 Stack pipe position – inside or outside of the building

Stack pipes are usually positioned inside the building or on an outside wall. They provide a conduit for air mixed with radon gas from the sump to exit at the pipe ending. The effectiveness of stack pipes are subject to many factors such as wind speed and direction, temperature differences, barometric pressure, geographical position of the building, position of the pipe exit on the building etc. External pipes are affected by additional factors such as the position relative to warming effect of the sun. Internal stacks are exposed to heating inside buildings: air inside the stack would be warmed and increase thermal buoyancy reducing pressure and moving air and radon away from the sump. This is partly demonstrated on a US occupied home which showed that depressurisation of the sump occurs best when the stack is open during the winter and spring months due to buoyancy-driven air flow up the stack, but not during the summer when temperatures inside and outside are similar (Holford and Freeman, 1996).

This analysis shows that the effectiveness of radon sumps connected to an internal stack pipe is marginally better than those positioned externally with reduction factors of 1.6 (38% reduction) and 1.5 (33% reduction) respectively (Table 3). BRE performed trials in the 1990s showing reduction factors of 1.9 (n=12) and 1.5 (n=5) for internal and external stacks respectively: however, the sample numbers were low (Scivyer, 2012). Although an internal stack may be marginally more effective, it is offset by cost and disruption during installation to the home owner.

It would be advisable to repeat this analysis when more data becomes available. The data currently available does not provide convincing evidence that an internal stack is more effective than an external stack.

4.3.2 Cowl types and passive sumps

Terminals (cowls) are used on the exhaust exit of ventilation systems; protecting against weather and animal entry. Certain types of cowl are designed to increase the movement of air through stacks and minimise flow-reversal. The cowl types represented in this study were the fixed type (basic types of cowl to prevent against the weather and animals), the rotating cowl (encouraging movement through the stack) and the ridge vent. Radon reduction factors for the ridge vent and fixed type were 1.7 (41% reduction) and 1.4 (29% reduction) respectively (Table 3). The rotating cowl achieved the greatest radon reduction factor of 2.1 (52% reduction) but the sample number was low (8).

Irish data based on work done on 7 homes using rotating cowls demonstrated a similar reduction of around 58% (personal communication, EPA Ireland).

BRE performed trials in 1990s showing the results of cowl types where the rotating cowl, ridge vent and H pot reduced radon concentrations by a factor of 2, 1.7 and 1.7 respectively but in all cases the sample number was less than 5 (Scivyer, 2012).

BRE also tested the flow resistance and wind performance of some common ventilation terminals (Welsh, 1995). As the effectiveness of passive sump systems is affected by the wind, the wind performance indicator (WPI) is a useful aid to select a suitable terminal type; the more negative the WPI the greater wind induced up-draught. Table 6 shows WPI for different terminal designs (Welsh, 1995).

Table 6 Pipe terminals and wind performance indicators

Terminal type	Wind performance indicator
To fit 110 mm diameter duct	
H Pot 1	-0.23
H Pot 2	-0.16
Balloon cowl	-0.16
Gas flue 1	-0.11
Grey vane	-0.09
Mushroom cap	Undefined, flow reversal possible
To fit 150 mm diameter duct	
Rotating cowl 1	-0.53
Rotating cowl 2	-0.12
Gas flue 2	-0.07
Aerodynamic cowl	-0.03
Chinese hat	Undefined, flow reversal possible

It is evident that H Pot 1 (fixed) and the rotating cowls assist the flow more than the others (a large negative WPI). The rotating cowl achieved the best performance. It is also worth noting that the mushroom cap and Chinese hat types of cowl may cause flow reversal under certain wind conditions.

BRE extended this study in 2012 to compare the effectiveness of rotary ventilators (fitted to the roof of delivery vans), a rotating cowl, a mushroom cowl and an open stack. The cowls were tested on a model roof in various positions in a wind tunnel and pressure readings were recorded inside the stack. The order of effectiveness was the rotating cowl, an open pipe, the van cowl and lastly the mushroom cowl, irrespective of the position of the terminal of the pipe on the roof. It was also noted in this analysis that terminals such as the open pipe, mushroom and Chinese hat were capable of causing blow-back and this is most likely to occur in passive systems.

A French (Abdelouhab et al, 2010) experimental dwelling was used to test the effectiveness of a passive sump with a basic stack pipe and the exit covered with a basic cowl (tile). This was compared to tests using a static extractor (the shape increases the natural flow over the exit pipe). Air flow rates using the static extractor were around twice the value of the basic cowl. The efficiency was greater during cold conditions, when radon levels can be higher in buildings due to convection of warm air. From the limited data and research done by others, the rotating cowl is more efficient.

4.4 Passive sumps and new properties

Building regulations require preventive measures to reduce radon levels in new homes in relevant areas (CLG, 2010). In areas where 'full' radon protection is required, properties are built with both a 'basic' radon membrane across the footprint of the building and a 'secondary' measure, a sump which is capped and not working or additional under-floor ventilation (Scivyer, 2015). Membranes are installed to reduce the radon entering a building. It is difficult to measure the effectiveness of a membrane but theoretically a well fitted membrane should reduce radon levels by reducing the entry of radon laden soil gas. The reduction may not be sufficient to reduce below a reference level but with a working passive sump, further reduction may be achieved.

Passive sumps could be installed with a stack at the building stage and 'working' to reduce radon levels rather than in 'standby mode' as present. The reduction in radon levels using passive sumps (RF 1.5, 33% reduction) observed in this analysis indicates that there would be immediate and ongoing benefit to the occupiers of new homes. Associated costs to the builder would be potentially low although a cost benefit analysis may be required to inform any changes to formal guidance.

Irish data based on work done on 4 homes showed an average radon reduction of 89% in homes when previously fitted 'non-working' sumps were converted to working passive sumps (personal communication, EPA Ireland).

If passive sumps were fitted in relevant areas, properties would benefit from radon reduction from the outset. This could also reduce the risk of poor positioning of sumps and pipe exits relative to doors and windows and ease the fitting of a fan if required after measurement of radon levels once the property is occupied.

4.5 Durability of passive systems

A study (Howarth, 2013) measuring the durability of passive systems which included membranes over the floor, natural under-floor ventilation and sealing of cracks, showed that 8 out of 13 systems (62%) failed to keep radon levels below the Action Level over the long term (a 15 year period). Failure of these passive systems was generally not serious as the initial radon concentration was above the Action Level but still relatively low (typically $< 400 \text{ Bq m}^{-3}$). The major reason for passive system failure was vegetation overgrowth covering vents installed to improve under-floor ventilation.

It was suggested by Howarth that long term failure rates of remedial systems, passive or active (using a fan) were similar (64%). All types of remedial measures can last more than 10 years but can fail in less than 5 years.

A key concern was the very low detection rate of failures in the passive systems by householders. This shows the importance of periodically testing a remediated property for radon every 5-10 years (HPA, 2010), to check that the system is working effectively.

4.6 Costs of passive remedial methods

When houses have been identified with radon levels above the Action Level, it is the responsibility of the householder or landlord to fund works to reduce levels. Cost is a common reason cited for not carrying out work to reduce radon levels (Bradley and Thomas, 1996).

Typical costs during the time period of data collection (between the years of 2000 to 2013), for passive sumps, natural under-floor ventilation, permanent ventilation and sealing were around £300, £130, £150 and £90 respectively. Typical costs for each individual method do not take into account price changes since 2013.

The lowest costs are most likely 'DIY' or those without labour costs. The highest will include outliers where the cost of remedial work was reported as part of other work on the home. This might include new floors installed with an internally located sump or new double glazed windows with trickle vents to provide permanent ventilation.

A consideration for householders is that a passive system could be installed initially. If sufficient radon reductions are not achieved then a fan can be added to the system. This could be a cost saving both during installation and operation.

5 Conclusions

This study shows that passive radon remediation systems, including sumps and under-floor ventilation, should be considered when the initial radon levels are in a range up to a few hundred Bq m⁻³. To implement this in practice, PHE advises that passive measures should be considered when radon concentrations are measured up to 300 Bq m⁻³ but recognise that they may still be effective over a slightly wider range. At this level, reductions below the Action Level can be reasonably expected; but not necessarily to below the Target Level. Sealing and indoor ventilation show limited radon reductions and could be considered as an additional method to reduce levels.

If the radon levels are higher, these methods would deliver some reduction and therefore risk saving, especially in situations where the householder considers fan assisted systems to be undesirable or unaffordable. If reduction in radon levels below the Action Level or Target Level is not achieved, a fan could be added subsequently to reduce radon levels further.

Passive systems increase energy efficiency by removing the need to run fans and they operate more quietly.

The main conclusions from this analysis and the review of other work are:

- a** Radon was reduced by almost 50% (RF 1.8), 33% (RF 1.5) for natural under-floor ventilation and passive sumps respectively and 23% (RF1.3) for both natural ventilation of the living space and sealing floors.
- b** When initial radon levels are in the range up to and around 300 Bq m⁻³, passive under-floor ventilation and passive sumps should be considered as remediation methods. These offer a good prospect of reducing radon levels to below the Action Level but are less likely to get below the Target Level.
- c** At higher initial radon levels (above 300 Bq m⁻³), the relative reduction may be greater but passive remediation methods are less likely to get below the Action Level and even less likely below the Target Level.
- d** There are limited radon reductions achieved by ventilating the living space and sealing floors. These could be used as additional methods.
- e** There is no conclusive evidence about the best positioning of stack pipes (internal or external to the building). It would be advisable to repeat this analysis when more data becomes available.
- f** Limited data shows rotating cowls (reduction factor ~ 2.1) are most effective compared to other cowl types.
- g** Other cowl types (mushroom cap and Chinese hat) may reduce the effectiveness when added to open pipes.
- h** Although reduction below the Action Level may not have been achieved with passive remediation, some reduction will reduce radon exposure and risk.
- i** Changing the configuration of “inactive” sumps installed in new properties so that they operate in passive mode may reduce radon levels, although a cost benefit study may be required to inform any decision changes to formal building control guidance. This could also reduce the risk of poor positioning of sumps and pipe exits relative to doors and windows and ease the fitting of a fan if required after measurement.

Guidance should be produced for householders to explain that passive radon remediation systems:

- can be used when radon levels are in a range up to and around 300 Bq m⁻³
- are cheaper to install and maintain than active measures
- with a rotating cowl may improve the effectiveness of a passive sump
- should be maintained and homes periodically tested for radon

The findings in this study support the PHE advice (HPA 2010) that householders who have remediated should carry out a radon retest periodically to determine whether their system is still working.

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