

An Analysis of Radon Remediation Methods

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ABSTRACT

Radon gas in the home is a major source of public radiation exposure and an established cause of lung cancer. A range of techniques are available to reduce high indoor radon concentrations in homes. Information on some 2,700 radon remediation projects has been analysed with the aim of identifying the factors that influence the performance of various remediation methods, including the specific remediation techniques applied, the physical characteristics of the home, the radon level before remediation and who carried out the work.

The analysis shows that each method used to reduce radon levels has a range of performance which is influenced by some factors but is independent of others. Each remediation method showed a trend in performance with respect to the initial radon concentration. Higher initial radon concentrations offer greater relative reductions when remediated. However, homes with higher initial concentrations measures were less likely to achieve reductions below the Action Level (200 Bq m⁻³). Overall, an active sump system is most likely to offer a substantial reduction, on average 6 fold. Other methods are less effective, reducing levels by a typical factor of about 2. Passive ventilation and sealing are least effective. This analysis does not support firm conclusions about the relative performance of different types of remediators and householders who do 'DIY'. Typical costs have been estimated with active sumps being the most expensive at around £800.

This information will be used to update guidance for householders and others such as contractors, using fact sheets, presentations at radon householder events and the UKradon website.

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1 INTRODUCTION

Radon in the home is the largest source of exposure to ionising radiation for the UK population and accounts for 50% of the total exposure on average (Watson et al, 2005). Levels vary significantly both by area and even between neighbouring properties with concentrations ranging from less than 10 to over 10,000 Bq m⁻³ (becquerels per cubic metre of air) (Wagland, 2006). The UK average is 20 Bq m⁻³ (Wrixon et al, 1988). Exposure to radon increases the risk of lung cancer (HPA, 2009).

In July 2010 Health Protection Agency (HPA) issued new advice (HPA, 2010), which recommends that the Action Level (AL) of 200 Bq m⁻³ is retained but introduced a Target Level of 100 Bq m⁻³. The data analysed in this report and the analysis pre-date this updated advice.

Before publication of the advice in 2010, the UK radon control strategy was based on the advice published in January 1990 by the National Radiological Protection Board (NRPB) now part of the HPA (NRPB 1990a). Advice was presented to Government covering the principles for the limitation of human exposure to radon in homes. A supporting document explored the practical applications and provided numerical limits and recommendations (NRPB, 1990b). These recommendations included:

Action should be taken to reduce radon concentrations in existing homes if the radon concentration exceeded an Action Level of 200 Bq m⁻³ in room air averaged over a year.

This approach was supported by the Government and a programme was initiated to identify homes with high radon levels and encourage householders or landlords to reduce levels using radon reduction techniques (Department of the Environment, 1990). Government Departments and the Devolved Administrations have continued to direct, fund and/or support many initiatives under the overall programme (Kendall et al. 2005) The HPA has worked in partnership with Local Authorities and drawn on the expertise of the Building Research Establishment (BRE) to encourage householders with high radon levels to remediate by offering free information, advice and a free post-remediation confirmatory measurement (Department of the Environment, 2000). The HPA and BRE provide information on radon reduction methods in the form of solution sheets, reports, Good Building Guides and websites (www.ukradon.org and www.bre.co.uk/radon/).

This study is based on some 2,700 remediation projects completed between the years of 2000 and 2007 in around 2,400 dwellings. It should be noted that the projects reported here do not represent all of the radon remediation work undertaken in the UK in that period, only those projects that have been reported to HPA and provide sufficient information to support analysis.

Information about these remediation projects has been extracted from the UK national radon database maintained by HPA. It contains data on 3 month measurements of radon in houses before and after remediation, the type of remediation deployed and characteristics of the properties. Information from the analysis of these data can be

used to improve advice given to the householder by HPA, BRE, Local Authorities and contractors by updating HPA and BRE publications, including websites and via other publications such as the Environmental Radon Newsletter for which an archive is available on www.ukradon.org.

The specific aims of the analysis are to determine the most effective methods of reducing radon concentrations in existing buildings whilst considering other factors such as house characteristics, costs and the effectiveness of the contractor employed. To achieve this, the following questions, amongst others, need to be answered:

- i. How effective are different remediation measures?
- ii. What factors govern the success of remedial measures in particular situations?
- iii. What are typical costs?
- iv. Does the implementation by different types of contractor or householder make a significant difference?

2 DATA COLLECTION

Information on radon measurements, property characteristics, location and remedial works is routinely collected on the UK National Radon Database. This study uses data which have been collected on remedies between the years of 2000-2007 in approximately 2,400 dwellings. A large proportion of the data were collected from Cornwall, Devon, Oxfordshire, Somerset, Derbyshire, Northwest England and Northamptonshire; reflecting areas of England with targeted programmes in the timeframe (Kendall et al, 2005).

2.1 Radon measurements

Measurements of radon in houses are made using integrating etched-track detectors. These passive detectors contain sensitive plastic which records damage tracks caused by alpha particles originating from radon or its short-lived decay products. Controlled etching enlarges the tracks so that they can be easily counted. The number of tracks is proportional to the time-integrated, average concentration of radon in the room in which the detector was placed (Ibrahimi and Miles, 2008).

Detectors are in position for three months; one in the main living area and one in a bedroom in regular use. The detectors are returned for processing and the annual average radon concentration is estimated (Wrixon et al, 1988). The effectiveness of remedial works is assessed by comparing the original result with a repeat measurement (taken within three years) after the works are completed.

2.2 Methods of radon reduction

Radon is a radioactive gas which originates from uranium which occurs in trace amounts in all rocks and most soils. Radon gas is mixed with the air that occupies the space between soil and rock particles; this air permeates through the ground and is commonly called soil gas. The soil gas enters buildings through gaps in the floor. These can be shrinkage cracks in solid concrete floors, gaps around service entries and through gaps in suspended wooden floors. The driving force is the small pressure differences inside houses compared with outside. Lower pressure inside buildings is caused by warmer, less dense interior air rising and by winds blowing over buildings. This creates a gentle suction at ground level in the building; this can be increased by the presence of chimneys and flues. Most inflowing air comes through doors and windows but some will come through the floor, perhaps around 1%, drawn in by lower indoor air pressure.

Remedial methods are designed to reduce radon levels as far as is practical and to remain durable over many years (Naismith, 1997). Effective methods remove or dilute radon gas before entering houses (active sumps and under-floor ventilation) or by increasing indoor ventilation by blowing fresh filtered air into a house (positive pressure ventilation units). Other methods such as sealing floors and passive ventilation have been used (Naismith, 1994, Henschel, 1994). The methods are outlined in Table 1 and described in more detail in Appendix B.

To determine the effectiveness of any remedy, a repeat measurement is necessary after remediation.

Table 1 Methods to reduce radon levels

Method of reduction	Description
Active sump	Sump (a small void) under a solid floor with a fan extract to the outside
Passive sump, pipe inside	Sump under a solid floor, no fan, extract pipe routed inside a building, exit through the roof.
Passive sump, pipe outside	Sump under a solid floor, no fan, extract pipe routed outside.
Positive ventilation	Fan in loft space blowing into living space, increasing ventilation in dwelling
Natural under-floor ventilation	Under-floor ventilation is increased by clearing airbricks or replacing with modern vents and/or increasing the number of vents
Active under-floor ventilation	Under-floor ventilation is increased by a fan either sucking or blowing
Passive ventilation	Trickle vents in windows
Sealing floors	Sealing cracks and gaps in floors, usually done in addition to other methods
Sealing the loft hatch	To reduce the upward flow of air and lower the negative pressure within the dwelling, usually in addition to other methods

2.3 House details

Information about each individual dwelling is collected via a short questionnaire (Appendix A) at the time of the initial measurement. The effectiveness of the remedial methods is tested against the house categories listed in Table 2. Each category reflects some of the common variables encountered in the UK housing stock. The sub-categories described in the 'date built' group up to 1992 are those used in General

Household surveys and in other statistical publications from the Office of National Statistics. They reflect major construction periods. After 1992, the dates reflect when significant changes were made to building regulations regarding radon protection (Scivyer, 2007).

Table 2 House characteristics

House Characteristic	Categories within each characteristic
House type	Detached, semi-detached, mid-terraced, flat
Date built	Before 1900, 1900-1919, 1920-1944, 1945-1964, 1965-1976, 1977-1992, 1993-2000, after 2000
Single storey or not	Single storey, multi-storey
Basement or not	Basement, no basement
Double glazing	Full double glazing, part double glazing, no double glazing
Ground floor type	All solid (direct onto earth), all suspended over a small space, a mixture of solid and suspended, over a basement or cellar
Basement effects	Basement, no basement
Type of heating	Central heating, central heating with open fire, open fire

After remediation, a second retest questionnaire (Appendix A), is completed by householders at the time of the repeat measurement. The questionnaire provides details on: the method used to reduce radon levels; the contractor; the costs of the works and the information previously collected on the house is confirmed. In a small number of cases the householders were unable or unwilling to answer some questions on the questionnaire. This was particularly prevalent for technical questions and for those related to the cost of remedial works. Consequently, some of the analyses will have totals which vary and therefore there are inconsistencies between some tables.

2.4 Contractor experience and costs

Radon remedial work, although generally technically simple, needs to be completed to a high standard to achieve the best results. The second retest questionnaire provided details about the contractor used and the cost of the work (Appendix A).

3 DATA, DEFINITIONS AND ANALYSIS

3.1 The overall dataset

The data analysed in this study comprises information collected from over 2,700 attempts at remedial works in approximately 2,400 dwellings. The remedial works vary in size, complexity and cost. All the main methods described in section 2.2 and Table 1 are represented and include works undertaken by householders themselves on a DIY basis as well as projects completed by both specialist and general contractors.

The dataset includes a range of house types – the largest single group being detached homes (65%) followed by semi-detached (23%). The homes vary in age across the

range shown in Table 2 with the pre-1900 and 1965-1976 being the two largest groups (28% and 23%). Initial Radon levels spanned a wide range with most homes starting above the AL and a limited number (10%) exceeding $1,000 \text{ Bq m}^{-3}$ before remediation. Most homes had only one radon remediation method applied (about 90%). The most prevalent methods were active sumps, natural under-floor ventilation and positive ventilation. The majority of the remediation projects were carried out by contractors and the remainder by householders (DIY).

3.2 Definitions and dose conventions

3.2.1 Effectiveness

Two criteria are used to quantify and compare the effectiveness of different remedial methods, the influence of other factors and the variability between different contractor types.

- The first is a test of whether the radon concentration is reduced to below the Action Level (success rate); expressed as a percentage. For example a 50% success rate means that one in two installations in a group reduced the radon concentration to below the Action Level.
- The second is the reduction factor: the initial radon concentration divided by the concentration after remediation to give a ratio. This equates directly to the proportionate reduction in the radon exposure of the occupants while in the home. A value greater than 1 indicates a reduction and a value of unity implies no effect: the greater the number the better the reduction. For example, a reduction from 600 Bq m^{-3} to 150 Bq m^{-3} would have a reduction factor of 4.

For an individual property, the measured values corrected for seasonal variations are used. For groups of properties the reduction factor is calculated using the geometric means as the distribution is approximately log-normal (O'Riordan et al, 1987), (Wrixon et al, 1988), (Gunby et al, 1993), (Naismith et al, 1998), (Appendix D). Such distributions are often found when a number of independent variables interact multiplicatively. Figure 1 shows the distribution of radon concentrations in homes before and after remediation from a total of 2,400 homes. Both distributions exhibit the long skewed-tail to high radon levels characteristic of log-normal distributions.

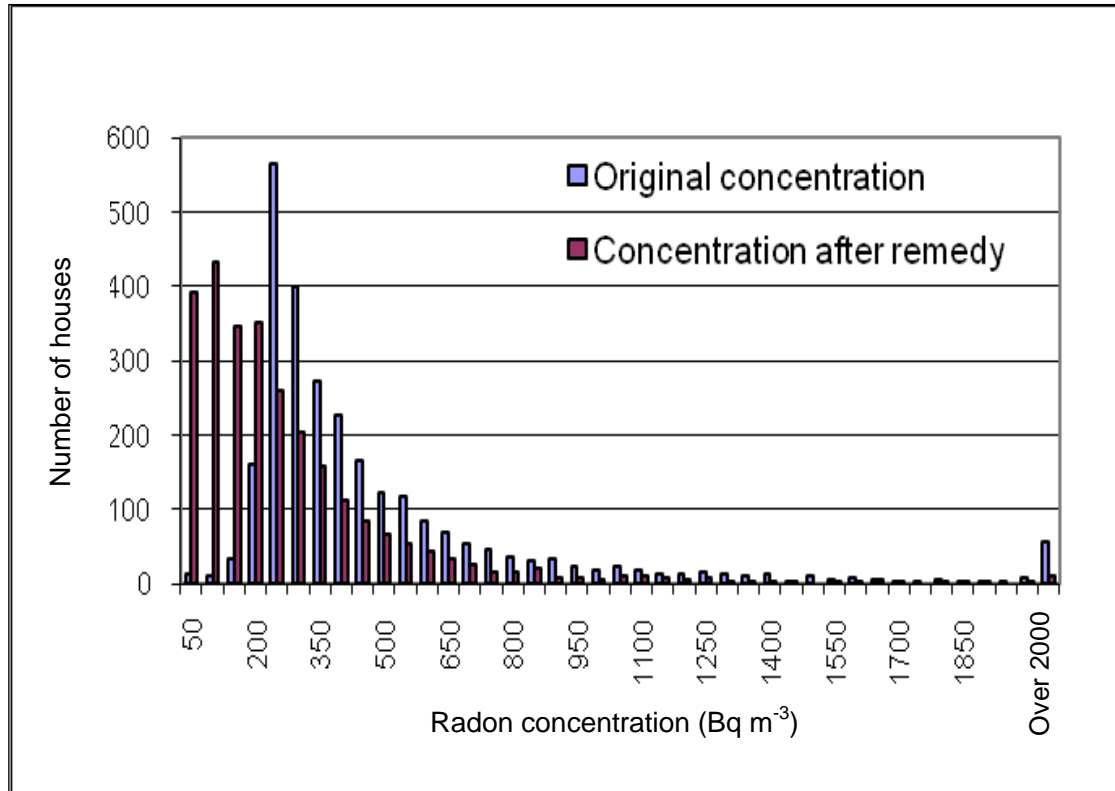


Figure 1 Distribution of radon concentrations before and after remediation

3.2.2 Dose convention and potential for dose saving

As radon inside buildings is the main source of human exposure to radiation in the United Kingdom, there is considerable scope for significant radiation dose reduction to the occupants of homes with significantly elevated concentrations. The effective radiation dose due to radon received by a member of the UK population, who lives in a home at the average level, is estimated to be 1.2 mSv each year assuming that radon concentrations in other buildings are similar to those in dwellings. As the radon concentration in a home increases so does the dose received by the occupants: living in a home at the Action Level (200 Bq m⁻³) would be equivalent to an effective dose of 10 mSv y⁻¹ (Birchall and Marsh, 2004). In the very highest homes identified so far in the UK with levels over 10,000 Bq m⁻³, the annual effective dose from radon is over 500 mSv y⁻¹.

3.3 Analysis method

Multiple regression analysis was used to assess the relative effectiveness of different methods of radon reduction and to assess the effectiveness when taking the different house characteristics into account. A standard multiple regression model was used to assess the influence on the concentration ratio of the various methods of radon reduction and of the different house characteristics listed in Table 2 and any interactions between the remediation method and the house characteristics.

The model has the following general form

$$(1) \quad \ln\left(\frac{\text{radon before}}{\text{radon after}}\right) = a_1x_1 + a_2x_2 + a_3x_3 + \dots$$

where the a_i are regression coefficients and x_i are predictive variables.

This can be rearranged to get

$$(2) \quad \text{radon after} = \frac{\text{radon before}}{\exp(a_1x_1)\exp(a_2x_2)\exp(a_3x_3)}$$

which indicates that each significant predictive variable will provide a multiplicative component to the relationship between the radon measurements made before and after remediation.

The main outcome sought from the analysis was to identify what factors govern the success of remedial measures in particular situations. A 5% statistical significance level was used in this analysis. The analyses were performed using the STATA 7.0 statistical packages (STATA Corp LP, College Station, TX).

The normal probit plot was used in order to assess whether the radon reduction factors (ratio of radon concentration before and after remediation) are approximately normally distributed. Further details can be found in Appendix D.

4 RESULTS

4.1 Effect of remedial method

The statistical analysis investigated the effectiveness of the method used to reduce radon levels and the relationships between parameters that may be relevant to remediation and the outcomes of remediation itself. The parameters considered are listed in Table 2. Two measures of performance were used; success rate and reduction factor (see section 3.2.1). Together these can indicate whether the remediation will achieve significant reductions in exposure and whether further reduction measures should be considered.

Attempts at reducing the radon concentrations in 2,700 cases are summarised (by the major method used) in Table 3. Figure 2 gives a graphical representation of the overall reduction factors and 95% confidence intervals for the more common remedial methods. The reduction factors have been calculated from the multiple regression analysis (see section 3.3 and Table C1 in Appendix C). The narrow confidence intervals of these factors, as shown on figure 2 and tabulated in Table C1, Appendix C ($p < 0.001$, except for sealing the loft hatch), indicate that they are good estimates.

Table 3 Statistical summary of radon concentrations and reductions resulting from various remediation methods

Principal Remediation method	Number of remediations (% of total)	Geometric Mean (Bq m ⁻³)			
		Before remediation	After remediation	Reduction factor	% reduced below AL
Active sump	771 (29)	523	88	6.0	74
Passive sump, pipe inside	77 (3)	360	189	1.9	42
Passive sump, pipe outside	131 (5)	348	193	1.8	47
Positive ventilation	495 (18)	371	176	2.1	56
Natural under-floor ventilation	636 (24)	317	189	1.7	50
Active under-floor ventilation	128 (5)	494	225	2.2	44
Active under-floor ventilation fan blowing	24/128 (<1)	535	258	2.1	42
Active under-floor ventilation fan sucking	70/128 (3)	482	187	2.6	49
Passive ventilation	259 (10)	291	226	1.3	44
Sealing floors	185 (7)	338	251	1.3	35
Sealing loft hatch	17 (<1)	260	219	1.2	35
Overall data	2700 (100)	386	157	2.5	56

In about a quarter of the cases, when active under-floor fans were used, it was unknown whether they were sucking or blowing.

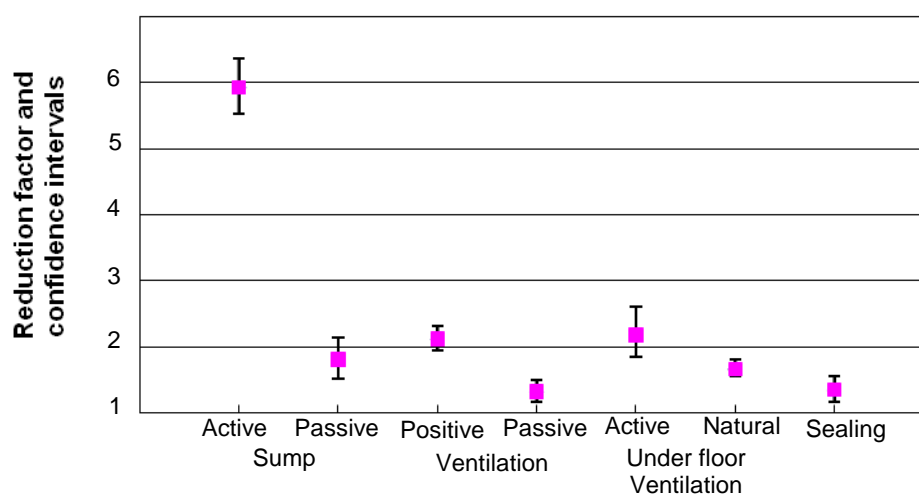


Figure 2 Comparison of the Relative Effectiveness of Remedial Methods (coefficient + 95% CI). The depth of the marker indicates the 95% confidence interval for each remedy.

The most frequently used methods are the active sump (~29%), natural under-floor ventilation (~24%) and positive ventilation (~18%). The main points arising from Table 3 are:-

- The most effective method is an active sump a typical reduction factor of 6 and a success rate of around 74%.
- A group of methods, (positive ventilation, active under-floor ventilation, passive sumps and natural under-floor ventilation) give a reduction factor around 2.

- The least effective methods are passively ventilating the living space and sealing floors, showing a reduction factor around 1.5.

Approximately 70% of the remediations led to a reduction in radon levels of at least 25%. Around 20% of the remediations resulted in a change of less than 25%. A small proportion (10%) gave rise to radon levels being increased by at least 25%.

4.1.1 Performance of remediation methods: single compared with combinations

In some homes, combinations of methods are used. This might be for a variety of reasons including cost (trying a lower cost option first) or because an initial attempt does not achieve sufficient reduction.

Table 4 shows the effectiveness of sole remedies compared with combinations of remedies. Most homes (around 2,100) used only a single remedy. The table shows that superficially combinations of remedies do not appear to offer a significant improvement compared with the single remedy. However, one of the reasons why a second remedy may be implemented is that the first method does not perform very well or it does not achieve a reduction sufficient to get below the Action Level. Thus, it is not surprising that in some cases the combined performance of two methods is not much greater than the general performance of a single method. The effect of multiple attempts at remediation is discussed below.

Active sumps are the most effective at reducing below the AL (74%); when an active sump and another remedy is used then there is a marginal increase in the numbers reducing below the AL (between 69 – 79%). For all other remediation types, there was little difference in the success rates or reduction factors.

Table 4 Effect of fitting one or more remedial methods

Method	Number of remediation projects (% of total)	Reduced below AL %	Geometric mean (Bq m ⁻³)		
			Before	After	Reduction Factor
Sole Remedies					
Active sump	629 (23)	74	525	87	6.0
Passive sump, pipe inside	77 (3)	42	360	189	1.9
Passive sump, pipe outside	131 (5)	47	348	193	1.8
Positive ventilation	421 (16)	57	370	174	2.1
Natural under-floor ventilation	405 (15)	49	320	187	1.7
Active under-floor ventilation	34 (1)	35	491	300	1.6
Active under-floor ventilation fan blowing	24 (1)	42	535	258	2.1
Active under-floor ventilation fan sucking	70 (3)	49	482	187	2.6
Passive ventilation	182 (7)	46	280	223	1.3
Sealing	143 (5)	32	343	265	1.3
Sealing loft hatch	17 (1)	35	260	219	1.2
Multiple remedies					
Active sump and Natural under-floor ventilation	38 (1)	79	497	94	5.3
Active sump and passive ventilation of living space	49 (2)	76	450	76	5.9
Active sump and sealing floors	55 (2)	69	598	106	5.6
Positive ventilation and passive ventilation of living space	41 (2)	56	332	164	2.0
Positive ventilation and sealing floors	33 (1)	48	438	209	2.1
Natural under-floor ventilation and passive ventilation of living space	59 (2)	58	286	176	1.6
Natural under-floor ventilation and sealing floors	84 (3)	44	310	215	1.4
Natural under-floor ventilation, passive ventilation and sealing floors	47 (2)	49	340	189	1.8
Natural under-floor ventilation, sealing floors and sealing loft hatch	41 (2)	61	315	177	1.8
Passive ventilation of living space and sealing floors	41 (2)	46	316	224	1.4
Passive ventilation of living space, sealing floors and loft hatch	36 (1)	36	327	246	1.3
Sealing floors and sealing loft hatch	42 (2)	43	320	236	1.4

4.1.2 Reductions using multiple attempts

Table 5 shows the performance of multiple remediation attempts. Each additional attempt after the initial work reflects an additional remediation method or an alteration to the original method (such as increasing the fan speed of a system).

The geometric mean of the initial radon concentration in the full dataset is 380 Bq m⁻³. In over half the houses, the radon is reduced below the Action Level at the first attempt. In approximately 36% of homes, the first remediation attempt did not get below the Action Level and no further attempts were made. Of the 1,114 homes that attempted remediation but were still above the Action Level after one attempt, 22% made further efforts to reduce the levels. Each subsequent attempt reduced the radon concentration below the Action Level in a third or more of the houses involved in each stage. This suggests that multiple attempts are often worthwhile when the radon level is still substantially above the Action Level.

The average initial radon levels in the homes, that were reduced below the Action Level at each successive stage, increases as the number of attempts increases. This indicates that homes having multiple attempts are generally those with higher initial concentrations and that multiple measures are sometimes needed to get below the Action Level.

The total number of houses that did not achieve reduction below the Action Level is 977 with an initial geometric mean radon level of 424.2 Bq m⁻³. The geometric mean after reduction was 392.0 Bq m⁻³; a reduction factor of 1.1. This implies that the selected remedies had little effect. In most of these homes (874), only one attempt was made. Further work would be needed to investigate the characteristics of homes and remediation methods that did not achieve reduction below the Action Level.

Table 5 Performance of multiple attempts to reduce radon levels below the Action Level

Number of attempts	Number of houses entering each attempt	Number of houses reduced below AL at each attempt	% Reduced below AL at each attempt	Geometric mean of the radon concentration in homes reduced below AL (Bq m ⁻³)		Reduction factor, initial radon concentration
				Initial	After	
1	2415	1301	54	338.5	75.7	4.5
2	240	108	45	412.9	90.3	4.6
3	59	19	32	631.5	87.5	7.2
4 or more	24	10	42	647.8	106.6	6.1

Figure 3 shows that around 60% of 2,415 homes had final radon concentrations below the Action Level. Most of these achieved this in the first attempt. Of those that did not get below the Action Level on the first attempt (40%), most 36% did not make further attempts. There may be further scope for remediation in these properties.

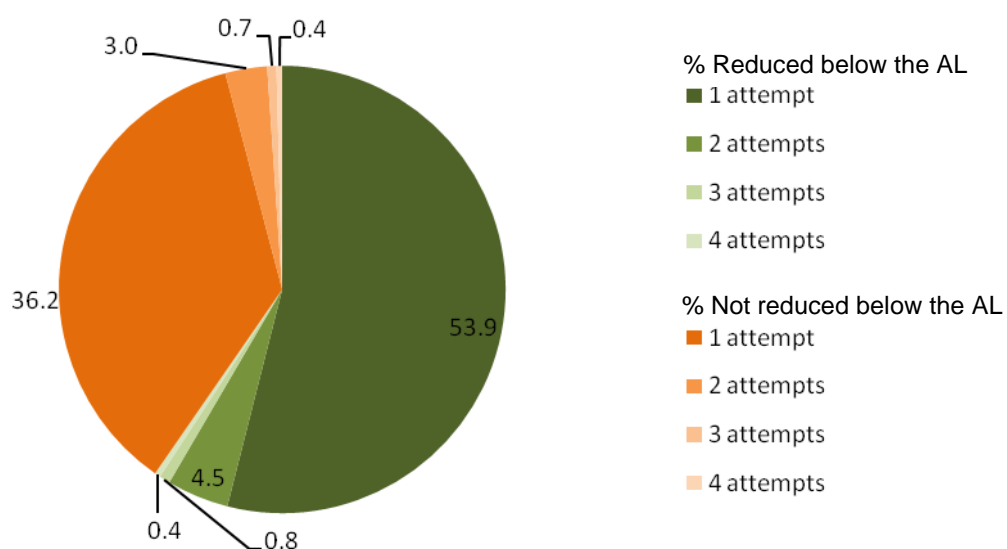


Figure 3 Performance by attempt to reduce radon concentrations below the Action Level (AL)

4.2 Effect of initial radon concentration

The success rate and the reduction factor vary depending on the initial radon concentration. Table 6 shows the success rates of remediation methods used alone, arbitrarily grouped by the initial radon concentration ranges of, under 300, 301 – 600, 601 – 1,000 and over 1,000 Bq m⁻³. Table 7 shows the reduction factor by the same parameters. Figures 4 and 5 are graphical representations of the results in Table 6 and 7 for the major remedial methods used. Results are not included when the individual number of homes using the remedial measure is less than 20.

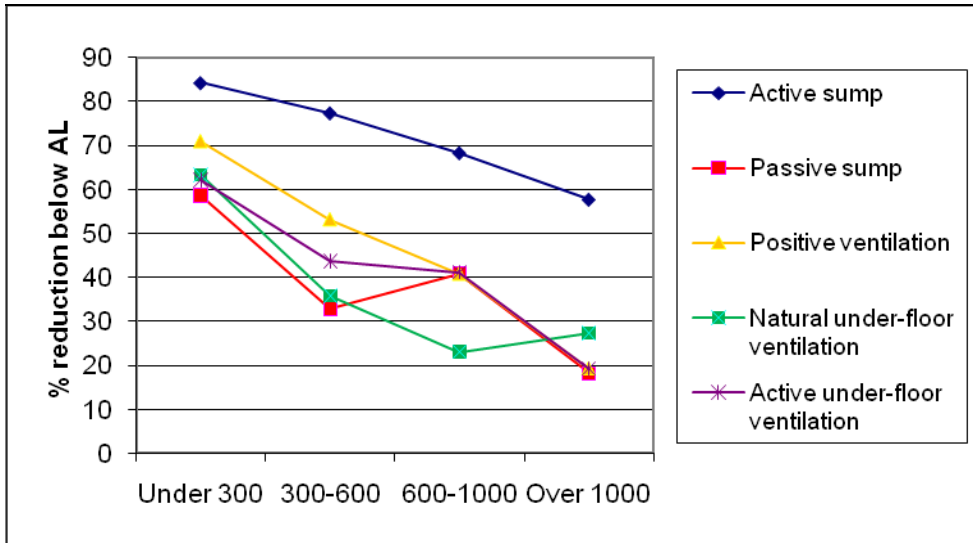


Figure 4 Percent reduction below the Action Level for each method: as a function of initial radon concentration

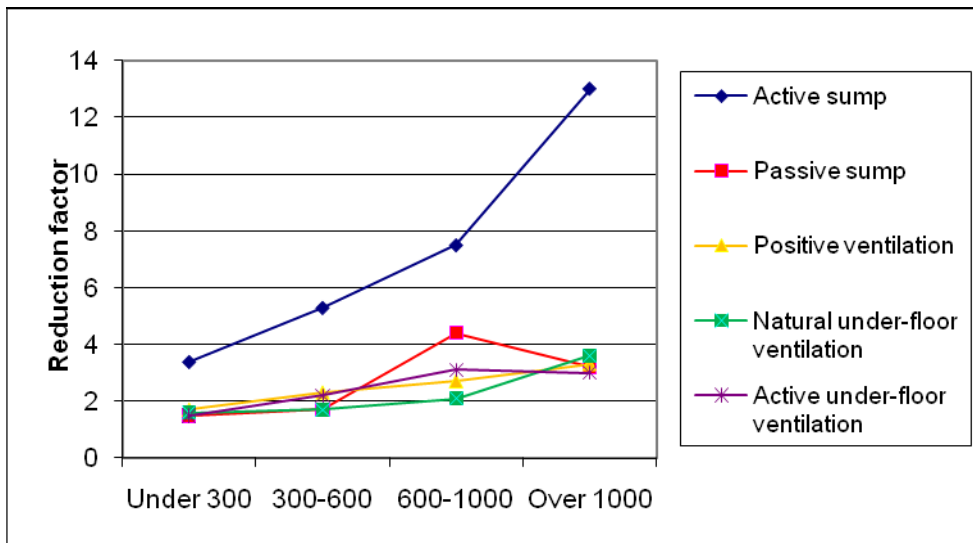


Figure 5 Reduction factors for each method: as a function of initial radon concentration.

Both Tables 6 and 7 and Figures 4 and 5 show a trend in the two effectiveness measures for each method in relation to the initial radon concentration. As the initial radon concentration rises, the measures are less likely to achieve a reduction below the Action Level but they are also more likely to deliver a greater reduction factor. The effect is strongest for active sumps.

Table 6 Success rates of remedial method depending on initial radon concentration

Remedy	Initial concentration range Bq m ⁻³			
	% reduced below AL, (total number of houses)			
	Under 300	300 – 600	600 - 1000	Over 1000
Active sump	84.2 (152)	77.4 (243)	68.3 (120)	57.8 (116)
Passive sump	58.6 (99)	32.9 (76)	40.9 (22)	18.2 (11)
Passive sump pipe inside	53.1 (32)	29.0 (31)	41.7 (12)	50.0 (2)
Passive sump pipe outside	61.2 (67)	35.6 (45)	40.0 (10)	11.1 (9)
Positive ventilation	71.0 (172)	53.1 (175)	40.8 (49)	19.2 (26)
Natural under-floor ventilation	63.3 (218)	35.8 (151)	23.1 (26)	27.3 (11)
Active under-floor ventilation	62.2 (37)	43.8 (48)	41.2 (17)	19.2 (26)
Active under-floor ventilation fan blowing	57.1 (7)	33.3 (9)	100 (1)	28.6 (7)
Active under-floor ventilation fan sucking	65.2 (23)	50.0 (24)	30.0 (10)	30.8 (13)
Passive ventilation	54.2 (131)	22.5 (40)	22.2 (9)	50.0 (2)
Sealing	47.2 (72)	17.7 (51)	21.4 (14)	14.3 (7)
Sealing loft hatch	38.5 (13)	25.0 (4)	NA	NA
Total reduction for all methods	64.8 (894)	50.8 (788)	50.2 (257)	42.5 (200)

NA: data not available

Table 7 Reduction factors of remedial method depending on initial radon concentration

Remedy	Initial concentration range Bq m ⁻³			
	Reduction factor, (total number of houses)			
	Under 300	300 - 600	600 - 1000	Over 1000
Active sump	3.4 (152)	5.3 (243)	7.5 (120)	13 (116)
Passive sump	1.5 (99)	1.7 (76)	4.4 (22)	3.2(11)
Passive sump pipe inside	1.7(32)	1.5 (31)	4.2 (12)	6.0 (2)
Passive sump pipe outside	1.4 (67)	1.9 (45)	4.7(10)	2.8 (9)
Positive ventilation	1.7 (172)	2.3 (175)	2.7 (49)	3.3 (26)
Natural under-floor ventilation	1.6 (218)	1.7 (151)	2.1 (26)	3.6 (11)
Active under-floor ventilation	1.5 (37)	2.2 (48)	3.1 (17)	3.0 (26)
Active under-floor ventilation fan blowing	1.4(7)	1.5 (9)	33 (1)	3.1 (7)
Active under-floor ventilation fan sucking	1.6 (23)	2.7 (24)	2.6 (10)	5.2(13)
Passive ventilation	1.2 (131)	1.2 (40)	1.8 (9)	2.8 (2)
Sealing	1.2 (72)	1.2 (51)	2.4 (14)	2.9(7)
Sealing loft hatch	1.2 (13)	1.3 (4)	NA	NA
Total reduction for all methods	1.7 (894)	2.5 (788)	4.4 (257)	7.2 (200)

4.3 Effect of house characteristics

The multiple regression model described in section 3.3 was used to investigate the relationship between each remedial method and the house characteristics listed in Table 2. The results are summarised below. Further details, including the confidence

intervals, are given in Appendix C. Note that in some cases the large confidence intervals are due to small sample sizes and blank spaces reflect insufficient data.

The objective of this study is to determine which house characteristics have an effect on the performance of remediation. The findings will stimulate future work to understand the mechanisms involved.

4.3.1 Effects of different house types

Investigation of the potential influence of house type (Appendix C, Table C2) shows that this has little effect on the effectiveness of any individual remedial method.

4.3.2 Effects of the date of build

The build date category reflects the major construction periods or the introduction of building standards and/or regulations (Section 2.3). The reduction factor varies significantly with the date of build for active sumps only: the trend shows they are better in newer homes (Appendix C, Table C3). The reduction factors after 1993 seem to be more variable, this is probably due to low sample numbers. For other methods, the age of the homes makes little or no difference.

4.3.3 Effects of the number of floors and basements

Investigation of the potential influence of single-storey and multi-storey homes (Appendix C, Table C4a) showed that both active sumps and positive ventilation were 1.5 and 1.25 times more effective respectively in single storey homes than in homes with more than one storey: a finding significant at the 95% confidence level. There are indications, not always significant at the 95% level that passive sumps (with the pipe outside) were approximately 1.5 times more effective in single storey homes and with the pipe inside they were slightly more effective in multi-storey homes. All other remedies were equally effective, regardless of the number of storeys.

The potential influence of basements on the effectiveness of remediation in homes (Appendix C, Table C4b) shows that active sumps are generally more effective in homes without a basement. This may be explained in part because of the greater prevalence of basements in older homes and the correlation of active sump performance with newer homes. The performance of other remediation methods are largely unaffected by the presence or absence of a basement.

4.3.4 Effects of double glazing

The influence of double glazing on remediation methods (Appendix C, Table C5) shows that the reduction factors tend to be higher, significant at the 95% confidence level, for active sumps when a home has full double glazing compared with no double glazing. Partly double-glazed homes lie in between. The effectiveness for positive ventilation seems slightly enhanced in fully double glazed homes, also significant at the 95% level. It should be noted that, in general terms, double-glazing is known to be a factor in increasing indoor radon levels (Wrixon et al 1988)

4.3.5 Effects of floor type

The influences of floor type on the effectiveness of remediation methods (Appendix C, Table C6), shows that active sumps are the most effective remedy, regardless of floor type. The likely explanation for this is that some respondents may have classed a suspended concrete floor as solid. Active under-floor ventilation is more effective than natural under-floor ventilation for solid floors. Active under-floor ventilation for basements (fan blowing) reduces levels by 7.5 times (CI 1-50). For all other remedies, floor type makes little difference to their effectiveness.

4.3.6 Effects of heating method

Investigation of the influence of heating method (Appendix C, Table C7) show that heating type, generally has no bearing on the effectiveness of any of the remediation methods.

4.4 Effect of different contractor types

Radon mitigations are carried out by; companies that specialise in this work, general builders and by householders themselves. The effectiveness of methods to reduce radon levels may depend on the quality of the work done as well as the other parameters explored here. This may vary according to the contractor. The difference in effectiveness of remedial measures was investigated in relation to the amount of experience and type of contractor carrying out the work. The work done by contractors here reflects their relative level of experience rather than absolute numbers.

Data used in this analysis do not include results where contractors have used measurement laboratories other than HPA. The remedial information is obtained from questionnaires and relies on the householders' interpretation and understanding of the questions and some of that information may be reduced in quality or this information may not have been available.

Analysis is complicated because the choice of contractor (experienced, general or DIY) may be biased by the initial radon concentration (Table 9). Table 9 shows that there is a positive correlation between higher initial concentrations being tackled by the experienced contractors rather than the others (general or DIY). It has already been shown in Figures 4 and 5 that initial radon concentration influences the potential for success. These factors have an influence on results in Table 8.

4.4.1 Contractor type

In this analysis, contractors who have carried out more than 10 remedial works which are reported here are classed as "experienced". Contractors who have carried out fewer than 10 remedial works are classed as "general".

Experienced contractors were further subdivided into categories; those having completed work on more than 30 houses and those completing work on between 10 and 29 houses. General contractors were assumed to have less experience and may

not necessarily specialise in radon remediation. These general contractors were further subdivided into categories; those who have completed between 5 and 10 works and those who have completed fewer than 5 works on houses respectively. Home owners doing their own work are categorised as DIY. If the contractor was unknown (not stated on the questionnaire), then the results were excluded from analysis.

Table 8 Contractor type and success rates

Contractor category	Total no houses	% reduced below AL		Average concentration of Radon Bq m ⁻³ after 1 attempt to reduce levels		Reduction factor
		Overall success	After 1 attempt	Before	After	
		Geometric Mean (GSD)				
Experienced						
All Experienced	803	62	51	467.6 (2.0)	115.8 (3.2)	4.0
Experienced >=30	618	60	48	474.5 (2.1)	120.0 (3.2)	4.0
Experienced >=10<30	185	70	60	445.9 (2.0)	103.1 (3.1)	4.3
General						
All General	549	50	43	403.0 (1.9)	170.0 (2.8)	2.4
>=5<10	95	60	54	455.3 (2.1)	126.2 (3.0)	3.6
Rest <5	454	48	41	392.8 (1.9)	180.9 (2.7)	2.2
DIY	445	49	43	351.6 (1.8)	177.5 (2.5)	2.0

Table 8 confirms that higher initial concentrations are correlated with greater reduction factors. The table shows that in general, the more experienced remediators deal with homes having higher initial concentrations.

These observations are further illustrated in Table 9 in relation to ranges of initial radon concentration. It is not clear whether the improved performance is due to the experience of the contractors, the higher initial concentration or a combination. In order to determine this, it would be necessary to analyse different types of remediators undertaking the same work on similar homes having the same initial concentration. This might be the subject of future work but this would need to have sufficient data to support statistically valid conclusions.

Table 9 Contractor effectiveness depending on initial radon concentration

Contractor	Reduction Factor (RF) and % reduced below AL								
	Initial concentration range Bq m ⁻³								
	Under 500			500 – 1000			Over 1000		
No Homes	RF	Success rate	No Homes	RF	Success rate	No Homes	RF	Success rate	
Experienced	470	3.0	74.5	205	5.4	61.5	109	8.5	45.0
General	377	1.8	55.7	115	3.1	38.3	55	9.2	49.1
DIY	347	1.7	55.3	65	2.9	38.5	32	5.3	40.6

4.4.2 Individual contractors

Table 10 shows the variation in success rates and reduction factors for individual contractors who had done the most number of works. It highlights the variability of performance for reducing radon levels.

Table 10 Contractor performance - individual

Contractor id	Total no houses	% Reduced below AL - number of attempts to reduce levels			Average concentration of radon Bq m ⁻³ after 1 attempt to reduce levels		Reduction factor
		Overall success	1	2	Geometric mean (GSD)		
					Before	After	
1	237	49	36	13	506.2 (2)	206.9 (2.3)	2.4
27	137	67	59	8	448.1 (1.9)	92.1 (3.6)	4.9
41	60	76	55	21	421.3 (2.1)	58.3 (3.6)	7.2
61	44	82	73	10	547.3 (2.4)	100.2 (2.3)	5.5

4.5 Costs of remediation

Information on cost was collected on the questionnaire. This sub dataset comprised 1533 entries for costs of single remedies. Unknown costs were excluded. The data in Table 11 reflect an underlying distribution of 'paid for work' (including labour costs in most cases). At the low cost end there are DIY and those possibly without labour costs and at the top end there are some outliers which might comprise 'difficult jobs' or jobs mixed in with other work and possibly some jobs that have been overcharged.

The costs for each method do not always follow either a normal or log-normal distribution: figures 6, 7 and 8 show the range of costs for the three most common methods. In order to estimate typical costs, Table 11 shows the arithmetic mean, geometric mean and median costs. Typical costs were estimated by rounding the geometric mean to the nearest £50.

Typical costs for the most often used remedies, active sumps, positive ventilation and natural under-floor ventilation are around £800, £500 and £150 respectively.

The period in which the remediation works were undertaken (2000-2007) was characterised generally by low inflation: during the period there was a general price rise of around 20%. Prices here are represented as they were in the same period. Prices since then may have changed.

Table 11 Costs for remedial methods employed to reduce radon levels in houses

Remedy	Frequency (n)	Cost £				
		Arithmetic mean	Geometric mean	Median	min	max
Active sump	418	915	770	800	30	5000
Passive sump	61	585	374	450	25	3200
Active under-floor ventilation	50	860	570	800	26	6205
Natural under-floor ventilation	147	260	134	150	8	4236
Positive ventilation	291	540	505	515	10	1600
Passive ventilation	39	700	130	80	10	7500
Sealing	29	455	95	75	5	3865
Active sumps (DIY)	28	305	258	300	50	750

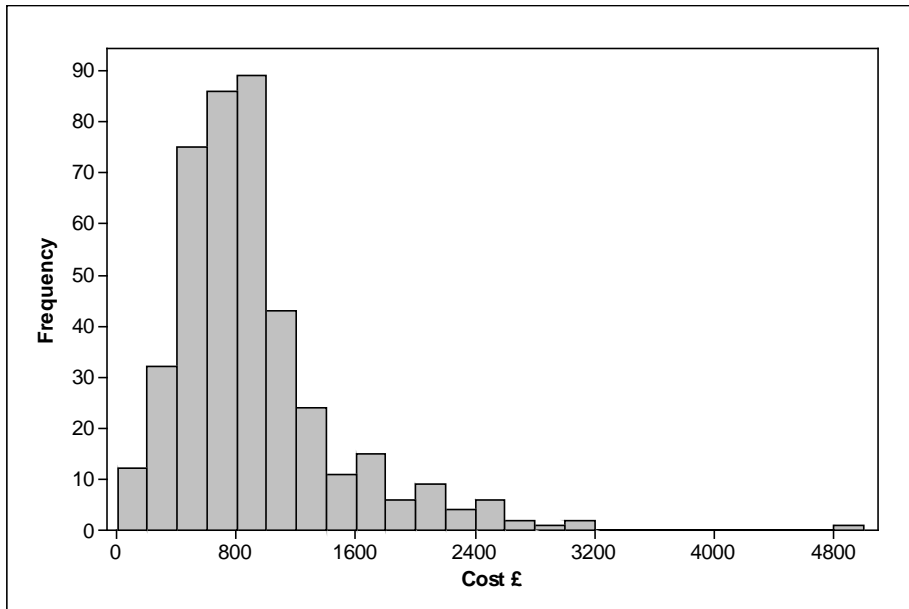


Figure 6 Range of costs: Active Sump

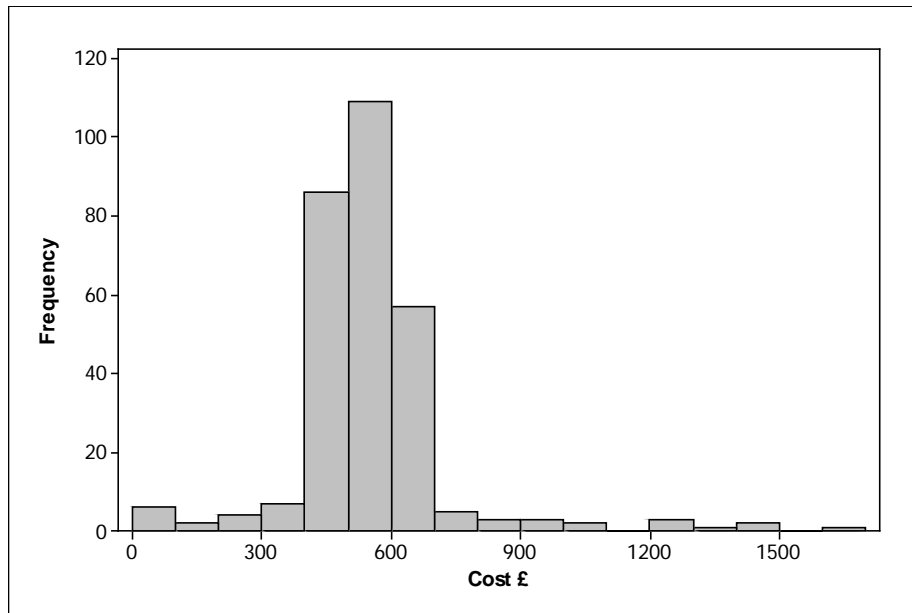


Figure 7 Range of costs: Positive Ventilation

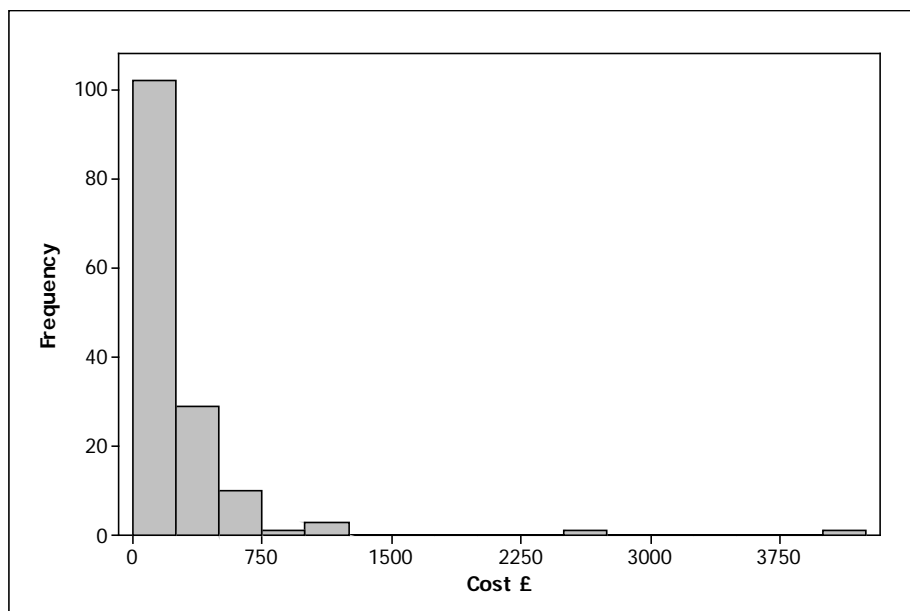


Figure 8 Range of costs: Natural under-floor ventilation

5 DISCUSSION

5.1 Is remediation effective?

Undoubtedly, remedial works can be successful at reducing radon concentrations. This is clearly shown by the downward shift of the distribution of post-remedial radon concentration relative to the initial distribution shown in Figure 1. Reduction factors and success rates in reducing below the Action Level are clearly illustrated in Tables 3 and 4.

5.2 The performance of remediation methods

The aim in radon remediation is generally to obtain a substantial reduction in the radon level and, if practicable, to reduce levels to below the Action Level. The analysis here has identified a number of parameters which influence these two outcomes: the choice of remediation method; the initial (pre-remediation) radon level; and the characteristics of the building being remediated. The most effective remediation method for an individual home can depend on each of these characteristics. It may be that if the same method were applied to the same home by different people, this might also have different performance although the database of information does not support this level of analysis.

The results are reported as success rate at reducing radon levels below the Action Level and as reduction factors in radon concentration. Generally, for all remedies the success rate decreases as the original radon level increases and reduction factors increase with increasing initial radon levels. It should be noted that even if the success rate is low, the reduction factor could be high. Although reduction below the AL may not have been achieved, the reduction of radon levels may still be large therefore the remedy was effective in substantially reducing radon exposure.

Active measures generally perform better than passive measures, for example active sumps are always more effective than passive sumps; positive ventilation is more effective than passive. In some cases, for example active and natural ventilation of under-floor space; there is overlap in performance.

5.2.1 Active sumps

This study found that an active sump is the most effective and widely used remedy across a wide range of circumstances and has the most success at reducing radon levels. It achieves a typical reduction factor of 6 and gets below the Action Level in 74% of homes when used as the primary remedial measure. This confirms the findings of others (Cliff et al, 1992), (Naismith et al, 1998) in the UK and in other countries (Henschel, 1994), (Arvela et al, 2008).

5.2.2 Passive sumps

Passive sumps are moderately effective at reducing radon concentrations. Overall, the trend with respect to initial concentration follows that shown by other remedial

measures, namely higher initial radon concentration is associated with greater reduction factors but low success rates at getting below the Action Level.

There appears to be an improvement in performance of passive sumps around several hundred Bq m⁻³. There is no obvious explanation and, as the sample is small, the statistical significance will be low.

In areas where there the potential for a radon concentration to be at or above the AL in 10% or more of dwellings, sumps and associated under-floor pipework are required to be installed in new buildings with solid floors. This is in addition to a membrane as a protective measure against radon (Communities and Local Government, 2004). It must be stressed that these sumps are capped and are not working as passive sumps.

5.2.3 Positive ventilation

Positive ventilation generally offers a reduction of radon by a factor of around 2. Previous work (Cliff et al, 1992) suggest that these systems will offer moderate reductions in radon levels, providing that the house is reasonably airtight and windows are kept closed. The performance of this method is largely unaffected by the characteristics of the home except for a slightly enhanced performance in fully double glazed properties: in line with the finding by Cliff et al. Positive ventilation systems were found to be slightly more effective in single storey houses, a similar finding to Naismith et al, 1998. This is to be expected as, in general terms, the magnitude of the stack-effect is proportional to the height of a building but the pressure exerted by a positive ventilation unit is constant.

5.2.4 Natural and active under-floor ventilation

Natural and active under floor ventilation typically offers a reduction in radon levels by a factor of around 2 and shows the same general trend in performance with respect to initial radon levels as other methods. Householders may achieve good results by increasing natural under floor ventilation, and if this fails there is still an option to activate using a fan if the radon reduction is insufficient.

5.2.5 Sealing floors and passive ventilation

These measures generally have the lowest performance with reduction factors less than 2 and the percentage reducing levels below the Action Level at the first attempt is around 32% for sealing and 44% for passive ventilation. The regression analysis and the success rate at reducing radon levels below the Action Level shows that sealing and passive ventilation are the least effective, especially at higher radon levels. It is very difficult to seal floors effectively and when used alone is unlikely to yield appreciable reductions. The results here are similar to those shown elsewhere (Naismith, 1994). However, it has been shown elsewhere that it would be advantageous to seal very large holes, block vents or cover large expanses of exposed earth with suitable membranes (Pye, 1993).

5.2.6 Performance of single methods compared with combinations

Combinations of remedial methods are only slightly more effective than single methods alone. The low sample number of multiple remedies in this report does not support firmer conclusions.

5.3 Performance of remedial measures as influenced by physical characteristics of a home

The analysis looked at the reduction factor achieved by each remedial measure and whether this is affected by the physical characteristics of the home. This may be important in helping householders to decide on the most appropriate measure for a specific home and to understand what factors might affect the performance of remedial measures.

The results are shown in Table 12 with further detail in Appendix C. The table indicates the degree of influence of each factor on the performance of each remedial measure. The main observations from Table 12 are:

- House type and heating type do not make a significant difference to the performance of any measures.
- Active sumps tend to perform better in newer homes. The build date has no significant influence on other measures.
- Active sumps, positive ventilation and passive sumps (pipes outside) are more effective in single storey than in multi-storey homes. The number of storeys has no significant influence on the performance of other measures.
- The presence of a basement diminishes the performance of active sumps but this may be correlated with the build date of the property. The presence of a basement makes no significant difference to the effectiveness of other measures.
- All measures are generally more effective when the home has double glazing.
- In general, floor type is not a major determinant of the performance of remedial measure. This is similar to the findings of Naismith et al, 1998.

Table 12 Effect of house characteristics on the performance of the remedial measure

Factors affecting performance	Method of reduction						
	Active sump	Passive sump	Positive ventilation	Passive ventilation	Natural under-floor ventilation	Active under-floor ventilation	Sealing Floors
House type	No Difference						ID
Date built	** Newer the house, the better	No Difference	No Difference	No Difference	No Difference	ID	No Difference
Single storey effects	** More effective in single storey homes	*More effective in single storey homes	**More effective in single storey homes	No Difference	No Difference	ID	No Difference
Basement effects	**More effective in homes without a basement	No Difference	No Difference	ID	No Difference	ID	ID
Double glazing	*Remedies are generally more effective with double glazing						
Ground floor type	No Difference	ID	No Difference	*Slightly more effective for suspended floors	No Difference	ID	ID
Type of heating	No Difference						

* Some effect
** Strong effect
ID - Insufficient Data

5.4 Contractor choice

There are no firm conclusions drawn from this analysis about the relative performance of the different types of remediators and householders who 'DIY'. This is largely due to the interaction with the effect of higher initial radon concentration on remediation performance. It has been shown that there are differences in performance between individual experienced contractors. While experienced contractors generally obtain better results, they also undertake a greater proportion of their work on the homes with the higher initial radon levels. It has been shown here that the higher initial radon homes offer greater reduction factors. It is therefore currently not possible to draw firm conclusions about the likely outcome of a remediation based solely on the past experience of the contractor.

There are however, some worthwhile questions that householders should ask when considering radon remediation. The questions are shown below. Some are common to many types of building work; others are specific to radon remediation.

- Have you got several quotes?
- Has the contractor been recommended by others?
- Do you have your own trusted builder/contractor?
- Does the contractor suggest realistic reductions for the proposed remedial measure suggested?
- Does the contractor make or suggest a post remedial measurement?
- Does the contractor inform you of post-remedial maintenance such as: periodic checking that fans are still running; being aware of the cost of running fans; checking radon levels every few years to ensure levels are still low; and re-testing after significant building work has been completed on the home? (Green and Hodgson, 2010).

It is also worth noting that, unlike many types of building work, the results of radon remediation are not directly visible but must be determined through measurement and are also aimed at reduction of a health risk rather than its elimination.

Householders should bear in mind that the performance of radon remediation measures varies according to many factors and there is no certainty of achieving a specific final radon level. Individual contractors might choose to offer such a "guarantee" but this may be problematic as there is insufficient evidence to suggest that a specific technique in a specific situation will definitely achieve a certain reduction factor. Householders should therefore have a realistic expectation that appropriate measures will, if properly carried out, reduce radon considerably but that further measures may be required. It is also important for householders to realise that even if radon levels are not reduced below the action level, if their indoor radon has been significantly reduced then this significantly reduces their lung cancer risk.

5.5 Costs

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

The methods show a distribution of costs generally characterised by a central peak in the distribution but with significant high and low outliers (for example, see figures 6, 7 and 8). It is likely that most of the low outliers are associated with some level of DIY not involving labour costs and the higher ones are understood to be often associated with the combination of other work on the home as part of the radon remediation. For example a sump may be constructed centrally in a house and the cost of replacement floors, carpets etc have been included. In a few homes, costs may be increased if the work is complicated or involves a large build area where several sumps may be required.

Table 13 shows typical cost for each measure, using the geometric mean rounded to the nearest £50.

Table 13 Typical costs for remediation measures

Remedy	Cost £
Active sump	800
Passive sump	400
Active under-floor ventilation	550
Natural under-floor ventilation	150
Positive ventilation	500
Passive ventilation	150
Sealing	100
Active sumps (DIY)	250

Typical costs for each individual measure do not take into account price changes since 2007. The distribution of costs is similar to a previous study (Bradley and Thomas 1996).

5.6 Dose saving after remediation

Radon is a proven carcinogen, implicated in over 1,000 lung cancer deaths in the UK each year (HPA, 2009). In addition, it is the largest contributor to the total radiation dose received by the population and shows a large variation. While the typical annual UK radon exposure is around 1.2 mSv, much higher exposures are received by people living in houses with high radon levels, exceptionally exceeding hundreds of millisieverts annually. The aim of radon remediation is to reduce high individual exposures.

A level of 200 Bq m⁻³ corresponds to an annual exposure of about 10 mSv y⁻¹ (Birchall and Marsh, 2004). The average reduction in radon concentrations for homes analysed

in this report suggest that dose savings for each occupant is around 11 mSv y^{-1} but with a large variability between homes. There are only a few other areas of radiation protection where intervention is able to regularly avert individual doses of this magnitude. Summing this dose saving over the total 2,400 homes and assuming that 2.5 people occupy each house, this suggests that around 70 man-sieverts are saved each year.

5.7 Guidance for the public, builders and professional bodies

The effectiveness of reducing high radon levels in a home depends on the initial radon level, the choice of remedy and good building practice. Even after accounting for these factors, the results presented here suggest that there may be significant variation in the performance of remedial measures. This analysis has brought together information which can be used to create simple and concise guidance for householders, builders and other professional bodies. It is intended that this information will be made accessible in updates to existing guidance documents and on the HPA's radon website (www.UKradon.org).

The development of flow diagrams and website applications that ask relevant questions and suggest solutions, would help householders choose an appropriate method to reduce their radon levels. Provision of this easily accessible information should encourage householders to do the work to reduce their radon levels in their homes.

6 CONCLUSIONS

1. An active sump system is most likely to offer a substantial reduction (typically 6 fold). Other methods such as passive sumps, positive ventilation, natural and active under-floor ventilation, are less effective offering a typical reduction factor of about 2. Passive ventilation and sealing are the least effective.
2. In some cases, multiple methods may be required to achieve significant reductions and to get below the Action Level.
3. Each remediation method showed a trend in performance with respect to the initial radon concentration. The higher the initial radon concentration, the better the reduction in exposure for most measures, but they are less likely to reduce below the Action Level. This effect was more pronounced for active sumps than other methods.
4. The type of home or its heating method does not significantly affect the performance of remedial measures. Double glazing generally improves remediation performance.
5. Active sumps are more effective in newer homes but other measures are largely unaffected by the age of the home.

6. Some measures (sumps and positive ventilation) are more effective in single storey homes.
7. The typical costs of most frequently used remediation methods are:
 - active sump (~£800)
 - positive ventilation of living space (~£500)
 - natural under-floor ventilation (~£150)
8. The analysis undertaken here does not support firm conclusions about the relative performance of different types of contractors and householders who “DIY”. This is largely because of the interaction with the effect of higher initial radon concentration on remediation performance.
9. Further guidance for householders, contractors and others, using information in this report, will be produced as fact sheets and information on the Ukradon website.
10. Further analysis would be required to assess the effectiveness of remedial measures at attaining levels less than the Target Level (100 Bq m⁻³) and in homes with initial radon levels in the range 100-200 Bq m⁻³ (between the Target and Action Levels).

7 GLOSSARY

Active sump. Sump under a solid floor or impermeable membrane with a fan sucking or blowing from the sump (Appendix B).

Active under-floor ventilation. Under-floor ventilation is increased by using a fan which extracts or blows (Appendix B).

Averages. The numerical radon results in this report are presented as arithmetic average and geometric average. The arithmetic average is the normal value used to describe numerical results: it is the sum of the results divided by the number of the results. The geometric average is the nth root of all the results multiplied together. The median is the most common value.

Becquerel. Symbol Bq. The unit of the amount or activity of a radionuclide. Describes the rate which transformations occur. 1 Bq = 1 transformation per second.

Becquerel per cubic metre of air. Symbol Bq m⁻³. The amount of a radionuclide in each cubic metre of air. Often referred to as the activity concentration.

Half life. The time taken for half the amount of a radioactive element to undergo a radioactive transformation and form a different element.

Isotopes. Chemically identical forms of an element with different masses. The mass is indicated by the number after the element.

Natural under-floor ventilation. Under-floor ventilation is increased by clearing airbricks or replacing with modern vents and/or increasing the number (Appendix B).

Pascal. Symbol Pa. A unit of pressure (1 N/m^2). Normal atmospheric pressure is 101,325 Pa, so, for example, 10 Pa is about 0.0015 psi.

Passive sump. Sump under a solid floor or impermeable membrane. No fan (Appendix B).

Passive ventilation. Trickle vents in windows or windows open on lockable catches (Appendix B).

Positive ventilation. Fan, usually in loft space, blowing into living space (Appendix B).

Radon Action Level (AL). The recommended upper limit for the activity concentration of radon in UK homes. Its value, expressed as the annual average radon gas concentration in the home, is 200 Bq m^{-3} .

Radon Affected Areas. Parts of the country with a 1% probability or more of present or future homes being above the Action Level.

Radioactivity. The spontaneous disintegration of unstable elements (*radionuclides*). During the process, energy is emitted as either alpha or beta particles or gamma rays or a combination of these.

Reduction Factor. In this report, the initial radon concentration is divided by the concentration after a remediation attempt. A value greater than 1 indicates a reduction and a value less than 1 indicates that the level has increased.

Sealing floors. Sealing cracks and gaps in floors, usually done in addition to other methods, unsuitable for timber floors (Appendix B).

Sealing the loft hatch. The upward flow of air is reduced and as a consequence, the negative pressure within the dwelling is reduced, usually sealing the loft hatch is done in addition to other methods (Appendix B).

Sievert. The SI unit name of equivalent dose, effective dose, and operational dose quantities. The unit is joule per kilogram (J kg^{-1}).

Success rate. In this report the success rate is expressed as a percentage. For example, 50% success indicates that 1 in 2 installations reduced the radon levels below the Action Level.

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Special thanks go to the householders who spent time and effort completing the questionnaires: otherwise this analysis would not have been possible.

APPENDIX A Survey questionnaires

A1 HOUSE DETAILS QUESTIONNAIRE

HPA RADON RECORD CARD

Batch no. ID no. Code no.

PLEASE COMPLETE THIS CARD. RETURN IT WITH THE TWO DETECTORS AT THE END OF THE **THREE-MONTH** MEASUREMENT PERIOD. USE THE PRE-PAID PADDED ENVELOPE PROVIDED (NO STAMP NEEDED)



Date detectors posted by HPA _____
 Date detectors placed by householder _____
 Date detectors removed by householder _____



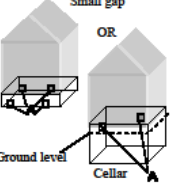
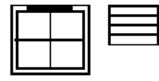
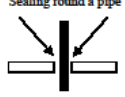
PLEASE REPLY TO THE QUESTIONS BY TICKING THE APPROPRIATE BOX OR WRITING IN THE SPACE

<p>Is your home?</p> <p>Detached <input type="checkbox"/> a</p> <p>Semi-detached <input type="checkbox"/> b</p> <p>Mid terraced <input type="checkbox"/> c</p> <p>Flat <input type="checkbox"/> d</p> <p>Other _____ e</p>	<p>Is the ground floor?</p> <p>All Solid <input type="checkbox"/> a</p> <p>All suspended <input type="checkbox"/> b</p> <p>Mixed <input type="checkbox"/> c</p> <p>Over a basement <input type="checkbox"/> d</p>	<p>Do you sleep with your bedroom window open</p> <p>Summer <input type="checkbox"/> a Always <input type="checkbox"/> a</p> <p><input type="checkbox"/> b Usually <input type="checkbox"/> b</p> <p><input type="checkbox"/> c Sometimes <input type="checkbox"/> c</p> <p><input type="checkbox"/> d Never <input type="checkbox"/> d</p> <p>Winter <input type="checkbox"/> a</p> <p><input type="checkbox"/> b</p> <p><input type="checkbox"/> c</p> <p><input type="checkbox"/> d</p>	<p>In the ROOMS you put the detectors</p> <p>Is the floor construction?</p> <p>living area? <input type="checkbox"/> a Solid (such as concrete or stone) <input type="checkbox"/> a</p> <p><input type="checkbox"/> b Suspended (such as wood or chipboard) <input type="checkbox"/> b</p> <p>c _____ Other _____ c</p>
<p>Is it single storey?</p> <p>Yes <input type="checkbox"/> No <input type="checkbox"/></p>	<p>Is the ground floor on one level?</p> <p>Yes <input type="checkbox"/> No <input type="checkbox"/></p>	<p>Does your home have?</p> <p>Double glazing <input type="checkbox"/> a Full <input type="checkbox"/> a</p> <p><input type="checkbox"/> b Partial <input type="checkbox"/> b</p> <p><input type="checkbox"/> c None <input type="checkbox"/> c</p> <p>Draught proofing <input type="checkbox"/> a</p> <p><input type="checkbox"/> b</p> <p><input type="checkbox"/> c</p>	<p>On what floor is the living area? bedroom?</p> <p><input type="checkbox"/> a Basement <input type="checkbox"/> a</p> <p><input type="checkbox"/> b Ground floor <input type="checkbox"/> b</p> <p><input type="checkbox"/> c First floor <input type="checkbox"/> c</p> <p><input type="checkbox"/> d Second floor <input type="checkbox"/> d</p> <p><input type="checkbox"/> e Third or above <input type="checkbox"/> e</p>
<p>When was it built?</p> <p>Before 1900 <input type="checkbox"/> a</p> <p>1900 - 1919 <input type="checkbox"/> b</p> <p>1920 - 1944 <input type="checkbox"/> c</p> <p>1945 - 1964 <input type="checkbox"/> d</p> <p>1965 - 1976 <input type="checkbox"/> e</p> <p>1977 - 1992 <input type="checkbox"/> h</p> <p>1993 - 2000 <input type="checkbox"/> j</p> <p>After 2000 <input type="checkbox"/> k</p> <p>Unknown <input type="checkbox"/> g</p>	<p>Do you</p> <p>Own your home <input type="checkbox"/> a</p> <p>*Rent from Council <input type="checkbox"/> b</p> <p>*Rent privately <input type="checkbox"/> c</p> <p>Other _____ d</p> <p>*Your landlord can request and will be given your result unless you ask us not to</p>		



A2 RETEST QUESTIONNAIRE

Section 1: What have you done to reduce the radon in your home since the last test?

	<p>1. Have you fitted a radon sump to your home? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p><i>Radon sump.</i> A radon sump is an empty space (S), about the volume of a bucket, under the floor. A pipe goes from the sump to the outside air. The pipe may be up the inside of the house (A) or up the outside (B). A cowl or ridge-vent at the top (C) stops the rain getting inside and there is often an electric fan fitted near to the top end of the pipe (F)</p>	<p>If Yes: Is the pipe from the sump inside (A) or outside (B) the building? Inside <input type="checkbox"/> Outside <input type="checkbox"/></p> <p>Is the pipe-top cowl (C), fixed (S), rotating (R), or a ridge vent S <input type="checkbox"/> R <input type="checkbox"/> V <input type="checkbox"/></p> <p>Is there a fan fitted to the sump? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>If Yes: Does the fan suck air out of the sump or blow air into the sump? Suck <input type="checkbox"/> Blow <input type="checkbox"/></p> <p>What is the make and model type of the fan?</p> <p>What is the wattage of the fan? watts.</p> <p>What is the setting on the fan (e. g. half speed, full speed)?</p>
	<p>2. Have you fitted a positive ventilation system in your home? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p><i>Positive ventilation or positive pressure</i> Air is blown continuously into the living space of a home. Often a fan unit (F) installed in the loft, blows air into the house. A fan blowing air in from the outside would have a similar effect.</p>	<p>If Yes: In which room is the outlet? (Please write in)</p> <p>What is the make and model type of the fan?</p> <p>What is the wattage of the fan? watts.</p> <p>What is the setting on the fan (e. g. half speed, full speed)?</p>
	<p>3. Have you increased the ventilation under a suspended floor? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p><i>Ventilation of the space under a suspended floor</i> The ventilation of the space or cellar under a suspended floor is increased by cleaning existing air-bricks or grills, replacing old ones and/or fitting extra ones. Air-bricks fitted in walls opposite each other will allow a cross-flow of air (A). The airflow can be increased by fitting an electric fan to either draw air out or blow fresh air in.</p>	<p>If Yes: How many airbricks /grills were there to start with? Please write in the number</p> <p>Is it an under floor gap? <input type="checkbox"/> Or Cellar? <input type="checkbox"/></p> <p>Have these existing airbricks/grills been cleaned and/or cleared? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>Did you have any original airbricks/grills in opposite walls? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>Have any of the old airbricks/grills been replaced with new ones? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>If yes: How many have been replaced?</p> <p>Have you added extra airbricks/grills? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>If yes: How many have been added?</p> <p>If you have replaced/added new airbricks/grills, what type was used? (Plastic, metal, claybrick or other, please write in.)</p> <p>Do you now have airbricks/grills (new or old) in opposite walls? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>Has a fan been fitted to improve the air flow under the floor? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>If yes: What is the wattage of the fan? watts</p> <p>Does the fan suck air out of or blow air into the underfloor space? Suck <input type="checkbox"/> Blow <input type="checkbox"/></p> <p>If yes: What is the make and model type of the fan?</p> <p>What is the setting on the fan (e. g. half speed)?</p>
	<p>4. Have you added extra permanent ventilation in your home? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p><i>Additional permanent ventilation</i> Ventilation of the living space is increased by fitting ventilation grills in outside walls, trickle vents in window frames or by locking windows permanently open. It should not be possible to close the vents or window completely. It can also be helpful to provide a direct air supply to a heating device by a vent or pipe to the outside (not to the underfloor space)</p>	<p>If Yes: Have trickle vents been added to your windows? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>How many windows have had added ventilation? If Yes: Downstairs..... Upstairs.....</p> <p>Do you have the windows open all the time on lockable catches? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>Have any rooms been fitted with ventilation grills in outside walls? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>If Yes: Which room(s).....</p> <p>Has the air supply to your heating been changed? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>If Yes: Does the air now draw directly from outside? No <input type="checkbox"/> Yes <input type="checkbox"/></p>
	<p>5. Have you sealed cracks to reduce radon entry into your home? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p><i>Sealing cracks and gaps</i> To be fully effective, every crack and gap in a solid floor needs to be sealed with a flexible sealant. However, sealing major cracks and gaps can be a useful addition to other methods. Note that fully sealing timber floors is not recommended as restricting ventilation may cause the wood to rot.</p>	<p>If Yes: Has the floor to wall join (often under the skirting board) been sealed? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>Have cracks and gaps in solid floors been sealed? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>Have cracks and gaps in suspended floors been sealed? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>Have gaps in the floor around cables and pipes been sealed? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>Has your loft hatch been sealed? No <input type="checkbox"/> Yes <input type="checkbox"/></p> <p>What other gaps and cracks have been sealed? (please write in)</p>
<p>6. Have you blocked up unused chimneys? No <input type="checkbox"/> Yes <input type="checkbox"/></p>	<p>If Yes: Have you left a small vent open to prevent damp in the flue? No <input type="checkbox"/> Yes <input type="checkbox"/></p>	<p>Please write any comments or extra details in the space below or on a separate sheet.</p>
<p>7. Did you employ someone to do the work? No (DIY) <input type="checkbox"/> Yes <input type="checkbox"/></p>	<p>If Yes: Name of the contractor:</p> <p>Address:</p> <p>.....</p> <p>.....</p>	<p>Including VAT, what did the work cost you? £.....</p> <p>Postcode: Telephone number:</p>

APPENDIX B Remediation methods

This appendix summarises methods used most commonly in the UK to reduce high radon levels. More detailed descriptions and specifications of the methods are given by the BRE (Scivyer, 1993; Building Research Establishment, 2005).

Radon in soil air (soil gas), is drawn from the ground into buildings through cracks and gaps in floors and walls of buildings: radon enters buildings because the pressure inside the building (P_i) is usually lower than the pressure outside of the building (P_o) (see Figure B1). The pressure difference ($\Delta P = P_o - P_i$) is caused warm air rising in buildings and by wind blowing over the outlets such as chimneys and roof vents. Typically, ΔP is very small, in the order of a few pascals.

Methods used to reduce radon levels are described briefly below. Methods used for houses with cellars and basements are also briefly described: to clarify, a cellar is an unoccupied area below a building, often used for storage; a basement is occupied and usually heated.

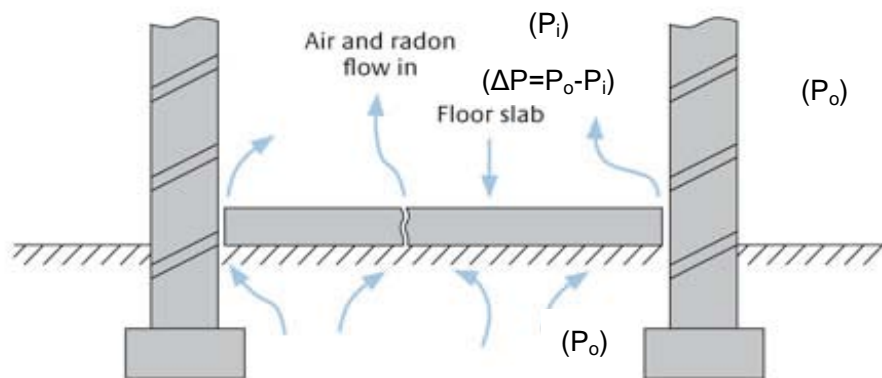


Figure B1: Diagram of airflow from the ground into buildings

B1 RADON SUMP

Sump systems (Scivyer et al, 1998a) are suitable for buildings with a concrete capping or an impermeable membrane over the soil. A passive sump is a space or void which is excavated under the concrete capping or a membrane, this is attached to an exit pipe. The end of the exit pipe is normally routed through the wall and up the side of the building to roof level. An active sump (Figure B1.1) is fitted with an in-line or other duct mounted centrifugal fan which can suck from or blow into the sump. In this case, the exit can be at a low level, ideally positioned away from openings such as doors and windows.

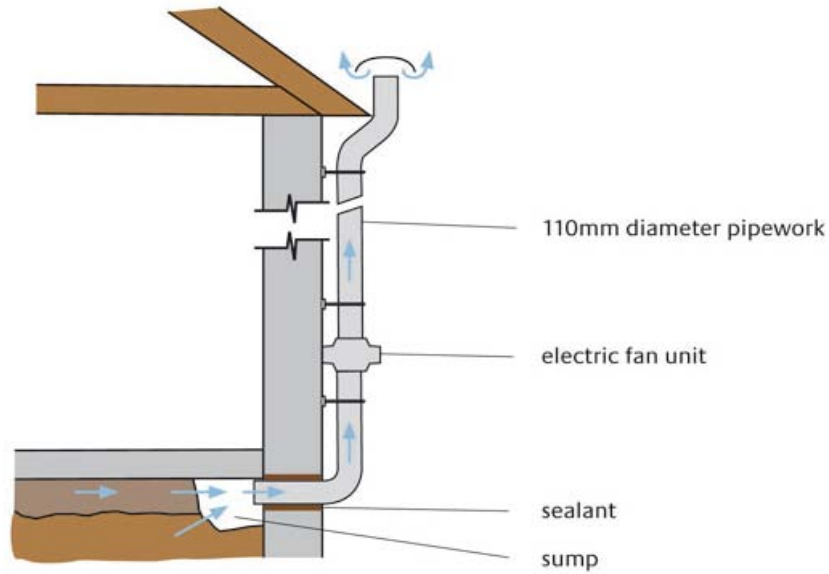


Figure B1.1: Diagram of a radon sump system

A fan sucking on the sump will reduce the pressure within the void and under the floor, provided this pressure (P_s) is less than the indoor pressure ($P_s < P_i$). The soil gas, contaminated with radon, is drawn preferentially through the under-floor material towards the sump void and is expelled to outside, see Figure B1.2. A typical radon sump under suction will extract radon in soil gas from a surrounding area of approximately 250 m² but can be effective up to distances of approximately 15 m from the sump, assuming no there are no obstructions. Sumps work most effectively where the fill beneath the slab is permeable (Scivyer, 1993).

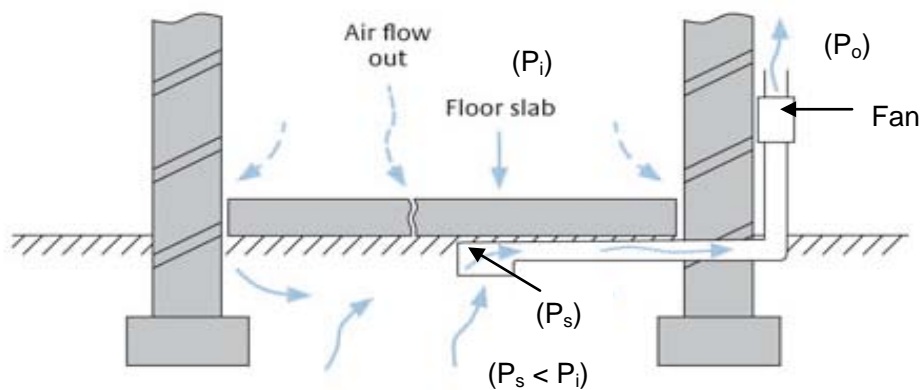


Figure B1.2 : The effect of a radon sump on airflow and radon

Alternatively, the fan can be reversed to blow fresh air into the sump creating a region of fresh air under the floor.

B2 POSITIVE VENTILATION OF LIVING SPACE

A positive ventilation unit, normally positioned in the roof space, uses a fan to blow filtered fresh air into a home. The air enters the house through a diffusing vent mounted in the ceiling of a central hallway or at the top of a stairway Figure B2.1. These units were originally designed to combat condensation problems in poorly ventilated houses.

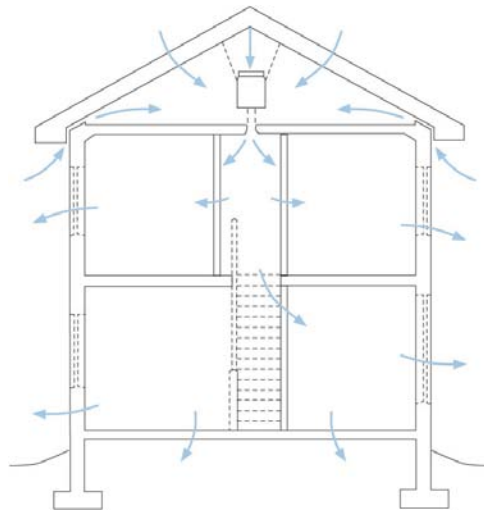


Figure B2.1 Diagram of Positive ventilation and air flow.

Positive ventilation reduces radon gas by one or both of the following processes. Firstly, radon is diluted by increasing the ventilation rate in the house. Secondly, if the house is particularly airtight, the pressure inside the building may be increased. This reduces the pressure difference between the house and the ground and consequently reduces the ingress of radon into the building. Pressures generated by these fans are small (typically 0.5 to 2 pascals) (Stephen, 1995). Radon reduction is obtained by a combined effect of these two processes, the extent of which depends on the air-tightness of the house.

B3 VENTILATION UNDER A SUSPENDED FLOOR

B3.1 Passive or natural under-floor ventilation

Buildings constructed with a suspended timber or concrete ground floor with a space or void underneath should be naturally well ventilated using air bricks, primarily to control moisture levels and prevent rot in timbers. Ideally, vents should be provided on at least two opposite outside walls and the opening should be at least 1500 mm^2 (Scivyer, 2007) for each metre run of wall. Typically vents, the size of a house brick, should be spaced every 1.5 – 2.0 m and not more than 450 mm from corners (Welsh and Pye, 1994). Figure B3.1.1 shows a diagram of the airflow under a suspended floor.

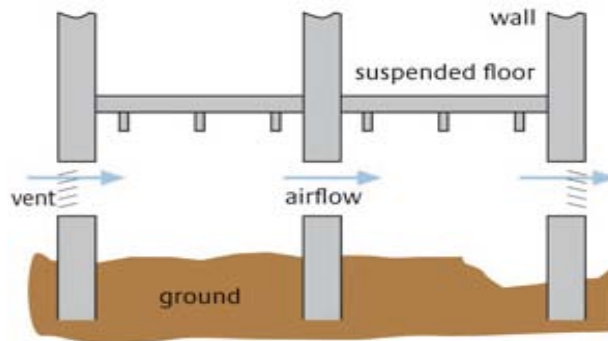


Figure B3.1.1 Airflow under a suspended floor

Increased ventilation of the under-floor space dilutes the radon concentration rising from the ground into the under-floor space. Consequently, less radon enters the building. Increased ventilation can be achieved by ensuring:

- existing under-floor vents are clear
- older 'terracotta' style under-floor vents are replaced with plastic air vents
- sufficient numbers of under-floor vents are incorporated into external walls, below the floor level
- under-floor vents should be spaced around the building to ensure a good cross flow of air

B3.2 Active under-floor ventilation

When natural under-floor ventilation does not reduce radon levels to acceptable levels, an electric fan can be installed to increase the air-flow under the floor. Fans can be installed to blow air into the under-floor space or extract air from it. Both supplying and extracting air can be successful, the success depends on many factors (Welsh and Pye, 1994). Figure B3.2.1 shows a cross section diagram of an under-floor fan.

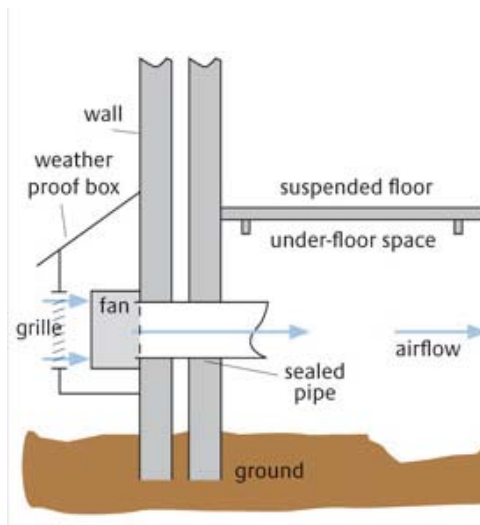


Figure B3.2.1 Active under-floor ventilation.

Active under-floor ventilation reduces radon levels by diluting the concentration of radon in the under-floor space. It should be noted that if the fan blows into the under-floor space service pipes, particularly central heating or water pipes, could be at risk through freezing and that draughts may be a problem inside the house. On the other hand, if suction is applied then the operation of open-flue combustion appliances may be affected (Scivyer, 2007).

B4 PASSIVE VENTILATION OF LIVING SPACE

Improvements to ventilation of the house (such as trickle ventilators) can reduce radon levels by diluting the concentration of radon in the building (Scivyer, 1993). Preferentially, the ventilators should be located on the lower floors of the house, to avoid increasing the “stack effect”, and be kept permanently open. However, some householders choose to keep these closed.

If the house has an open-flue chimney; an adequate air supply should be provided directly from outside to replace large volumes of air drawn through the chimney. The aim is to reduce the pressure differential between the inside and outside of the building. Alternatively, unused chimneys can be blocked. It should be noted that if chimneys are permanently blocked then action should be taken to prevent condensation from building up inside the chimney (Scivyer, 2007).

B5 SEALING FLOORS AND LOFT HATCHES

Sealing the floor seems to be an obvious method for reducing the entry of radon, but it is difficult to implement effectively (Pye, 1993). Completely sealing a suspended timber floor with a membrane is not recommended; this can cause timber rot problems if there is inadequate under-floor ventilation and consequently a build up of damp. However, sealing large gaps, such as those around service pipes entering the property through the floor, can reduce radon levels to a limited degree.

In some properties, floor vents link the under-floor space to the inside of the building. These vents usually provide ventilation for the under-floor space or to an open flue combustion appliance. Sealing these vents can reduce radon but alternative air supplies must be provided in their place.

Loft hatches can also be sealed to reduce bulk movement of air through the dwelling from the ground floor (stack effect) which in turn will reduce the negative pressure within the dwelling and hence reduce the accumulation of radon in the building.

B6 BASEMENTS

Radon sumps are used for houses with basements (usually occupied as a living area) and cellars (generally used as a storage area). Under certain conditions the sump can be located under the floor of the basement (Scivyer and Jaggs, 1998b).

Cellars can be positively ventilated using a fan to blow in fresh air. Radon in the cellar is diluted and ingress of radon from the ground can be reduced due to a possible increase in air pressure (Scivyer and Jaggs, 1998b). It is important that the doors to the main house have a good seal.

APPENDIX C Detailed results of remedial analysis

The results of the regression analysis are listed in Tables C1 to C7. These tables show the reduction factor as the relative effectiveness of the methods employed. The confidence interval (CI) indicates the range of values within which there is 95% chance that the true mean lies in the interval. The statistical significance of the results is indicated by the p-value. Confidence Intervals tend to be large when the sample size is small.

Table C1 shows the overall relative effectiveness of remediation methods employed. A brief discussion is given in the main text (Section 4.1.1).

Table C1 Distribution and performance of methods to reduce radon levels in homes

Remediation	Frequency	%	Reduction factor	95% confidence interval	
Active sump	771	29	6.0**	5.5	6.4
Passive (pipe inside house)	77	3	1.9**	1.5	2.4
Passive sump (pipe outside house)	131	5	1.8**	1.5	2.1
Positive ventilation	495	18	2.1**	1.9	2.3
Natural under-floor ventilation	636	24	1.7**	1.6	1.8
Active under-floor ventilation	128	5	2.2**	1.8	2.6
Active under-floor ventilation fan blowing	(24/128)	<1	2.1**	1.4	3.1
Active under-floor ventilation fan sucking	(70/128)	3	2.6**	2.0	3.3
Passive ventilation	259	10	1.3**	1.2	1.5
Sealing floors	185	7	1.3**	1.2	1.6
Sealing loft hatch	17	<1	1.2	0.74	1.9
Total	2700	100			

*p<0.05 **p<0.001

Table C2 shows the effect on remediation methods for detached, semi detached, mid-terraced houses and flats.

- Generally house type makes little difference to the reduction factors for each remedial type.
- In some cases there are wider variations in the reduction factor when the sample size is small, for example with passive sumps (pipe inside) in flats.
- The sample of flats is small and the floor level of each was not recorded. This may account for a large range in the CI.

Table C2 House type Effects

Remedial measure	House type – reduction factor (95% confidence intervals)			
	Detached	Semi-detached	Mid terraced	Flat
Frequency	1668	593	205	85
Active sump	5.9**(5.2-6.7)	6.4**(5.3-7.7)	4.8**(3.4-6.7)	6.1**(4.4-8.6)
Passive sump (pipe inside house)	1.8**(1.3-2.5)	1.8*(1.0-3.3)	2.7(0.94-7.6)	16.8*(1.6-174)
Passive sump (pipe outside house)	1.6**(1.3-2.0)	1.9**(1.4-2.7)	2.8*(1.5-5.2)	3.7*(1.4-10.0)
Positive ventilation	2.1**(2.0-2.3)	2.0**(1.7-2.3)	2.2**(1.7-2.8)	2.5**(1.5-4.3)
Natural under-floor ventilation	1.6**(1.5-1.7)	1.9**(1.7-2.2)	2.1**(1.7-2.7)	1.7(0.90-3.1)
Active under-floor ventilation	1.6*(1.1-2.3)	1.4(0.68-2.9)	1.7(0.68-4.1)	2.1(0.35-12.4)
Active under-floor ventilation fan blowing	2.3*(1.2-4.4)	1.0(0.34-3.0)	16.3*(1.4-185)	4.3(0.38-48)
Active under-floor ventilation fan sucking	2.7**(1.9-3.8)	1.9(0.96-3.6)	2.6*(1.1-6.2)	
Passive ventilation	1.3**(1.2-1.5)	1.3*(1.1-1.7)	1.3(0.91-1.9)	1.2(0.57-2.6)
Sealing floors	1.4**(1.2-1.6)	1.3(0.97-1.6)	1.3(0.85-1.9)	0.86(0.19-3.9)
Sealing loft hatch	1.2(0.86-1.6)	1.4(0.61-3.1)		

*p<0.05 **p<0.001

Table C3 shows the effect of the age of the home on the performance of remediation methods :

- Active sumps are more effective in newer houses. The reduction factors after 1993 are more variable, possibly due to the low sample size. Reduction factors increase from around 4 to 8 times from older (before 1900) to newer (up to 1992) properties.
- For all other remedial measures, the date of build makes little difference. In some cases there are wider variations on the reduction factor when the sample size is lower.

Table C3 Date built effects

Remedial measure	Date built – reduction factor (95% confidence intervals)							
	Before 1900	1900-1919	1920-1944	1945-1964	1965-1976	1977-1992	1993-2000	After 2000
Frequency	673	122	232	426	556	348	39	30
Active sump	3.8**(3.2-4.5)	4.2**(2.6-6.8)	4.9**(3.3-7.3)	6.8**(5.3-8.8)	8.1**(6.6-9.9)	8.3**(6.6-10.5)	15**(7.0-30)	5.4*(1.5-19)
Passive sump (pipe inside house)	1.9*(1.2-3.1)	1.8(0.44-7.3)	2.0(0.49-8.2)	1.8*(1.0-3.2)	1.5(0.71-3.1)	2.3*(1.1-4.8)		7.8(0.68-87)
Passive sump (pipe outside house)	1.4(0.98-2.0)	1.2(0.58-2.6)	1.2(0.60-2.5)	2.3**(1.4-3.8)	2.5**(1.7-3.8)	1.9*(1.2-3.1)	1.2(0.44-3.2)	5.1*(1.2-21)
Positive ventilation	1.8**(1.6-2.1)	2.5**(1.8-3.5)	2.4**(1.7-3.3)	2.2**(1.8-2.5)	2.4**(2.0-2.8)	2.0**(1.7-2.4)	2.2*(1.2-4.2)	0.95(0.32-2.8)
Natural under-floor ventilation	1.6**(1.3-1.8)	1.2(0.96-1.6)	1.5**(1.3-1.8)	1.7**(1.5-1.9)	1.8**(1.6-2.1)	1.8**(1.4-2.3)	2.8**(1.7-4.6)	1.9*(1.3-3.1)
Active under-floor ventilation	1.3(0.7-2.3)	2.4(0.98-6.1)	1.3(0.59-2.6)	1.3(0.52-3.3)	1.4(0.49-4.0)	2.4(0.65-8.6)		
Active under-floor ventilation fan blowing	1.8(0.7-4.5)	0.99(0.16-6.3)	1.3(0.28-5.8)	1.8(0.41-8.3)	2.2(0.5-10)	34*(2.5-450)		8.8(0.66-120)
Active under-floor ventilation fan sucking	2.1*(1.3-3.2)	4.3*(1.5-12)	3.0**(1.6-5.6)	2.1(0.85-4.9)	3.7(0.96-14)	3.3*(1.6-6.9)		
Passive ventilation	1.2(0.97-1.5)	0.92(0.49-1.7)	1.2(0.76-1.8)	1.7**(1.3-2.2)	1.4**(1.2-1.8)	1.2(0.89-1.6)	1.5(0.79-2.8)	1.1(0.56-2.0)
Sealing floors	1.2*(1.0-1.5)	1.2(0.71-1.2)	1.2(0.73-2.1)	1.4(0.89-2.2)	1.3*(1.1-1.7)	1.8**(1.3-2.5)	1.2(0.25-5.4)	0.86(0.29-2.5)
Sealing loft hatch	0.79(0.31-2.0)	1.6(0.64-3.9)	2.6(0.73-9.6)	0.95(0.45-2.0)	1.2(0.65-2.4)	1.2(0.58-2.6)		

*p<0.05 **p<0.001

Table C4a compares the reduction factors achieved by various remedial methods in single storey and multi-storey homes:

- Active sumps were about 1.4 times more effective in single storey properties than multi-storey properties.
- In single storey properties, passive sumps with the pipe outside were about 1.6 times more effective and with the pipe inside they were slightly more effective in multi-storey homes.
- Positive ventilation is 1.25 times more effective in single storey properties.
- The performance of other remedies, with statistically significant results, is largely unaffected by the home being single or multi-storey.

Table C4a Single storey and multi-storey effects

Remedial measure	Storey – reduction factor (95% confidence intervals)	
	Single	Multi-storey
Frequency	621	1048
Active sump	7.7**(6.4-9.4)	5.4**(4.7-6.3)
Passive sump (pipe inside house)	1.6(0.9-2.8)	2.1**(1.4-3.2)
Passive sump (pipe outside house)	2.8**(1.7-4.4)	1.8**(1.3-2.4)
Positive ventilation	2.5**(2.2-2.8)	2.0**(1.8-2.2)
Natural under-floor ventilation	1.8**(1.6-2.0)	1.8**(1.6-2.0)
Active under-floor ventilation	1.8(0.84-4.0)	1.5(0.92-2.6)
Active under-floor ventilation fan blowing	3.9(0.81-19)	1.9(0.88-4.0)
Active under-floor ventilation fan sucking	2.9*(1.5-5.5)	2.5**(1.6-3.8)
Passive ventilation	1.5*(1.1-1.9)	1.5**(1.2-1.7)
Sealing floors	1.7*(1.2-2.4)	1.4**(1.2-1.7)
Sealing loft hatch	1.8**(1.4-2.5)	0.90(0.66-1.3)

*p<0.05 **p<0.001

Table C4b shows the reduction factors by remedial method for homes with and without basements.

- Active sumps in homes without a basement are generally more effective than in homes with a basement. This may be explained in part because of the greater prevalence of basements in older homes and the correlation of active sump performance with newer homes.
- For other remediation methods, with statistically significant results, the presence of a basement either makes little difference to remedial performance

Table C4b Basement effects

Remedial measure	Reduction factor (95% confidence intervals)	
	Basement	No basement
Frequency	247	1711
Active sump	3.8**(2.8-5.2)	6.4**(5.6-7.1)
Passive sump (pipe inside house)	2.0(0.51-7.8)	2.1**(1.4-3.1)
Passive sump (pipe outside house)	1.3(0.31-5.3)	1.7**(1.4-2.1)
Positive ventilation	2.2**(1.5-3.0)	2.1**(1.9-2.2)
Natural under-floor ventilation	1.8**(1.5-2.1)	1.7**(1.5-1.8)
Active under-floor ventilation	1.7(0.94-3.1)	1.3(0.84-2.1)
Active under-floor ventilation fan blowing	1.8(0.91-3.6)	2.1*(1.0-4.3)
Active under-floor ventilation fan sucking	1.9*(1.2-3.1)	2.9**(2.1-4.3)
Passive ventilation	0.95(0.60-1.5)	1.3**(1.2-1.5)
Sealing floors	1.2(0.82-1.9)	1.3**(1.2-1.5)
Sealing loft hatch		1.2(0.88-1.7)

*p<0.05 **p<0.001

Table C5 shows the effects on remedial methods when a house has full, part or no double glazing: there is a small trend for most remedial measures to be more effective when there is more double glazing.

Table C5 Double glazing effects

Remedial measure	Amount of double glazing – reduction factor (95% confidence intervals)		
	Full	Part	None
Frequency	1763	408	368
Active sump	6.6**(5.8-7.3)	6.0**(4.7-7.6)	4.7**(3.7-6.0)
Passive sump (pipe inside house)	2.2**(1.6-3.2)	1.6(0.82-3.0)	1.4(0.72-2.8)
Passive sump (pipe outside house)	1.9**(1.5-2.3)	2.2*(1.3-3.7)	1.2(0.79-1.9)
Positive ventilation	2.3**(2.1-2.5)	1.9**(1.6-2.2)	1.8**(1.6-2.2)
Natural under-floor ventilation	1.8**(1.6-1.9)	1.6**(1.4-1.9)	1.4**(1.2-1.8)
Active under-floor ventilation	1.5*(1.2-2.1)	0.64(0.28-1.5)	5.3**(2.3-12)
Active under-floor ventilation fan blowing	2.2*(1.1-4.8)	1.8(0.58-5.9)	1.6(0.21-12)
Active under-floor ventilation fan sucking	3.2**(2.2-4.8)	2.3**(1.4-3.8)	2.0(0.93-4.2)
Passive ventilation	1.4**(1.2-1.6)	1.2(0.95-1.6)	1.1(0.82-1.53)
Sealing floors	1.4**(1.2-1.6)	1.3(0.97-1.6)	1.2(0.93-1.6)
Sealing loft hatch	1.2(0.89-1.7)	0.91(0.39-2.1)	

*p<0.05 **p<0.001

Table C6 shows the effectiveness of methods in houses with different floor types.

- For all floor types, active sumps are the most effective remedy.
- Active under-floor ventilation is more effective than natural under-floor ventilation for solid floors. Active under floor ventilation for basements (fan blowing) reduces levels by 7.5 times (reduction factor range: 1 to 50 times, probably due to small sample numbers).

- For other remedies, the floor type makes little difference.

Table C6 Effects of ground floor type for each type of remediation

Remedial measure	Ground floor type – reduction factor (95% confidence intervals)			
	All solid (direct onto solid earth)	All suspended over a small space	Mix of solid and suspended	Over a basement or cellar (floor type not known)
Frequency	1087	342	582	94
Active sump	6.3**(5.6-7.2)	7.1**(4.5-11)	4.0**(3.1-5.2)	3.6**(2.3-5.5)
Passive sump (pipe inside house)	2.3**(1.6-3.5)	0.70(0.06-8.5)	2.4(0.70-8.5)	0.95(0.08-12)
Passive sump (pipe outside house)	1.9**(1.5-2.4)	1.9(0.80-4.6)	1.2(0.72-2.1)	
Positive ventilation	2.2**(2.0-2.4)	2.0**(1.6-2.5)	1.9**(1.6-2.2)	3.3**(1.9-5.7)
Natural under-floor ventilation	1.4*(1.1-1.8)	1.7**(1.6-1.9)	1.7**(1.5-1.8)	2.1**(1.6-2.7)
Active under-floor ventilation	2.9*(1.2-6.8)	1.2(0.70-2.0)	1.6*(1.0-2.5)	
Active under-floor ventilation fan blowing	2.2(0.61-8.4)	2.9*(1.0-8.6)	1.3(0.58-3.1)	7.5*(1.2-48)
Active under-floor ventilation fan sucking		1.9*(1.1-3.2)	3.1**(2.1-4.4)	1.9(0.95-3.6)
Passive ventilation	1.3**(1.1-1.5)	1.9**(1.3-2.7)	1.2(0.90-1.6)	0.96(0.29-3.2)
Sealing floors	1.4**(1.2-1.6)	1.1(0.7-1.6)	0.97(0.74-1.3)	1.5(0.82-2.7)
Sealing loft hatch	1.2(0.79-1.8)		0.90(0.32-2.5)	

*p<0.05 **p<0.001

Table C7 shows the effectiveness of remediation methods with heating types

- Heating type has little effect on the effectiveness of all methods.
- Performance in homes with central heating is generally better when there is not an open fire.

Table C7 Effects of heating type

Remedial measure	Heating type – reduction factor (95% confidence intervals)		
	Central heating	Central heating with open fire	Open fire
Frequency	1289	938	83
Active sump	6.4**(5.7-7.5)	5.2**(4.4-6.2)	6.6**(3.9-11)
Passive sump (pipe inside house)	2.2**(1.4-3.5)	1.9*(1.2-3.2)	1.9(0.36-10)
Passive sump (pipe outside house)	2.0**(1.5-2.6)	1.4*(1.1-1.9)	1.3(0.18-9.4)
Positive ventilation	2.3**(2.1-2.5)	1.9**(1.7-2.1)	2.9**(2.0-4.1)
Natural under-floor ventilation	1.7**(1.6-1.8)	1.6**(1.5-1.8)	1.4(1.0-1.9)
Active under-floor ventilation	1.3(0.83-2.1)	1.7*(1.0-2.8)	
Active under-floor ventilation fan blowing	4.3**(2.0-9.5)	1.4(0.81-2.6)	
Active under-floor ventilation fan sucking	2.9**(2.0-4.1)	2.0*(1.3-3.2)	3.2(0.87-12)
Passive ventilation	1.3**(1.1-1.5)	1.2*(1.0-1.5)	1.3(0.72-2.3)
Sealing floors	1.5**(1.2-1.8)	1.2(0.98-1.4)	2.0*(1.0-3.9)
Sealing loft hatch	1.1(0.78-1.6)	1.3(0.84-2.1)	

*p<0.05 **p<0.001

APPENDIX D Probit plot

As expected, a range of reduction factors was observed in the study. To compare the likely reduction factor in different situations, it is useful to have a measure of the reduction factor that adequately represents the observed distribution. Where observed values fit a normal distribution, the arithmetic mean is an appropriate measure. For distributions that are more log-normally distributed, the geometric mean is a more appropriate measure.

The log-normal probit plot was used in order to assess whether the radon reduction factors (ratio of radon concentration before and after remediation) are approximately normally distributed (2,400 homes). Figure D1 shows a probit plot of radon reduction factors with a logarithmic scale on the Y axis. Using the data from the radon reduction factors, the probit can be calculated. The probit is the value of standard normal distribution which corresponds to the cumulative percentage of the radon reduction factors. The probit determined from this dataset is then plotted against the radon reduction factors. If the curve is linear then this indicates a log-normal distribution. This plot of reduction factors shows that there is deviation from linearity in the upper and lower tails of the distribution. These two upward curves suggest a mixture of two log-normal distributions. One explanation is that one remediation method has a much higher radon reduction factor than the other methods. Therefore, adding all the data together from different remediation methods, the data might not be expected to be normally distributed (Fig.2). Individual remedies plotted separately show log-normal distribution; our findings were similar to Naismith et al. 1998 (Naismith et al, 1998). For the purpose of this study, we can treat the plots as log-normal distributions and use the geometric mean as the characteristic measure.

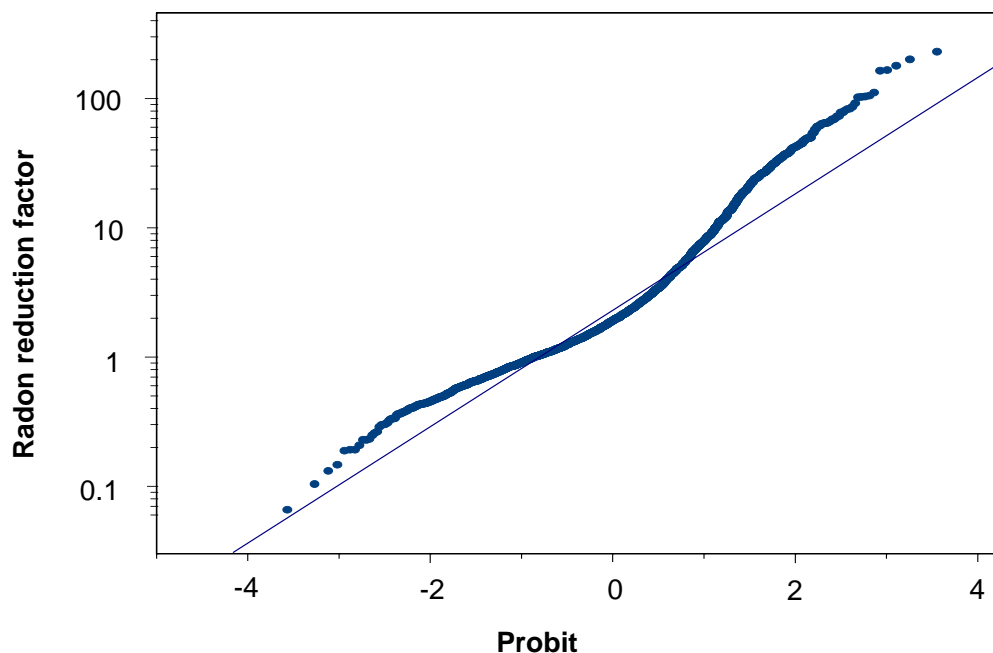


Figure D1: Normal probit plot of radon reduction factor for all remedies