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The Impact of Various Ventilation Remedies on Radon Levels and Local Building Environment in a UK Test House - Some Preliminary Results

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1.0 Summary

The Building Research Establishment is currently investigating the impact of various radon remedies at a radon affected test house. Tests aim to assess how different ventilation strategies affect indoor radon levels and the building environment. Those examined include natural underfloor ventilation, mechanical underfloor ventilation (supply and extract), and whole house pressurisation.

The test house has a suspended timber floor with an inaccessible underfloor space and is typical of much of the UK housing stock except for indoor radon levels regularly in excess of $1000Bqm^{-3}$. It is fitted with a comprehensive range of monitoring equipment which closely records important environmental parameters.

This paper presents some preliminary results including radon levels and whole house ventilation rates. Mechanical underfloor extract ventilation is shown to produce a 94% reduction in indoor radon levels, the greatest recorded. Mechanical underfloor supply ventilation causes the largest change in house ventilation rate with an approximate energy cost of £50 per year. These results, and future data, will allow for the assessment of remedies to be based on their total impact to the building rather than radon reduction alone.

2.0 Definitions

Airbrick: a purpose built vent in the external wall of an underfloor space to promote natural underfloor ventilation.

Underfloor space: the space beneath a suspended floor. In the US this is often referred to as a crawl-space. Underfloor spaces in the UK are usually inaccessible and poorly ventilated.

Underfloor extract ventilation: mechanical extract ventilation of the underfloor space. Air is discharged to outside.

Underfloor supply ventilation: mechanical supply ventilation of the underfloor space using outside air.

3.0 Introduction

Radon remedies for houses with inaccessible underfloor spaces often involve some form of underfloor or whole house ventilation [1]. Very large radon reductions have been achieved using these approaches [2] but in general they are not well demonstrated or well understood. In addition there are many concerns about possible side-effects such as the cost of changes in house ventilation rates, the risk of freezing to underfloor water pipes and the possibility of combustion products from combustion appliances spilling into living areas.

To help increase our understanding of radon remedies involving ventilation BRE (the Building Research Establishment) have purchased a radon affected house with a suspended timber floor. Controlled tests will help answer a number of important points allowing for a more informed choice of solution, based not only on radon reduction as is often the case.

4.0 The test house

The house is typical of much of the UK housing stock being semi-detached (internal volume of about 200 m^3) with a timber floor suspended about 0.35 m above the soil. It was built in the 1930's and has a slightly higher than typical UK leakage [3] of about 17.6 air changes at 50 Pa. Figure 1 shows a plan of the ground floor.

The tongue and grooved timber boards sit on timber joists which in turn, sit on a timber wall plate. Generally the floor is in good condition expect for a cupboard area where there are signs of advanced wood rot and large gaps between the floor boards. The living room, dining room and hall area are covered with carpet tiles which are taped in position. The kitchen has a poor linoleum finish. The area beneath the stairs is bare.

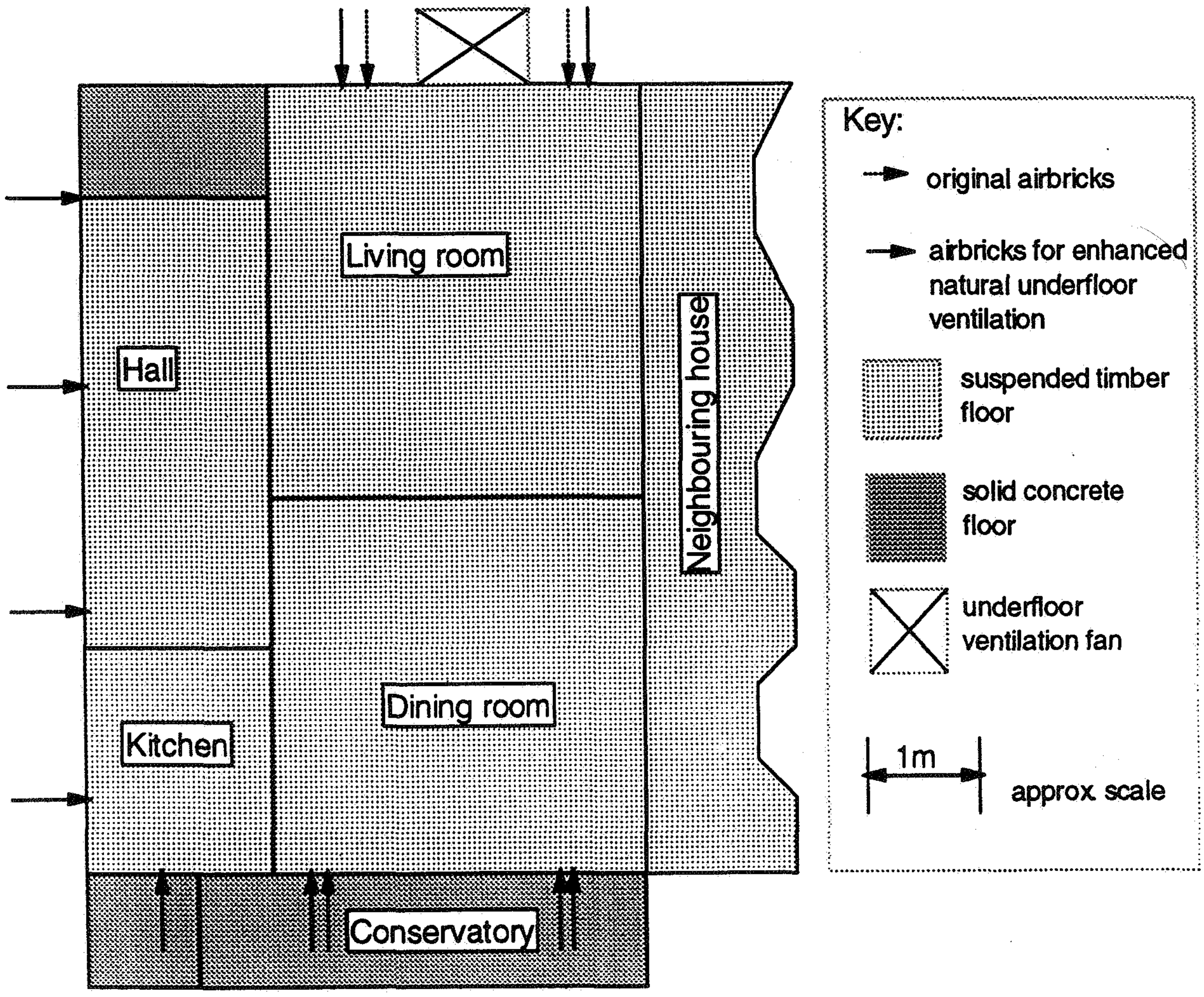

Figure 1: Ground floor plan of test house

The underfloor space is split into four sections by underfloor walls but cross ventilation is promoted through purpose built gaps. The underfloor volume is about 14 m^3. When purchased there were four airbricks, two at the front which were largely blocked, and two at the rear venting into the conservatory. The free area of these [4] is estimated to be about 10,000 mm^2.

During the heating season the temperature within the house is controlled using a gas central heating system on a timer and remote thermostatic radiator valves. Downstairs is at about 21 ^{0}C with upstairs being a couple of degrees cooler. A small humidifier maintains the living room relative humidity above 45%.

5.0 Monitoring equipment

Living room and living room underfloor radon levels are continuously monitored using 'Alphaguard' units. These units use a pulse ionisation chamber to monitor radon levels and have an accuracy of about ±7%.

A separate data-logger continuously monitors a number of environmental parameters. These include:

- 11 temperatures (4 underfloor, 4 ground floor, 1 bedroom, 1 loft and 1 external)
- 3 relative humidities (living room, living room underfloor, external)
- atmospheric pressure
- 4 floor pressure differences (each ground floor room)
- 4 room to outside pressure differences (each ground floor room)
- wind speed and wind direction

All but the wind direction are monitored every two minutes and half hourly averages are stored. The wind direction is monitored as a spot reading every half hour.

In addition to the above, timber moisture levels at eight locations are recorded manually before and after tests. Three locations are at the front of the living room, three at the rear of the dining room, and two beneath the stairs. For each location the moisture level is recorded for the joist top, joist bottom, and wall plate.

6.0 Radon remedies

The radon remedies installed in the house are discussed below.

6.1 Whole house pressurisation

A fan mounted in the loft space forces air from the loft, into the area at the top of the stairs. The fan has a maximum flow rate of about 180 m^3h^{-1}. It is claimed that these systems reduce radon levels by positively pressurising the house with respect to the soil. However field experience carried out by BRE has shown that the pressure changes are often very small, commonly being less than 1 Pa. This small amount of pressurisation indicates that the increase in house ventilation rate may be responsible for a significant proportion of any radon reduction.

6.2 Enhanced natural underfloor ventilation
Initially the underfloor space was poorly ventilated by four airbricks with a total free area of about 10,000 mm^2. To enhance the natural ventilation the number of airbricks was increased from four to nine, increasing the free area to about 41,000 mm^2. They are positioned on three walls (Fig. 1) and can be open or closed according to requirements.

Enhancement of the natural underfloor ventilation can reduce indoor radon levels by lowering the level of natural depressurisation and by dilution.

6.3 Mechanical underfloor ventilation
A fan at the front of the house (Fig. 1) is used to force the ventilation of the underfloor space. It is connected to a pipe which runs to beneath the centre of the living room. The inclusion of the pipe aims to increase the area of influence and helps prevent air short-circuiting the system by passing through any airbricks. The airbricks can be open or closed according to requirements. Opening them increases the underfloor ventilation and decreases any pressure effects. With the airbricks closed the converse is true.

The fan can be set to obtain the following flow rates: 430, 390, 195 and 75 m^{3}h^{-1}. Thus the underfloor air change rate can be varied from 5 to 30 per hour. This air change rate will not be uniformly distributed throughout the space because of the irregularity of the air flow paths and fan pressure distribution.

Extract ventilation draws air from beneath the floor and discharges it outside. It reduces indoor radon levels by two mechanisms namely dilution and changes in pressure differences. Dilution takes place as the extracted underfloor air is replaced by 'radon-free' air. The pressure effect reduces, or ideally reverses the floor pressure difference, which reduces the radon flow through the floor. These two beneficial responses are partially offset by an increase in the level of underfloor depressurisation which increases the pressure driven radon entry rate from the soil.

Supply ventilation blows air from outside to beneath the floor. The mechanisms responsible for the radon reduction are dilution together with pressurisation (which reduces the pressure driven radon entry rate from the soil). This reduction will be partially offset by an increase in the air flowing from the underfloor space to the rooms above.

7.0 Test details

7.1 Radon reduction study
Remedies are left running for a period of a least 25 days to obtain sufficient data for reliable assessment. During the test period all internal doors are left open and all external windows and doors are closed. The house is left undisturbed.

To date five different scenarios have been closely monitored. The first is with the house 'as purchased' without any remedy and with poor natural underfloor ventilation. Second is the whole house pressurisation system operating on the house in the 'as purchased' condition. This was followed by enhanced natural underfloor ventilation. The final two tests were on underfloor extract and supply ventilation. For both of these the fan was set to full speed and all of the airbricks from the enhanced natural ventilation were left open.

Radon reductions caused by the different remedies are directly compared to each other. However since the tests are held at different times of the year any seasonal variations in radon levels will be superimposed on the results. To assess the level of seasonal variation, remedies will be tested twice at different times of the year. To date this has only been performed for enhanced natural underfloor ventilation.

7.2 Impact of remedies on ventilation rate

Ventilation tests were held separately to the testing mentioned above. A gas analyser and injection system continuously monitored the fresh air change rate of the whole house by injecting a tracer gas, Sulphur Hexafloride, to two downstairs areas and two areas upstairs at such a rate as to maintain a constant concentration of 10ppm. The gas concentration was monitored at six different locations and a number of fans were used to ensure adequate mixing throughout the house.

To investigate the impact of the different remedies on the whole house ventilation rate each remedy is cycled on for two hours then off for two. Provided that the weather between the on and off periods is similar, a direct comparison of the ventilation rates can be made. The remedies investigated are listed in Table 2 of the results section 8.2.

8.0 Results

The following sections detail some of the results as recorded for each remedy. Details are given on radon levels and whole house ventilation changes. The results given are discussed very briefly.

8.1 Variation of radon levels

Table 1 summarises the radon results. The percentage radon reductions relate either to the 'as purchased' results or the 'enhanced natural underfloor ventilation' results depending on the condition the house was in before the remedy was used.

Initial tests in the 'as purchased' condition show that the radon level above the floor is roughly half that below. Thus, assuming the radon levels are representative of the average level of the whole space in which the measurements are taken, and that the underfloor space is the only radon source, half of the house ventilation air comes via the underfloor space. The level above the floor varies in a similar fashion to the levels below the floor, highlighting the underfloor space as a major radon entry route. During this test the average ground floor pressure difference is about -0.3 Pa, indicating an upwards flow (the pressure difference transducer takes the underfloor pressure from the room pressure). It ranges from 0.0 to -1.0 Pa and is similar for each room.

On average the whole house pressurisation system reduced the indoor radon level by 52%, however it was below the UK Action level (200 Bqm^{-3}) for 20% of the time, most of which was over one period. This emphasises the importance of long term monitoring. The floor pressure difference was reduced to an average of between -0.1 and -0.2 Pa. Thus air stills flows upwards through the floor but in reduced quantity. Assuming that this flow is proportional to the root of the pressure difference [4], this remedy reduces the upwards flow by about 30%.

Remedy type	Period of test	Location	Rn Average (Bqm^{-3})	Rn Range (Bqm^{-3})	Indoor Rn reduction
House as purchased (no remedy and poor underfloor ventilation)	24 May - 25 Aug 1994	living room	1,600	110 - 6,020	-
		underfloor	3,210	650 - 10,110	-
Whole house pressurisation (with poor underfloor ventilation)	22 Oct - 21 Nov 1994	living room	770	50 - 2,450	52%
		underfloor	unavailable	unavailable	-
Enhanced natural underfloor ventilation (nine airbricks open)	23 Dec 1994 - 30 Jan 1995	living room	1,130	97 - 3,540	29%
		underfloor	2,250	250 - 11,000	-
	8 Apr - 16 May 1995	living room	1,096	74 - 3,632	32%
		underfloor	2,030	426 - 11,392	-
Underfloor extract ventilation (fan on full and nine airbricks open)	1 Feb - 26 Feb 1995	living room	66	12 - 380	94%
		underfloor	2,570	1,300 - 5,890	-
Underfloor supply ventilation (fan on full and nine airbricks open)	1 Mar - 26 Mar 1995	living room	170	25 - 1,300	85%
		underfloor	140	45 - 680	-

Table 1: Radon statistics and reductions

The two tests with enhanced natural underfloor ventilation indicate little seasonal variation between the monitoring periods. This remedy reduced indoor radon levels by about 30%. Again the level above the floor is roughly half that below which, by the same assumptions as before, indicates that half of the house ventilation air comes via the underfloor space. The floor pressure differences average to about -0.9 Pa indicating an increase in air flow through the floor. This is to be expected as air can move freely through the airbricks to feed the stack effect, reducing the natural level of underfloor depressurisation. With the same assumption as before this increase in pressure difference represents an increase in flow of about 70%, representing an increase in house ventilation rate of 70%.

Underfloor extract ventilation reduces indoor radon levels to an average of 66 Bqm^{-3}, a reduction of 94%. The floor pressure difference in the living room averages to about +0.4 Pa, indicating that on average, air flows downwards through the floor eliminating pressure driven radon entry. For the areas further from the fan the floor pressures range between -0.2 and -0.3 Pa, indicating an upwards air flow. Thus the fan does not depressurise the whole underfloor area with respect to the rooms above. Rather it causes a pressure gradient which diminishes with the distance from the fan because of the underfloor walls and gaps in the floor.

Extract ventilation gives a high radon level beneath the floor due to the depressurising effect of the fan which increases the pressure driven soil gas flow into the underfloor space. As the underfloor level is similar to that with enhanced natural ventilation any increased dilution of the underfloor radon caused by the fan, appears to be offset by the increase in soil gas entry. This suggests that the floor pressure difference is the main radon reduction mechanism. Assuming the exhaust concentration to be similar to that measured in the void (2570 Bqm^{-3}) the possibility of exhaust air entering into living areas is a worry . However, provided the exhaust is sited away from windows and doors this should not prove a problem.

Underfloor supply ventilation reduces indoor levels by 85%, to 170 Bqm^{-3}, and underfloor levels to 140 Bqm^{-3}. The low underfloor level reflects the fact that outside air is supplied directly beneath the living room where the radon is measured. The floor pressures vary between -1.4 and -2.3 Pa with the largest difference being across the living room floor which is closest to the fan. These pressures show an increase in upwards air flow through the floor.

Assuming the underfloor space is the only radon source for the test house, the lower level in the living room underfloor space indicates the living room is being contaminated via routes other than through the living room floor. It is suggested that the radon levels in the underfloor areas far from the fan are higher than those close to the fan, causing a radon gradient within the ground floor rooms. Of these the living room is the lowest and thus susceptible to room to room cross-contamination. Alternatively radon may be travelling through the cavity walls or via some other convoluted route.

8.2 Changes in whole house ventilation rate

The various remedies investigated for their impact on whole house ventilation rates are listed in Table 2. Any remedy using mechanical ventilation has the fan set on maximum flow rate.

The tests are split into two categories according to the condition of the nine airbricks used for 'enhanced natural underfloor ventilation'. The table shows the impact of the remedy as a percentage change in air change rate per hour. In addition the average air changes are given for the conditions with remedy on and remedy off. All differences are highly significant at the 99% level.

Condition of airbricks (from 'enhanced natural underfloor ventilation')	**Remedy cycled on and off**	**Average air change rate (h^{-1}) with remedy..**		**change in air change rate (h^{-1}) caused by remedy**
		OFF	**ON**	
Airbricks closed	Airbricks open	0.84	0.96	+14%
	Whole house pressurisation	0.75	1.09	+45%
	Underfloor extract ventilation	1.02	1.30	+27%
	Underfloor supply ventilation	0.76	1.24	+62%
Airbricks open	Whole house pressurisation	1.14	1.46	+29%
	Underfloor extract ventilation (test 1)	1.43	1.31	-8%
	Underfloor extract ventilation (test 2)	1.04	0.97	-7%
	Underfloor supply ventilation	1.04	1.29	+24%

Table 2: Remedies tested for impact on house ventilation rate

Enhancing natural underfloor ventilation is seen to increase the house ventilation rate by about 14%; a much smaller figure than that predicted in section 8.1. This may indicate that the radon measurements in the house do not facilitate ventilation predictions. For example the radon measurement taken under the living room may not truly reflect the whole underfloor average, which is possible if the radon entry across the soil area is irregular and there is poor underfloor mixing. Alternatively it may indicate the difficulty in measuring very small pressures such as those across the floor. According to the manufacturers literature the error in this measurement should be less than ± 0.2 Pa, but this is still considerable when the pressures differences are often less than 1 Pa.

The changes in air change rates for remedies using fans are, as expected, significantly higher with the airbricks closed. Extract ventilation with airbricks open actually decreases the ventilation rate, probably as it competes against the natural upwards flow of house air. All other remedies and airbrick combinations cause an increase of between 24% and 62%.

The measured ventilation changes can be used to estimate a ventilation energy cost for each strategy. To do this a number of assumptions are made to keep the analysis simple. These include:

- whole house air change rate of 1.0 per hour (with remedy off)
- average outside temperature of 7 °C during the heating season
- average indoor temperature of 20 °C
- heating on for 6 hours a day, October to April inclusive
- thermal storage effects ignored
- 100% efficient heating system
- cost of fuel £0.07 per kWh

For the worst case scenario experienced with the test house these assumptions lead to a ventilation energy cost of about £50 per year, which is comparable to the cost of running a 75 W fan all year round.

9.0 Conclusions

This short report demonstrates the abilities of different ventilation strategies with regards to reductions in indoor radon levels.

The underfloor extract system proves to be the most effective, producing a 94% reduction getting indoor levels down to 66 Bqm^{-3}. The levels beneath the floor averaged to 2570 Bqm^{-3} presenting a small risk should any of the exhaust air find its way back into the house. The high level beneath the floor and low level above indicates that the floor pressure difference is the crucial radon reduction mechanism. Any increase in underfloor ventilation, causing dilution of the underfloor radon, appears to be offset by an increase in radon entry rate due to the level of underfloor depressurisation. Floor pressure data show that the fan does not manage to depressurise the whole underfloor space with respect to the rooms above. It does manage to reverse the floor air flow in the living room (directly above the fan) but not for any other areas.

Underfloor supply ventilation is seen to produce a reduction of 85%, indoor levels falling to an average of 170 Bqm^{-3}. As with extract ventilation, pressure readings show that the fan produces a floor pressure gradient which diminishes with the distance from the fan. Floor pressures indicate an increase in upwards air flow through the floor.

Although only the above two remedies 'solved' the radon problem (ie. reduced the indoor level below the UK Action level of 200 Bqm^{-3}) the others tested did reduce indoor radon figures. Enhanced natural underfloor ventilation gave a 30% reduction and the whole house pressurisation system achieved 52%. These reductions are considerable and the reason for them not solving the house only reflects the very high indoor radon concentrations initially associated with the house.

A large level of fluctuation in indoor radon levels is demonstrated reinforcing the philosophy of long term measurements if an accurate yearly average is to be obtained. For example a one week monitor during the whole house pressurisation test could have obtained the result 221 Bqm^{-3} when in fact the monthly average gave 770 Bqm^{-3}.

Using the radon levels as a tracer gas technique for assessing the amount of house ventilation coming through the underfloor space gave some interesting results. For both poor and enhanced natural underfloor ventilation, the radon level above the floor was half that below it, indicating that about 50% of the house ventilation air comes through the floor (with certain assumptions as given in section 8.1). Floor pressure differences suggested that by enhancing the natural underfloor ventilation, the flow through the floor increased by about 70%, representing a 70% whole house ventilation increase. However results from whole house tracer gas experiments disagree with this figure, indicating an increase of only 14%. This discrepancy is probably due to the difficulty in monitoring very small pressures. In addition any differences in the weather conditions during the different tests will be superimposed over the results.

The brief analysis of the changes in house ventilation rate caused by the various remedies show that the likely ventilation energy cost should be no more than about £50 per year. Mechanical supply ventilation increased the house air change rate by 62% when the airbricks were closed, which represents the largest individual change. All of the mechanical remedies (those with fans) cause larger changes in ventilation rates when the airbricks are sealed compared to when they are open. The measured increase in house ventilation rate caused by enhanced natural ventilation was much smaller than that predicted by the floor pressure measurements.

10.0 References

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