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# REDUCING INDOOR RADON LEVELS IN A UK TEST HOUSE USING DIFFERENT VENTILATION STRATEGIES

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## ABSTRACT

This paper reports on some of the most recent tests involving a number of studies in an unoccupied radon test house. The house has a suspended timber floor and naturally elevated indoor radon levels, peaking at times above 6000 Bqm$^{-3}$. Various sensors monitor how different ventilation strategies affect indoor radon levels and the building environment. Data from five different scenarios is presented. Initially the house was monitored as purchased with poor natural underfloor ventilation. This was followed by testing whole house pressurisation, improved natural underfloor ventilation, and two types of mechanical underfloor ventilation.

The results from these and future studies may be used to make a more informed choice of remedy, based on a whole number of aspects, not only radon reduction as is frequently the case.

## DEFINITIONS

To assist the reader it is necessary to explain some of the terms used in this paper.

*Airbrick*: a purpose built vent positioned in the external wall of an underfloor space to promote air movement.

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

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

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

*Spillage*: the flow of combustion gases *into the room* in which the combustion appliance is sited. This only occurs for combustion appliances which are naturally ventilated by room air. Spillage is often referred to as 'back-draughting'.

## INTRODUCTION

The Building Research Establishment have been conducting research into radon remedies over the past ten years or so. This has led to the publication of a comprehensive range of practical guidance reports detailing the various types of radon remedies and protection methods for new constructions. The guidance offered deals with most types of UK construction including the two most common: dwellings with solid floors and dwellings with suspended timber floors.

BRE research and similar work demonstrates that the present remedies for dwellings with solid floors (in particular active sump systems) are very effective. However treatments for dwellings with inaccessible underfloor spaces [1] are demonstrated to a far lesser degree, with large variations in results [2,3].

Remedies for houses with suspended floors often involve some form of underfloor ventilation or house ventilation [1,2,3]. In addition to their poor demonstration there are also some concerns with regards to the side-effects of different ventilation strategies. These are numerous and are very dependant on the type of ventilation remedy. Those of immediate interest include: the risk of spillage of combustion gases from open-flued combustion appliances due to local depressurisation[4,5], the energy penalty due to changes in house ventilation rates, the risk of freezing exposed underfloor pipes and the moisture threat to the floor timbers.

In the UK the majority of the housing stock have either all, or part of the ground floor constructed from suspended timber. A vast number of these have shallow underfloor spaces. Although in theory the naturally ventilated space should provide some radon protection, in the UK such houses are found with very high indoor radon concentrations. Possible reasons for this include poor underfloor ventilation and the multitude of radon entry paths provided by suspended timber floors. In most instances the open area provided by a timber floor will be much greater than that associated with a solid concrete floor. Therefore, in dwellings with both solid and suspended floors the suspended area is often highlighted as the main radon entry route.

To help provide accurate and useful advice to the occupants of affected dwellings, BRE purchased a radon affected house for test purposes. Equipment in the house closely monitors radon levels, temperatures, pressure differences and other key environmental data. Five different scenarios have been examined so far. Initially the house was tested for a three month period in the condition 'as purchased', with poor underfloor ventilation. Studies then tested whole house pressurisation, increased natural underfloor ventilation, underfloor extract ventilation and underfloor supply ventilation.

This paper reports on the experimental detail of the house and some of the preliminary findings. Data reported for the various remedies include radon levels, floor pressure differences, underfloor temperatures and finally the moisture levels of the floor timbers.

## THE TEST HOUSE

Built in the 1930's the house is typical of much of the UK housing stock. It is semi-detached, has three bedrooms and external dimensions of approximately 5 m × 8 m × 5 m (width × length × height). The whole ground floor is constructed from timber, suspended about 0.35 m above the soil. The timber floor boards are tongue and grooved and are supported by timber joists. The joists sit on a timber wall plate. The floor is covered by carpet tiles in all areas except the kitchen, which has a linoleum finish, and the cupboard under the stairs which is bare. The floor beneath the stairs shows advanced stages of wood rot with large gaps in places.

The underfloor space is inaccessible and is split into four sections by load bearing sleeper walls. However, air is free to move between the sections through purpose built gaps ie the walls are 'honey-combed'. The wall adjoining the neighbouring underfloor area is also honey-combed. Initially the underfloor space was poorly ventilated by four airbricks (Fig. 1); two at the front of the property being largely covered by soil, and two at the rear venting into the conservatory. The underfloor volume is about 14 $m^3$.

A blower door test conducted at pressurisation then depressurisation gave an average air change rate of 17.6 per hour at 50 Pa. This is a typical UK leakage [6]. The house is exposed to the prevailing wind which blows onto the conservatory wall, but all other walls are less exposed being sheltered from nearby houses.

Gas central heating is controlled using a timer to simulate a typical heating pattern. It comes on during the heating season between 6.00 - 8.30 and 17.00 - 21.30 hours. The radiators are controlled by remote thermostatic radiator valves which maintain the ground floor temperatures at about 21 °C and upstairs areas at about 19 °C.

To prevent the house from drying-out a humidifier maintains the living room relative humidity above 45%. The humidifier is located in the dining room and is controlled by two remote humidistats, one in the living room the other in the dining room.

Initial radon monitoring during the previous occupation indicated radon levels well in excess of the UK Action level of 200 $Bqm^{-3}$.

## MONITORING EQUIPMENT

Radon levels in the living room and living room underfloor space are monitored continuously using 'Alphaguard' radon monitors (accurate to about ±7%). These are set with a one hour integration period which means hourly averages are stored. Alphaguards monitor radon using a pulse ionisation chamber.

A data-logger monitors a number of parameters which are detailed below. All parameters (except the wind direction) are measured every two minutes and half hourly averages are stored. The wind direction is recorded as a spot reading every 30 minutes.

Room temperatures are measured in all rooms downstairs and the front bedroom using thermistors. Temperatures are also monitored in the four underfloor areas (beneath each of the ground floor rooms), in the loft, and outside in a Stevenson screen. The error in the temperature measurement is less than ±0.5 °C.

The relative humidity is monitored in the living room, living room underfloor space and outside in the Stevenson screen. These probes are accurate to better than ±5% and have a long-term stability of ±1% per year.

Atmospheric pressure is monitored outside in the Stevenson screen to an accuracy of about ±1 mbar. The wind speed and wind direction are monitored above a garage which is located at the rear of the house. This is not ideal as the local environment does influence the wind at this location. However by cross-checking the recorded data with data from a local weather centre the wind direction is shown to be reliable. The wind speed is reliable for winds blowing towards the conservatory face of the house (the prevailing direction) but not so reliable for the other directions.

Pressure differences are measured across the floor of each ground floor room using a differential pressure transducer. The pressure difference is taken as the room pressure less the underfloor pressure. Each pressure difference is the average of four underfloor locations and four room locations. Room to outside pressure differences are recorded again for each ground floor room as the room pressure less the external pressure. The external pressure is taken at a single location, measured at the rear of the house.

Moisture levels in the timber floor joists are monitored at 8 different locations. Three are at the front of the living room, three at the rear of the dining room, with the remaining two beneath the stairs. For each location the moisture level is recorded for the joist top, joist bottom and wall plate. Moisture readings are taken at the very start and end of a test.

## RADON REMEDIES

The radon remedies installed in the house are discussed below.

### 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.

Enhanced natural underfloor ventilation

Initially the underfloor space was poorly ventilated by four airbricks with an equivalent free open area [7] of about 10,000 $mm^2$. To enhance the natural ventilation the number of airbricks was increased from four to nine, increasing the equivalent free open 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 ventilation can reduce indoor radon levels by lowering the level of natural depressurisation and by dilution.

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 moves the position of air movement from the building perimeter to a more central location. This 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 $m^3h^{-1}$. Thus the 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 the pressure distribution diminishing with the distance from the fan.

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 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.

## TEST DETAILS

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.

## RESULTS OF LONG TERM TESTS

The following sections detail some of the results as recorded for each remedy. Details are given on radon levels, floor pressure differences, underfloor temperatures and timber moisture levels of the joists. The results given are briefly discussed.

### Variation of radon levels

The radon results of long term testing are summarised in Table 1. It shows the test dates, living room and living room underfloor radon levels, and percentage reduction of indoor radon levels. The percentage reductions are related to either the 'as purchased' readings (house with poor natural underfloor ventilation) or the 'enhanced natural underfloor ventilation' depending on whether the test was conducted with the nine airbricks open or closed.

Monitoring the house for 3 months in the 'as purchased' condition showed that the variations in the living room radon levels follow those beneath the floor (Fig. 2). The radon levels below the floor are generally twice those above.

Assuming that the underfloor space acts as the only radon source for the house, and that the radon measurements reflect true averages of the whole spaces in which they are sited, the points above indicate that more than 50% of the house ventilation air comes though the floor.

The whole house pressurisation system reduced indoor radon levels by 52%. During this test indoor radon levels were observed to be below the UK Action level of 200 Bqm$^{-3}$ for 20% of the time, most of which was continuous. Unfortunately the underfloor radon data is not available for this period.

| **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

Two tests have been conducted with enhanced natural underfloor ventilation. They were held at different times of the year but the results are very similar indicating that any seasonal variation between the two periods is small. Again the underfloor radon level is roughly twice the living room level showing (by the same assumptions as before) that more than 50% of the house ventilation air comes through the floor. The variations beneath the floor are mimicked by similar changes in the level above the floor. The increase in natural underfloor ventilation reduced the indoor radon level by about 30%, compared to the 'as purchased' levels. This is low compared to the common reduction of 50% [2,3], especially given the large increase in airbrick open area.

Underfloor extract ventilation (with nine airbricks open) is shown to be most effective at reducing indoor radon levels, producing a 94% reduction (relative to the results from 'enhanced natural underfloor ventilation', 23/12/94 to 30/1/95). Levels beneath the floor are high in comparison, as would be expected from underfloor depressurisation, but the average is similar to that for enhanced natural underfloor ventilation. This indicates that any increase in radon levels due to underfloor depressurisation is offset by dilution.

Underfloor supply ventilation provides a reduction of 85% (relative to 'enhanced natural underfloor ventilation', 23/12/94 to 30/1/95). The level beneath the floor is very low compared to all other tests, which is to be expected with the introduction of outside air direct to the underfloor space. The living room radon level is higher than that underfloor suggesting that the living room is being contaminated via a route other than the living room underfloor space. It is shown later that the underfloor fan causes a pressure gradient which diminishes with distance from the fan. This will cause a radon gradient beneath the house; low levels are expected close to the fan with higher levels in areas further away. This, in turn, leads to different room levels, with the living room being the lowest. Thus room-to-room contamination will take place as air within the house mixes. Alternatively radon may be entering the living room via an entirely different route such as through the cavity walls.

### Variation of floor pressure differences

For the majority of dwellings the floor pressure difference is of significant interest; this is what drives the majority of radon into the house. Floor pressure differences are influenced by a range of effects including temperature differences (stack effects), wind induced pressures, floor tightness, free open area of the airbricks, underfloor ventilation strategy, etc.

Table 2 summarises the average floor pressure differences together with the standard deviation and range of values experienced during the different tests.

In the 'as purchased' condition the floor pressure difference is consistently negative, averaging -0.3 Pa (ie air flows upwards through the floor). The pressure does fluctuate slightly but remains between -1.1 and 0.0 Pa and is very similar for each room.

The whole house pressurisation unit reduces the average difference to between -0.2 and -0.1 Pa ie the upwards flow through the floor is reduced but not reversed. This is a small but significant difference. The pressure differences for this system are more stable than the 'as purchased' condition and are similar for the various rooms. Assuming that the flow across the floor is proportional to the root of the pressure difference, the whole house pressurisation system reduces the original flow by about 30%.

The addition of extra airbricks increases the negative floor pressure difference to an average of about -0.9 Pa and it remains negative at all times. By the same assumption as above, this indicates an increase in the upwards flow through the floor of more than 70% (compared to the 'as purchased' data). The pressure differences are observed to vary to a larger extent which is to be expected as the underfloor space is coupled more to the exterior. However they are similar for each room.

| **Remedy type** | **Period of test** | **Floor pressure difference measurement (Pa) (relative to room)** | | | |
|---|---|---|---|---|---|
| | | **living room** | **dining room** | **kitchen** | **hall** |
| *House as purchased (no remedy and poor underfloor ventilation)* | 24 May - 25 Aug 1994 | **-0.3** *<br>0.14 **<br>*-1.1 to 0.0*<br>*** | **-0.3**<br>0.14<br>*-1.1 to 0.0* | **-0.3**<br>0.14<br>*-1.0 to 0.0* | **-0.3**<br>0.13<br>*-1.0 to 0.0* |
| *Whole house pressurisation (with poor underfloor ventilation)* | 22 Oct - 21 Nov 1994 | **-0.2**<br>0.08<br>*-0.6 to 0.0* | **-0.2**<br>0.08<br>*-0.5 to 0.0* | **-0.1**<br>0.07<br>*-0.4 to 0.0* | **-0.1**<br>0.07<br>*-0.5 to 0.0* |
| *Enhanced natural underfloor ventilation (nine airbricks open)* | 23 Dec 1994 - 30 Jan 1995 | **-1.0**<br>0.23<br>*-2.4 to -0.5* | **-0.9**<br>0.23<br>*-2.0 to -0.4* | **-0.9**<br>0.23<br>*-1.8 to -0.3* | **-0.9**<br>0.22<br>*-2.0 to -0.4* |
| *Underfloor extract ventilation (fan on full and nine airbricks open)* | 1 Feb - 26 Feb 1995 | **+0.4**<br>0.16<br>*-0.2 to +0.9* | **-0.2**<br>0.19<br>*-1.0 to +0.2* | **-0.3**<br>0.19<br>*-1.3 to +0.2* | **-0.2**<br>0.17<br>*-0.9 to +0.2* |
| *Underfloor supply ventilation (fan on full and nine airbricks open)* | 1 Mar - 26 Mar 1995 | **-2.3**<br>0.38<br>*-4.2 to -1.6* | **-1.6**<br>0.45<br>*-4.1 to -0. 9* | **-1.4**<br>0.39<br>*-3.7 to -0.7* | **-1.4**<br>0.38<br>*-3.7 to -0.8* |
| * AVERAGE ** STANDARD DEVIATION *** *RANGE OF VALUES* (±0.05 Pa) | | | | | |

Table 2: Floor pressure statistics

The floor pressure differences for underfloor extract ventilation vary depending on the room location and its position relative to the fan. For the living room floor, the pressure difference is positive ie the fan is successfully depressurising the living room underfloor space with respect to the living room. This means that on average the air flows from the living room to the underfloor space, eliminating pressure driven radon flow. The pressure differences elsewhere have negative averages although positive values do occur at times. Thus, on average, the fan does not manage to depressurise the whole underfloor space; it causes a pressure gradient which diminishes with the distance from the fan.

With underfloor supply ventilation the pressure differences become more negative, indicating a greater flow upwards through the floor. Again the greatest effect is seen beneath the living room, close to the fan. The pressure fluctuations with this remedy are the greatest of all those tested, lying between -4.2 and -0.7 Pa.

Dependence of living room underfloor temperature on external temperature

A plot of the living room underfloor temperature against external temperature gives a quick appreciation of any relationship between the two. Linear regression has been performed on the raw data from the various tests, providing a relationship in equation form (Table 3). A t-test performed on the correlation coefficient (R) shows that all of the relationships are highly significant at the 99% level.

The relationships indicate that the living room underfloor temperature is dependent on the external temperature, regardless of remedy. The coefficient of proportionality varies considerably depending on the degree of coupling between the underfloor air and the external air. It is greatest with supply ventilation and least with whole house pressurisation.

| **Remedy type** | **Relationship** | **$R^2$** |
|---|---|---|
| *House as purchased (no remedy and poor underfloor ventilation)* | $T_{uf} = 0.24\ T_{ext} + 15.6$ | 0.62 |
| *Whole house pressurisation (with poor underfloor ventilation)* | $T_{uf} = 0.18\ T_{ext} + 12.8$ | 0.39 |
| *Enhanced natural underfloor ventilation (nine airbricks open)* | $T_{uf} = 0.42\ T_{ext} + 7.1$ | 0.80 |
| *Underfloor extract ventilation (fan on full and nine airbricks open)* | $T_{uf} = 0.27\ T_{ext} + 9.6$ | 0.49 |
| *Underfloor supply ventilation (fan on full and nine airbricks open)* | $T_{uf} = 0.68\ T_{ext} + 3.8$ | 0.94 |
| $T_{uf}$ - living room underfloor temperature $T_{ext}$ - external temperature $R^2$ - square of the correlation coefficient | | |

Table 3: Relating living room underfloor temperature to external temperature

Of all the remedies so far tested underfloor supply ventilation provides the maximum freezing risk to underfloor pipes. This is expected as external air enters directly to the underfloor space. The risk will be greatest to the pipes nearest the fan.

Underfloor extract ventilation is seen to present less of a freezing risk than natural ventilation. This is because the fan reverses the flow through the living room floor, drawing warm air downwards. Although this reduced risk has been observed for the living room underfloor space, it is unlikely to occur for the other areas as the floor pressure differences remain negative.

The dependence relationships are useful as they can determine the external air temperature required to bring the underfloor temperatures below freezing. Using this information together with meteorological data an assessment of the freezing risk can be made for different areas of the country.

### Changes in timber moisture content

The variations in the moisture content of the three living room and three dining room joists are given in this section. The measurements from beneath the stairs are not discussed as the wood is rotten in this area and thus many of the results are off scale.

The timber moisture results from the start of a test are compared to those recorded after. There are 18 measurements in total, three from each location. A paired sample t-test is used to test for any significant difference between the before and after measurements. The data are given in Table 4. Readings and changes are given to the nearest 0.1% and the level of significance relating to any difference is given in brackets.

Although the differences are significant they cannot, with any degree of certainty, be attributed to the different ventilation strategies. There are several possible reasons for the differences, the most obvious being due to climatic conditions causing variations in rain fall, relative humidity etc. Another factor is the response rate of the timber moisture levels to changing conditions. The test periods may not be of a sufficient time for the timber to respond. Alternatively if the timber responds quickly then any change in underfloor ventilation prior to starting a test resulting from say lifting the floor timbers to install airbricks) will cause the response to be missed; levels are only recorded at the very start and end of a test.

| **Remedy type** | **Period of test** | **Average moisture levels in the timber floor (%)** | | |
|---|---|---|---|---|
| | | **Before test** | **After test** | **Change and (level of significance)** |
| *House as purchased (no remedy and poor underfloor ventilation)* | 24 May - 25 Aug 1994 | 21.8 | 22.3 | +0.5<br>(95% level of sig.) |
| *Whole house pressurisation (with poor underfloor ventilation)* | 22 Oct - 21 Nov 1994 | 23.2 | 22.8 | -0.4<br>(95% level of sig.) |
| *Enhanced natural underfloor ventilation (nine airbricks open)* | 23 Dec 1994 - 30 Jan 1995 | 21.6 | 21.3 | -0.3<br>(90% level of sig.) |
| *Underfloor extract ventilation (fan on full and nine airbricks open)* | 1 Feb - 26 Feb 1995 | 21.3 | 20.8 | -0.5<br>(95% level of sig.) |
| *Underfloor supply ventilation (fan on full and nine airbricks open)* | 1 Mar - 26 Mar 1995 | 20.8 | 19.9 | -1.0<br>(95% level of sig.) |

Table 4: Moisture levels in the timber floor

## CONCLUSION

The radon reductions show mechanical underfloor ventilation to be the most effective remedy (of those tested). Underfloor extract ventilation gives a reduction of 94%, a higher figure than supply which provides 85%. Enhanced natural underfloor ventilation provides a reduction of only 30% whilst whole house pressurisation gives 52%. The two tests on enhanced natural underfloor ventilation in different seasons indicate only a very small seasonal variation giving some confidence in the comparison of the different radon reductions.

With natural underfloor ventilation a large proportion of the house ventilation air is observed to come from the underfloor space. It is estimated that more than 50% of the house ventilation air comes through the floor (using the assumptions given in 8.1). The provision of extra airbricks for enhanced natural underfloor ventilation increased the floor pressure difference from -0.3 Pa to -0.9 Pa, indicating a significant increase in air flow upwards through the floor (greater than 70%). The whole house pressurisation system (with poor natural underfloor ventilation) failed to reverse the floor pressure difference. It did however manage to reduce it to about -0.1 to -0.2 Pa, causing a decrease in the flow through the floor of about 30%.

The dependence of living room underfloor temperature on the external temperature is well demonstrated to a high level of significance. From this dependence (and with meteorological data) the increased risk of underfloor pipes freezing can be assessed for various parts of the UK. Underfloor supply ventilation is shown to be the remedy which creates the greatest risk. Underfloor extract ventilation is shown to create a smaller risk to the living room underfloor than natural ventilation.

For each remedy results show significant changes in the moisture content of the floor joists. However these changes cannot be solely attributed to the remedy. Climatic conditions will be superimposed over the data and the timber-moisture response time may affect the results.

Although this paper brings together only a few of the results recorded so far, the project is already showing how useful controlled, undisturbed tests can be.

## FUTURE WORK

There is still a large quantity of data to analyse and there are a vast number of tests that are possible and interesting to conduct. A few of the more important issues are mentioned here.

The risk of freezing to underfloor pipes will be examined more closely using the data already recorded. Risks can be assessed for the various radon affected areas of the UK to investigate the suitability of remedies for areas with differing climates.

The variation of indoor and underfloor radon levels can be correlated against various climate parameters in an attempt to model radon fluctuations. This may lead to correction procedures for short term radon measurements, increasing the confidence in short term results.

Changes in whole house ventilation rates caused by the various remedies have been monitored using tracer gas techniques. The results will provide a ventilation energy cost for each remedy, allowing for a more accurate cost analysis.

The assessment of seasonal variation in radon levels will continue. Although the two tests on enhanced natural underfloor ventilation show the variation to be small, more comparisons are required to increase confidence.

Risks of spillage will be examined at a later date. Different remedies will also be assessed, including: different fan flow rates for the mechanical underfloor ventilation (so far the fan has only been tested on full speed), mechanical underfloor ventilation with varying amounts of airbricks open/closed (to extenuate pressure or ventilation effects), multi-fan underfloor ventilation, floor replacement and sump systems.

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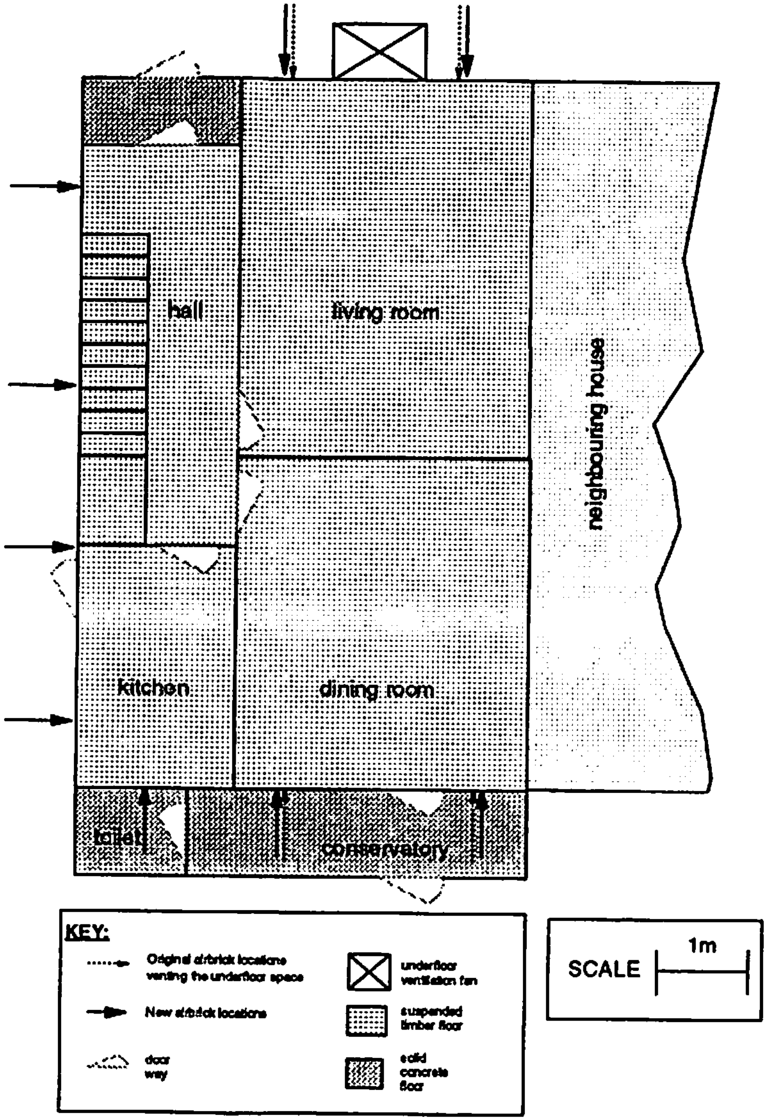

FIGURE 1 : HOUSE FLOOR PLAN

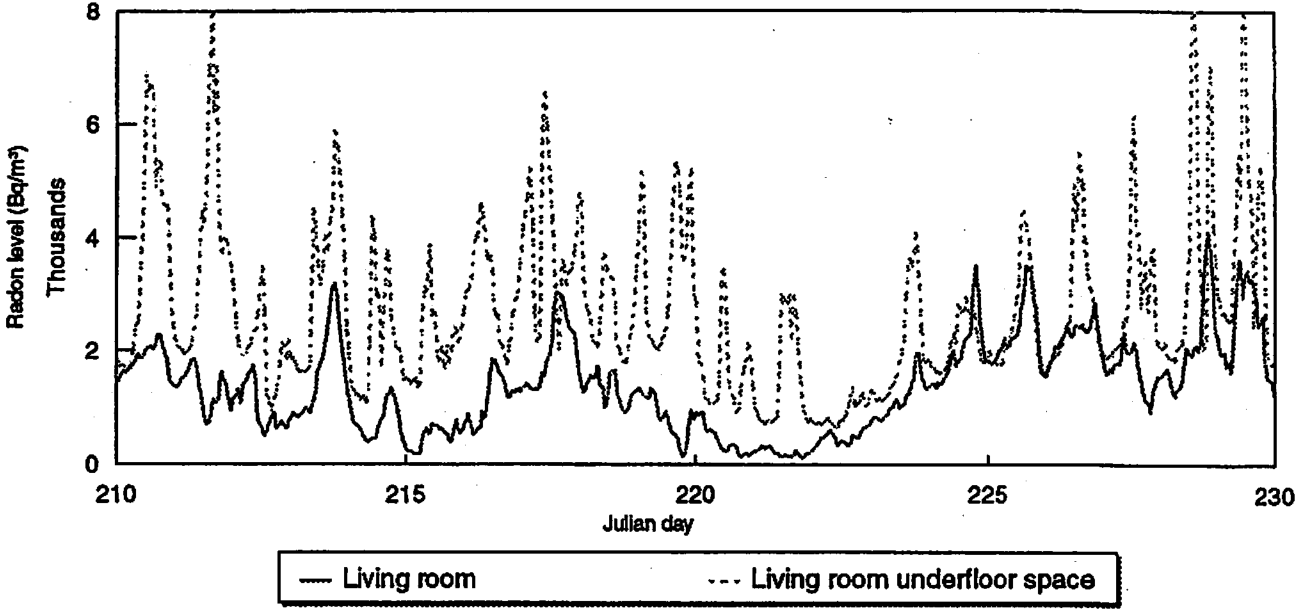

Figure 2: Variations in underfloor space and living room radon levels for house 'as purchased'