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RADON: REMEDIATION OF DWELLINGS CONSTRUCTED WITH SUSPENDED TIMBER FLOORS

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ABSTRACT

Dwellings in the UK with suspended timber floors and high radon levels are proving difficult to remediate. This paper reports on the experience of the Building Research Establishment in dealing with such dwellings. Remediation techniques are discussed in some detail and attention is given to the drawbacks of each system. Details of the remediation of 18 dwellings are given, and comparisons are made between the effectiveness of the different techniques adopted.

Sump systems are shown to be very effective at reducing radon levels, but unfortunately they are not practical to install for the majority of cases. Natural ventilation, mechanical supply ventilation and mechanical extract ventilation are three alternative techniques that have been used successfully.

INTRODUCTION

Radon entry into dwellings and the health risks posed by exposure to high concentrations are issues now well documented. In 1988 the British government set a radon "action level" of 200Bqm^{-3} (Department of the Environment - 1992). It is recommended that indoor radon levels in living spaces are kept below this value.

The objective of this paper is to discuss the experience of the Building Research Establishment (BRE) in dealing with radon affected dwellings constructed with suspended timber floors. Various remedy approaches are explained in some detail and the drawbacks for each technique are examined. Details of 18 case studies are given. This work forms part of the radon research program carried out at the BRE for the Department of the Environment (UK).

CONSTRUCTION OF UK DWELLINGS

Floor types found in dwellings in the UK can be split into three groups: solid concrete floors which lie on the ground, those that are suspended above ground level, and those that are a mixture of the two. It is unusual for dwellings in the UK to have a cellar.

Solid Floors

Dwellings with solid floors only, account for less than 10% of the entire housing stock in the UK. Solid floors in existing buildings (ie. constructed prior to the introduction of radon protection) usually consist of a concrete layer which has been poured between load bearing walls, over a layer of "hardcore" or "fill". The fill is often rubble or gravel, and is therefore quite permeable. A damp proof membrane may or may not cover the entire floor area.

Concrete rafts are also used although less common. In this form of construction, the concrete varies in thickness according to the position of the load bearing walls, where it is at its thickest. The walls are built directly off the slab.

Remedial techniques for dwellings with solid floors usually involve sump systems (BRE Report BR227). This remedy is very well established and is usually very effective in reducing indoor radon levels.

Suspended Floors

Suspended floors are usually either timber (constructed from either plain or tongue & groove boards), reinforced concrete, or "block and beam" (concrete blocks supported by a series of inverted "T" beams) with a ventilated space below. The lower surface of this space will either be exposed soil or covered with a thin layer of concrete. The space is often inaccessible and frequently split into several compartments by sleeper walls. Approximately 20% of the entire housing stock have suspended timber floors.

Mixed Floors

70% of the existing housing stock contains dwellings with both suspended timber and solid floors. There may be a concrete oversite beneath the suspended timber floor although it is unusual because mixed floor dwellings tend to be of the older variety. Underfloor spaces in the UK are usually inaccessible often being less than 0.3m deep.

The dwellings that are proving the most difficult to solve are those with mixed flooring and no oversite. The lack of an oversite removes sumps as a practical remedy unless a membrane can be easily laid over the soil. The major radon entry route is probably through the suspended timber floor because of its comparative leakiness. This is further supported in cases where cross ventilation through the space does not exist because of the location of the solid floor areas. Suspended areas are usually treated first, but how this treatment affects the radon entry through the solid floor is difficult to say.

RADON ENTRY

Radon enters a dwelling by diffusion and pressure driven flow, with the latter usually being the dominant factor. There are two approaches to remediation: either the radon is prevented from entering the structure, or it is removed after entry. The latter principally involves changing the ventilation of the dwelling, which is outside the scope of this paper. The former, which we examine, can also be split into two subsets:

(a) radon can either be prevented from entering the under-floor space or,

(b) radon can be prevented from entering the dwelling after it enters that space.

Sump systems (sub-slab depressurisation) and under-floor pressurisation fall into category (a), while under-floor depressurisation falls into (b). Natural ventilation of the under-floor space is somewhere between the two. Sump systems are regarded as the most successful technique but they are not always practical to install primarily because not all underfloor spaces have oversites, and membranes may be impractical to install because it may involve lifting up the entire floor area. For these reasons employing an under-floor ventilation technique may be more appropriate and is, for the moment, the preferred remediation technique for these particular dwellings. This area needs to be researched further to determine under what conditions ventilation methods work best.

The sealing of suspended timber floors using a polythene membrane was used as a remedial measure during the early stages of the research program at BRE with only limited success. This approach is now not recommended because of possible moisture problems leading to rotting of the timber.

The sections which follow briefly discuss various remediation techniques used on dwellings with suspended timber floors.

PASSIVE VENTILATION

Significant increases in the under-floor ventilation rate, which may successfully reduce indoor radon levels, can be achieved either by increasing the number of airbricks venting the space, or by replacing existing vents with airbricks that have a larger free open area (Nazaroff & Doyle, 1985). Increased flow of outside air into the under-floor space and a decrease in the pressure driven flow of soil gases will reduce levels. However it is possible that the air flow from the under-floor space into the dwelling will increase the quantity of radon entering the living quarters.

Current data suggests that indoor radon reductions will probably be no more than 50% (Henschel, 1992) although dwellings with initially poor under-floor ventilation may benefit much more. This approach is frequently used in South West UK because there are often insufficient airbricks or the airbricks may be blocked. This approach is passive, cheap, and has few if any drawbacks except that it will only usually work for dwellings with a moderate level (say $<500 Bqm^{-3}$), although this figure does depend on the initial underfloor ventilation. As an approximate guide the exterior wall surrounding an under-floor space should have ventilation openings of approximately $1500 mm^2$ per metre run of wall (Buildings Regulations 1992, Approved Document C).

How this approach alters the radon entry in any solid floor areas of a house will vary from case to case. It is likely that, because air can readily move from outside to inside through airbricks feeding the stack effect, the radon entry through the solid floor will decrease.

MECHANICAL SUPPLY VENTILATION

A fan, forcing air into an under-floor space can have a number of effects. By increasing the pressure within the space, with respect to the soil, the pressure driven flow from the soil into the space will decrease. This together with an increased ventilation rate go towards reducing indoor levels. A counteractive effect is that the flow through the floor into the dwelling increases. To increase the dilution effect, more airbricks may be opened, while sealing them will tend to increase the pressurisation.

The successful remediation of a dwelling depends on the dominant effects and the particulars of the dwelling and geographical site. If pressure driven flow is the major contributor to the indoor radon content, as is usually the case, then it is possible to decrease or reverse this flow by pressurising the under-floor space. However, if diffusion is the dominant entry force (as may be the case when the radon source is close to the soil surface) then this process could aggravate the problem because the flow through the floor, into the dwelling, is increased.

Sleeper walls under the floor can mean that pressure differences within the underfloor space do not extend throughout the entire area. This is not usually a problem because the walls tend to have significant gaps that allow air communication between the various cells.

Heat Losses From The Dwelling

This system introduces cold air from outside into the underfloor space, and inevitably into the living quarters. It is possible to heat the incoming air but this is not common because of the costs involved. So, there will be some heat loss from indoors, and the temperature in the underfloor space will be comparable to that outside which, during winter could lead to the freezing of underfloor pipes. Closing airbricks, whilst increasing the pressurisation (possibly a desired affect with regards to radon) will probably increase the quantity of cold air entering the house.

Introduction Of Spores Into The Living Space

There is some concern among scientists in America that by blowing air into the underfloor space, spores which may exist in the space, can be introduced into the living quarters contributing more significantly to ill-health than the radon itself. To date this area has not yet been researched.

Noise

Noise, both from the fan and from the air movement is common and householders often prefer to switch systems off rather than listen to them. Systems should be sited away from noise sensitive areas (bedrooms, living rooms etc) if at all possible. Fans can be silenced to a degree, but it is quite difficult, if not impossible to have a noise-free underfloor ventilation system.

Carpet Lift

In a *very* few cases carpets may lift. This problem is inherent in some dwellings at exposed locations in the South West UK without fan supply systems, usually resulting in the covering of airbricks which in turn aggravates the radon problem and will increase moisture levels. By introducing a supply ventilation system, it is unlikely that this alone (ie. a significant wind is still required) will cause carpet lift, but it may increase the likelihood.

Where Does The Radon Go?

By using supply ventilation radon may well be prevented from entering the space, but it may also be forced out any vents/gaps in the perimeter wall. If the dwelling is mid-terrace or semi-detached remedying one house may aggravate the radon problem nextdoor.

MECHANICAL EXTRACT VENTILATION

An extract fan can decrease the pressure within an underfloor space, with respect to the living quarters above, which can reduce or possibly even reverse the pressure driven flow through the floor. Together with an increased air change rate these factors go towards reducing the indoor radon levels. However, the pressure driven flow from the soil into the space will increase, increasing the radon concentration beneath the floor. The dominant effects will decide the effectiveness of extract ventilation. As with supply ventilation, should the airbricks be left open or sealed closed?

Sleeper walls may cause poor air communication between the various underfloor cells. The fan and exhaust should be located away from noise sensitive areas, and away from windows and doors to prevent possible re-entrainment.

Heat Loss From The Dwelling

Warm air from the dwelling will probably be extracted from the house, increasing the temperature of the underfloor space during cold periods, delaying the freezing of any underfloor pipes, but still resulting in an increased heating bill. Blocking airbricks, whilst increasing the depressurisation of the space (possibly a desired affect with regards to radon) can increase the quantity of air drawn from the dwelling, increasing the heating bill further, and increasing the likelihood of spillage of combustion appliances from some heating appliances.

The Spillage Of Combustion Products From Open-flued Combustion Appliances

There are cases where extract systems, not only from beneath suspended timber floor but also sump extract systems beneath solid floors (even those *with* membranes) cause combustion gases to spill from open-flued combustion appliances. This is a result of the fan extract drawing air from the living space, reducing the pressure near the combustion appliance, which results in a back draught down the chimney or flue. When this occurs it is serious problem, but there are steps we can take to reduce the risk of this happening (Welsh 1993).

SUMP SYSTEMS

Usually, for a sump system (installed beneath a suspended floor) to be effective it should be covered by either a membrane or a layer of concrete. The covering prevents air entering the sump directly from the underfloor space and increases the pressure extension. The aim is to depressurise the soil/hardcore beneath a concrete layer/membrane. Provided the soil/hardcore is sufficiently permeable the pressure driven flows, from the soil into the space above that normally occur can be reversed leaving diffusion as the only entry force. Also outside air may flow, through the soil, under the exterior walls and into the sump, diluting the soil gases. These two separate effects usually prove successful.

For dwellings with timber floors without oversite, sumps will often fail unless the soil surface is covered. The covering process can prove very disruptive and expensive and is not always practical due to the shallow depth of many UK underfloor spaces and the partitions that occur as a result of sleeper walls. For those dwellings where the underfloor space is accessible (as most are in the USA) and where the space is not split into small cells by internal load bearing walls, the soil may be covered with a thin layer of gravel which is then covered by a membrane which is weighted either with gravel or a concrete oversite. The sump, constructed prior to the laying of the membrane can be activated, and because of the permeable gravel beneath the membrane, a large pressure extension should exist.

For those dwellings where the soil under the floor is already covered with an oversite, sumps provide a very effective remedy with few drawbacks and often achieve very high reduction ratios.

Possible Problems With Sumps Under Suspended Timber Floors

These systems tend to be the quietest mechanically driven remedy although as with any such system the fan should be mounted carefully to minimise noise disturbance. The fan exhaust should be located away from windows and other openings to prevent possible re-entrainment.

Usually only a small amount of air will be drawn from the house making heat losses minimal, and spillage has not been found to be a problem and is very unlikely to occur.

CASE STUDIES

So far 18 dwellings with suspended floors have been remediated by BRE. Table 1 displays brief details of each case, which are discussed in more detail below. All figures are approximate.

Case 1.

A detached house with only a small area (about 20% of the entire floor area) of suspended timber flooring. This area was not remediated in any way but the deteriorating timber was replaced. This reduced indoor levels from $1800Bqm^{-3}$ to $1500Bqm^{-3}$.

Case 2.

A large bungalow, built in the 1970's, on an exposed site. About 75% of the floor area is suspended timber made from tongue & groove boards and covered with chipboard. The under-floor space with a volume of $100m^3$ is ventilated by 12 partially blocked airbricks. Initial indoor radon levels = $1000Bqm^{-3}$.
Remediation technique and results: replacement of existing terra-cotta airbricks for a plastic louvred type brick, which have about twice the free open area, reduced levels successfully to $150Bqm^{-3}$, a reduction ratio of about 7.

Case 3.

A averaged size two bedroomed bungalow with 80% of its floor area being suspended timber. The underfloor space appeared to be well ventilated, although it could be possible that the vents were blocked by cavity insulation. The initial indoor radon levels = $750Bqm^{-3}$.
Remediation technique and results: replacement of the 11 existing airbricks for the plastic louvred type brick (approximately twice the free open area). Levels reduced to $300Bqm^{-3}$, a reduction ratio of 2.5.

Case 4.

A dwelling with mixed flooring. The suspended timber area was inadequately vented by several partially blocked airbricks. Initial indoor radon level = $250Bqm^{-3}$.
Remediation technique and results: replacing the airbricks for ones with a larger free open area reduced levels to $150Bqm^{-3}$.

Case 5.

A large detached house, built in 1904 on an exposed site, with a new extension. Approximately 75% of the entire floor area is suspended timber with soil beneath it. The floor consists of tongue & grooved boards in the newer areas while the older floors have plain boards. The volume of the under-floor space measures $35m^3$ and is ventilated by a significant number of airbricks. Initial indoor radon level = $700Bqm^{-3}$.

Remediation technique and results: increasing cross ventilation with mechanical air extraction at a rate of $350m^3h^{-1}$, ie.10 air changes per hour (ach), reduced the level to $250Bqm^{-3}$.

Case 6.

A mid-terrace house with approximately 50% of the floor area being suspended timber. The underfloor space is inaccessible, being less than 0.3m deep. The partition walls are particularly well sealed. The property, built in the late 18th century, has thick stone walls and no concrete oversite. Initial radon level = $1400Bqm^{-3}$.

Remediation technique and results: Using underfloor extract ventilation (at a rate of approximately $180m^3h^{-1}$), the radon level was reduced by a factor of 2 to $750Bqm^{-3}$.

Case 7.

A large detached house, built in 1904, that has a suspended timber floor over soil, covering approximately 75% of the site. The timber boards are plain sided and loose. The under-floor space with a volume of about $100m^3$, is vented by only 4 airbricks although the site is exposed. Initial indoor radon level = 1400Bqm-3.

Remediation technique and results: By extracting $180m^3h^{-1}$ of air (2 ach), the level fell to $350Bqm^{-3}$.

Case 8.

An old cottage with thick granite walls, dug into the hill side, with a newer extension. The suspended timber floor covers 75% of the site. The under-floor space is inadequately vented. Initial indoor radon level = $600Bqm^{-3}$.

Remediation technique and results: Air extraction of $350m^3h^{-1}$ reduced the level successfully to $20Bqm^{-3}$.

Case 9.

A converted mining engine house. The dwelling has a suspended timber floor above a cellar, with all other areas being solid. A large chimney that used to ventilate the engine room now ventilates the cellar. Initial indoor radon levels = $1900Bqm^{-3}$

Remediation technique and results: Sealing the timber floor reduced levels to $1000Bqm^{-3}$. By ventilating the cellar with a small extract fan the level was further reduced to $300Bqm^{-3}$.

Case 10.

A large detached house, built in 1890, with a mixed floor, approximately two thirds being suspended timber with soil beneath it, in a sheltered site. The entire timber floor was constructed using plain floor boards which fit very loosely. The under-floor space, about $50m^3$, is poorly ventilated. Initial indoor radon level = $5000Bqm^{-3}$.

Remediation technique and results: Extraction of 350 m^3h^{-1} of air (7ach), reduced levels to $500Bqm^{-3}$. Increasing this extraction rate to $700m^3h^{-1}$(14ach) did not change this level significantly.

Case 11.

A three bedroomed semi-detached house with half suspended timber and half solid flooring. Initial indoor radon level = $1900Bqm^{-3}$.

Remediation technique and results: Sealing the timber floor area with a polythene layer and hardboard did not lower the radon level. Air extraction of $350m^3h^{-1}$ reduced levels to $400Bqm^{-3}$. Supply ventilation with a similar flow rate reduced levels successfully to $100Bqm^{-3}$.

Case 12.

A mid-terrace house, built in 1900, with the front living areas (50% of the entire area), on suspended timber. Air is free to move between the under-floor spaces of neighbouring dwellings however the space is very poorly ventilated. The floorboards are plain edged. The site is sheltered and close to mine workings. An oversized extract fan is often used in the kitchen. Initial indoor radon levels = 4500Bqm^{-3}.
Remediation technique and results: Replacing the extract fan for a more suitably sized unit, sealing the timber area with polythene and hardboard, repairing the solid floor area, and air extraction from the under-floor space (a flow rate of 350m^{3}h^{-1}) reduced radon levels to 1200Bqm^{-3}. Reversing the flow direction of the fan reduced levels more significantly to 500Bqm^{-3}.

Case 13.

A modern three bedroomed bungalow with a suspended timber floor throughout. The underfloor space is approximately 0.75m deep and well ventilated on two opposite sides. The soil is covered with a membrane and oversite. Initial radon levels = 2100Bqm^{-3}.
Remediation technique and results: By placing two airbricks on each gable end, to increase the ventilation rate of the space, levels were reduced by a factor of 1.5 to 1400Bqm^{-3}. Using forced ventilation (a flow rate of 350m^{3}h^{-1}) reduced levels to 30Bqm^{-3}, a reduction ratio of 70.

Case 14.

An old school with a section of suspended timber flooring. Initial radon levels = 600Bqm^{-3}.
Remediation technique and results: Using the supply ventilation techniques levels were reduced to an average of 45Bqm^{-3}, a factor of 13.

Case 15.

A large modern detached bungalow with suspended timber flooring throughout and a concrete oversite covering the soil below. The under-floor space is very accessible being 1.5m deep. Initial indoor radon level = 3000Bqm^{-3}
Remediation technique and results: A multiple sump system successfully reduced the radon levels to 100Bqm^{-3}.

Case 16.

A modern detached bungalow with suspended timber flooring and a concrete oversite covering the soil below. Initial indoor radon level = 800Bqm^{-3}
Remediation technique and results: A multiple sump system successfully reduced the radon levels to 50Bqm^{-3}.

Case 17.

A large detached bungalow, built in the 1950s. The suspended timber floor, constructed from tongue and grooved boards, seems quite air tight although there are many pipes that penetrate though it. A concrete oversite covers the soil and the under-floor space is inadequately ventilated. Initial indoor radon level of 1200 Bqm^{-3}.
Remediation technique and results: Air extraction from the under-floor space (a flow rate 350m^{3}h^{-1}) reduced levels to 600Bqm^{-3}. Replacing this fan with a sump system successfully reduced levels to 50Bqm^{-3}.

Case 18.

A large bungalow built in the 1970's. The space beneath the timber floor measures 35m^3 and is well ventilated. A concrete layer covers the site. Initial indoor radon level = 3000Bqm^{-3}.
Remediation technique and results: Sealing the floor with polythene and air extraction of 350m^{3}h^{-1} from the space, after blocking all but one airbricks, lowered the level to 2200Bqm^{-3}. When replaced with a sump system the level was lowered to 900Bqm^{-3}.

DISCUSSION OF RESULTS

Radon Reduction Ratio And Measures Of Success

An *indication of the effectiveness* of a particular technique can be gained by calculating a "radon reduction ratio" as shown in the table. This value is defined as the radon level prior to remediation divided by that after remediation. For a technique to prove *successful* it should reduce the radon level to below the action level.

Passive Measures

Dwellings 2 & 4, remediated successfully by passive measures, show that increasing natural under-floor ventilation can be effective against radon entry. The indoor radon level of house number 2 was reduced by a factor of 7 by replacing the existing airbricks for a plastic louvred type (with approximately twice the free open area).

Replacing the airbricks for case 3, although not successful, has been effective in reducing levels. The airbricks that replaced the existing vents will themselves be replaced for ones twice as large. This should reduce indoor levels to below the action level.

The success of this method is highly dependant on the level of ventilation before remediation. Dwellings with poor under-floor ventilation will usually experience a larger than normal reduction ratio with the additional benefit of decreasing the moisture level beneath the floor.

Supply Ventilation

Cases 13 and 14 show that supply ventilation can be a highly effective remedy, with reduction ratios of 70 and 13 respectively.

For case 11, changing to supply ventilation from extract, increases the radon reduction ratio from 5 to 19. Similarly case 12 shows supply to be more effective but because the reduction results from various simultaneous changes is it difficult to isolate the precise effects of the ventilation.

Extract Ventilation

The radon reduction ratios of houses remediated by air extraction vary from 1.5 to 30 and tend to be lower than 5.

Case 10 shows that very high indoor radon levels can be reduced to much more acceptable levels by adopting this technique although only case 8 was successfully remediated.

Sump Systems (sub-slab depressurisation)

Houses 15, 16, 17, and 18 all have systems that involve the extraction of soil gases from beneath a concrete oversite. All but one of the systems successfully remediated the respective dwelling to below $200Bqm^{-3}$.

Cases 17 & 18 show that, in these particular cases, sump systems are more effective than ventilation techniques. It is the experience of the BRE that a sump system is the most effective method achieving the largest reduction factors.

Variation Between Results

The wide variation found is not surprising when the variables are considered. Constructional details, geographical details and occupancy behaviour will all have a considerable bearing on the success of a remedial measure. A further problem is that workmanship can be substandard and specifications may not be accurately followed. Because the work is completed below floor level, systems can be difficult if not impossible to inspect.

Both passive and forced underfloor ventilation techniques change the pressures and air flows beneath/inside a dwelling. The exact changes are difficult to quantify and depend on the average permeability of the soil, the leakage paths through the floor and walls, the driving forces causing the radon entry, and the radon entry routes. Under-floor spaces are also often split into several compartments which can prevent remedial techniques from affecting the entire space, causing only local remediation. It is unlikely that any two dwellings will be similar in all of these respects and thus a variation is expected.

To complicate the situation further, houses with suspended timber floors often have some areas with solid flooring. The suspended area is usually highlighted as the major radon entry route (which is a fair assumption - Henschel, 1992) and remediated accordingly. However, the extent to which this remediates the whole house depends on the approach adopted and whether the entry routes through the solid floor are significant. How the remediation of a suspended floor affects radon flow through a solid floor, or indeed vice-versa, is not a well understood process but is fundamental for the remediation of properties with mixed flooring.

CONCLUSION

Passive ventilation, mechanical supply ventilation, and mechanical extract ventilation of the under-floor space can successfully reduce radon levels within a dwelling, but the results are shown to be highly variable. Sump systems, where practical, are shown to be the most effective solution.

As an initial step increasing the natural ventilation of the space is a simple and cheap option. This will usually reduce the levels by about 50%, although if the space is initially very poorly ventilated then larger reductions can be achieved. Mechanical ventilation may be employed and the results suggest that this is more effective than extract ventilation. There is some concern about possible side-effects of the remedies and these need to be considered.

Sumps systems are the most reliable remedy producing the highest reduction ratios with few side-effects, although they are only applicable in some circumstances.

The results given in this paper for passive and mechanical ventilation methods may paint an unrealistically pessimistic picture for these approaches because the dwellings that are referred to BRE are generally those with elevated radon levels (typically >1500Bqm^{-3}) and/or construction details that make remediation complicated. This selection does not represent the majority of UK radon high houses, which will usually have levels significantly below 1000Bqm^{-3}, and thus these remedies are considered to be valid, even though the success demonstrated in this paper may be limited.

A greater understanding of the dominant mechanisms by which mechanical ventilation reduces indoor radon levels is needed. Probably the main question to be answered with regards to the ventilation approaches is: "Are indoor radon levels reduced largely by increased ventilation beneath the floor, or is a reduction in pressure driven flows more significant?".

FUTURE WORK

The effectiveness of different remedial processes are being assessed in the BRE research programme. Controlled experiments, conducted on two test cells with simulated radon levels at the BRE "Radon Test Site", will indicate whether supply ventilation is a more appropriate technique than extract ventilation. Tests will also indicate whether pressurisation/depressurisation is preferable to simply increasing the cross ventilation by mechanical means. Similar research will be conducted at a BRE test house, situated in south-west UK, which has very high radon levels. Field studies of occupied dwellings with high radon levels and mathematical modelling will continue.

Research so far has examined various remedies that the majority of people can afford. This enables suitable remedies to be highlighted for a particular construction type and radon level. As this continues it is also important to study householder comfort levels with regards to noise and draughts and whether householders prefer to take radon remediation step-by-step or whether they want guaranteed first time success. We require a greater understanding of the side-effects of each approach eg. heat losses from buildings due to the remedy, possible introduction of spores into the living area from beneath the floor, possibility of spillage of combustion products etc. These side-effects together with the comfort element must be costed so that the real price of the remedy can be established. It is possible that after this type of analysis some remedies will no longer be acceptable due to the extra costs, both real and those of comfort.

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TABLE 1 - REMEDIATION DETAILS OF CASE STUDIES

HOUSE	FLOOR TYPE	C.O.$	REMEDIATION METHOD	RADON LEVELS Bqm⁻³ BEFORE	RADON LEVELS Bqm⁻³ AFTER	R.R.*
1	kitchen suspended timber. All else solid	no	renew timber floor and part of solid	1800	1500	1
2	suspended timber (75%) and solid mix	yes	increase natural ventilation of void	1000	150	6.5
3	suspended timber (80%) and solid mix	yes	increase natural ventilation of void	750	300	2.5
4	suspended timber and solid mix	?	increase natural ventilation of void	250	150	1.5
5	suspended timber (75%) and solid mix	no	mechanical extract ventilation	700	250	3
6	suspended timber (50%) and solid mix	no	mechanical extract ventilation	1400	750	2
7	suspended timber (75%) and solid mix	no	mechanical extract ventilation (fan at ½ speed - noise problems)	1400	350	4
8	suspended timber (75%) and solid mix	no	mechanical extract ventilation	600	20	30
9	suspended timber over cellar and solid mix	n/a	seal timber floor	1900	1000	2
			mechanical extract ventilation from cellar	1000	300	3.5
10	suspended timber (66%) and solid mix	no	mechanical extract ventilation	5000	500	10
			mechanical extract ventilation - larger fan	5000	500	10
11	suspended timber and solid mix	no	seal timber floor	1900	2000	–
			mechanical extract ventilation	1900	400	5
			mechanical supply ventilation	1900	100	19
12	suspended timber (50%) and solid mix	no	seal timber floor, repair solid floor, replace kitchen extract fan for smaller model, and mechanical extract ventilation	4500	1200	4
			seal timber floor, repair solid floor, replace kitchen extract fan for smaller model, and mechanical supply ventilation	4500	500	9
13	suspended timber	yes	increased underfloor ventilation	2100	1400	1.5
			mechanical supply ventilation	2100	30	70
14	suspended timber	no	mechanical supply ventilation	600	45	13
15	suspended timber	yes	multiple sump system	3000	100	30
16	suspended timber	yes	multiple sump system	800	50	16
17	suspended timber	yes	mechanical extract ventilation	1200	600	2
			sump system	1200	50	24
18	suspended timber	yes	seal timber floor and mechanical extract ventilation	3000	2200	1.5
			sump system	3000	900	3.5

C.O.$ - CONCRETE OVERSITE R.R.* - RADON REDUCTION RATIO