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Exposure to Radon in UK Dwellings

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Abstract

Doses from radon are the largest component of the average radiation exposure of the UK population. This report outlines the risks of radon exposure, the factors affecting radon concentrations in buildings and how these concentrations can be measured. A comprehensive programme of radon measurements, largely funded by government, is under way in the UK. This is described and the results are summarised.

In order to concentrate resources most effectively, NRPB defines radon Affected Areas where the appropriate authorities may declare that radon preventative measures are needed in new houses and where existing houses with high radon levels should be identified and remedied. The principles for defining Affected Areas, and those already defined, are described.

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1 Introduction

All of the minerals in the earth's crust contain small and variable amounts of naturally occurring radioactive nuclides, in particular, isotopes of uranium and thorium. These undergo a series of radioactive decays until they reach stable isotopes. The decay chains for the most important nuclides, ^{232}Th and ^{238}U, are shown in Figures 1 and 2. In both cases the chains include unstable isotopes of the element radon: ^{220}Rn in the chain starting with ^{232}Th and ^{222}Rn from the ^{238}U chain. Because of its parent nuclide, ^{220}Rn is sometimes also known as thoron. Unusually for a heavy element, radon is a gas and this means that it can escape from the rocks which contained its radioactive parents.

Both ^{222}Rn and ^{220}Rn have relatively short radioactive half-lives and decay to isotopes of solid elements known as radon (or thoron) progeny. When the atoms are first produced they are chemically and physically very reactive and will attach themselves firstly to water or other molecules in the atmosphere and, if the opportunity offers, to particles of natural aerosols (including dusts) in the air. Radon progeny are said to be 'unattached' if they are associated only with a few small molecules or 'attached' if they are on larger aerosol particles (where dimension might typically be up to one micrometre). If they are breathed in, a large proportion of both the attached and unattached radon progeny will be trapped in the lungs where they will often be retained for long periods, thus giving considerable opportunities for lung tissue to be irradiated by later decays. Conversely, if radon gas is inhaled it is largely breathed out again and it is unlikely that radioactive decay will take place in the lung. It is thus the radioactive progeny rather than radon itself which present the greatest health hazard. However, it is the movement of radon gas which determines the potential for exposure and it is often convenient to use 'radon' in a generic sense to include both the parent gas and the radioactive progeny.

If radon reaches the open air it is mixed into the atmosphere and has no significant effect on health. However, if it is trapped in confined spaces, particularly underground tunnels or cavities, but also houses, then concentrations can build up. That breathing the air in certain mines was dangerous was known long before science had developed to the point where the reason could be understood. Agricola, writing in the sixteenth century[1], noted that 'critics say further that mining is a perilous occupation to pursue because the miners are sometimes killed by the pestilential air which they breathe; sometimes their lungs rot away'. He also reported that some women from the Carpathian mountains had had seven husbands, all of whom had been carried off by this terrible consumption. Two decades earlier, Paracelsus[2], in his 'On the miners' sickness and other miners' diseases', had written the first treatise on the diseases of an occupational group. Paracelsus appeared to believe that the origin of the disease of the lungs is to be sought in the air, although these early writings lack the conceptual framework within which a modern account would be placed and it is difficult to be sure whether these references are to overtly noxious agents or to insidious ones.

No sophisticated statistical techniques were needed for Agricola to notice the enormous death rates in early miners. However, modern epidemiological methods have repeatedly demonstrated excesses of lung cancer in those working in certain types of mine throughout the last few decades. These excesses of lung cancer have been correlated with estimates of radon progeny concentrations. It is less easy to demonstrate the effects of domestic exposure to radon since concentrations in homes are usually less than those in mines and it is less easy to estimate radon exposures over a lifetime in a number of houses than over a period of occupational exposure,

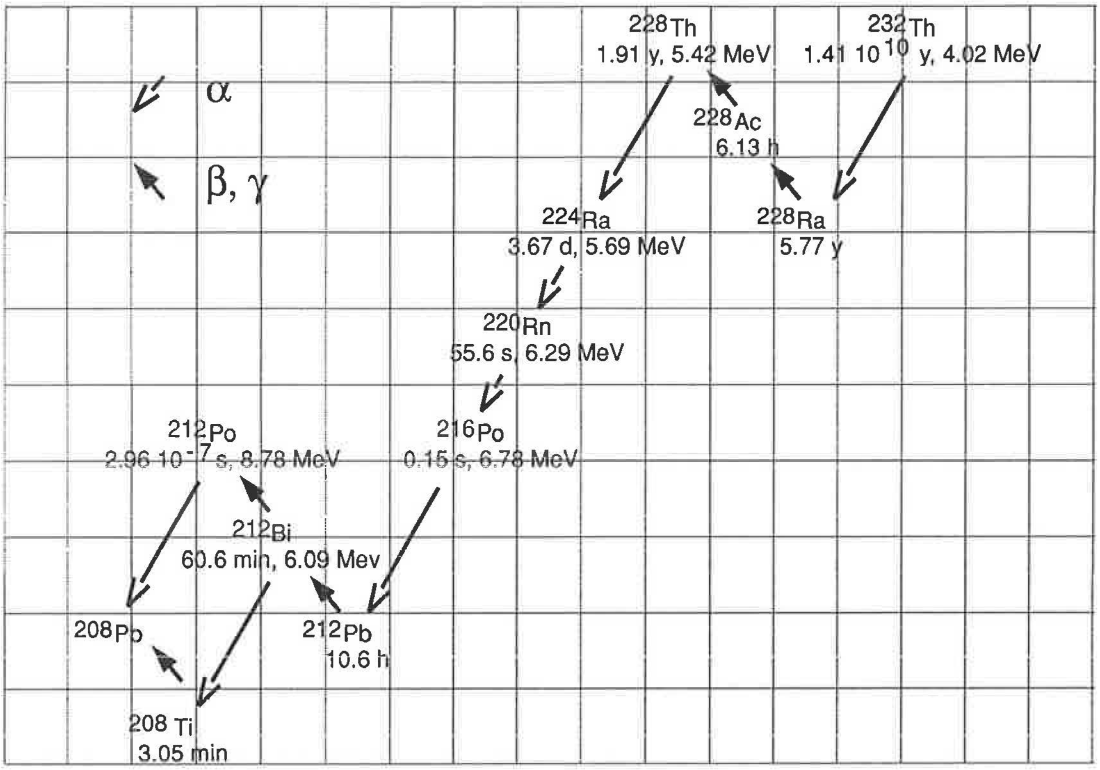

FIGURE 1 Principal decay scheme of thorium-232

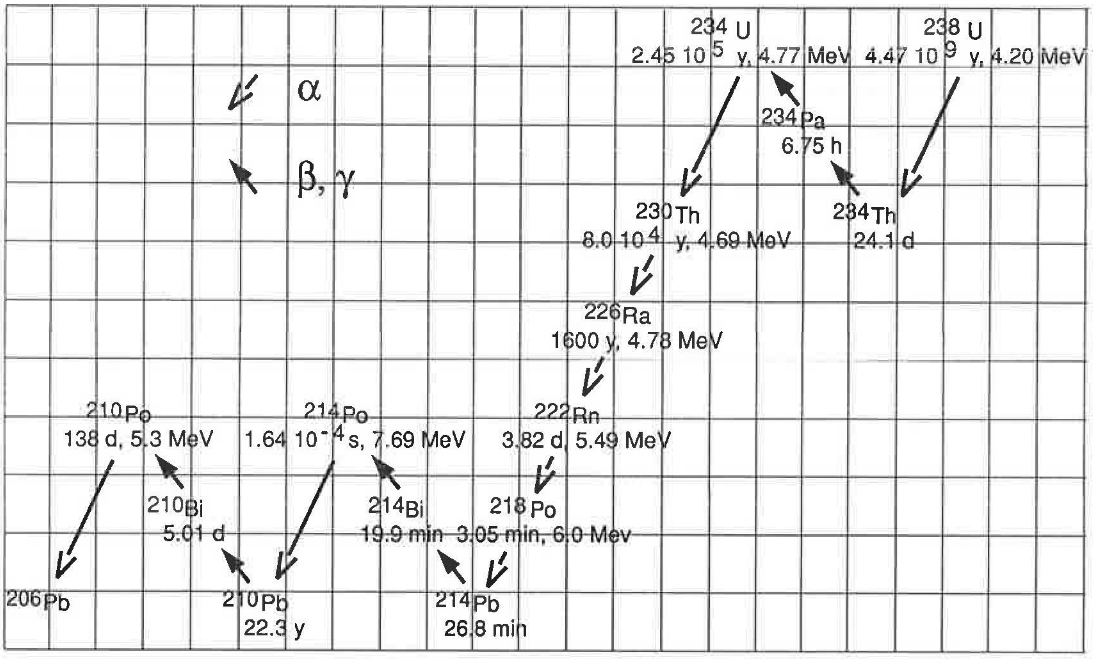

FIGURE 2 Principal decay scheme of uranium-238

frequently in a single mine. However, recent case–control studies are beginning to provide direct evidence on the effect of radon in houses on lung cancer rates. This topic is reviewed in more detail in Section 2.

Until about 1980 there had been relatively few measurements of radon concentrations in UK dwellings. However, in the early 1980s NRPB set up a programme to investigate this subject[3]. It was found that the mean radon concentration was around 20 Bq m^{-3} but that there was very large variation with a significant number of homes having radon concentrations of 1000 Bq m^{-3} or more. In 1987[4,5] NRPB proposed that action should be taken to reduce levels of radon in dwellings where levels were high and that building practices in selected high radon areas should be modified to reduce the levels in new houses. This NRPB advice was consistent with the recommendations that the International Commission on Radiological Protection (ICRP) had made in 1984 in Publication 39[6] and also the recommendations of the Royal Commission on Environmental Pollution[7]. The advice was accepted by government[8], which also funded surveys by NRPB to identify dwellings with high radon levels. The procedures and results of the early surveys were described in 1988[9] and are summarised and updated in this report.

In 1990, NRPB updated and simplified its advice on radon in homes[10] and introduced the concept of a radon Affected Area – a part of the country where an appreciable fraction of the dwellings were likely to have concentrations of radon above the prescribed Action Level, which was set at 200 Bq m^{-3}. NRPB recommended that steps should be taken to reduce radon concentrations in dwellings found to be above the Action Level and that the appropriate authorities should delimit localities within the Affected Areas for preventative measures against radon in new dwellings. The principles for defining radon Affected Areas and details of those already announced are given in Section 5.

In 1991 the House of Commons Environment Committee reviewed radon in a report on indoor pollution[11]. It recommended that the government should commit itself to ensuring the identification of the majority of homes above the Action Level by the year 2000. The government supported this objective and anticipated that the surveys being undertaken would achieve this goal[12].

The UK is not alone in the identification of indoor radon as a potentially serious problem in public health. There are broadly similar radon programmes in other European countries, with those in Sweden and the UK perhaps the most well developed[13]. The Commission of the European Communities made a recommendation on the control of radon in dwellings in 1990[14]. A reference level of 400 Bq m^{-3} was put forward for existing buildings above which remedial measures should be considered; preventative measures in new buildings should be aimed at ensuring that 200 Bq m^{-3} was not exceeded. This recommendation is supported by a comprehensive and coordinated research programme covering mechanisms of exposure, radon metrology and countermeasures[15]. These topics are discussed in Sections 3 and 7 of the present report.

Recently ICRP, in Publication 65[16], has surveyed the accumulated evidence on the risks of exposure to radon and on the practicabilities of controlling exposures. In authoritative recommendations it has refined its previous approaches to controlling doses from radon in both the domestic and occupational setting. ICRP recommendations do allow national authorities a significant degree of autonomy in setting Action Levels. However, its suggested ranges of 200–600 Bq m^{-3} in dwellings and 500–1500 Bq m^{-3} in workplaces are consistent with the UK and European Action Levels in dwellings and very similar to the Action Levels for workplaces.

2 Risks of radon exposure

There is overwhelming evidence that exposure to radon, or rather its progeny, leads to lung cancer in miners. The twelve main studies are summarised in Table 1. These include the eleven studies reviewed by NRPB[29] and also a recently published French study which is broadly consistent with the other data. The total number of miners (all male) is about 60,000 with an aggregated follow-up of about a million man-years. The observed number of lung cancers is over 2600, far in excess of the expected total of about 750. In fact, there is a statistically significant excess of observed lung cancer deaths over the expected total in each of the studies. Since smoking is such a dominant cause of lung cancer, overall excesses (or deficits) of lung cancer could, in principle, arise from uncorrected differences in smoking habits. Another possibility that might be considered to explain the excess is exposure to other occupational carcinogens. There is, however, a positive trend in lung cancer rates with increasing radon exposure in each of the miner studies and this provides compelling evidence for a causal association between radon exposure and lung cancer. Supporting evidence for a causative effect comes from animal studies, which show similar patterns of raised lung cancer risks in rats and dogs exposed chronically to radon[30]. There is also a body of radiobiological evidence relevant to the mechanism by which ionising radiation causes cancers.

TABLE 1 Mortality from lung cancer among miners exposed to radon

Mine(s) (follow-up period)	Number	Mean WLM	Man-years	Number of lung cancer deaths	
				Observed	Expected
Colorado Plateau, USA (1951–82)[17]	3,346	821	73,642	256	59.1
Ontario, Canada (1955–81)[18]	13,469	30	–	152	67.6
Beaverlodge, Canada (1950–80)[19]	8,487	13	114,170	65	34.2
Port Radium, Canada (1950–80)[20]	2,103	144	52,930	57	24.7
West Bohemia, Czech Republic (1953–90)[21]	4,320	219	–	702	138
Malmberget, Sweden (1951–76)[22]	1,294	94	27,397	51	14.9
New Mexico, USA (1977–85)[23]	3,469	111	59,000	68	17.0
Newfoundland, Canada (1950–84)[24]	1,772	383	38,500	113	21.5
Yunnan Province, China (1976–87)[25]	17,143	217	175,406	981	267
Cornwall, UK (1941–86)[26]	3,010	~100	–	105	66.6
Radium Hill, Australia (1952–87)[27]	1,429	7	–	32	23.1
France (1946–85)[28]	1,785	70	44,995	45	21.1

Against this background the International Agency for Research on Cancer[31] has concluded that there is sufficient evidence to classify radon as a carcinogen in human beings.

Although there is general agreement that the miner data show a dose related association between radon exposure and lung cancer, there is less certainty about the manner in which the risk is distributed between smokers and non-smokers. Additive, multiplicative and intermediate types of model have been used to try to fit the data on lung cancers as a function of radon exposure and smoking status. In an additive model, the absolute risk for a given radon exposure will be the same in smokers and in non-smokers. In a multiplicative model, a given radon exposure will multiply the baseline rate for smokers (including any increase from smoking) and non-smokers by the same factor. Since lung cancer rates are much higher in smokers, the multiplicative model implies that risks of radon exposure are also higher in smokers than in non-smokers. Although the truth may lie somewhere between the two extremes, the evidence increasingly suggests that the additive model should be rejected and that the best fit lies closer to a multiplicative model. This whole question is discussed in more detail elsewhere, together with other uncertainties such as the effect of other carcinogens and of dose rate[29].

Whereas the miner data clearly demonstrate the effect of occupational radon exposures on lung cancer rates, extrapolation is needed to obtain risk estimates applicable to the general population. One of the most authoritative estimates of the risks of radon exposure in domestic circumstances has been made by the American Committee on the Biological Effects of Ionizing Radiations (BEIR IV)[30] which undertook a synthesis of the Colorado Plateau, Ontario, Beaverlodge and Malmberget cohorts. The resulting model involved an elevated relative risk at 5–14 years after exposure with a lower risk beyond 15 years. There was also a lower risk for those exposed at older ages. ICRP[16] in recent recommendations on the control of radon at home and at work compared the BEIR IV model and a model in which the relative risk falls off exponentially 12 years after exposure and also decreases with age at exposure. These two models, and also a combined analysis of cohorts totalling over 60,000 miners[32] by Lubin *et al*, give similar overall estimates of the lifetime risk from indoor radon exposure. The risk factor finally adopted by ICRP is based on the BEIR IV model, but applied to the world average population rather than to the population of the USA. It is $1.6\ 10^{-6}\ (\mathrm{Bq\ m^{-3}\ y})^{-1}$ equivalent to $8\ 10^{-5}\ (\mathrm{mJ\ h\ m^{-3}})^{-1}$ ($3\ 10^{-4}\ \mathrm{WLM}^{-1}$), all values being rounded; see Appendix A for a discussion of units. In view of the uncertainties, ICRP recommended the same risk factor for members of the public as for workers and also that this risk factor should be applied to both sexes.

It is notable that some of the miner studies show a statistically significant increased risk for exposures only a factor of two to five above the mean lifetime indoor exposure in the UK and less than the lifetime exposure in dwellings at the UK Action Level of 200 $\mathrm{Bq\ m^{-3}}$. It should also be noted that since radon progeny emit alpha particles, there are radiobiological grounds to expect that the dose–response relationship will be linear at low doses. Nevertheless, direct evidence on the risk of lung cancer associated with indoor radon exposure is being sought by researchers. A number of geographical correlation studies have been published in which attempts were made to look for associations between average radon concentrations and average lung cancer rates in geographical areas of various sizes. Such studies face severe methodological difficulties[33] and are far less reliable than studies that rely upon individual measurements of radon in homes and individual smoking histories. Several case–control studies have been published for which radon measurements had been made in homes and smoking histories had been collected; a further ten or so studies are currently in progress, mainly in Europe and North America. Most of the published studies are consistent with the miner data, although the confidence limits on the risk estimates derived are wide[29]. The one study that appears to be inconsistent was performed in an area of China with particularly high levels of other indoor air pollutants[34].

Results from the largest domestic case–control study to date were recently published by researchers in Sweden[35,36]. This study was based on 1360 lung cancer cases and roughly twice as many controls, and involved radon measurements in nearly 9000 dwellings occupied by the study subjects over a period of more than 30 years. The lung cancer risk was shown to increase to a statistically significant degree with increasing radon exposure. In particular, the relative risk was 1.3 (95% confidence interval 1.1–1.6) for an average radon concentration in the range 140–400 Bq m^{-3} and 1.8 (95% confidence interval 1.1–2.9) for concentrations in excess of 400 Bq m^{-3}. These risk estimates are consistent with those from the miner studies. Moreover, there was statistically significant evidence that the joint effect of radon and smoking exceeded additivity, and the data were consistent with a multiplicative effect.

This Swedish study therefore provides direct evidence of excess lung cancer risks following domestic radon exposures. The quantification of risk in all such studies is, however, hampered by a lack of statistical power in detecting low levels of risk and the problem of how to allow for the effects of smoking. For example, a very recent Canadian study[37] with about half the number of cases included in the Swedish study failed to detect an effect on lung cancer of residential radon exposure. Researchers are therefore discussing plans for pooling the various indoor studies, taking care to ensure comparability of data and using a common method of analysis. Such pooling should provide more precise risk estimates for exposures to radon concentrations of the order of the UK Action Level, although precise quantification may not be possible at lower exposures owing to the lower predicted risks and the difficulty in eliminating the residual confounding from smoking.

There is thus clear epidemiological and biological evidence for the role of radon in inducing lung cancer. Although there are some uncertainties in quantifying the risk, particularly at low radon exposures, the information available has allowed ICRP and other authoritative bodies to adopt risk factors that can be used as the basis of programmes to prevent excessive human exposure by adopting remedial and preventative measures.

3 Sources of radon in buildings

There are five possible sources of radon in buildings: the ground underneath the building, the building materials, the water supply, the gas supply and outside air. In the UK, most domestic water is supplied from surface waters, and no public supplies with high radon levels have been found[9]. Similarly, gas supplies have very low concentrations of radon and do not contribute significantly to indoor radon levels[38]. Radon in outside air contributes a background to radon concentrations indoors because of exchange with indoor air. Wrixon *et al*[9] surveyed outdoor radon levels around the UK and found a mean of 4 Bq m^{-3} with no significant variation. This is lower than that found in most countries because Britain is an island and the sea, unlike the land, is not a significant source of radon. The lack of significant variation may be due to the fact that the area with the highest radon levels in soil gas, the southwest, is relatively windy and is a peninsula. It remains possible, however, that places with particular topology and geology might be found where radon concentrations were higher. Building materials in the UK are not usually a significant source of radon and are estimated to contribute no more than a few becquerels per cubic metre in dwellings[39].

Most of the radon indoors is contributed by the ground underneath buildings. This is particularly true in buildings with high radon levels: no house above the Action Level for dwellings has been found in the UK where radon has come from sources other than the ground. The amount of radon entering buildings from the ground is influenced by the following four factors.

(a) *Radon concentration in soil gas* This depends on the concentration of the immediate precursor of ^{222}Rn, ^{226}Ra, in rocks and soils. Elevated levels of radium are found in some granites, limestones and sandstones and other geologies.

(b) *Permeability of the ground* This depends on the nature of the rock and soil under the building. Disturbed ground can have greatly increased permeability. Usually the radon comes from the ground within a few metres of the building, but if the ground is particularly permeable or fissured it may come from a greater distance.

(c) *Entry routes into homes* Concrete floors often have cracks around the edges and gaps around service entries such as mains water supply, electricity or sewage pipes. If homes have suspended timber floors the gaps between the floorboards are the major route of entry. Pathways for soil gas to enter houses are often concealed, and vary between apparently identical houses.

(d) *Underpressure of homes* Atmospheric pressure is usually lower indoors than outdoors owing to the warm indoor air rising; this creates a gentle suction at ground level in the building through the so-called 'stack effect'. Wind blowing across chimneys and windows can also create an underpressure (the 'Bernoulli effect'). The result is that the building draws in outside air, typically at the rate of one air change an hour. Most of this inflow comes through doors and windows, but perhaps 1% or so comes from the ground. In an average house, this amounts to a couple of cubic metres of soil gas entering the house each hour.

The radon concentration in a building depends on the rate of entry of the radon and the rate at which it is removed by ventilation. Increasing the ventilation rate will not always decrease the radon concentration, however, because ventilation rate and underpressure are related, and some ways of increasing ventilation, such as the use of extract fans or opening upstairs windows, can also increase the underpressure.

The factors described above vary greatly from one dwelling to another and lead to large differences in radon concentrations. The underpressure and ventilation rate also vary with time in all buildings. Underpressure tends to be highest in cold weather and at night because the difference in temperature between indoors and outdoors is greatest. At these times, ventilation routes such as windows and doors are generally closed, so a higher proportion of the air drawn in by underpressure comes from the soil, thus causing higher radon concentrations.

4 Measurement of radon levels

Measurements may be made of radon or radon progeny concentrations and may be instantaneous or last for days or months. The quantity to be measured should be as closely related as possible to risk and measurements should be cheap and convenient since large surveys need to be undertaken. As indicated above, essentially all the dose to lung arises from inhaled short-lived radon progeny. However, the dose depends[40] strongly on the 'unattached' fraction of these progeny (ie those in very small particles, up to 3 nm) and on the proportion of the attached progeny on small particles below 10 nm. The proportion of activity in these categories is dependent on the submicron aerosol concentration. Determination of the size distribution of radon progeny in air requires sophisticated equipment with skilled operators, precluding its use for large surveys. However, other things being equal, as the ventilation rate decreases the fraction of the total activity that is on submicron aerosols decreases while the total activity increases. As a result, the average radon gas concentration is a better surrogate for the activity on submicron aerosol particles and thus a better indicator of dose to lung[41] than is a simple measurement of the total energy potentially released by the decay of all the radon progeny.

Radon gas concentrations can be determined by taking samples of air and measuring the activity with appropriate electronic apparatus. However, such short-term measurements can be quite misleading in assessing the exposure of people to radon because of the considerable variations in levels from night to day (Figure 3) and from season to season (Figure 4).

To determine annual average values it is far better to make measurements lasting a few months so that the effects of short-term variations are averaged. This can be done by using passive radon detectors which are left in place in dwellings during the measurement period. The detector consists of a small chamber containing a sensitive plastic material, PADC[42]. Radon diffuses into the chamber and decays through its chain of decay products. Some of the alpha particles emitted damage the plastic detector, and this damage is revealed later by etching the plastic in a solution of sodium hydroxide. The damage tracks are counted with an automatic image analyser, and their number is proportional to the exposure of the detector to radon. The detectors are small enough to go through the post and are relatively inexpensive and so are suitable for large surveys of radon in dwellings.

The results presented in this report are based on measurements using this type of detector. Two detectors are sent to each home, one for the living room and one for an occupied bedroom, and left in place for at least 3 months. The seasonal variation in average radon concentrations has been previously assessed and used to derive correction factors for measurements lasting 3 or 6 months[43]. These factors have been applied in estimating the annual average radon concentrations in homes presented in this report.

For a discussion of quantities and units, see Appendix A.

5 Radon Affected Areas

5.1 Principles for declaring radon Affected Areas

In January 1990 NRPB recommended that the Action Level for radon in existing homes should be 200 Bq m^{-3} averaged over a year[10]. Parts of the country with 1% probability or more of present or future homes being above the Action Level should be regarded as Affected Areas[10]: such areas should be identified from radiological evidence. NRPB recommended that steps should be taken to reduce radon concentrations in dwellings which were found to be above the Action Level and that the appropriate authorities should delimit localities within the Affected Areas for preventative measures against radon in new dwellings.

Radon Affected Areas are defined using maps of mean radon concentrations in houses which are based on data from the radon surveys described in Section 6. Mapping may be carried out using various types of boundary between areas: local government boundaries, postcode boundaries, Ordnance Survey grid lines and others. Administrative areas are most appropriate when applying recommendations because the application of building regulations is most convenient on such a basis. However, administrative areas vary widely in size and shape, and techniques are not

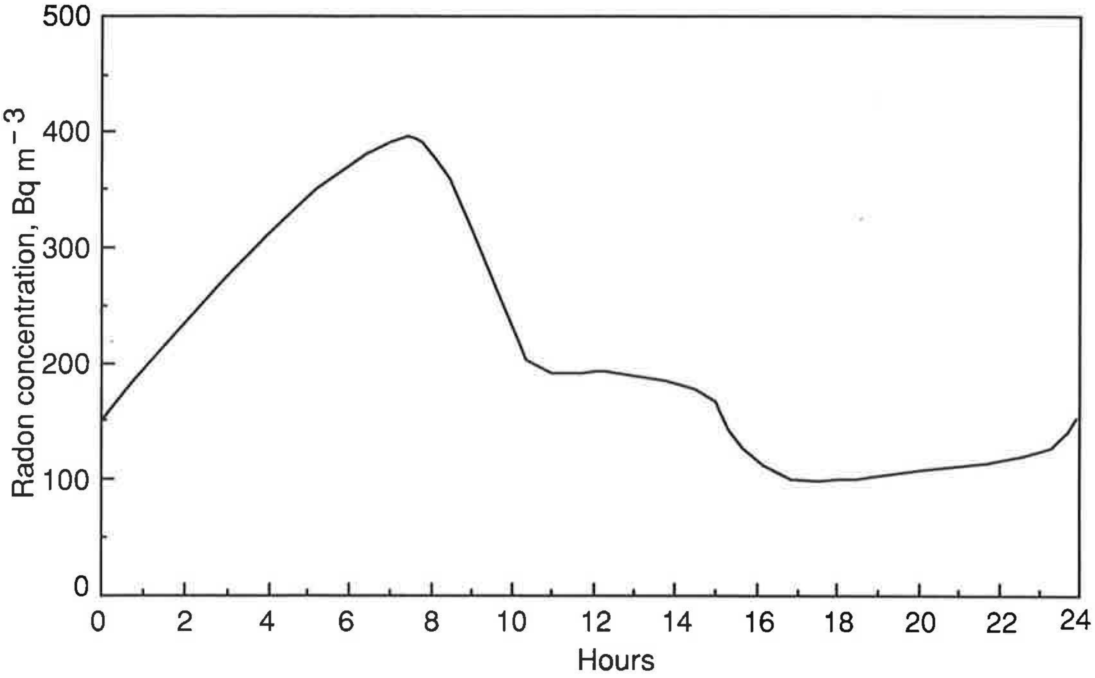

FIGURE 3 Variation of radon levels in a house over a 24-hour period

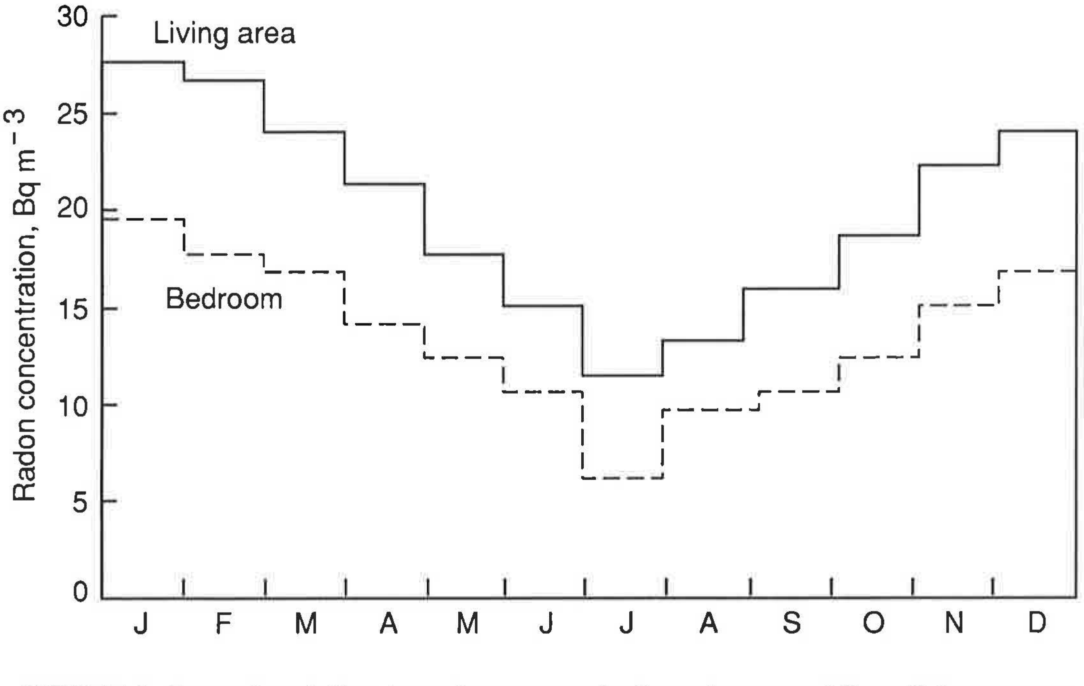

FIGURE 4 Annual variation in radon concentrations in ground-floor living rooms and first-floor bedrooms

available to apply any meaningful statistical smoothing between such areas. Such smoothing can be very important in improving the interpretation of the data and in reducing the need for extra measurements. Grid squares were chosen as the most appropriate basis for mapping radon concentrations in order to declare Affected Areas. The choice of size of grid square for mapping is a compromise between different requirements: small squares allow areas to be defined more precisely, but large squares contain more data and so allow more accurate estimates. After an examination of maps at different resolutions it was decided that 5 km grid squares gave the best compromise. Smaller squares than this are generally unnecessary for defining boundaries of Affected Areas and often contained few or no homes, and larger squares covered areas with different radon levels and could overlap significantly different administrative boundaries, such as parishes.

In order to identify radon Affected Areas, the initial national or regional surveys were, if necessary, augmented with extra measurements, typically with the aim of obtaining at least five measurements in each 5 km grid square. This goal cannot always be met, for example in areas of low population density, and data from adjoining squares are then used as described below.

As mentioned in Section 3, indoor radon concentrations are affected by indoor and outdoor temperatures, by winds, ventilation conditions and other factors. This leads to seasonal variations in radon concentrations, so the results of measurements made over short periods may be misleading. The average seasonal variation in radon in UK homes was used to derive correction factors to allow the annual average concentrations to be estimated in homes with shorter measurement periods of a few months' duration[43]. A correction was also applied to allow for the fact that the dwellings in the surveys are not always fully representative of the national housing stock. Thus, for example, radon levels tend to be higher in detached houses than in terraces and lower in flats.

It is possible to use statistical observations on the distribution of radon concentrations to improve estimates of the number of houses above the Action Level in a grid square, in part by using data from neighbouring squares in a data smoothing exercise. This increases the efficiency of the measurement programme and means that the overall number of measurements can be kept within reasonable bounds. The distribution of radon concentrations in homes is found to a good approximation to follow a log–normal distribution whether the sample is taken from the whole housing stock or a single grid square[9]. If the geometric mean (GM) and geometric standard deviation (GSD) of a log–normal distribution are known, the fraction of the distribution exceeding any threshold can be calculated. Smoothing techniques are used to improve the estimate of the fraction of the housing stock exceeding the Action Level in each grid square. First, however, the outdoor radon concentration is subtracted from each result as this improves the fit of the results to the log–normal distribution[42]. The values of the GM are smoothed between adjacent squares to remove any anomalies that might be caused by small numbers of results in some squares. The average value of GSD over the area of interest is used in estimating the fraction of the housing stock above the Action Level. For the county, region or district, a final Affected Area map is produced, showing areas with <1%, 1–3%, 3–10% 10–30% and >30% of homes above the Action Level. Contours other than 1% are shown on these maps in order to facilitate determination by government of localities requiring appropriate action.

For administrative and economic reasons, it is desirable not to have a patchwork of small Affected Areas around the UK. Thus isolated 5 km squares where mean domestic radon levels might exceed 200 Bq m^{-3} would not qualify for Affected Areas status if they were in a locality where concentrations were, on average, below this level. Similarly, isolated 5 km squares with lower radon concentrations would not be excluded from Affected Area status if they were in a locality where concentrations were generally above the Action Level. This approach is adopted because the proportion of homes above the Action Level in such isolated squares was usually not significantly different from the surrounding squares. A fragmented picture would also be confusing to local householders, and would not be helpful to the government in applying building regulations. In addition, it was difficult to define the borders of such small areas in the surveys which, for practical reasons, need to take a broader approach. Nevertheless, information about these isolated small areas with high radon levels in homes will be published by NRPB in due course so that householders and local authorities can make themselves aware.

5.2 Defined Affected Areas

NRPB has defined Affected Areas in Cornwall, Devon, Derbyshire, Northamptonshire, Somerset and parts of Scotland and Northern Ireland[43-46]. It recommended that the parts of the counties and regions shown in Figures 5–11 with 1% probability or more of being above the Action Level should be regarded as Affected Areas for the purposes of the NRPB statement on radon in homes[10].

It should be noted that further Affected Areas may be defined, particularly adjoining those already defined. Parts of Wales are also likely to be included. The measurement programmes on which the existing and future Affected Areas are based are discussed below.

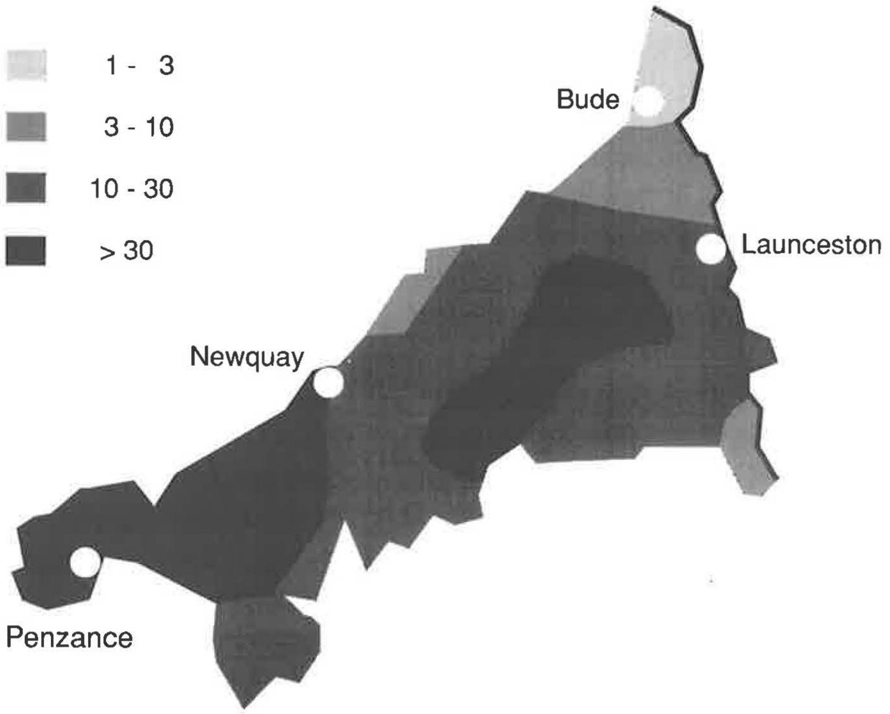

FIGURE 5 Percentage of homes with radon levels greater than 200 Bq m^{-3} in Cornwall

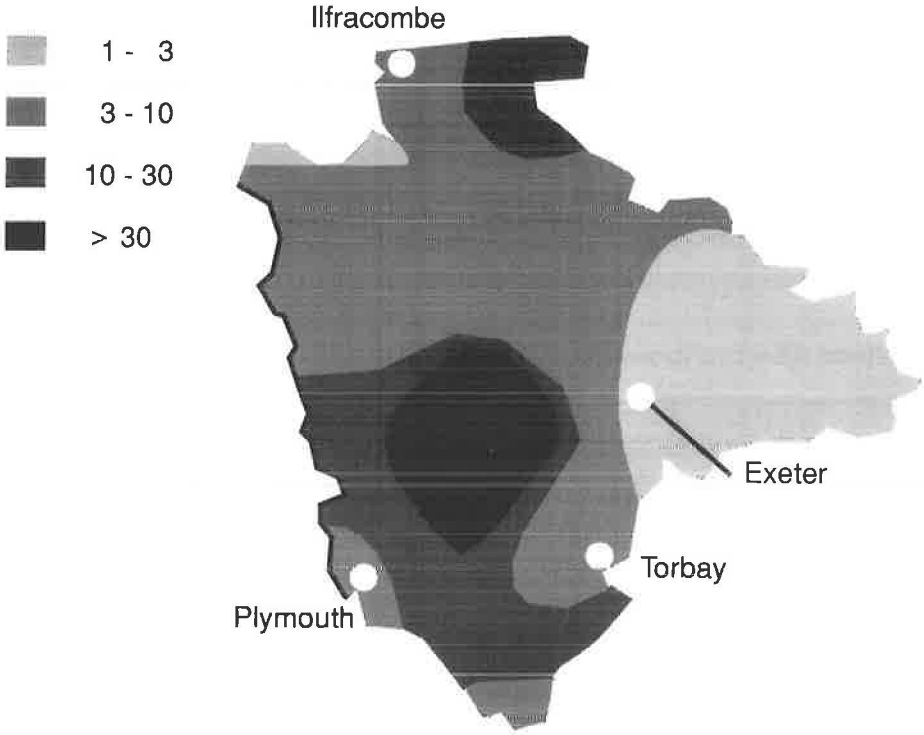

FIGURE 6 **Percentage of homes with radon levels greater than 200 Bq m^{-3} in Devon**

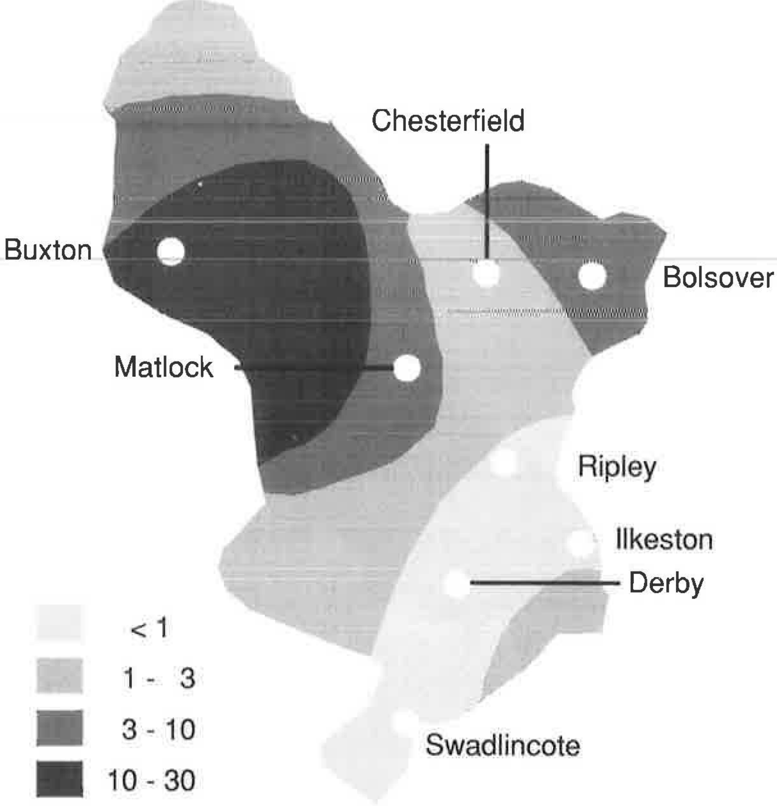

FIGURE 7 **Percentage of homes with radon levels greater than 200 Bq m^{-3} in Derbyshire**

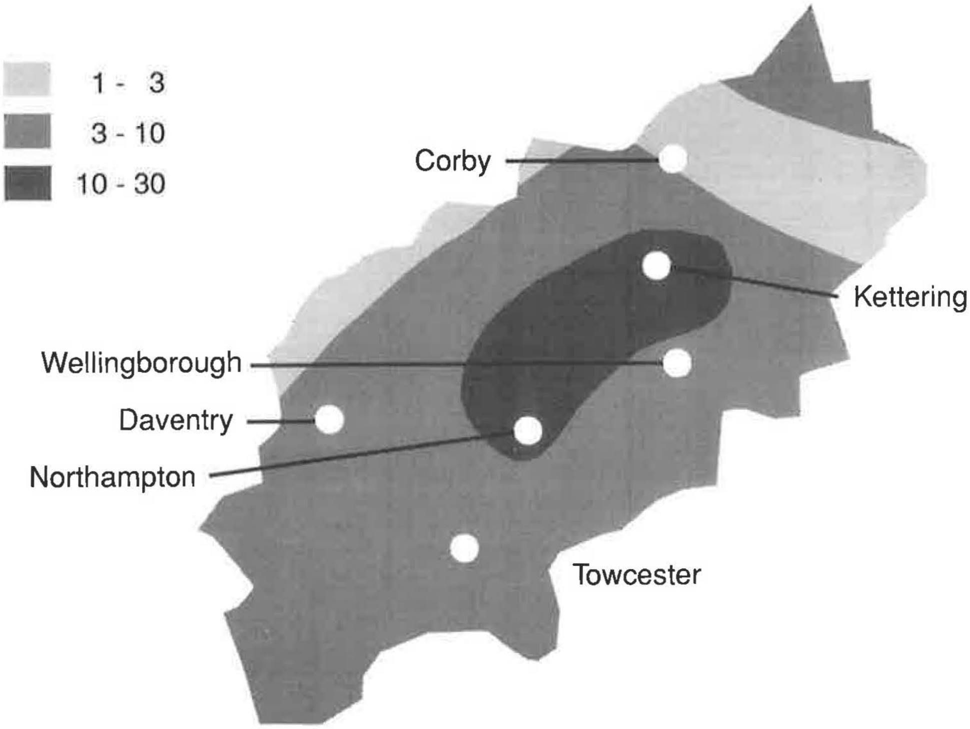

FIGURE 8 **Percentage of homes with radon levels greater than 200 Bq m^{-3} in Northamptonshire**

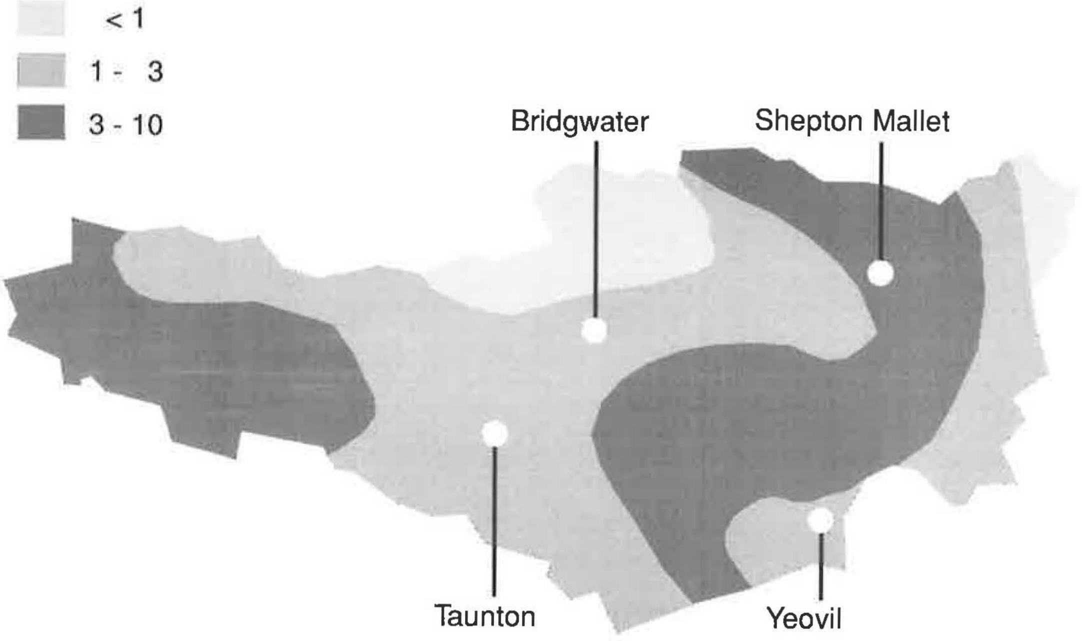

FIGURE 9 **Percentage of homes with radon levels greater than 200 Bq m^{-3} in Somerset**

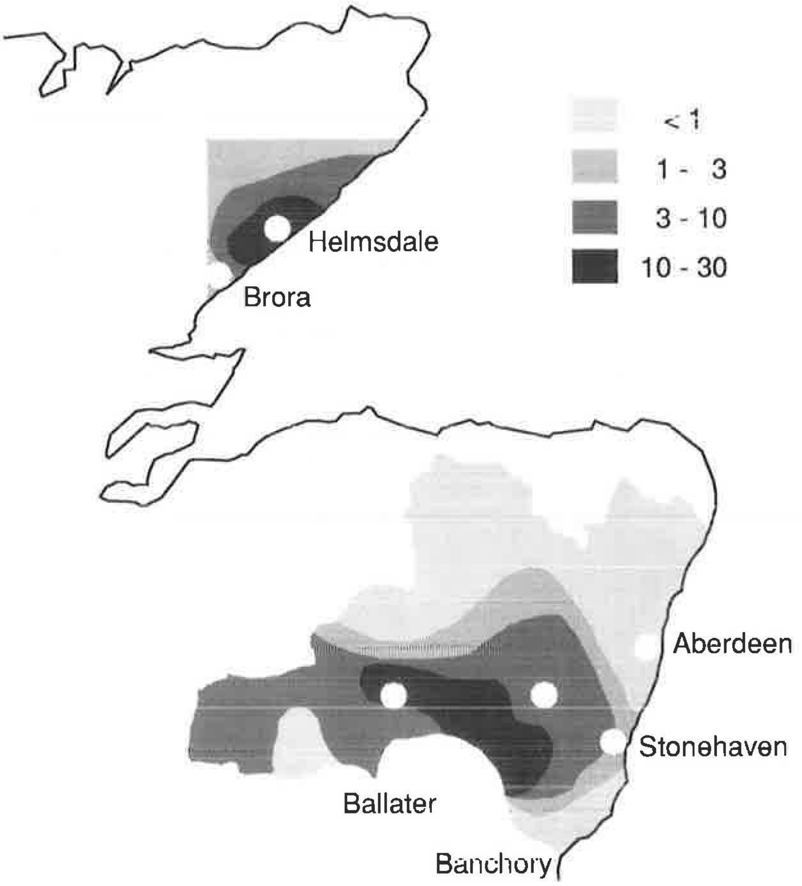

FIGURE 10 **Percentage of homes with radon levels greater than 200 Bq m^{-3} in Scotland**

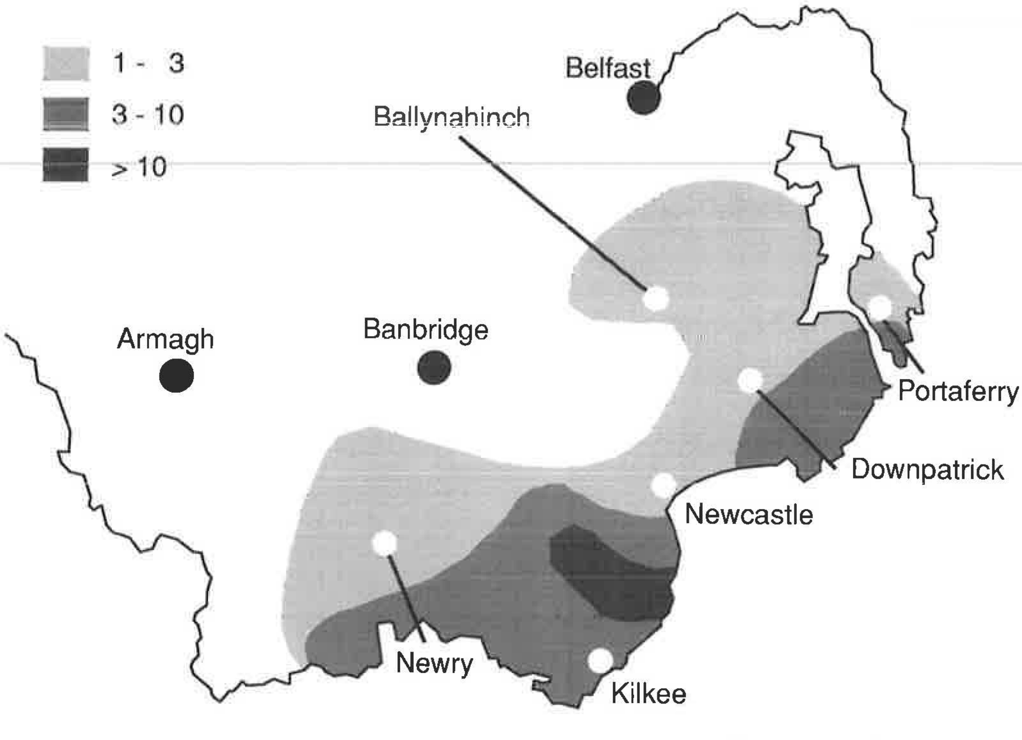

FIGURE 11 **Percentage of homes with radon levels greater than 200 Bq m^{-3} in Northern Ireland**

6 Radon surveys in UK dwellings

6.1 Introduction

At the time of writing, measurements have been made in over 200,000 homes throughout the UK in a series of surveys initiated by NRPB or undertaken on behalf of central and local government, other public bodies, private organisations and individual householders[47]. The structure and design of each survey varies somewhat to fulfil the specific objectives, but there is a common core to them all.

The common elements are a standard measurement protocol involving long-term integrated measurements with passive radon detectors (see Section 4), a unified house indexing methodology based on the postcode, a policy of confidentiality regarding individual results for particular properties and an efficient and streamlined system for the despatch and return of detectors, the notification of results, and the provision of appropriate advice. The standard measurement protocol ensures that data from different surveys are fully compatible. The postcode indexing allows the use of the hierarchical nature of the postcode, rapid linkage to other data sets such as Ordnance Survey grid reference, administrative divisions, and population data; it also facilitates contact with householders as the postcode is normally well known and can be quoted in telephone conversations and included, as a matter of course, in correspondence. Confidentiality is an important safeguard for the householders since it gives them the assurance that results will not be divulged to third parties. The efficiency of the surveying techniques enable measurements to be made in typically 70,000 homes each year in a cost-effective manner[48].

6.2 Survey types

The four main types of survey may be termed representative, directed, general and responsive. Representative surveys aim to determine typical domestic radon levels across an area of interest. Directed surveys try to pick out high radon houses using data already known about the area, whereas general surveys target all dwellings in particularly high radon areas. Responsive surveys are stimulated by requests from householders. In the first three types of survey, contact with the householder is initiated by NRPB or some other organisation working with NRPB. Contact is normally by letter, but occasionally by personal visit. Extensive use is made of the Post Office address file, available on CD-ROM, which lists every address in the UK[49]. For responsive surveys, the initial contact is from the householder, often as a result of information campaigns or media coverage.

The selection of truly representative samples, whether by population or by area, is crucial to the success of surveys designed to provide the average radon level for selected parts of the UK such as county, district or square of the Ordnance Survey grid. To obtain a population-weighted sample of, say, a county, all residential addresses in the county are listed in postcode order using the Post Office address file and a random sample of addresses is selected. The householders at the selected addresses are contacted and invited to participate. Not all householders agree to do so; the response rate varies but is normally between 20% and 25%. The initial sample size must be large enough to produce the required number of measurements, and any iterative procedures to complete parts of the sample must avoid bias.

Directed surveys are a means of increasing the chances of finding dwellings with elevated radon levels. Houses in small areas which are known to have high levels of radon are used as starting points, surrounding properties are identified, and a sample of the households selected and invited to have a radon measurement. General surveys are the extension of this technique for particularly high radon areas. All the addresses in the area are identified and letters of invitation sent to all householders who have not already had a radon measurement.

In contrast to other studies, it is householders who initiate measurements in responsive surveys. These normally originate in the form of written requests to NRPB, although a significant minority are received through the environmental health departments of local authorities or by telephone. Such requests for measurement are usually the result of leaflet drops or other initiatives organised by central government, public information campaigns by local authorities, or some form of media coverage. The last of these is sometimes spontaneous but more often follows a press release on the publication of a report on radon or formal advice to government. There is also a steady and growing number of requests, directly from householders, following surveyors' reports for mortgage companies or house-purchasers and generally because of the increasing public awareness about radon in buildings.

In addition to the measurement programmes mentioned above, measurements of indoor radon levels are carried out in support of epidemiological studies, in particular the case–control study of lung cancer in Cornwall and Devon being conducted by the Imperial Cancer Research Fund in conjunction with NRPB and the leukaemia study organised by the UK Coordinating Committee for Cancer Research. Such studies may need an assessment of the radon exposure of specific people over the past 30 years or so by measuring the radon level in every dwelling occupied during this period. Since radon concentrations vary from house to house it is important to place detectors in the actual dwellings occupied by the people in question rather than in a sample house from the same area. This in turn requires much more effort, even to the extent of personal visits to past dwellings by trained interviewers, if there is no response to a sustained postal approach.

The publication of the results of the initial population based UK survey conducted by NRPB and more detailed surveys, in selected areas where raised levels were expected to occur, laid the groundwork for all of the later studies[9]. Credit here must be given to the Commission of the European Communities which supported the initiatives. The number and extent of the later studies in each of the constituent parts of the UK have varied according to the estimated severity of the problem and the programmes of the relevant government departments. These studies are now discussed in more detail.

6.3 England

The early surveys of domestic radon exposures in England had indicated that levels were highest in the southwest, and the Department of the Environment commissioned further studies, at first in Cornwall and Devon. Directed, representative and responsive surveys were undertaken. The representative survey provided data for the delineation of radon Affected Areas and the directed surveys facilitated the discovery of homes above the Action Level. A measurement service was also made available to householders throughout England and was financed by DoE except in areas where radon levels were known to be low. Following the formal advice to government that the whole of the counties of Cornwall and Devon should be regarded as an Affected Area[44], DoE arranged for an explanatory leaflet, offering free measurements, to be delivered to each of the 650,000 homes in the two counties[50]. This initiative has so far enabled measurements to be completed in 34,000 homes throughout Cornwall, 15% of the total housing stock, and in over 57,000 homes throughout Devon, 11% of the housing stock[51]. Similar exercises have since been undertaken in the counties of Derbyshire and Northamptonshire and will take place soon in Somerset: Affected Areas have been designated in all these counties. Some of the district councils in the Affected Areas have also commissioned surveys of a sample of council-owned dwellings.

A comprehensive survey covering all of England is virtually complete. The aim is to draw a definitive radon map of the whole country and identify any other areas with raised radon levels that might qualify for Affected Area status. The plan, wherever possible, is to measure at least 12 homes evenly spread throughout each 10 km square of the Ordnance Survey grid. Where mean radon concentrations are close to the Action Level, approaches are made to other householders to obtain five measurements in each 5 km grid square. This survey involves a total of about 18,000 measurements.

6.4 Scotland

In the light of the findings of the initial UK survey, Scottish Office Environment Department commissioned further surveys in parts of Grampian and Highland Regions. Directed, representative and responsive surveys, similar to those in England, were undertaken, although on a smaller scale appropriate to the lower population density. Following the publication of the results and the declaration of Affected Areas in parts of Kincardine and Deeside and Gordon Districts in Grampian Region and in parts of Caithness and Sutherland Districts in Highland Region[45,52], Scottish Office Environment Department has published an information leaflet for householders[53] and commissioned further surveys.

The leaflet has been made available to the public in Affected Areas through district councils. It explains the facts about radon, has clear maps of the Affected Areas and recommends concerned owner-occupiers to write to NRPB for a measurement. Furthermore, NRPB has been commissioned to write to each of the 2500 homes with the highest probability of elevated levels, enclosing a copy of the leaflet and encouraging householders to apply for a measurement.

All measurements, for owner-occupiers in the Affected Areas, are sponsored by Scottish Office and are therefore free of charge to the householder. At the time of writing, over 800 householders have taken up this offer of free measurements. In addition to this initiative taken by central government, some local district councils, housing associations and private estates have commissioned surveys in the Affected Areas. These are in properties owned by the organisations and occupied by tenants. To date, a total of 900 dwellings are being monitored in these surveys.

In the longer term, Scottish Office Environment Department intends to commission measurements throughout Scotland to develop a radon map of the whole country. The intention is to follow the methodology used elsewhere in the UK. The procedure is based on the 10 km Ordnance Survey grid. A random sample of householders in each grid is identified from the Post Office address file and invited, by letter, to participate. Experience has shown that about one in five householders so contacted agrees to take part in the survey.

6.5 Wales

The Welsh Office commissioned an outline representative survey of the country and more detailed directed surveys in those areas where the initial UK survey had shown elevated radon levels. A smaller responsive survey was also undertaken. Following the publication of the results of these studies in 1992[54], further directed and representative surveys were commissioned. The directed survey, concentrating in those parts of the country where high levels have been found, will provide data to delineate the boundaries of any Affected Areas. These more detailed surveys are being undertaken in the districts of Alyn and Deeside, Delyn and Glyndwr, Radnor, Ynys Mon, Preseli Pembrokeshire and South Pembrokeshire. The representative survey, covering all of Wales, will facilitate the completion of a radon map of the country and will show any other areas with raised radon levels.

In addition, the policy of offering measurements on demand to concerned householders is being continued. Such measurements are free of charge to the householder except in areas where the levels are known to be low.

The total number of houses to be measured under the Welsh Office scheme during the current year is 2500. To date, detectors have been sent to 2200 home, the majority in the directed and representative surveys. Some smaller surveys are also being carried out on behalf of local district councils. Letters and leaflets for the Welsh campaigns are in both English and Welsh.

6.6 Northern Ireland

The initial UK survey did not discover any homes in Northern Ireland with radon levels in excess of 200 Bq m^{-3}, but an analysis of the distribution indicated that there are likely to be some areas, notably in the granite regions of the southeast, where a few per cent of dwellings might be above the Action Level. The Environment Service of the Department of the Environment for Northern Ireland commissioned more detailed representative and directed surveys – the latter in parts of the counties of Down, Armagh, Tyrone, and Fermanagh. The results of these surveys were published in 1989[55]. The indications were that, for the majority of the population of Northern Ireland, indoor radon was not a problem but that several hundred dwellings, many in the southeast, would have radon levels in excess of 200 Bq m^{-3}.

The Environment Service commissioned further surveys to complete the radon map for the whole of Northern Ireland and to provide data to delineate the boundaries of an Affected Area. The policy of offering surveys on demand to householders without charge was also continued. The results of these studies and formal advice of the Affected Area in Down and Armagh were published in 1993[46,56]. Following publication, the Environment Service made arrangements for radon measurements to be available, free of charge, to all householders within the Affected Area. NRPB was commissioned to write to the householders with details of the measurement scheme and to encourage them to participate. To date, letters have been sent to over 13,000 householders in the areas with the highest probability of elevated levels and some 2,800 have agreed to a survey and have been sent detectors. In addition, further studies are planned in other, much smaller areas of Northern Ireland where the indications are that a few homes may have radon levels slightly above the Action Level.

6.7 Results

Detailed results for each constituent country of the UK have been published separately at appropriate stages in the various programmes. These detailed reports will be updated in due course when further major parts of the programmes currently in progress are sufficiently advanced. However, representative surveys and responsive measurements are still being made, and a brief summary of the results currently available for the UK as a whole is given here.

Table 2 provides a summary of the available data by country and shows that almost 20% of the estimated 100,000 homes with radon concentrations above the Action Level have been identified to date. This percentage is mainly determined by England where substantial directed surveys have been completed. It is expected, however, that increasing percentages will be found in Scotland, Wales and Northern Ireland.

TABLE 2 Radon measurements in the countries of the UK

	England	Scotland	Wales	Northern Ireland	United Kingdom
Total housing stock	19,000,000	2,000,000	1,100,000	600,000	22,000,000
Population weighted average radon concentration (Bq m^{-3})	21	16	20	19	20
Number of results available	185,000	2,600	1,700	1,600	191,000
Number in progress	24,000	300	130	700	25,000
Number at or above the Action Level	17,500	83	85	35	17,700
Number estimated above the Action Level	100,000	2,000	3,000	500	100,000
Percentage above the Action Level found	17.5%	4%	3%	7%	18%

Table 3 has similar data for each county or region which has been wholly or partially declared a radon Affected Area. It is noteworthy that around one-quarter of the estimated total number of homes with elevated radon levels have been identified in the English counties of Cornwall, Devon and Northamptonshire. Nevertheless considerably more work needs to be done to achieve the target of identifying the majority of homes above the Action Level by the year 2000, the target set by the Select Committee[11] and endorsed in principle by government[12].

The three-dimensional map in Figure 12 indicates the wide variation in radon levels across the UK. It has been constructed from the arithmetic mean indoor radon levels found in each 10 km square of the Ordnance Survey grid. The relevant country average has been used for squares where insufficient numbers of results are presently available. As more measurements are made it will be possible to refine this map further. However, Affected Areas will be declared on the basis of maps generated as described in Section 5. The purpose of the three-dimensional map is purely illustrative.

7 Countermeasures in new and existing dwellings

The preceding sections show how NRPB has identified areas of the country where high natural levels of radon are likely to occur and also houses that have high radon concentrations. This, of itself, does not solve the problem. It is necessary firstly to ensure that the radon concentration is reduced in those houses where it is high and secondly to ensure that new houses are built in such a way that high radon levels do not arise. Reducing high radon levels in existing houses is known as remediation and ensuring that levels are low in new houses as prevention. These topics are outlined in turn below. A more detailed discussion is given in Appendix B.

TABLE 3 Radon measurements in Affected Areas

	Cornwall	Devon	Derbyshire[*]	Northamptonshire	Somerset[*]	Grampian[*]	Highland[*]	Down[*] and Armagh
Total housing stock	200,000	440,000	280,000	245,000	190,000	65,000	1,500	70,000[†]
Population weighted average radon concentration (Bq m^{-3})	114	72	41[†]	46	58[†]	16[†]	28[†]	59[†]
Number of results available	34,000	57,300	25,400	42,000	5,000	1,600	440	1,500
Number in progress	200	400	400	16,700	100	300	10	1,000
Number at or above the Action Level so far	8,500	4,100	1,600	2,400	210	54	27	35
Number estimated above the Action Level	36,000	17,000	13,000	10,000	4,000	1,000	100	200[‡]
Percentage above the Action Level found	24%	24%	12%	24%	5%	5%	27%	18%

[*] Only parts of these regions have been declared Affected Areas; the figures apply to these areas.
[†] Apply to whole county/region.
[‡] Approximate figure.

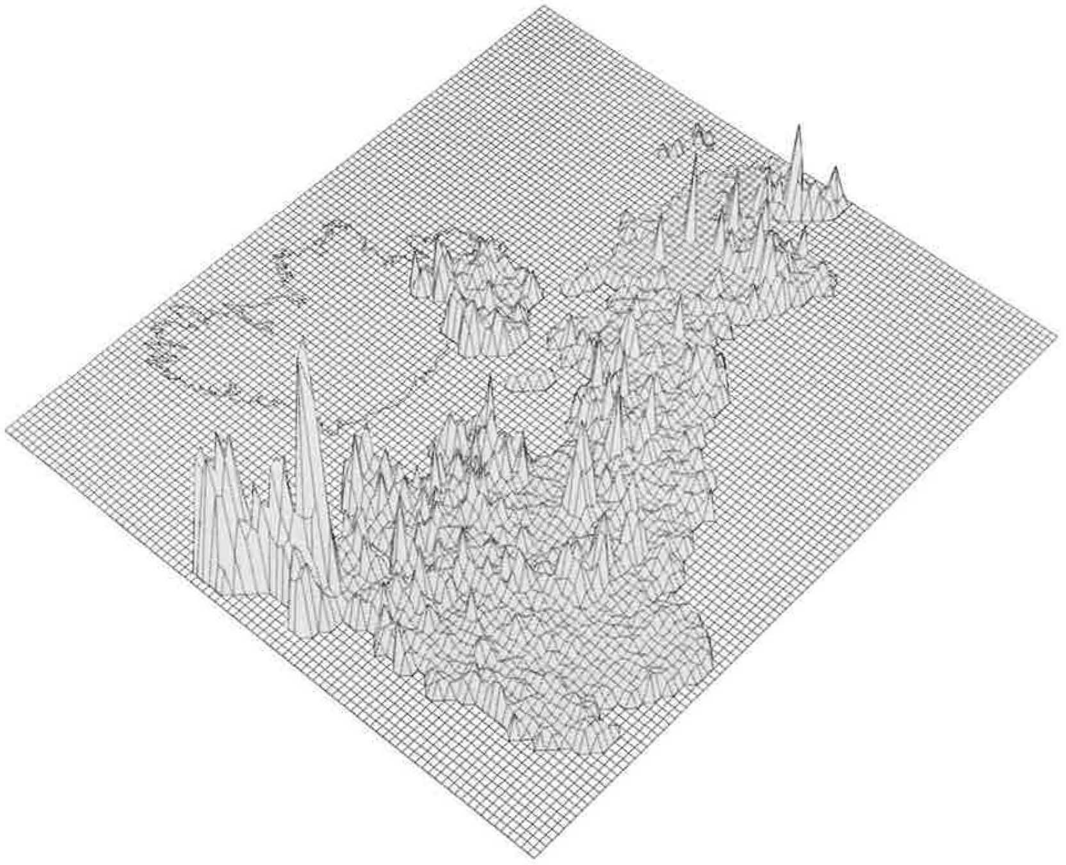

FIGURE 12 Surface map of radon levels in UK dwellings

7.1 Remedial measures in existing dwellings

Government has accepted NRPB recommendations and advises the owners of houses found to have radon concentrations above the Action Level of 200 Bq m^{-3} to undertake remedial work to reduce them. The Action Level is not a boundary between safe and unsafe radon concentrations, and householders are advised to reduce levels as much as reasonably possible and not just to undertake the minimum necessary remedial work to edge radon concentrations below 200 Bq m^{-3}. Similarly, householders who find that their radon levels are approaching the Action Level, although not above it, are invited to consider remedial work.

As mentioned earlier, high radon levels in houses are caused by the flow of soil gas through gaps and cracks in the floors. This flow is driven by small differences in pressure between the air in the soil and in the houses. Remedial measures can be chosen to reduce or eliminate the pressure difference, seal the floor of the house, or remove the radon once it has entered the house, usually by increasing ventilation.

The Building Research Establishment (BRE) has undertaken a comprehensive study of various radon remedial measures in buildings. Reduction factors achieved by various methods are given in Table 4, where the reduction factor is the ratio of a seasonally-corrected 3 month measurement before action to that after action was taken. The arithmetic mean of the reduction factors is much affected by the occasional occurrence of an atypical high value. The geometric mean is not so affected and is, in most cases, more representative of the reduction likely to be achieved. The effectiveness of each method is now discussed.

TABLE 4 Effectiveness of different approaches to reducing radon levels in homes. The reduction factor is calculated as the ratio of radon levels before and after remedial action was taken

		Reduction factor			
Method	Number of houses	Arithmetic average	Geometric mean	Maximum	Typical cost (£)
Additional natural ventilation	48	3.0	1.9	25	300
Positive ventilation	95	3.2	2.2	24	500
Additional natural ventilation of the underfloor void	82	2.6	1.8	23	300
Mechanical ventilation of the underfloor void	33	6.1	2.6	58	300
Sealing only	53	2.1	1.4	32	1000*
Membrane covering floor	24	2.0	1.7	6.5	700
Sump installations	258	16	8.4	130	1000†
Combination of methods without sump	79	2.8	2.0	17	700

* £50 if undertaken by the householder.
† £300 if undertaken by the householder.

Increasing the natural ventilation of the house, for example by trickle vents on windows, will help dilute the radon but is unlikely to reduce radon levels by a large factor. Positive ventilation, in which filtered loft-space air is blown into the occupied spaces by a small fan, is only marginally more effective. Natural or mechanical ventilation of the underfloor void usually give reductions similar to those from increased ventilation of the house itself.

An instinctive reaction to the knowledge that radon is entering the house through cracks and gaps in the floor is to try to seal them. This may also be attractively cheap if the householder is prepared to do the work, although it is often expensive if contractors are employed. However, a very high proportion of the openings must be sealed for this measure to be successful: if only half the openings are blocked, the radon will come in almost twice as fast through those that remain[57]. An alternative to sealing cracks in the floor is to lay a radon-proof membrane across it. This is often ineffective, however, and can lead to serious problems with rot in timber floors if ventilation is inadequate. The method is no longer recommended.

A sump system[58] is one where a small cavity is excavated below a ground-supported concrete floor, or below a concrete oversite under a suspended timber floor. Sumps may also be created by excavating outside an external wall and putting a pipe through the foundation wall to connect to the underfloor space. A pipe extends from the sump to a point away from the building or internally through the roof, and is terminated by a suitable fan. The exhaust from the fan must be well away from windows and doors. The fan creates a reduced pressure in the sump and draws soil gas with radon into the sump and discharges it to the atmosphere. Sumps can be installed by the householder, but a considerable degree of expertise is required to make them effective and unobtrusive.

Most houses with high radon levels can be remedied quite easily although there have been some instances where the action taken was ineffective (see Figure 13). The procedure most likely to be successful and to show the largest reduction in radon level is the sump. Where sumps have

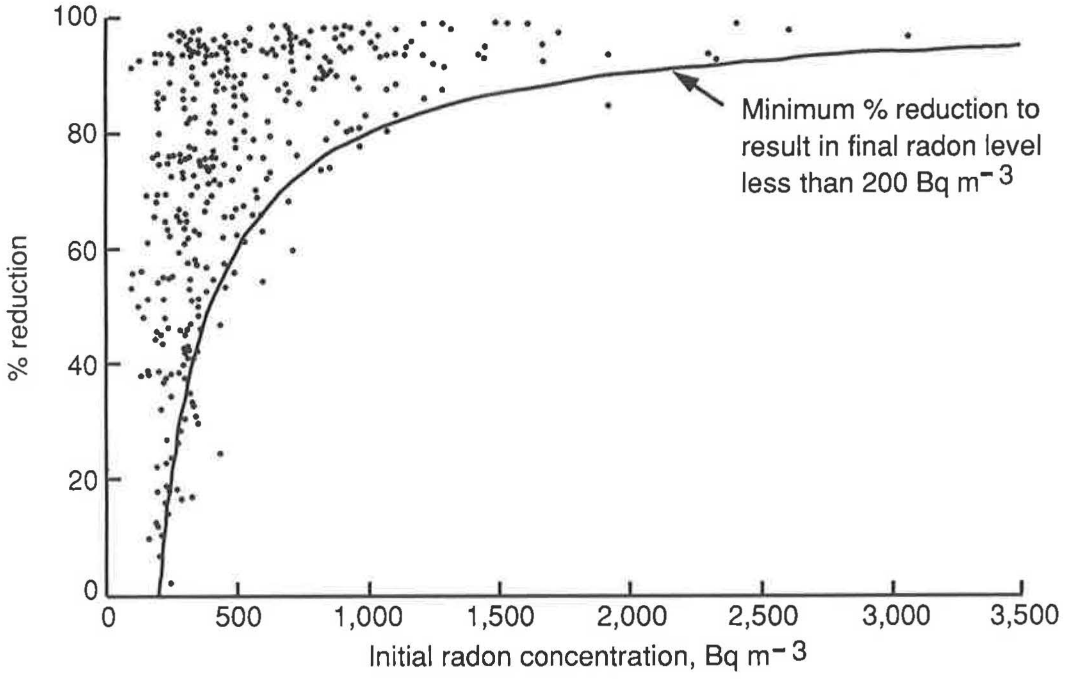

FIGURE 13 Reduction in radon level by remedial actions

failed, the reasons have generally been that the fan was of an inappropriate type, or the exhaust was discharged in the loft-space or too close to windows.

Typical costs of radon remedial works vary from a few tens of pounds where the householder attempts to seal cracks and gaps in the floor to about £1000 for a sump system installed by an experienced firm with a guarantee of success. More details can be found in Appendix B. The cost of remedial work is not great, either in absolute terms or as a proportion of the value of the property.

7.2 Radon preventative measures in new homes

In order to ensure that new houses are most unlikely to have high radon levels, the Building Regulations 1991[59] stipulate that radon preventative measures must be incorporated into the construction of new homes in specified areas. In support of the Regulations, BRE has published guidance on radon preventative construction[60]. The protective measures for new homes are either:

(a) full preventative measures, that is a barrier to soil gas entry that extends across the entire foundation of the building and provision for future subfloor ventilation or depressurisation,

(b) provision for future subfloor ventilation or depressurisation.

The radon-proof barrier is known as primary protection and the provision for subfloor ventilation or depressurisation (to be activated if necessary after the building is occupied) as secondary protection. Full preventative measures typically cost between £180 and £250. Secondary measures cost between £50 and £100[61]; in addition, there will be running costs for the pump of about £50 per year. As experience is gained the cost of installing preventative measures is falling. The possibility of using the same membrane as a barrier against both moisture and radon suggests that the difference in cost between full and secondary measures might, in due course, become negligible. As well as ensuring a decisive reduction in the number of homes above the Action

Level, the introduction of preventative measures in new homes will, over time, help to reduce the collective dose to the population.

In the most affected localities, full and secondary radon preventative measures are required; in the less affected localities, secondary preventative measures alone are sufficient. The locations requiring preventative measures in new dwellings are, for administrative convenience, defined by parish in the guidance[60] published by BRE for England and Wales. In Scotland and Northern Ireland, they are defined on maps by the appropriate government departments.

BRE has been studying the effectiveness of radon preventative measures in Affected Areas and has found[62] that they are normally very successful. In homes with block and beam suspended concrete floors, only 1% of those incorporating preventative measures exceeded the Action Level, whereas 21% of those without preventative measures did. With ground-supported concrete floors, the figures were 7% and 25% for those with and without preventative measures, respectively; most of the failures making up the 7% were on one building site and were caused by the builder rather than the design[60].

8 Public attitudes to radon

Large sections of the population are very concerned about radiation arising from the nuclear fuel cycle despite the fact that doses are extremely small. It is therefore something of a paradox that there is much less concern about radon which delivers doses orders of magnitudes higher to many more people. Social scientists explore the reasons for this difference using concepts such as the familiarity of the hazard, its controllability, and the degree to which exposures are voluntary[63]. Such discussions are beyond the scope of the present report. However, it has been pointed out that it is strikingly inconsistent to argue that the fact that radiation in general, and radon in particular, is colourless, odourless and tasteless explains both the public's fear of man-made radiation and the relative unconcern at that from natural sources[63].

The fundamental objective of the radon programme for existing houses is to identify those with high radon levels and to have effective and durable remedial work carried out. The various steps in this process have been examined in a recent report[64]. In simplified terms, householders in Affected Areas should:

(a) be aware of the potential risks from radon and the possibility of free measurements,
(b) request a measurement, place the dosemeters, and return them for assessment,
(c) recognise the need for action if the radon levels are high,
(d) if necessary, select and implement an appropriate remedial measure and retest to ensure that the remedy was effective.

The author of the report points out that improving the percentage of householders moving from any of these steps to the next will improve the overall effectiveness of the programme and makes a number of useful suggestions for each stage.

There is little doubt, however, that the step about which householders are most hesitant is the final one – simply taking action. Unless householders apply for a second measurement to confirm the effectiveness of remedial work, NRPB has no automatic way of determining the number who do take action. A recent investigation by NRPB[65] suggests, however, that only about one in ten do so.

It is clear therefore that there is substantial scope for improving the efficiency of the radon programme by increasing the percentage of owners with homes above the Action Level who undertake remedial measures. Some improvements have already been made. Early NRPB advice, based on sound logic but poor psychology, was that the timing of remediation should be determined by the degree to which a dwelling exceeded the Action Level; remediation was less urgent in houses only just above the Action Level. This invitation to procrastination has now been dropped. Inadequate access to sound advice about options for remediation and probable costs has also been a problem but matters are now much improved. It is likely nevertheless that a number of other techniques of communication will need to be applied in order to raise public awareness and responsiveness to radon. It is encouraging that awareness of the potential problem does seem to be increasing. It is also encouraging to note that a number of mortgage companies are now requiring prospective purchasers to have radon levels measured and, if necessary, reduced.

9 Summary

The UK has responded positively to the realisation that indoor exposure to radon is a hazard to public health. NRPB advised central government on the broad features of anti-radon strategies and government departments throughout the UK are implementing them. Common features of the implementation have been government funding to identify high radon areas and then to encourage measurements, free of charge, for householders within these areas. Fairly good progress is being made towards the goal of identifying the majority of houses above the Action Level by the year 2000. It is important that this programme be continued and complemented by measures to persuade owners with houses above the Action Level to remedy them in a timely and inexpensive manner.

10 Acknowledgements

The development of the UK radon programme owes a great deal to numerous colleagues and organisations. We are particularly grateful to members of staff of the Department of the Environment, the Scottish Office, the Welsh Office, and the Department of the Environment for Northern Ireland who were responsible for refining and realising the recommendations put to them by NRPB. Practical questions about radon control frequently go to local councils, and we are especially grateful for the support of members of the Chartered Institute of Environmental Health. Colleagues at the Building Research Establishment have been responsible for developing and testing many of the radon remedial and preventative measures, and the discussion of these topics leans heavily on their work. We also acknowledge the many colleagues at NRPB who have contributed to the radon programme. Research on radon countermeasures is funded by the Commission of the European Communities under contract number F13P CT92 0064.

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APPENDIX A

Quantities and Units Used in Radon Surveys

The standard SI unit of *activity* is the becquerel (Bq). An activity of 1 Bq corresponds, on average, to one nuclear disintegration per second. Most of the data given in this report are in terms of *activity concentrations*, becquerels per cubic metre (Bq m^{-3}), the activity in a cubic metre of, for example, room air.

Time integrated exposures to radon are given as Bq m^{-3} h or Bq m^{-3} y, where h and y stand for hours and years. Thus spending 8000 hours in an atmosphere containing an activity concentration of 100 Bq m^{-3} of radon would give a time integrated exposure of 8 10^5 Bq m^{-3} h or about 70 Bq m^{-3} y, given that people usually spend about 80% of their time at home indoors.

In radon work it is convenient to consider the *potential alpha energy concentration* (PAEC) of a mixture of short-lived radon progeny in air. This is the sum of the alpha energies that the progeny will emit in decaying to long-lived radionuclides. The units are J m^{-3}. At radioactive equilibrium, if no progeny are lost (for example, by plating out or by being swept away by ventilation), there will equal activities of radon and all its progeny in air. This situation is rarely approached in practice and the *equilibrium equivalent radon concentration* (EER) is the concentration of radon gas, in equilibrium with its short-lived progeny, which has the same PAEC as the actual mixture in question.

The *equilibrium factor*, F, is the ratio of the PAEC for the actual mixture of progeny to that which would apply at radioactive equilibrium. This is the same as the ratio of the equilibrium equivalent concentration of radon to the actual concentration. F is normally found to be in the range 0.3 to 0.5 in homes and in above-ground workplaces; the values in mines are much more variable.

The historical unit of PAEC, the 'Working Level', is still encountered. This was originally defined as 100 pCi l^{-1} (3700 Bq m^{-3}) of radon gas in equilibrium with its progeny. The definition has since been modified slightly (by 1.2%). In SI units the Working Level (WL) is defined by 1 J m^{-3} = 48017 WL. A Working Level Month (WLM) is defined as exposure to 1 WL for a working month of 170 hours. With an equilibrium factor of 0.5, 1 WL is approximately equal to 7500 Bq m^{-3} of radon and 1 WLM to a radon exposure of 1.26 10^6 Bq m^{-3} h or about 144 Bq m^{-3} y.

APPENDIX B

Radon Remedial and Preventative Measures in Dwellings

1 Radon remedial measures in existing dwellings

1.1 Introduction

NRPB has data on radon measurements of 3 months or longer duration in over 200,000 homes. The annual average radon level in close to 20,000 of these homes exceeds the UK Action Level of 200 Bq m^{-3}. These householders have been informed of the situation and provided with information on ways[1] to reduce radon levels. If, as advised, the householder decides to take action to reduce radon levels in the home, NRPB offers follow-up monitoring to determine the effectiveness of the action taken. This is free to the householder, provided that details of the action taken are supplied and the action is likely to result in a sustainable reduction to a value substantially below the Action Level.

This section of the appendix describes methods that can be used to reduce radon levels if these are found to be high. It also discusses the durability of such remedial work. The discussion aims to be comprehensive in its coverage and describes some measures that do not find wide practical implementation in the UK.

The Building Research Establishment (BRE), as part of its research programme, has planned and supervised radon remedial works for some homes having the highest radon levels so far discovered in the UK. Some results from the BRE research programme together with early results from the NRPB retest programme[2] for all householders have been published. The results from 592 householders on the NRPB retest database are discussed here.

1.2 Methods for reducing radon in existing dwellings

BRE has undertaken a comprehensive programme to investigate the effectiveness of various remedial measures. Many actions may be taken to reduce radon levels in buildings. Some, however, are unlikely to be sustained, eg more frequent window opening, while some permanent installations are more likely to be successful, and bring about larger reductions in level, than others. The likelihood of success and magnitude of reduction in radon level required are important factors, but cost and degree of disturbance during installation are also important considerations for homeowners.

It has been found that, where elevated levels of radon in indoor air occur, the reason is usually the bulk movement of radon-laden soil gas into the building from the subjacent ground[3]. Diffusion of radon from building materials, or through the fabric of the building in contact with the ground, does not usually account for the observed radon levels in indoor air. That diffusion of radon into buildings is a minor contributor to indoor radon has been demonstrated elsewhere, including the UK. Only in Sweden has a building material[4] been a significant source of indoor radon. That material was lightweight alum shale based concrete, having a typical ^{226}Ra content of 1300 Bq m^{-3}, and manufactured from 1929 until production was discontinued in 1975.

The air pressure at the level of the lowest floor of a building is frequently somewhat lower than that outside the building or in the soil. The reduced pressure is due to the effects of higher temperatures indoors than outdoors (the stack effect), and of wind blowing over the building. These small differences in pressure, typically 5 Pa, induce soil gas, carrying radon, to move into the building through penetrations in the fabric of the building linking the occupied spaces to the subjacent ground. The most successful methods of reducing indoor radon levels are those that reverse or reduce these pressure differences. Other methods are to seal the floor or to remove the radon progeny once they have entered the house.

Although essentially all the dose to lung tissue arises from inhaled short-lived radon progeny, a measure of the aggregate radon progeny concentration, the potential alpha energy concentration (PAEC), in air is a poor indicator of lung dose. Dose to lung depends[5] strongly on the fraction of the progeny existing in the size range below 10 nm, and the proportion of small particles and the unattached fraction are dependent on the submicron aerosol concentration. Determination of the size distribution of radon progeny in air requires sophisticated equipment with skilled operators, precluding its use for large surveys. There is an inverse relationship between the concentration of submicron aerosols in indoor air and ventilation rate, however, and, as a result, the average radon gas concentration is a better indicator of dose to lung[6] than is a simple measurement of PAEC.

Several methods have been proposed for the removal of radon progeny from room air. These include filtration[7-9], ion generation with enhanced air movement[10] and electrostatic precipitators[11]. Although these devices reduce substantially the total PAEC, they produce a far from commensurate reduction[12] in dose to lung tissue. None of the devices affects radon gas concentration, and there is no simple method by which a householder can determine how effective such a device is in reducing radon progeny concentration. They do not find wide practical application and are described here for completeness.

Air cleaning devices for use in dwellings are generally effective only in the room in which they are installed. Since they have no effect on radon gas, radon progeny will continue to be formed from the gas as it moves away from the cleaning device. Thus, even if air cleaning was an effective method of reducing the dose to lung from radon-laden atmospheres, several devices would be required in a home. This would prove more costly than the installation of more certain remedies that prevent, or reduce, the ingress of radon into the dwelling, and they would also be more costly to operate. It is better to treat the cause, not the symptoms, of elevated indoor radon. Methods that have been used widely to reduce radon levels in homes are described below.

1.2.1 Positive ventilation

Balanced ventilation systems, with or without heat recovery, may be used to reduce radon levels by dilution. These systems supply fresh air to some rooms while extracting air from other rooms and discharging it to the atmosphere. If the system is adjusted to supply more air than is extracted, the pressure difference across the ground floor will be reduced and less soil gas will be drawn into the building. The installation of whole-house systems in existing dwellings is very costly. Single room units are marketed, but will have diminishing effect on radon levels in rooms remote from the installation. Such systems are useful only where infiltration is unusually low; it is unusual for such systems to provide more than 1.5 air changes an hour. These systems are not of wide practical importance.

Positive, or supply, ventilation, in which filtered roof-space air is pumped into the occupied spaces, has been used in the UK for many years to reduce condensation and is now being adopted for radon reduction. These systems are sometimes referred to as positive pressure systems. This should not be taken as implying that they overpressure the dwelling and hence reverse the pressure difference across the lowest floors. It is most unlikely that the small fan used, typically 65 W, can achieve this.

Although these devices increase the ventilation to a degree, and hence reduce radon levels by dilution, they also lower the height of the neutral plane, the level of the building at which indoor air pressure is the same as that outdoors, and hence reduce the rate of soil gas entry. The height of the neutral plane also determines natural infiltration of air from outside the house and some of the additional air supplied from the loft space compensates for the reduction in this source of low radon air. The increased ventilation resulting from the use of these devices is usually not as great as would be calculated to result from the rate at which air is supplied to the occupied spaces.

1.2.2 Additional natural ventilation

Additional natural ventilation may be provided by trickle vents, preferably ones that cannot be closed, which are normally fitted in window frames. An increased stack effect arises frequently in homes, particularly those with double glazing where during winter all ground-floor windows are closed, but windows in first-floor bedrooms are opened to air the rooms. To reduce the stack effect it is better to have trickle vents fitted in ground-floor windows and on all sides of a building rather than in windows in upper storeys. Catches that keep a window open slightly but prevent its being opened from outside are another possibility, although these are usually not permanently fixed.

1.2.3 Ventilation of underfloor voids

There are two approaches recommended for increasing the ventilation of the void beneath suspended floors of timber or concrete. Increased natural ventilation of the underfloor void, by the provision of additional air grilles and, if necessary, the clearing of existing ones, or by mechanically enhanced ventilation of the void. Air movement at ground level can be quite low even for moderate windspeeds, and particularly so in areas of high density housing. The degree of underfloor ventilation required to avoid problems of timber rot is frequently inadequate to reduce radon levels in the void sufficiently to reduce elevated radon levels indoors, and air bricks in excess of the number dictated by building regulations may have to be installed.

Where indoor radon levels are much elevated, or the dwelling is in a sheltered position, mechanical ventilation of the underfloor void may be necessary. Mechanical underfloor ventilation may extract air from the void or supply outdoor air to it. If air is supplied to the void, it is essential that water services running in the void be well lagged to prevent freezing; also, floors may be cold in winter. In all cases of mechanical ventilation of the underfloor void, a sufficient number of air bricks must be provided to ensure an adequate flow of air across the entire void.

1.2.4 Sealing

Sealing of penetrations linking the occupied space to the underlying ground may be effective in reducing radon levels. The resistance of the underlying soil to the movement of soil gas through it is much higher than that of cracks and gaps in the fabric of the building in contact with the soil. Essentially all penetrations must be sealed for sealing alone to be effective. Where ground-contact concrete floors are poured between the walls, a common form of construction, a major penetration will occur at the floor–wall joints since the concrete shrinks from the walls while setting. This gap will generally be hidden by skirting boards and not readily accessible. Readily accessible gaps and cracks in concrete floors should be sealed and BRE has issued guidance[13] on procedures and sealants for doing this. More extensive sealing may be carried out by the enthusiastic householder, but may be expensive if done by a contractor as it is labour intensive.

1.2.5 Membrane covering a floor

Where the ground-floor construction is of suspended timber, early advice was that radon levels might be reduced by covering the floor with a membrane and sealing it to the walls. It was stressed that the underfloor void must be adequately ventilated to prevent conditions conducive to rot. The use of a membrane is no longer recommended because it was found not to be very effective and was difficult to install, and because adequate underfloor ventilation is difficult to define. Several householders, however, have adopted this approach.

1.2.6 Radon sump

A cavity, or sump, may be excavated beneath a concrete slab floor and an extract pipe taken via a fan to a discharge point outside the home. Soil gas, and some house air, is drawn into the sump, reversing the normal flow pattern of soil gas entering the home, and discharged to the atmosphere away from doors and windows. This remedy has been used widely in Scandinavia[14] and North America[15,16] as well as in the UK. The fan used must have a non-stalling and non-overloading characteristic. One model frequently used in the USA and UK is of 75 W power, and a study of installations in the USA using this fan[17] indicated a mean time to failure of 15 years. For a sump system to be effective, there must exist beneath the concrete floor a layer of material of comparatively high air permeability, such as hardcore with little fines. If such a layer is not present, more than one sump may be necessary, but in many cases these can be manifolded to one fan.

The most common configuration for a sump system is to have the fan extracting gases from the sump. When the air permeability of the underlying ground is very high, the system may be more effective[18,19] if air is blown into the sump.

The sump may consist of no more than a cavity roughly excavated by hand in the hardcore beneath the floor, or be formed by two or three courses of open perpend brickwork separated by two paving slabs. Alternatively, there are a number of preformed sumps, of concrete or plastic, produced commercially. In many instances the cavity is formed from outside the building by making an opening through the foundation wall to accommodate the extract pipe. BRE has issued guidance[20] on sump systems, covering the various approaches that have been used. Sump systems will often be the best way of reducing radon levels in houses. They generally result in substantial reductions at reasonable cost and failures are rare.

It is possible to use a passive sump system which differs only in that a fan is not fitted; should this prove ineffective, it is a simple matter to add a fan. Limited experience[2] in the UK with passive sumps has shown that modest reductions may be achieved, but it is necessary to route the extract pipe through the building to discharge at or above roof level, to benefit from the stack effect.

A sump system may also be used with suspended floors where there is concrete over the floor of the underfloor void. If there is no concrete oversite, a polyethylene sheet may be laid over the soil and suction effected[21] from beneath it. However, it is necessary to ensure that the polythene sheet is properly sealed and the method is likely to be expensive. It is not generally advocated in the UK.

1.3 Results for effectiveness

The ratio of the seasonally-adjusted radon measurement before remedial action was taken to that after is used as an indication of success and is termed the reduction factor. The maximum reduction factor achievable is determined by the initial radon level: there is an irreducible minimum indoor radon level determined by the level in outdoor air and the small contribution from building materials. Figure B1 demonstrates that where initial radon levels are only moderately above the Action Level, the absolute reduction in radon level (ie the difference between radon levels before and after remedial action) generally increases for increasing initial radon level.

The reduction factors achieved by a variety of techniques, for three ranges of initial radon level are shown in Table B1. Two householders installed single room mechanical ventilation with heat recovery systems: in neither case was there a significant change in the radon levels so they are excluded from the table. In many cases remedial actions were supplemented by sealing some cracks around service entries, but these are not differentiated in Table B1. The arithmetic mean (AM) of the reduction factors can be misleading, as it is much affected by the occasional very high value. The geometric mean (GM) is not so distorted, and is often a better indication of the typical reduction to be expected. Both are given. It is only in exceptional circumstances that any of the

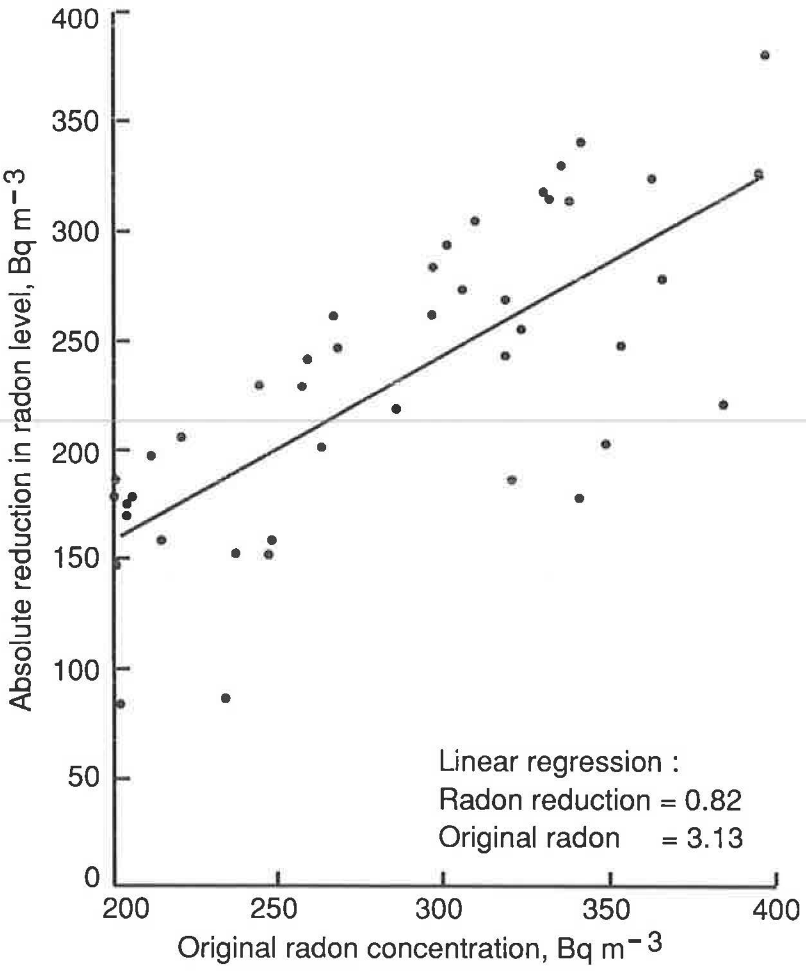

FIGURE B1 Absolute reduction in radon level as a function of initial concentration

TABLE B1 Radon reduction factors for different radon remedial actions in existing homes. The reduction factor is the ratio of the seasonally-corrected radon measurement before remedial action was undertaken to that after the work was completed

	Original radon concentration														
	200–749 Bq m^{-3}					750–1500 Bq m^{-3}					>1500 Bq m^{-3}				
		Reduction factor					Reduction factor					Reduction factor			
Method	N	AM	GM	Min	Max	N	AM	GM	Min	Max	N	AM	GM	Min	Max
Positive ventilation	79	2.6	2.0	1	15	16	6.6	4.3	1	24	0	–	–	–	–
Additional natural ventilation	45	2.8	1.8	1	25	3	7.3	4.8	2.4	17	0	–	–	–	–
Additional natural ventilation of underfloor void	74	2.6	1.9	1	23	7	1.7	1.5	1	3.1	1	–	–	–	9.7
Mechanical ventilation of underfloor void (assumed to be extract)	29	5.9	2.9	1	58	3	1.4	1.1	1	2.5	1	–	–	–	39
Sealing only	48	2.0	2.0	1	32	4	2.1	2.0	1.3	2.6	1	–	–	–	5.6
Membrane covering floor	22	1.8	1.6	1	6.5	1	–	–	–	2.4	1	–	–	–	6.2
Sump	173	12	6.7	1	83	70	23	12	1	130	15	29	15	1.3	100
Sump with other method(s)	48	10	3.8	1	67	11	15	9.9	1.9	51	5	12	7.0	1.6	26
Combination of methods, no sump	69	2.7	1.8	1	17	10	2.9	2.4	1	6.1	0	–	–	–	–

radon remedial measures listed would aggravate the situation, ie lead to an increase in radon level. Measured reduction factors below unity do occur occasionally, but these usually arise because of statistical variations in the measurement technique and of imprecisions introduced by the use of average seasonal correction factors. In Table B1 the minimum reduction factor is given as unity, indicating no change in radon level, in some cases. When calculating the AM and GM, the measured values, not unity, are used, so as not to bias the results.

As Table B1 demonstrates, all approaches to radon reduction can be successful and, in some cases, exceptionally so. Some methods have produced an occasional reduction in radon level that is much larger than expected, as indicated by the difference between the GM and the maximum reduction achieved by that method. It might be tempting to use one of these methods, that may be cheaper or less disruptive to install, in cases where the pre-existing radon level is very high, rather than to employ a more certain technique from the outset. It should be emphasised that a sequential approach, in which simple and comparatively inexpensive techniques are used at the outset, may ultimately result in a much greater total expense before a satisfactory reduction in radon level is achieved: in many cases the more certain approach will be that which is finally installed. It must also be remembered that the aim is to achieve a substantial reduction in radon concentrations, not merely to reduce radon concentrations to just below the Action Level.

A positive ventilation system is, perhaps, the least disruptive system to install, and is likely to result in a reduction in radon level by about a factor of two. Such systems appear to be most successful where the fabric of the building is quite tight. They may also reduce problems of condensation, which may be seen by the homeowner as a benefit in those cases where the reduction in radon level is disappointing.

Natural ventilation, whether of the living spaces or the underfloor void, typically reduces radon levels by no more than a factor of two. The reduction achieved is dependent on prevailing climatic conditions, resulting in more variable indoor radon levels than in those systems whose effectiveness depends on an electric fan. Counter-intuitively, radon levels in buildings with suspended timber floors have proved more difficult to reduce substantially than those in buildings with ground-supported concrete floors. In a limited number of cases, blowing outdoor air into the underfloor void has proved more successful than extracting air from it. Where mechanical ventilation of the underfloor void is employed, the aim is to move as much air as possible across the void, not to develop a substantial pressure across the fan. Here, axial fans have better characteristics than centrifugal fans, although axial fans may be more bulky.

Sealing cracks and holes in the floor is seldom successful as a radon remedial action, with reductions exceeding a factor of two being uncommon. Sealing is time-consuming, and the greatest reductions in radon levels have been achieved by the homeowners carrying out the work and after several attempts. The use of a membrane covering a timber floor and sealed to the walls is to be discouraged for reasons given earlier. In any case, sealing the membrane adequately to the walls is difficult, gaining access to enable the membrane to be laid is frequently disruptive, and the results are usually disappointing.

As can be seen from Table B1, the most common installations are those of sump systems. These have been used where pre-mitigation radon levels have been only moderately in excess of the Action Level as well as where initial radon levels have been many times the Action Level, but have demonstrated that in the majority of cases indoor radon levels can be reduced below 100 Bq m^{-3}. Distributions of reduction factors achieved for sump systems where the post-mitigation radon level is below the Action Level are shown in Figure B2. Where sump systems have failed this has

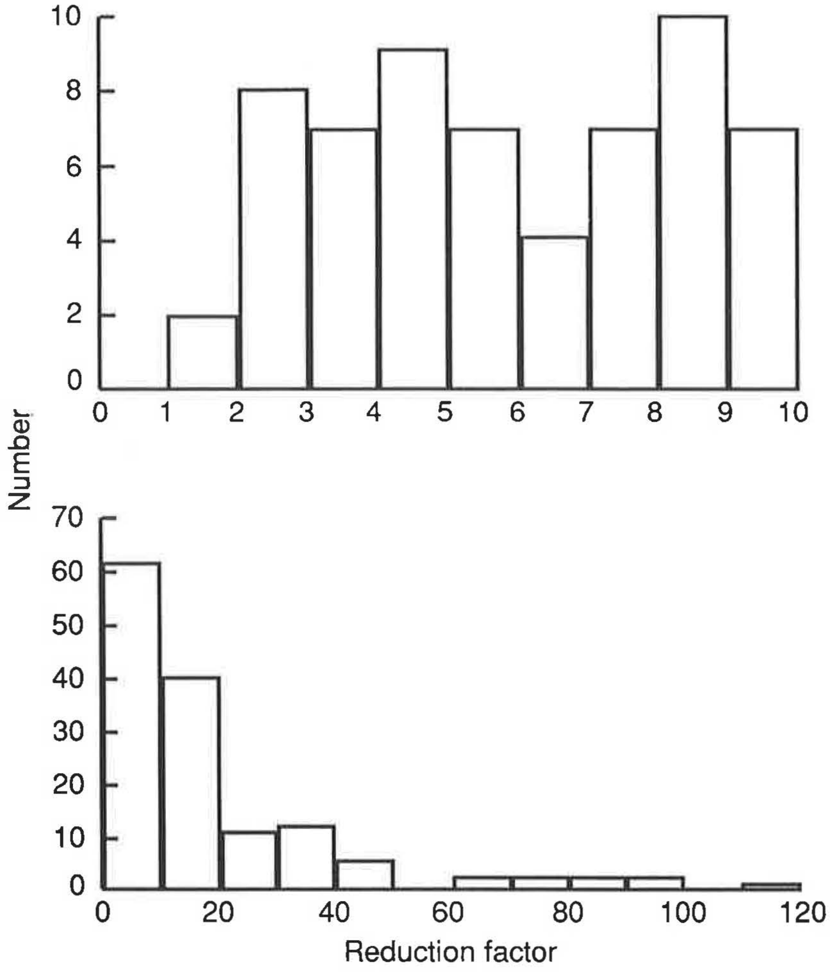

FIGURE B2 Distribution of reduction factors for sumps

usually been due to the use of an inappropriate fan, radon from the sump being discharged within the building, or the absence of a layer of permeable material below the floor slab.

There are a few companies offering radon remedial services throughout the UK, but in many instances the work is carried out by a local builder. Radon reduction systems can be installed by any competent builder, who will have sufficient knowledge to ensure that the installation is compatible with the structure of the building, and should notice other building-related problems such as the existence of dry rot. Competent householders have also undertake remedial work themselves, and published guidance[1,13,20] is available to assist them.

Reduction factors achieved by commercial contractors installing sump systems are shown in Table B2, with costs per unit activity concentration reduction and average costs of installation shown in Table B3. Likewise, Tables B4 and B5 show the corresponding data for installation of sumps by householders themselves. Successful sump systems may be installed by the householder at a cost that is generally below one-third that incurred by employing a contractor. Contractors, however, have been successful in securing the greatest reductions for very high initial radon levels. As is to be expected, the higher the initial radon levels the lower the cost per unit activity concentration reduction: in most cases the cost of installing a sump system is independent of the initial radon concentration.

TABLE B2 Reduction factors achieved for sump systems installed by contractors

Original radon concentration ($Bq m^{-3}$)	All installations					Installations where final radon concentration <200 $Bq m^{-3}$				
		Reduction factor					Reduction factor			
	N	AM	GM	Min	Max	N	AM	GM	Min	Max
200–749	135	13	7.7	1	83	118	15	9.8	1.6	83
750–1500	58	22	12	1.1	130	45	28	19	4.8	130
>1500	8	35	18	2.2	100	6	45	31	1.3	100

TABLE B3 Costs of sump systems installed by contractors

Original radon concentration ($Bq m^{-3}$)	Average cost of all installations (£)	Cost per unit activity concentration reduction for all installations (£ per $Bq m^{-3}$)			Average cost of successful installations (£)	Cost per unit activity concentration reduction, where final level <200 $Bq m^{-3}$ (£ per $Bq m^{-3}$)		
		AM	Min	Max		AM	Min	Max
200–749	1063	6.53	–	201.07	1076	3.82	0.77	34.97
750–1500	1123	1.95	0.54	18.01	1158	1.48	0.54	8.85
>1500	1838	1.15	0.23	2.36	1617	0.86	0.23	1.48

[*] In a few cases, no reduction was achieved and there was an insignificant increase in measured radon level. This results in negative incremental costs.

TABLE B4 Reduction factors achieved for sump systems installed by the householder

Original radon concentration ($Bq m^{-3}$)	All installations					Installations where final radon concentration <200 $Bq m^{-3}$				
		Reduction factor					Reduction factor			
	N	AM	GM	Min	Max	N	AM	GM	Min	Max
200–749	25	11	5.5	1.1	68	20	13	7.4	1.5	68
750–1500	8	20	9.9	1	86	6	27	19	10	86
>1500	7	23	12	1.3	66	4	38	32	11	66

TABLE B5 Costs of sump systems installed by the householder

Original radon concentration ($Bq m^{-3}$)	Average cost of all installations (£)	Cost per unit activity concentration reduction for all installations (£ per $Bq m^{-3}$)			Average cost of successful installations (£)	Cost per unit activity concentration reduction, where final level <200 $Bq m^{-3}$ (£ per $Bq m^{-3}$)		
		AM	Min	Max		AM	Min	Max
200–749	241	1.25	–*	5.12	255	1.18	0.18	3.91
750–1500	301	3.17	0.17	24.84	335	0.36	0.17	0.72
>1500	233	0.12	<0.01	0.27	225	0.11	0.03	0.23

[*] In a few cases, no reduction was achieved and there was an insignificant increase in measured radon level. This results in negative incremental costs.

1.4 Durability of remedial action

It is important that once successful action has been taken to reduce indoor radon levels, they remain low well into the future. Radon levels in 36 homes, in which a variety of remedial actions had been completed by January 1992, are being remonitored for 3 months, commencing in January each year, to determine the durability of the radon initially achieved. The ratio of the radon level in a subsequent year to that determined from the first measurement following successful remediation is taken as a measure of durability. At the time of remeasurement, the householders are requested to complete a short questionnaire to ascertain whether any unusual attention to the mitigation system has been necessary during the preceding year, for example replacing a fan, and whether any other changes to the home have occurred that might affect radon level, such as the installation of double glazing. Table B6 presents the results of repeated measurements in 1993 and 1994. Generally, radon reductions achieved initially have been maintained or have not significantly worsened.

TABLE B6 Durability of radon remedial measures. Values of 1.00 or less indicate no change or an increase in radon reduction, ie durability

	Durability year 1		Durability year 2	
Method	Average	Range	Average	Range
Positive ventilation	0.97	1.37–0.36	1.33	2.50–0.85
Additional natural ventilation of the underfloor void	1.41	2.78–0.45	1.42	2.17–0.34
Mechanical ventilation of the underfloor void	2.63*	9.09–0.64*	0.89	1.20–0.46
Sealing only	1.26	1.64–0.64	0.87	1.06–0.71
Membrane covering the floor	1.13	–	0.70	–
Sump	1.01	2.08–0.66†	1.04	2.50–0.61†

*One system failed, and the radon level increased to 1500 Bq m^{-3}. The average with this case removed is 1.02.

†See the text for an explanation of the apparent worsening situation in some sump systems.

In one instance, where the remedial action had been to increase the natural ventilation of an underfloor void, the remeasurement in 1993 indicated a radon level exceeding 200 Bq m^{-3}. Repeated measurements through 1993 confirmed that radon levels were indeed above the Action Level. The pre-mitigation radon level at this home was 170 Bq m^{-3}, and this case demonstrates the uncertain effectiveness of mitigation methods that rely upon natural ventilation. Three of the sump systems at homes remeasured in 1993 appeared to have reduced effectiveness, but these had very low radon levels, about 40 Bq m^{-3}, after the systems were installed, whereas pre-remedial action the levels were 1600, 1100 and 780 Bq m^{-3}. In the 1994 remeasurement of these three homes the annual average radon levels were assessed as 44, 48 and 30 Bq m^{-3}, respectively.

There had been no necessity for fan replacement or maintenance in any of the cases where a fan was in use, between the successful installation of the system and the remeasurement in 1993. The 1994 questionnaire replies indicated that no maintenance of any system had been necessary. In one case, however, of mechanical ventilation of the underfloor void, the radon level had risen to 1500 Bq m^{-3}. This clearly indicates a failure of the fan. This result has been sent to the householder, but there has been no response.

2 Radon preventative measures in new dwellings

2.1 Introduction

It was recognised that, should new homes in radon Affected Areas continue to be built according to traditional practices, the problem of high indoor radon levels would be continued indefinitely[22]. Also, it was recognised that it would be less costly to incorporate measures at the construction stage to restrict the entry of soil gas into the completed structure, than to remedy the situation in completed dwellings should high indoor radon levels occur.

Interim guidance on radon preventative measures in new dwelling was issued[23] by the Department of the Environment in June 1988, under the Building Regulations 1985. Requirement C2 of the Building Regulations 1985 stated that 'precautions shall be taken to avoid danger to health caused by substances found on or in the ground to be covered by the building'. The Approved Document in support of the Regulations included in the contaminants in or on the ground against which precautions should be taken '..any substance which is ... radioactive ...': this was deemed to include radon.

The interim guidance suggested that full preventative measures be taken in new dwellings to be constructed within those parts of Cornwall and Devon falling within an area taken to indicate the extent of the near-surface granite intrusions in those counties. Lesser preventative measures were advocated in other parts of the counties.

In January 1990, the Action Level for radon in existing homes was revised[24] to its current value of 200 Bq m^{-3} and the concept of radon Affected Areas was introduced. The first radon Affected Areas to be defined, later in 1990, were the counties of Cornwall and Devon[25]. Building regulations were revised and the Building Regulations 1991, which came into force in June 1992, covered specifically radon preventative measures in new dwellings in radon Affected Areas. Guidance on the construction of dwellings in areas susceptible to radon has been published by the BRE. The precise areas where measures should be taken are reviewed by the Department of the Environment in the light of advice from NRPB as this becomes available, and are listed in the BRE report, which is updated as necessary. Current information on the areas delimited by DoE for the purposes of building regulations can be obtained from the local authority building control officers or from approved inspectors.

In the present BRE guidance document, locations within radon Affected Areas in England where radon preventative measures are required are defined by parish. The first edition of the guidance document covered the counties of Cornwall and Devon only. In 1992, further radon Affected Areas were defined[26] for Derbyshire, Northamptonshire and Somerset, and the BRE guidance document[27] was revised to cover the five affected counties. Affected Areas have also been declared in parts of Scotland and in Northern Ireland (see Section 5 of the main report).

2.2 Radon preventative methods

Full radon preventative measures involve a membrane continuous from the outer leaf of the exterior walls across the entire building, usually within the floor. All services penetrating this membrane must be well sealed so that the membrane isolates the living spaces from the underlying ground. It was realised that some membranes were likely to be improperly installed and hence not act as a total barrier to soil gas ingress. Consequently, secondary radon preventative measures are also required that provide for the easy extraction of soil gas from below ground floors. In some circumstances (see below) secondary measures alone are required.

A form of floor construction becoming increasingly popular is the suspended concrete, block and beam, floor. Here, the advice is that the void beneath the floor be provided with natural ventilation by means of air grilles. Should high radon levels occur in the completed dwelling, provision of mechanically enhanced ventilation of the underfloor void would be simple and inexpensive.

Another secondary preventative measure is the provision of a sump system with the extract pipe brought to a point external to the building and capped. Should high radon levels occur in the completed building, it is a simple matter to extend the extract pipe and fit an appropriate fan. The provision of an inactive sump system applies to ground-supported concrete floors and to suspended timber floors. In the latter case, the sump is installed beneath the concrete oversite covering the floor of the underfloor void. The provision of a concrete oversight for suspended timber floors, originally required to limit moisture entry from the soil into the underfloor void, is a long-standing requirement of the building regulations.

Full radon preventative measures, the provision of the continuous membrane together with secondary preventative measures, the sump or ventilated underfloor void, are required in the worst affected areas. Secondary preventative measures only are required in those parts of the Affected Areas where the probability of existing houses exceeding the Action Level is lower. The areas where full and secondary preventative measures are required are decided by government.

2.3 Effectiveness of radon preventative measures

In order to determine the effectiveness of the radon preventative features incorporated in newly built homes, BRE[28-30] has studied 416 homes, some with preventative measures and some without. Those homes without preventative measures were close to those with the measures; in some cases they were on the same building site. The areas where full and secondary radon preventative measures are required in newly built homes are considerably smaller than that where secondary measures only are required, and in many cases more sparsely populated. Thus, of the 416 homes studied, 295 were in areas requiring secondary preventative measures only, and 121 were in areas requiring full preventative measures. Homes studied had either block and beam suspended concrete floors or ground-supported concrete floors. For homes incorporating radon preventative measures, only 1% of those with block and beam floors were found to have radon levels exceeding 200 Bq m^{-3}; for those with ground-supported floors the figure was 7%, although nearly all of these occurred on one site and the failures may have been the result of improper application of the preventative measures. In homes without preventative measures, 21% of those with block and beam floors, and 25% of those with ground-supported floors, exceeded the Action Level.

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