



Radon mitigation in domestic properties and its health implications—a comparison between during-construction and post-construction radon reduction

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Abstract

Although United Kingdom (UK) Building Regulations applicable to houses constructed since 1992 in Radon Affected Areas address the health issues arising from the presence of radon in domestic properties and specify the installation of radon-mitigation measures during construction, no legislative requirement currently exists for monitoring the effectiveness of such remediation once construction is completed and the houses are occupied. To assess the relative effectiveness of During-Construction radon reduction and Post-Construction remediation, radon concentration data from houses constructed before and after 1992 in Northamptonshire, UK, a designated Radon Affected Area, was analysed. Post-Construction remediation of 73 pre-1992 houses using conventional fan-assisted sump technology proved to be extremely effective, with radon concentrations reduced to the Action Level, or below, in all cases. Of 64 houses constructed since 1992 in a well-defined geographical area, and known to have had radon-barrier membranes installed during construction, 11% exhibited radon concentrations in excess of the Action Level. This compares with the estimated average for all houses in the same area of 17%, suggesting that, in some 60% of the houses surveyed, installation of a membrane has not resulted in reduction of mean annual radon concentrations to below the Action Level. Detailed comparison of the two data sets reveals marked differences in the degree of mitigation achieved by remediation. There is therefore an ongoing need for research to resolve definitively the issue of radon mitigation and to define truly effective anti-radon measures, readily installed in domestic properties at the time of construction. It is therefore recommended that mandatory testing be introduced for all new houses in Radon Affected Areas.

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1. Introduction

Radon is a naturally occurring radioactive gas with variable geographical occurrence, which concentrates in the built environment, including within domestic properties, and which contributes around 50% to the average background radiation dose received by the United Kingdom (UK) population (Darby et al., 2001). At high concentrations in

uranium mines, radon has been shown to be associated with increased risk of lung cancers in miners and extrapolation from the miners' data has suggested that residents of high-radon areas are similarly at increased risk from lung cancer (BEIR VI, 1999). A meta-analysis of eight national epidemiological studies (Lubin and Boice, 1997), a case-control study in the South West of England (Darby et al., 1998) and, most recently, collaborative analyses of individual data from 13 European case-control studies (Darby et al., 2005) and from 7 North American studies (Krewski et al., 2005), all support this view.

Responding to the threat to health raised by the presence of radon in domestic properties, the UK National Radiological

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Protection Board (NRPB), now part of the Health Protection Agency (HPA), established an Action Level of $200 \text{ Bq}\cdot\text{m}^{-3}$ for domestic properties and designated a number of Radon Affected Areas, geographical areas where more than 1% of the housing stock are predicted to have radon concentrations greater than the Action Level. The County of Northamptonshire, situated in central England, is such an area (Miles et al., 1992). To give practical governmental support to this concern, successive iterations of the UK Building Regulations governing the construction of new houses (Department of the Environment, 2000) require that “precautions shall be taken to avoid danger to health and safety caused by substances found on or in the ground to be covered by the building”. Geographical areas requiring provision of protective measures against radon, and recommended technical solutions, are discussed in documentation published by the UK Building Research Establishment (BRE) (Building Research Establishment, 1992, 1999) and, since 1992, all new houses in such areas must be built with radon protection. Basic Protection, appropriate to areas of moderate radon concentrations, comprises the use of a radon-barrier membrane (300 μm minimum polythene sheet) as the damp-proof course, modified by the inclusion of a cavity tray, to which the membrane is sealed, together with ‘weep-holes’ for drainage at the base of the cavity wall. In high radon areas, Full Protection, comprising a membrane, as described, supplemented by a sump (without a fan) is required.

Despite this regulatory background, however, UK practice does not require newly constructed houses in Radon Affected Areas to be tested for radon concentrations. Results from separate surveys in different parts of Northamptonshire have confirmed that property developers and estate agents rarely have effective procedures in place for informing buyers that an area is radon affected, or that radon preventative measures have been taken (Phillips et al., 2000). In addition, unlike the situation pertaining in certain other countries (Snihs, 1992), UK legislation places no obligation on either the builder or the householder to remediate houses found to exhibit radon concentrations in excess of the Action Level.

As part of our ongoing studies of radon in the built environment, we have studied the precision with which the results obtained from the various available technologies for short-term and medium-term measurement of radon concentration accurately reflect the mean annual radon concentrations, and have identified a range of values within which it is not possible to specify whether the indicated radon concentration is above or below the Action Level (Phillips et al., 2004; Groves-Kirkby et al., in press). For track-etch detectors exposed for 3-month periods, this ‘equivocal range’ extends from $112 \text{ Bq}\cdot\text{m}^{-3}$ to $356 \text{ Bq}\cdot\text{m}^{-3}$. For indicated radon concentrations in excess of $356 \text{ Bq}\cdot\text{m}^{-3}$, the house has concentrations that are definitely above the Action Level; for indicated concentrations below $112 \text{ Bq}\cdot\text{m}^{-3}$ the radon concentrations are definitely below the Action Level.

Although the cost-effectiveness in health terms of radon remediation has been discussed in the literature (Coskeran et al., 2005), little evidence is available from the UK regarding

the relative effectiveness of radon-barrier membranes installed during the construction of a house and of remediation installed subsequent to construction. We present here a preliminary comparative analysis of data from a housing development constructed subsequent to 1992 in a Radon Affected Area in the Northamptonshire village of Brixworth, and results from an ongoing programme of Post-Construction remediation encompassing Brixworth and surrounding areas of Northamptonshire.

Fig. 1 shows a radon map of the UK (Miles and Appleton, 2005), indicating the position of Northamptonshire, together with a more detailed map of the county, showing the location of the major population centres and the boundaries of the county’s postcode (zip code) districts, the second smallest unit in the UK postal code hierarchy. The village of Brixworth is situated in postcode sector NN6 9 (third hierarchical postal code level), which encompasses 3500 houses. Of these, some 1300 houses have been tested for radon, with 17.7% of those tested exhibiting radon concentrations in excess of the Action Level (Green et al., 2003).

2. Method

2.1. Detector protocols

All houses surveyed in the study were monitored for radon using track-etch detectors, supplied and processed by validated laboratories (Howarth and Miles, 2001) and deployed in accordance with the NRPB Measurement Protocol (Wrixon et al., 1998). This protocol uses two track-etch detectors, one in the principal bedroom, one in the main living area, exposed for nominal 3-month periods, and calculates a weighted average of the two readings, with the principal bedroom and living room being assigned weightings of 0.55 and 0.45, respectively, reflecting the relative occupancies. The weighted average of the two measurements was seasonally corrected and compared to the Action Level. In each case, detectors were placed and recovered by trained project personnel, ensuring that devices were situated in suitable locations and that exposure durations were accurately controlled at 90 ± 2 days.

2.2. Post-construction radon mitigation

As an outcome of previous study (Denman et al., 2002; Denman et al., 2005a), extensive data was available concerning pre-remediation and post-remediation radon concentrations in a set of houses in Northamptonshire that had been remediated during the period 1995–2001, using fan-assisted sump technology installed by a commercial organisation following UK Radon Council good practice (The Radon Council, 1995). This dataset represented 73 houses, with 162 residents. Of these houses, a total of seven were situated in the NN6 9 postcode sector, permitting direct comparison with the results from the houses constructed with membrane radon-barriers.

2.3. During-Construction radon reduction

Since designation of Brixworth as a Radon Affected Area in 1992, three residential developments, comprising 444 new 3-, 4- or 5-bedroom detached houses, have been constructed; in compliance with current legislation, all of these incorporate radon-barrier membranes. Considerable development of the village had also occurred before 1992, with similar housing built by the same builders, but without protective membranes.

As a result of extensive contact with residents in the post-1992 development, 105 householders expressed interest in participating in a programme to investigate the effectiveness of the radon-barrier membranes incorporated in their houses during construction, and in receiving free radon tests in their properties. However, following counselling on the implications of

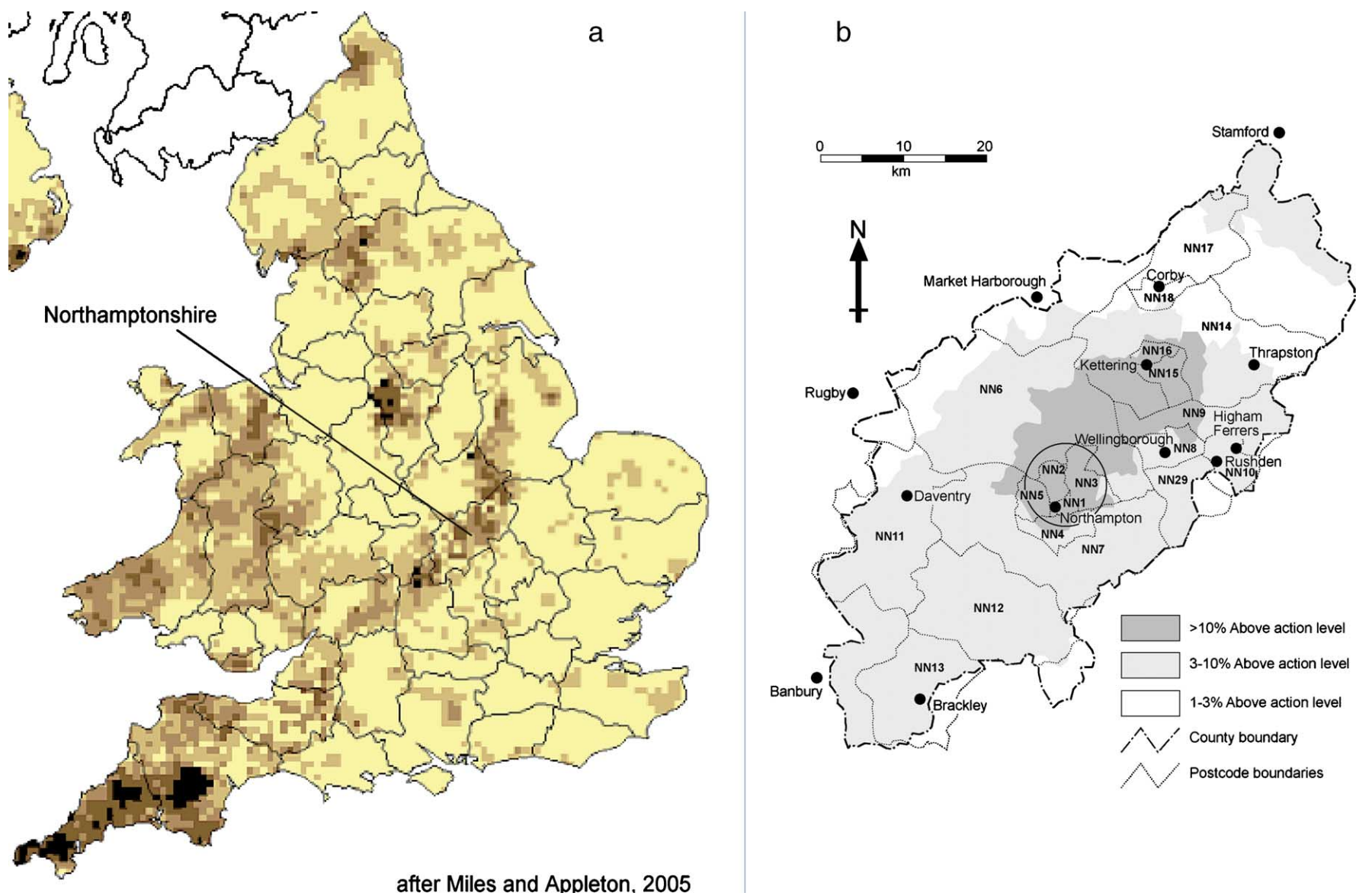


Fig. 1. (a) Radon Map of England and Wales, indicating county boundaries and showing the position of Northamptonshire (Miles and Appleton, 2005). (b) Outline map of Northamptonshire, showing major population centres, postcode district boundaries.

Table 1
Statistical summary of experimental data

Remediation method	Location	Number of houses	Before Remediation		After Remediation	
			Mean [Bq·m ⁻³]	S.D. [Bq·m ⁻³]	Mean [Bq·m ⁻³]	S.D. [Bq·m ⁻³]
Post-Construction	Full set	73	515.8	304.5	59.7	50.6
	NN6 9	7	458.0	201.8	107.0	62.5
During-Construction	NN6 9	64	N/A	N/A	74.7	126.7

the programme, 37 householders declined to proceed, leaving a population of 68 properties for testing.

3. Results

3.1. Radon concentrations and their distribution

Table 1 summarises the radon concentration results returned from the two surveys. Although the geographical scope of the Post-Construction remediation survey extended beyond the NN6 9 postcode area, 9.6% of the houses surveyed were situated in that postcode sector, providing the basis for a preliminary comparison.

3.2. Post-Construction remediation

A total of 73 households, 7 of them (9.6%) situated in the NN6 9 postcode sector and of essentially the same construction and style, returned valid pre-remediation and post-remediation radon data. Fig. 2 shows the distributions of pre- and post-remediation radon concentrations, confirming the significant degrees of radon mitigation achieved by remediation. Also shown are the UK Action Level (200 Bq·m⁻³) and the upper and lower boundaries of the equivocal range (Phillips et al., 2004). In each case, the returned radon concentrations exhibited the lognormal distribution typical of sets of radon measurements (Gunby et al., 1993). Prior to remediation, virtually all of the returned results fell in the region above the Action Level, with a significant proportion of these falling above the upper boundary of the equivocal region. Following remediation, all of the properties concerned showed radon concentrations below the Action Level, with the majority being below the lower boundary of the equivocal region.

3.3. During-Construction radon reduction

Detectors were returned from a total of 68 dwellings in which radon mitigation was installed during construction, all situated in the NN6 9 postcode sector. Of these, 4 detectors were spoiled, leaving 64 usable results. Mean radon concentrations again exhibited a lognormal distribution, as shown in Fig. 3, and were significantly lower than those found in the unremediated houses in the same postcode sector (cf. Table 1). On the assumption that the pre-remediation radon concentrations returned by the latter provide a benchmark for the local area, the results provide convincing evidence that During-Construction radon reduction provides protection against the ingress of radon. Despite this, however, seven houses (11%) returned radon concentrations above the Action Level of 200 Bq·m⁻³. Overall, 47 (73%) of these houses exhibited radon concentrations below the lower boundary of the Equivocal Range, 112 Bq·m⁻³, and these can therefore be regarded as having concentrations definitively below the Action Level. Sixteen houses (25%) returned results within the equivocal range and would therefore, in practice, require to be repeated, while one house (1.6%) returned a radon concentration above the upper bound of the Equivocal Range, and therefore definitely in excess of the Action Level.

4. Discussion

Assessment of the relative efficiency of During-Construction and Post-Construction radon reduction is facilitated by the introduction of the Mitigation Factor, defined as the ratio of the mean annual radon concentrations before and after remediation.

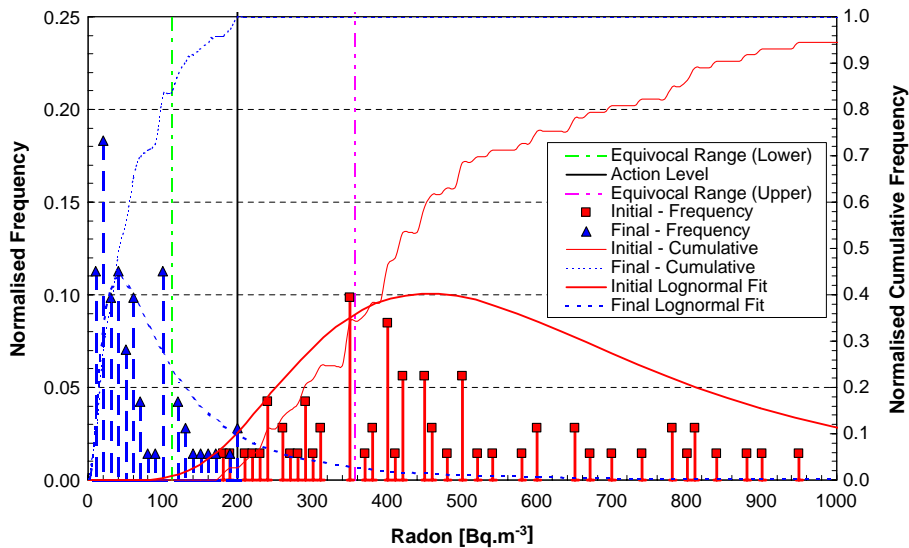


Fig. 2. Normalised distributions of radon levels in Post-Construction remediation series, with fitted lognormal distributions (broad-line plots) and normalised cumulative frequencies (narrow-line plots). Solid plots and bars (triangle markers): Before-Remediation distribution. Dashed plots and bars (square markers): Post-Remediation distribution. Vertical lines indicate lower (single chain-dashed) and upper (double chain-dashed) boundaries of the Equivocal Range, and the UK Action Level (solid line).

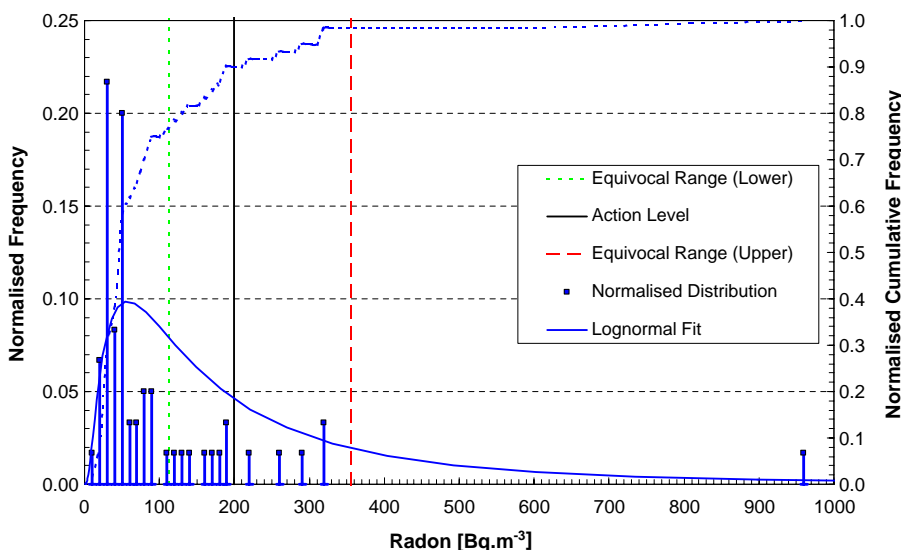


Fig. 3. Normalised distribution of radon levels in During-Construction Remediation Series, with fitted lognormal distribution and normalised cumulative frequency. Vertical lines indicate lower (single chain-dashed) and upper (double chain-dashed) boundaries of the Equivocal Range, and the UK Action Level (solid line).

4.1. Post-Construction remediation

In this set of houses, the availability of pre-remediation and post-remediation radon concentrations permitted absolute determination of both the mitigation factor for each house in the Post-Construction remediation set and the distribution of mitigation factors among the properties studied. Overall, Post-Construction remediation achieved its objectives, with all properties returning radon mean annual radon concentrations at or below the Action Level of 200 Bq·m⁻³. As shown in Fig. 4, the distribution of achieved mitigation as function of initial radon concentration in the Post-Construction Remediation Series exhibits monotonic behaviour, with post-mitigation concentrations equivalent to 20% or less of the pre-remediation concentration in nearly 75% of the remediated houses.

While Post-Construction remediation is generally extremely effective, as demonstrated by the figures presented here, there is evidence that radon levels in Post-Construction remediated

houses show a tendency to rise in the years after remediation. Causes reported include total or partial system failure, householder interference and modifications to the house (Scivyer and Noonan, 2001).

4.2. During-Construction radon reduction

Unfortunately, the very nature of the During-Construction approach to radon mitigation implies the absence of a pre-remediation radon concentration against which to reference the degree of mitigation achieved by remediation. However, the NRPB Radon Atlas of England and Wales (Green et al., 2003) provides tabulated Arithmetic Mean and Geometric Mean (AM and GM) domestic radon concentrations on a postcode sector basis. For the NN6 9 area, covering the village of Brixworth, reported AM and GM values for 1300 measurements in unremediated houses are 117 Bq·m⁻³ and 59 Bq·m⁻³, respectively.

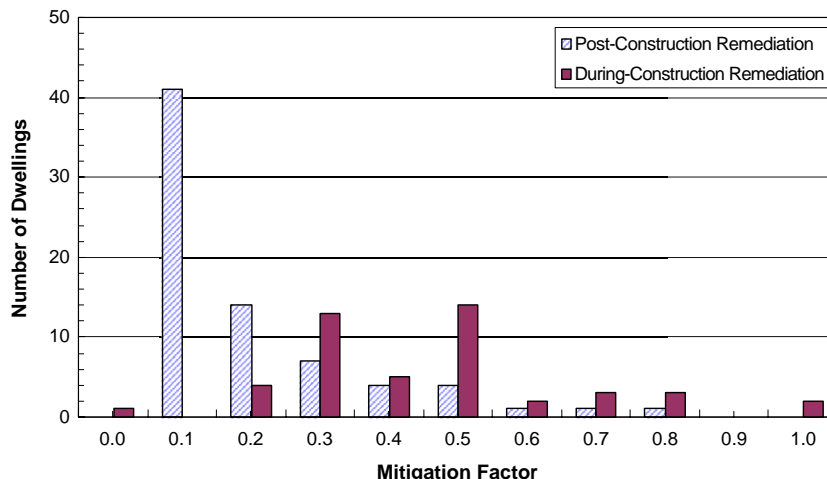


Fig. 4. Effectiveness of mitigation achieved by During-Construction and Post-Construction techniques (adopting the mean radon concentration for the NN6 9 postcode sector as reference). Hatched bars: Post-Construction Remediation. Solid Bars: During-Construction Remediation.

Despite considerable publicity over many years, only 30% of householders in Northamptonshire have organised radon tests in their homes (Green et al., 2003). In addition, recent estimates suggest that, nationally, only 10% of householders finding radon concentrations in excess of the Action Level have taken remedial action (Hansard, 2002; Arthur, 2003), leading to the conclusion that the majority of the results in the NRPB survey come from unremediated houses. The Health Protection Agency, publishers of the Radon Atlas, confirm (private communication, 2005) that the radon concentrations reported in the Atlas represent the first measurements from each house tested; in the vast majority of cases, these can therefore be assumed to represent the situation prior to any remediation that might have been carried out. An assumed arithmetic mean Pre-Remediation radon concentration of around $120 \text{ Bq}\cdot\text{m}^{-3}$ is therefore used in the remainder of this discussion.

Fig. 4 shows the distribution of mitigation factors achieved in the During-Construction set, based on the assumption of a $120 \text{ Bq}\cdot\text{m}^{-3}$ reference concentration. The distribution is bimodal, with maxima around 0.3 and 0.5, and, at the assumed reference concentration, the overall mitigation levels achieved are generally lower than those resulting from Post-Construction remediation. Use of a higher or lower reference concentration merely shifts the plot towards lower or higher mitigation factors respectively, but does not affect the form of the distribution.

If a radon barrier installed during construction were fully effective, i.e. the Mitigation Factor were essentially zero, then all radon results would be expected to be below the Action Level. However, the present study indicates that 11% of the 64 houses constructed with radon-barrier membranes have mean annual radon concentrations above the Action Level, compared to the 17.7% of unremediated houses overall in the NN6 9 post code sector with concentrations above the Action Level, suggesting that the membranes provide inadequate protection in a maximum of around 60% (0.11/0.177) of cases. Extrapolation suggests that a total of 49 of the 444 new houses constructed in Brixworth since 1992 might have radon concentrations above the Action Level. Within the County of Northamptonshire as a whole, where 6.3% of existing houses exceed the Action Level (Green et al., 2003), 3196 new houses were built in 2002–2003, with similar numbers annually in preceding years. Assuming that the results found here apply countywide, some 120 of the houses built in 2002–2003, and a total of approximately 1500 of those built since 1992, could have radon concentrations over the Action Level.

Synnott et al. (2004) studied radon concentrations in houses constructed with radon-barrier membranes in two separate areas of the Republic of Ireland, where Building Regulations (Department of Environment and Local Government, 1997) require houses commenced after July 1998 to have an inactive radon sump, supplemented, in High Radon Areas, by a membrane across the entire footprint of the house. The results were similar to those obtained from the present study. In Ennis, Co. Clare, where the Irish National Radon survey (Fennel et al., 2002) indicated that 27% of existing houses exceed the $200 \text{ Bq}\cdot\text{m}^{-3}$ Reference Level, 12% (11 out of 90) of houses with

membranes returned mean radon concentrations in excess of the Reference Level. Similarly, in Tralee, Co. Kerry, where 45% of a set of control houses constructed prior to the 1998 regulations exceed the Reference Level, 20% (9 houses out of 44) of houses with membranes exhibited raised concentrations. In each case, the most likely cause of these results was postulated to be damage to the membrane during building construction, but post-completion alterations or settlement of the house may also be responsible. Similar findings have recently been reported from Kilkenny, where 10% of post-1998 houses returned radon concentrations in excess of the Reference Level (RPII, 2005).

4.3. Inter-survey comparison

As shown in Fig. 4 the distributions of mitigation factors achieved by During-Construction and Post-Construction radon reduction differ markedly. Post-Construction remediation is characterised by a high incidence of good mitigation outcomes, with more than 75% of the sample exhibiting mitigation factors of 0.2 or better, decreasing monotonically at poorer mitigation factors. In contrast, During-Construction radon reduction is characterised by a bi-modal behaviour, with approximately equal maxima in the regions of 0.3 and 0.5. One possible explanation for this is that the data reflects the existence of two distributions of mitigation efficiency in the population, one deriving from well-installed membranes, exhibiting an intrinsic mitigation factor around 0.3, and the other representing a defective membrane population, affording only 0.5 mitigation. Arafa (2002) reports the permeability constant and permeability of $375 \mu\text{m}$ polythene to be $3.6 \times 10^{-12} \text{ m}^2\cdot\text{s}^{-2}$ and 0.123, respectively, a figure which, while not in very good agreement, is not incompatible with the above suggestion. Alternatively, however, it must be remembered that detailed analysis of the During-Construction data set is hindered by the intrinsic absence of absolute reference data for each house in the sample. While derivation of an imputed mean from measurements of other properties in the locality offers a reasonable course of action, it suffers from the fact that much of the distributional information in the reference sample is lost in the statistical processing, a situation that may well be reflected in the form of the observed mitigation distribution.

Further investigation of these points is in progress, and will be reported elsewhere.

4.4. Construction standards

Correct design and installation of a radon-barrier is essential to prevent radon from entering a house. Any gaps, tears or imperfections in the fitted membrane, resulting from use of poor quality materials, lack of training for installers, poor supervision on site, lack of inspection, placement or, probably, all of these in combination, will provide ready ingress routes for radon.

Since retrospective examination of the integrity of the radon barrier is virtually impossible once construction has progressed much beyond its point of installation, it is essential to ensure

that adequate inspection is carried out at a stage in construction where defects can be located and where rectification is possible. In the UK, Building Regulations are enforced by Building Inspectors, representing the local planning authority, visiting the site to assess compliance during the various stages of construction. While there is evidence that this inspection process is inconsistent across the UK and that it can, on occasions, be inadequate or non-existent, there is also evidence that the combination of increased experience gained from routine installation and the development of improved materials is resulting in better outcomes and more effective mitigation (Scivyer, 2001). It could, therefore, be argued that a stricter inspection regime would both improve the success rate of radon-barrier membrane installation, and would further enhance the effectiveness of other public health measures. In particular, since the radon-barrier membrane also acts as a damp-proof course and prevents ingress from the underlying ground of spores responsible for mould, asthma and other health-related problems, poorly installed or absent membranes can be a prime cause of other health issues.

Although the current measurement protocol in the UK is based on the use of track-etch detectors with a three-month exposure period, it is evident that this does not provide sufficiently rapid response to be applicable prior to sale and occupation of a newly constructed house. Recent evaluation of the accuracy of 7-day measurements using a variety of different short-term detector technologies has confirmed that this approach is realistic, although accompanied by higher variance and larger equivocal range, and is suitable to be adopted as a mandatory assessment by the builder, prior to releasing a newly constructed house to the purchaser (Phillips et al., 2004; Denman et al., 2005b). However, radon concentrations have been shown to be significantly different in occupied and unoccupied houses (Miles, 2001), due principally to the dissipative/diffusive effects of normal daily living and the air-flows accompanying ventilation and the use of central heating, and it may therefore be more appropriate to wait until the householder has been resident for a short period of time before making a measurement. In this case, any indemnity provided by the builder or the builder's registering body (in the UK the National House-Building Council (NHBC)) should ensure that the cost of any remediation (such as fitting a fan in the sump) is borne by the builder, and not by the occupier.

The Housing Health and Safety Rating System, introduced in the UK in November 2004, addresses a range of issues, including radon, and gives Environmental Health Inspectors powers to inspect premises and assess the health risks from any identified hazards (HM Government, 2004). At present, this system is being applied to rented accommodation and to properties owned by Housing Associations (non-profit-making organisations that build, improve and manage homes for rent). The associated guidance (Office of the Deputy Prime Minister, 2004) specifies the requirement that "all new buildings in Radon Affected Areas should be constructed to achieve radon concentrations as low as possible" and notes that "as radon concentrations can vary widely between apparently identical houses, the only way to determine whether or not there is a

threat to health is by measurement." However, it falls short of specifically requiring such measurements in new houses.

4.5. Health issues

The discovery that a significant proportion of houses constructed with radon-barrier membranes exhibit radon concentrations in excess of the Action Level introduces a public health dimension. As discussed elsewhere (Denman et al., 2002), an economic cost on society can be laid at the door of environmental radon, and the cost-effectiveness of remediation measures, in Northamptonshire (Denman et al., 2000, 2005c) and more generally (Ford et al., 1999), can readily be calculated. Recent studies in Northamptonshire (Denman et al., 2000) considered the impact of various remediation scenarios on cost-effectiveness and confirmed that, in areas with 10% or more of existing houses above the Action Level and with active programmes of new house building, During-Construction remediation using radon-barrier membranes is justified financially, and can lead to a small but significant saving in lung cancers, but only if 100% membrane efficacy can be guaranteed.

5. Conclusions

Study of two samples of houses in Northamptonshire, a designated Radon Affected Area, has revealed significant differences in radon mitigation characteristics between houses remediated subsequent to construction, using fan-assisted sump technology, and those incorporating radon-barrier membranes installed during construction. The results suggest that while Post-Construction remediation is largely successful, radon-barrier membranes currently incorporated in new houses constructed in the UK do not consistently provide adequate radon protection, specifically failing to reduce the internal radon to concentrations below the UK Action Level of 200 Bq·m⁻³. Although the proportion of houses with radon concentrations in excess of the Action Level was found to be reduced relative to that found in existing housing without radon precautions, this figure is still around 60%, consistent with the findings of Irish studies assessing geographically separated areas.

Although an improved inspection regime may reduce the percentage of failed membranes, each newly constructed house has to be treated individually and affected houses can only be identified by measuring their radon concentrations. However, the UK currently has no requirement to test radon concentrations in newly constructed houses, leading to the situation in which a significant proportion of new houses, while technically compliant with current building regulations, in practice exhibit radon concentrations in excess of the Action Level. With in excess of 150,000 new house constructions commencing annually in England, and with major housing developments currently being proposed for a large area of central England underlain by Jurassic bedrock associated with high radon levels (Hains and Horton, 1969), the number of houses at risk is anticipated to increase, rather than decrease, in the short and medium term.

There is compelling evidence, therefore, to support the case for radon measurements in new houses once construction is complete in order to identify those where the membrane provides inadequate protection. It is recommended that, once the house is completed but before it is released for occupation, the builders should be required to perform a 7-day radon measurement, using an approved protocol, to confirm that it has low radon concentrations. This test should be carried out with the central heating operative, in order to simulate the air-flows anticipated during residential occupation. Furthermore, since there already exists a large inventory of houses constructed in Radon Affected Areas since 1992 and therefore incorporating protective membranes, the present results highlight the need to test these retrospectively, to identify those in which the membrane is ineffective.

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