A cost-effectiveness analysis of radon protection methods in domestic properties: a comparative case study in Brixworth, Northamptonshire, UK

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Abstract

Building regulations in the UK have since 1992 required that radon-proof membranes be installed in new domestic properties to protect residents against the adverse effects of radon. This study compares the cost-effectiveness of the current regulatory regime with an alternative that would entail new properties being tested for radon after construction, and being remediated if necessary. The alternative regime is found to be more cost-effective for a sample of properties in Brixworth, Northamptonshire, UK. For this regime, the central estimate of cost per quality-adjusted life-year gained, the measure of cost-effectiveness used, is £2869 compared to £6182 for installing membranes, results suggesting a case for re-examining the current...
regulations on radon protection in new properties. Pilot studies will, however, be needed to consider how different means of protecting residents of new properties against radon might operate in practice and to provide improved evidence on their relative cost-effectiveness.

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Keywords: Building regulation; Cost-effectiveness analysis; Lung cancer; Membranes; Radon remediation

1. Introduction

Radon is a naturally occurring radioactive gas, which, as it decays, produces radioactive progeny that can deliver a dose of radiation to those exposed to it (Hughes, 1999). When concentrated in domestic properties radon will, because of associated radiation, threaten human health. A number of studies in recent years have demonstrated a link between high levels of radon in domestic properties and a higher incidence of lung cancer among those living in the properties (Lubin and Boice, 1997; Denman and Phillips, 1998; Darby et al., 1998, 2001, 2005; Kreienbrock et al., 2001; Krewski et al., 2005).

Faced with the threat to human health that radon represents, the National Radiological Protection Board (NRPB) in the UK (since 2005 part of the UK’s Health Protection Agency) identified in 1990 an “Action Level” of 200 Becquerels per cubic metre (Bq m\(^{-3}\)). Areas where more than 1% of domestic properties have radon readings above this level are classified by the NRPB as radon “Affected Areas” and, if readings above the Action Level occur in specific existing domestic properties, householders are advised to remediate against the gas’ effects. The primary method of remediation in the UK is to install an under floor sump fitted with a fan that captures and then expels the radon into the atmosphere. The method can also be applied in new properties, the sump and fan being fitted during construction, but an alternative available in these is to install a radon-proof membrane during construction that prevents the gas from entering the property.

As a consequence of evidence emerging on radon’s effects, the Building Research Establishment (BRE) (1992) recommended that all new properties in specified geographical areas in the UK be built with radon protection, advice recognised by legislation in 1993. This was updated in 1999 since when regulations require that all new properties have a membrane installed if 3% or more of existing properties in an area are above the Action Level (BRE, 1999). The regulations do not apply, therefore, in all Affected Areas. New properties must also be fitted with a sump if more than 10% of properties in an area have readings above the Action Level. A fan can then be added if subsequent tests reveal that one is needed to reduce radon levels further.

The current regulations are in force in the village of Brixworth, Northamptonshire, UK, the geographical location of which is shown in Fig. 1. Brixworth lies in a radon Affected Area and is well known for its high-indoor radon levels. Green et al. (2002) report 16.2% of properties to be above the Action Level in the postcode sector (NN6 9) that covers the village. This sector, it should be noted, covers a wider geographical area than that of Brixworth, so the value is not an exact representation of radon levels in the village. It is, however, the most detailed available in the public domain. Moreover, all other villages within the postcode sector share the geology that gives rise to the elevated radon levels in Brixworth. The local bedrock is of Inferior Oolite material and the villages are situated on hills of Northamptonshire Sand (Hains and Horton,
1969), a permeable rock formation regarded as a significant radon source in Northamptonshire (Sutherland and Sharman, 1996). The proportion of properties above the Action Level reported by Green et al. (2002) is, therefore, highly likely to reflect radon levels in Brixworth.

Despite BRE regulations, however, Denman et al. (2005) found, when they tested a sample of properties for radon in the village, all of which were fitted with membranes and sumps, that a significant number had readings above the Action Level. This result is consistent with those from two Irish studies reported upon by Synnott et al. (2004), suggesting that experience with the sample is not an isolated case. These failures are most likely caused by problems during construction, although later alterations or settling of properties after construction may also be factors.

Potential problems with membranes could have implications for their cost-effectiveness and it is this aspect of their use in the sample of properties tested by Denman et al. (2005) that is considered in this study. Their estimated cost-effectiveness is then compared with that of an alternative regulatory regime. While the results relate to the particular case of Brixworth, the analysis has wider implications for protecting new properties against radon’s effects and for the regulations that support this aim.
In Section 2, the nature of the alternative regulatory regime considered is outlined briefly. Section 3 then describes the method used to estimate the cost-effectiveness of the two regimes. The results obtained from applying the method described are presented in Section 4. These show the alternative regime to be more cost-effective than the current one. The subsequent discussion in Section 5 considers the implications of the results and their limitations. Section 6 concludes with proposals for further research to establish whether a change in the current regulatory approach is justified.

2. An alternative regulatory regime

Although membrane use has been the method required by building regulations in the UK for some years, it is possible to envisage alternative regimes in which protection against radon in new properties is achieved by different means. The alternative regulatory regime considered in this study is the following:

1. construct all new properties without protection against radon;
2. upon completion, test all new properties for radon using NRPB protocols (Wrixon et al., 1988);
3. remediate properties above the Action Level by installing a sump and fan; and
4. re-test these properties to verify that they are below the Action Level and require no additional remediation.

The regime is based on current practice for remediating existing properties in the UK and would place an obligation on house builders, backed up by legislation, to conduct and cover the costs of testing and remediating properties against radon. This requirement would be equivalent to the obligation to install membranes imposed on builders under existing regulations.

The regime would also address a potential problem that buyers of new properties may, in practice, neither test nor remediate once they had bought their new property. For existing properties, Bradley (1996) found that 90% of residents did not remediate when they obtained test results above the Action Level. This percentage could be even higher in new properties, as buyers may feel less able to carry out testing or remedial work, given the expenses already incurred when buying a new property. Placing responsibility to act with householders could, therefore, potentially undermine the alternative regime. Instead, the burden of regulatory compliance is best left with house builders, who can be more easily policed and who could face potentially serious reputational losses from contravening regulations.

3. Method

Analysis of the two regimes was based on results from the radon tests reported in Denman et al. (2005), who also detail how the sample and readings were obtained. The tests were conducted between December 2003 and May 2004 in 65 houses built in Brixworth since 1992. All the properties had membranes and sumps installed during construction, a point confirmed with the house builders concerned. The cost-effectiveness of both regimes was estimated using cost per “quality-adjusted life-year” (QALY) gained, a measure that picks up how an intervention affects both the length of individuals’ lives and the quality of those lives. It also permits comparison between policy approaches designed to achieve the same ends, making it valuable for comparing the two regimes in this study. More generally, it is useful for policy makers when assessing the relative merits of different health technologies, and its use for this purpose is widespread.
The method used in this study to arrive at an estimate for each regime is summarised in Fig. 2. As this shows, estimates were first needed of what radon levels would have been in the Brixworth properties had no measures to protect against radon been taken. To obtain these, hypothetical readings were derived by assuming that radon levels in the properties would be log-normally distributed. Miles (1998) discusses how this distribution should apply to groups of properties in a particular geographical area. Given this assumption, a random log-normal distribution of 65 observations was then generated from log mean and log standard deviation values taken from two mean values reported in Green et al. (2002), namely the arithmetic (AM) and geometric (GM) means of radiation levels in properties that have been measured within postcode sector NN6 9. These means were 117 Bq m$^{-3}$ and 59 Bq m$^{-3}$ respectively. Details of the calculations used to generate the random distribution are given in Appendix A.

The random distribution was re-estimated 1000 times; the 65 values in each of the random distributions were then ranked; and a mean for the 65 properties was calculated from the 1000 ranked distributions. These hypothetical values were those used for both regimes as the test results that would have been obtained if no protective measures had been taken in the 65 properties.

To estimate the effects of installing membranes and sumps in the sample, the hypothetical readings were compared with the actual test results from Denman et al. (2005). For the alternative regime, however, the assumption was made that a sump and fan would be installed in properties with hypothetical readings above the Action Level. The estimated effect this would have on radon levels in the properties was based
on data from studies in existing Northamptonshire properties (Denman and Phillips, 1998; Kennedy et al., 1999; Coskeran et al., 2002, 2005). These show that on average remediation programmes based on installing sumps and fans reduce radon levels by over 80%. In this case, a reduction of 80.3% was assumed for each property, this being the average for ten existing properties for which data were available in postcode district NN6. It is at the lower end of average reductions found in Northamptonshire properties where sumps and fans have been installed. Coskeran et al. (2005), for example, report average cuts in radon levels for existing properties in four Northamptonshire Primary Care Trusts (PCTs) of between 84.0 and 89.7%. These estimated readings (80.3% of the hypothetical values) were those compared with the original hypothetical values to determine the effect of the alternative regime.

The reduced exposure to radon and radiation that resulted from both regimes, the number of estimated lung cancers averted due to the reduced annual radiation dose, and the extra life-years derived from each lung cancer averted were estimated following procedures outlined in Coskeran et al. (2005). As in that previous study, it was also assumed, in the absence of data on residents’ ages, that the regimes would reduce exposure to radon over 40 years.

Finding the improved quality of life due to the two regimes required estimates of quality of life both with and without them in place. To find the quality of life for residents in the sample with no protective regime, mean utility scores (quality of life indicators) for England’s population, derived from the EuroQol EQ-5D measure and used in the Health Survey for England (HSforE) 1996, were taken from Department of Health (1998). The scores rate quality of life on a scale from zero to one, where zero represents death and one perfect health. As the HSforE breaks down scores by age group from the age of 16 upwards, it was possible to estimate an average utility score for Brixworth by weighting the quality of life scores for age groups in the HSforE by the percentages in the relevant age groups for Brixworth. Population figures for this purpose were obtained from the 2001 UK Population Census.

Mean quality of life for the Brixworth sample over a whole lifetime with no protection against radon was estimated by this procedure to be 0.8523. Multiplying this score by the sum total of residents in the sample and the number of years they were on average expected to live after remediation (assumed to be 40 years) gave the total QALYs for the sample without radon protection as 5960.99.

To derive average quality of life when each regime was in place, the approach adopted in Coskeran et al. (2006) was used. In this, a utility score for lung cancer sufferers on the EuroQol EQ-5D scale, taken from Trippoli et al. (2001), was applied. They suggest a value of 0.58 derived from patient responses to the EuroQol survey. It is similar to that reported by Clegg et al. (2002), who found that oncology professionals indicated values between 0.53 and 0.60. The estimate from Trippoli et al. (2001) is preferred here, as patient responses are generally held to be better indicators of utility scores. Sensitivity analysis was, though, conducted around the use of this value.

The approach to estimating the change in QALYs due to each regime also followed that in Coskeran et al. (2006). As they explain, improved quality of life applies not only to additional life-years resulting from reduced exposure to radon. Individuals will experience all life-years at the higher quality of life. In estimating additional life-years, only the effect each regime had on averting lung cancers was considered, although both can deliver other health benefits. In the case of membranes, access of spores and chemical contaminants that can cause asthma and other health problems can be prevented. And installing a sump and fan may reduce levels of dampness in a property with consequent potential benefits for health. But in the absence of data on the extent of these effects in the two regimes, no allowance was made for them. Instead, they were assumed to be equal. Similarly, possible reductions in the incidence of skin cancer, suggested by Denman et al. (2003), were not incorporated in the analysis for either regime. In both cases, therefore, the estimates are likely to be conservative measures of absolute cost-effectiveness but reasonable measures of relative cost-effectiveness.

Costs in the current regime were taken to be those of installing membranes and sumps, £310 per property. As for all values in this paper, this is in UK pounds at 2004 prices rounded to the nearest pound, although unrounded values were used in calculations. Cost per property was the same nominal value applied by Denman et al. (2000), implying a fall in the real price of installation over time. Ideally, the costs used would have been actual installation costs for each property, updated to 2004 prices, but these were unavailable.
For the alternative regime, the categories of cost used were the same as those applied in earlier studies of remediation in existing properties, for example, Coskeran et al., 2002. These were derived from contractor estimates and were those for testing (£32 per property), fan operation (£52 per year per property), and replacing fans every 10 years (£106 per property per fan). Unlike in the earlier studies, however, actual remediation costs for individual properties were unavailable on this occasion. Instead, an estimated cost (£803 per property) was used. This was the average for a group of remediated properties in postcode district NN6 and is a figure that slightly exceeds that for all existing Northamptonshire properties for which data were available (£784 per property), again contributing to the notion that the estimates of absolute cost-effectiveness are conservative.

The present value of the regime’s costs divided by the present value of QALYs gained gave cost per QALY gained for each regime. Costs and QALYs gained were discounted, where appropriate, at 3%, following the advice in HM Treasury (2003) for projects exceeding 30 years, as was assumed for this study. QALYs gained and fan operating costs were taken to be spread equally over 40 years and discounted on that basis.

Sensitivity analysis was conducted to test for the effect of assuming that QALYs gained would be achieved only after a time lag and would not be spread evenly over 40 years. Kennedy et al. (2002), for example, suggest that additional QALYs should be spread over the last 15 years of a 40-year period and discounted on that basis to allow for a lag between initial exposure to radon and lung cancer developing. Adjusting the calculation in this way affects the estimated present value of the QALYs gained and the consequent cost-effectiveness.

4. Results

The distribution of hypothetical readings for the 65 properties in the sample, shown in Fig. 3, was the starting point for considering the effects of both regimes. For the current regime, when these values were compared with the actual test readings from Denman et al. (2005) the reduced exposure to radon in the properties and the consequent fall in radiation dose due to the membranes and sumps could be estimated. Results for these two effects are given in Table 1. Also summarised in Table 1 are the lung cancers averted and life-years gained from the reduced radiation among residents of the 65 properties.

Mean quality of life over a whole lifetime in Brixworth, QALYs with and without the membranes and sumps installed, the present value of the QALYs gained, and the cost per QALY

![Fig. 3. Frequency distribution of estimated readings in Brixworth new properties.](image-url)
gained are summarised in Table 2. The figure of £6182 for cost per QALY gained reported for this regime was based on total costs for installing membranes and sumps in the 65 properties of £20 150.

For the alternative regime, remediation was held to be necessary in 10 properties that had hypothetical readings above the Action Level. As for the current regime, the estimated effects of remediation on total exposure, dose, lung cancers and life-years gained from the alternative regime are given in Table 1, and the impact on quality of life, QALYs and QALYs gained provided in Table 2. Table 3 details the costs of the alternative regime. When the total costs in this table are divided by the present value of the QALYs gained shown in Table 2, estimated cost per QALY gained for the alternative regime is £2869. This compares with £6182 for installing membranes and sumps in the same group of properties.

One-way sensitivity analysis was conducted on the key assumptions used to derive the cost-effectiveness estimates of the regimes. Where possible, the same changes to the assumptions employed were applied to both regimes. Results are given in Table 4 and are compared for the two regimes in Fig. 4, which confirms that estimates for the alternative regime are lower than for installing membranes and sumps. Only when the assumed utility of lung cancer sufferers is adjusted does cost-effectiveness of the two approaches overlap.

The percentage change in cost per QALY gained following changes in the various assumptions was also calculated for the two regimes and was mostly identical for both, since the assumptions affected the benefits gained from each equally. When assumptions about the AM and

<table>
<thead>
<tr>
<th>Table 1</th>
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<tr>
<td>Estimated reduction in exposure and dose for two regulatory regimes in Brixworth</td>
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<table>
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<th>Current regime (membranes and sumps)</th>
<th>Alternative regime (test and remediate)</th>
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<tbody>
<tr>
<td>Total reduction in exposure (Bq m⁻³)</td>
<td>1299</td>
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<tr>
<td>Total reduction in annual dose all households (mSv)</td>
<td>174.43</td>
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<td>Lung cancers averted per year</td>
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<td>Lung cancers averted over 40 years</td>
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<tr>
<td>Total life-years gained over 40 years</td>
<td>3.299</td>
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<tr>
<td>Present value of life-years gained</td>
<td>1.964</td>
</tr>
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</table>

a Assuming 13.51 life-years gained for each lung cancer averted.

b Assuming life-years gained are spread evenly over 40 years.

<table>
<thead>
<tr>
<th>Table 2</th>
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<tr>
<td>QALYs and costs per QALY gained for two regulatory regimes in Brixworth</td>
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<table>
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<tr>
<th>Current regime (membranes and sumps)</th>
<th>Alternative regime (test and remediate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality of life without membranes</td>
<td>0.8523</td>
</tr>
<tr>
<td>Quality of life with membranes</td>
<td>0.8527</td>
</tr>
<tr>
<td>QALYs assuming no regime</td>
<td>5960.99</td>
</tr>
<tr>
<td>QALYs with regime in operation</td>
<td>5966.46</td>
</tr>
<tr>
<td>QALYs gained from regime</td>
<td>5.48</td>
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<tr>
<td>Present value of QALYs gained from regimea</td>
<td>3.26</td>
</tr>
<tr>
<td>Cost per QALY gained (£)</td>
<td>6182</td>
</tr>
</tbody>
</table>

a Assuming QALYs gained are spread evenly over 40 years.
GM of Brixworth radon levels and the discount rate were altered, however, differences did arise. Estimated cost per QALY gained proved less sensitive in the alternative regime to changes in these two assumptions than in the current regime. Relevant values are provided for comparison in Table 5.

Different reasons lie behind these two disparities. When the assumed levels of AM and GM were reduced for the hypothetical distribution and applied to the current regime, the actual readings obtained were unaffected, as they were fixed at the levels found by Denman et al. (2005). The beneficial effect of the membranes and sumps is, therefore, unambiguously reduced. On the other hand, for the alternative regime, reducing the readings from the hypothetical distribution also reduced post-remediation levels, as these were an assumed proportion (80.3%) of the estimated values. This effect partially offsets that of reducing the assumed initial radon levels. The less sensitive estimates for the alternative regime are, therefore, due to the estimation procedure.

With the assumed discount rate, the differences in sensitivity relate to the timing of costs associated with the two regimes. If a higher discount rate is used, the present value of QALYs gained is cut for both. But only in the alternative regime are the present values of certain costs (maintenance and replacement) reduced. No such effect occurs with the current regime, where all costs are assumed to be immediate. The sensitivity of the cost per QALY gained of the current regime to changing the discount rate is, therefore, greater, as no counterbalancing effect arises from a fall in the present value of costs.

A “worst-case scenario” was also constructed in which the least favourable of the assumptions in Table 4 were applied to both regimes. This gave a cost per QALY gained for the current regime of £56,531 and a similarly estimated value for the alternative regime of £36,650. These results are not, though, directly comparable as different assumptions were altered in each case. At the other extreme, the “best-case scenario” was estimated at £1,893 per QALY gained for the current regime and £892 for the alternative.

5. Discussion

Given these results, the alternative regime would appear for the Brixworth sample to be both more cost-effective than installing membranes and sumps and more robust to changing certain assumptions. That said, the cost-effectiveness of both regimes compares well with those of other medical interventions, as Fig. 5 demonstrates. Similarly, both estimates are considerably below the threshold of £30,000 per QALY gained implicitly adopted by the UK’s National
Institute for Health and Clinical Excellence (NICE) as an indicator of a cost-effective medical treatment. If they were assessed by NICE as forms of treatment, therefore, both regimes could be recommended.

Each regime also compares well to the value society places on a QALY. If cost per QALY gained is below this valuation, then an intervention is, in principle, justified. While estimates of a QALY’s value can vary from as little as £5556 (Gyrd-Hansen, 2003) to £97 808 (Hirth et al., 2000), the cost per QALY gained of both regimes is below most plausible values. In fact, estimates for the alternative regime, including those derived from the sensitivity analysis shown in Table 4, are beneath even Gyrd-Hansen’s valuation. And it is only against the Gyrd-Hansen valuation that the central estimate of the current regime fails on this score.

Despite these positive results, there are limitations with the estimates. One issue is that the cost-effectiveness of the alternative regime has been determined from imputed radon levels for both pre- and post-remediation. While these reflect well-established features of the effects that

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Original assumption</th>
<th>New assumptions</th>
<th>Cost per QALY gained (£)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Current regime</td>
<td>Alternative regime</td>
</tr>
<tr>
<td>Number of residents per household</td>
<td>2.69</td>
<td>2.36 (England average) 7047</td>
<td>3228</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.45 (Daventry average) 6788</td>
<td>3110</td>
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<tr>
<td>Average occupancy</td>
<td>17.28 h</td>
<td>16 h</td>
<td>6677</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20 h</td>
<td>5340</td>
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<tr>
<td>Period over which QALYs gained are spread</td>
<td>Equally spread over 40 years</td>
<td>Spread over last</td>
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<tr>
<td></td>
<td></td>
<td>10 years</td>
<td>10 164</td>
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<td>20 years</td>
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<td></td>
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<td>25 years</td>
<td>7990</td>
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<td></td>
<td></td>
<td>30 years</td>
<td>7348</td>
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<tr>
<td>Arithmetic mean (AM) and geometric mean (GM) used to estimate random sample</td>
<td>AM = 117; GM = 59</td>
<td>AM = 100; GM = 57.45 14 558</td>
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<tr>
<td></td>
<td></td>
<td>AM = 105; GM = 57.5 11 372</td>
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<td></td>
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<td>AM = 110; GM = 58 9223</td>
<td>2987</td>
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<td></td>
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<td>AM = 113.5; GM = 58.5 7999</td>
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<td>Discount rate</td>
<td>3%</td>
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<td>3.5%</td>
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<td></td>
<td></td>
<td>0%</td>
<td>3679</td>
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<tr>
<td>Utility of lung cancer sufferers</td>
<td>0.58</td>
<td>0.85</td>
<td>11 944</td>
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<tr>
<td></td>
<td></td>
<td>0.8</td>
<td>10 186</td>
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<td></td>
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<td>3682</td>
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<td>Percentage reduction in radiation after remediation</td>
<td>80.3%</td>
<td>70% Not applicable 3255</td>
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<td></td>
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<td>90%</td>
<td></td>
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<tr>
<td>Average cost of remediation</td>
<td>£803</td>
<td>£1800 (maximum actual recorded value) Not applicable 3999</td>
<td>2946</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td>£700</td>
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<tr>
<td></td>
<td></td>
<td>£200 (minimum actual recorded value) 2127</td>
<td>2712</td>
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Table 4
One-way sensitivity analysis of assumptions for two regulatory regimes in Brixworth

While these reflect well-established features of the effects that
remediation can have and the functional form of the distribution of radon levels, using two such estimates could be problematic. It suggests a need for further work to establish reliable estimates of the alternative regime’s cost-effectiveness.

Equally, problems exist with the estimate for the current regime, which ignored inspection costs associated with ensuring that membranes and sumps were correctly installed. These costs might, at the margin, be zero, since building inspectors will be dealing with other aspects of construction while inspecting installation of radon membranes, and such was assumed in this study. But if these costs are positive they should be incorporated in the analysis. To do so would, of course, then make any presumption in favour of the alternative regime that much greater.

The case for the alternative regime could be strengthened yet more in geographical areas where the proportion of properties above the Action Level is relatively low. Adopting the alternative regime in these would mean that resources could be concentrated on the relatively small number of properties where remediation is needed, instead of being spread across a large number that do not require it, as happens when membranes and sumps are installed. This feature of the alternative regime could, therefore, make it especially attractive in areas where the

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**Table 5**

<table>
<thead>
<tr>
<th>Assumption</th>
<th>New assumption(s)</th>
<th>Percentage change in current regime</th>
<th>Percentage change in alternative regime</th>
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<tbody>
<tr>
<td>Arithmetic and geometric means used to estimate random sample</td>
<td>AM = 100; GM = 57.45</td>
<td>135.5</td>
<td>17.8</td>
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<td></td>
<td>AM = 105; GM = 57.5</td>
<td>84.0</td>
<td>12.3</td>
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<td>AM = 110; GM = 58</td>
<td>49.2</td>
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<td></td>
<td>AM = 113.5; GM = 58.5</td>
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<td>Discount rate</td>
<td>5%</td>
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<td></td>
<td>3.5%</td>
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<td></td>
<td>0%</td>
<td>−40.5</td>
<td>−15.6</td>
</tr>
</tbody>
</table>

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Fig. 4. Sensitivity of cost-effectiveness estimates — maximum and minimum values.
proportion of properties above the Action Level is below 3%, the current threshold for the building regulations. The use of membranes and sumps in areas where a much higher percentage of properties are above the Action Level, such as Cornwall in the south-west of England, might, of course, for the same reason be economically advantageous, as in these areas fewer resources would go to properties not requiring remediation.

Despite its apparent superiority, however, the alternative regime raises concerns that properties would be built that would not be “fit-for-purpose” when buyers took ownership. In a minority of cases, buyers would, at least in the first instance, be provided with a property that fell short of regulatory standards. However, the same can be said about installing membranes, which, as Synnott et al. (2004) and Denman et al. (2005) have shown, can lead in a limited number of properties to house buyers not having full protection against radon. Indeed, the situation may be worse, as in the current regime there is no mechanism built in for dealing with properties requiring further remediation or for identifying properties where residents are at risk. In contrast, the proposed alternative regime contains a safeguard in the form of post-construction testing.

The alternative regime would also require a proper protocol, and this could have certain implications. As Miles (2001) has shown, radon levels in unoccupied properties can be much lower than when occupied, as heating and occupancy can affect them. If readings from an unoccupied property could be corrected to allow for this effect, it would not be an issue. But if this could not be done reliably, testing would have to happen after an owner had taken possession. This would represent an increased risk for householders, who could be living with elevated radon levels until remediation was conducted. The risk, however, is likely to be negligible and no more than that to which owners of existing properties are exposed when they test their properties.

A further issue with the alternative regime is that testing, and potential remediation, that would take place after householders had moved into their new property, might inconvenience them. In principle, they would be compensated for this inconvenience, at least partly, by a reduced property price, since no membrane and sump would have been installed (although this effect, at just 0.2% of the current average house price in the UK, might be hard to detect). Those
householders requiring remediation would, though, face additional disruption not allowed for in this study, but which could influence cost-effectiveness.

The distribution of costs and benefits from the alternative regime would then also require consideration. Those householders not having to remediate would, in fact, benefit from buying their house at the lower price and only incur the minor inconvenience of testing. In contrast, those with properties where remediation was required would incur both the inconvenience of remediation and subsequent operating and maintenance costs they would have avoided with properly installed membranes and sumps. One solution, if this outcome were thought inequitable, would be for house builders to make a one-off payment to affected buyers at the time of remediation. In principle, if inconvenience effects were ignored, the sum to be paid would be the present value of future running costs. In the Brixworth sample, this would imply builders paying £1377 to each household where remediation was necessary; the sum would come from the savings builders make by not having to install membranes and sumps in every property.

A final factor with the alternative regime is that, by requiring post-construction testing, and possible remediation, it has a number of stages involving compliance by house buyers, builders, or, indeed, environmental health officers. It, therefore, has a greater potential for breakdown and being incomplete. In contrast, if the current regime were functioning correctly and membrane installation were 100% effective, then all properties would be built “fit-for-purpose”, and no compliance issues would arise. Thus, the simplicity of the current regime could prove decisive if a full analysis of the relative merits of the two regimes were conducted. That said, various studies have shown that around 50% of membranes do not reduce the radon level sufficiently, and that post-construction testing is still necessary, so that in practice compliance problems may remain even when membranes are used.

6. Conclusions

Overall, the evidence presented suggests the alternative regime for protecting those in new properties against the effects of radon is more cost-effective in Brixworth than the current regime, and makes a prima facie case for re-examining the present approach. It also raises concerns that the current trigger of 3% of properties above the Action Level for installing membranes and sumps is suspect. If the proposed alternative regime is more cost-effective than installing membranes and sumps in Brixworth, where 16.2% of properties are above the Action Level, it will be even more the case where lower proportions of properties exceed the Action Level.

These conclusions might, at first sight, seem counterintuitive, given that the alternative regime involves carrying out remedial building works on new properties rather than simply constructing them “fit-for-purpose”. That view, however, overlooks the point that in the current regime many new properties are unnecessarily fitted with membranes and sumps. Even in a relatively high-radon area like Brixworth the vast majority of properties (83.8%) do not need remediation of any sort. The alternative regime is, therefore, more cost-effective because resources are not diverted to properties where remediation is unnecessary but, rather, are focused on those that need it.

These results have, nevertheless, been obtained from a sample in an area with a specific proportion of properties above the Action Level (16.2%). It may be that where higher proportions of properties are above the Action Level, the relative cost-effectiveness of the regimes would differ. There are also, as has been observed, issues with how the cost-effectiveness of both
regimes was estimated. And the current regime is itself cost-effective compared to both other medical interventions and the NICE threshold of cost-effectiveness. As a result, before changes to building regulations were mooted, further research would be needed to see if radon protection in new properties could be better achieved by an alternative approach.

Central to this research would be pilot studies conducted in new housing developments in radon Affected Areas. The alternative regime could, for instance, be applied in a given group of properties with the purpose of assessing cost-effectiveness and pinpointing practical problems that might arise. Such problems might include householders ignoring the new regime and choosing not to remediate. If the potential for non-compliance were determined, however, estimates of its extent could be used in both the cost-effectiveness analysis of the pilot studies and as a benchmark for future research. In addition, the studies could help to clarify levels of inconvenience that households might experience when remediation was required.

Longer-term issues about the alternative regime, including those such as whether householders would properly maintain the fans installed, would also need to be addressed. This research could be based on experience in existing properties where, in some instances, remediation measures based on installation of fan and sumps have been in place for a number of years. The need to establish the effectiveness of these measures would, therefore, be part of a wider effort to determine if remediation measures aimed at existing properties are cost-effective.

The pilot studies would, as well, allow measurement of the cost-effectiveness of other regimes that could protect new properties against radon. One such possibility could require installing membranes in new properties, as currently happens, but then having mandatory testing of properties with, if necessary, remediation. This approach would be less disruptive for house buyers than the alternative regime, but would give the potential advantage that properties where radon is above the Action Level would be identified and then made safe. The current regime could, therefore, be beneficially modified, although just how cost-effective this would be will need to be established.

A further alternative could make it obligatory to install a sump during construction in all radon Affected Areas, either with or without a membrane. Mandatory testing would then determine if a fan should be fitted to the sump when radon levels were above the Action Level. A regime based on soil gas measurement before construction to identify areas where there are potential at-risk properties could also be considered. Such an approach has not been adopted in the UK previously, and its cost-effectiveness would rely on there being a strong correlation between soil gas and domestic radon levels. In practice, as Albering et al. (1996) and Kemski et al. (2001) have shown, this may not always be the case. There would, therefore, still need to be testing of individual properties to determine radon levels, something that would need to be factored into any assessment of cost-effectiveness. Finally, pilot studies could assess if more rigorous building inspection that would improve standards of membrane installation would also improve cost-effectiveness. In particular, these studies could consider how the extra costs of more inspection would weigh against potential reductions in residents’ exposure to radon.

Valuable evidence on the cost-effectiveness of different regulatory approaches towards protecting new domestic properties against the effects of radon should then emerge from such studies. This will be crucial, given that this study has suggested the current regulatory regime may not be the most cost-effective approach available, even when a high proportion of properties are above the Action Level. If that result were confirmed, therefore, it would signal a need to change the current regulatory regime in order to ensure that the regime adopted for tackling
an important matter of public health concern employs scarce resources in a socially beneficial manner.

Appendix A

In a log-normal distribution, the mean of the logarithm of a variable’s distribution \( m \) is given by

\[
m = \log \left( \mu^2 / \sqrt{\sigma^2 + \mu^2} \right)
\]  (A.1)

where \( \mu \) is the mean of the variable and \( \sigma \) is the standard deviation of the variable.

The standard deviation of the logarithm of the variable \( s \) is given by

\[
s = \sqrt{\log \left( \frac{\sigma}{\mu} \right)^2 + 1)}
\]  (A.2)

And the geometric mean \( G \) for the variable is given by

\[
G = \exp(m) \Rightarrow m = \log G
\]

Substituting the expression for \( m \) into Eq. (A.1) gives

\[
\log G = \log \left( \frac{\mu^2}{\sqrt{\sigma^2 + \mu^2}} \right)
\Rightarrow G = \left( \frac{\mu^2}{\sqrt{\sigma^2 + \mu^2}} \right)
\]  (A.3)

Rearranging Eq. (A.3):

\[
\sigma = \sqrt{\left( \frac{\mu^2}{G} \right)^2 - \mu^2}
\]  (A.4)

Where \( G \) and \( \mu \) are known (and Green et al., 2002 provide these) \( \sigma \) can first be estimated from Eq. (A.4) and this value then used in Eq. (A.2), along with \( \mu \), to estimate \( s \). With \( m \) and \( s \) known, a random log-normal distribution can be generated for a specified number of observations using the random data generator in the Minitab software.

References


