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An etched track detector for short-term screening measurements of radon

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Abstract
An etched track detector has been developed for use in screening or indicative measurements of radon in homes over an exposure period of 14 days. If the annual mean radon concentration estimated from screening detector results is within a factor of two of the UK radon Action Level (200 Bq m$^{-3}$), the householder is told that the result is uncertain, and advice on whether the home is above or below the Action Level must be based on the result of a (standard) 90 day measurement. The screening detectors are always supplied to householders together with detectors to be exposed for 90 days, so that if the screening result is reported as being uncertain (within the range 100–400 Bq m$^{-3}$), a long-term measurement in the home is already under way. Comparison of the results of the screening (14 day) and standard (90 day) detectors exposed in the same homes shows that reporting screening results in this way did not result in any householders being wrongly advised. Short-term measurements can therefore be offered in those circumstances where a householder needs a faster indication of radon levels in a property (for example a house sale), with the caveat that a 14 day exposure result within a factor of two of the Action Level requires a long-term measurement to confirm whether the dwelling is above or below the Action Level. A precautionary uncertainty range for use with charcoal detector measurements is also given (75–500 Bq m$^{-3}$).

1. Introduction

The Radiation Protection Division of the Health Protection Agency (HPA), previously the National Radiological Protection Board (NRPB), has been producing passive radon detectors...
for use in homes since 1981 (Miles and Dew 1982). The NRPB issued formal advice on limiting radon exposure in UK homes, setting a radon Action Level of 200 Bq m$^{-3}$ in 1990 (NRPB 1990).

The Action Level refers to the annual mean radon concentration in a home; but radon levels indoors vary substantially from day to day, as they are influenced by weather conditions. Ideally, radon measurements would be carried out over a full year, but householders are very reluctant to wait that long, and detectors left in place for so long are often lost. Also, the sensitivity of a detector may change if it is exposed for a year, increasing the uncertainty associated with the result (Hardcastle and Miles 1996). For these reasons, HPA standard radon measurements are normally carried out over a period of 3 months, using one detector in the main living area and one in an occupied bedroom. Measurement results for the two detectors are combined using occupancy weighting factors (Miles and Howarth 2000). The 3 month exposure period was chosen as a compromise between the need for a long exposure period to provide a reliable estimate of the annual mean radon concentration and the problems associated with year-long measurements. All results are corrected to the estimated annual mean radon concentration before they are reported to the householder, using correction factors based on the typical seasonal variation in radon concentrations in UK homes (Miles and Howarth 2000).

In some cases, householders are anxious to obtain a radon result in a much shorter time than 3 months, often because they are buying or selling a home. The NRPB and HPA have advised that short-term measurements have higher uncertainties, but that they can be used for screening purposes (NRPB 2001). In many cases, particularly in lower risk areas, such short-term measurements will show such a low radon level that it is reasonably certain that the annual mean radon concentration is below the Action Level. In these circumstances, further testing is not required. However, in some dwellings, most often in high radon areas, the screening measurement will give a result closer to the UK Action Level for radon. Long-term measurements are then required to determine whether or not the annual mean radon concentration is above the Action Level.

Because of the continuing demand from some householders for short-term screening measurements, HPA decided to offer such a service. Charcoal detectors offer one option for providing such a service. Although charcoal detectors can be accurate in determining the radon concentration over a few days, the limited exposure period possible with such detectors leads to large uncertainty ranges when estimating the annual mean radon concentration. Charcoal detector response gives undue weight to the final 1–2 days of exposure and is affected by temperature and humidity (Tommasino 1990). An etched track screening detector service is preferable to a charcoal detector service because it allows a longer minimum exposure period, giving a smaller uncertainty range.

It was decided that the HPA radon screening service should be based on the etched track system used for standard measurements, which had the advantage that the equipment and staff experience was already available in the laboratory. An etched track detector exposed for a short period requires a large area of the detector to be scanned for tracks, to provide sufficient sensitivity (Tommasino 1990). The HPA passive radon detector meets this requirement, since tracks are counted over an area of more than 5 cm$^2$ (Ibrahimi and Miles 2008).

The screening detectors are exposed for a minimum of 2 weeks, to reduce the effects of short-term variations in radon concentrations on the results. Table 1 shows the smaller uncertainty range for the HPA screening detector (100–400 Bq m$^{-3}$) compared with charcoal detectors (75–500 Bq m$^{-3}$) when determining whether a property is above or below the UK Action Level, due to lengthening the exposure period to a minimum of 14 days. It was also decided that screening detectors would be offered only as part of a package of two screening detectors and two standard (long-term) detectors. In the event that the results from the screening
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Table 1. Threshold concentrations for reporting radon results obtained over different exposure periods.

<table>
<thead>
<tr>
<th>Type of detector</th>
<th>Measurement exposure period</th>
<th>Measurement result indicating annual mean radon concentration in home is likely to be below UK Action Level of 200 Bq m(^{-3})</th>
<th>Measurement result indicating annual mean radon concentration in home is likely to be above UK Action Level of 200 Bq m(^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charcoal detector</td>
<td>4–7 days</td>
<td>(\leq 75) Bq m(^{-3})</td>
<td>(\geq 500) Bq m(^{-3})</td>
</tr>
<tr>
<td>HPA screening detector</td>
<td>(\geq 14) days</td>
<td>(\leq 100) Bq m(^{-3})</td>
<td>(\geq 400) Bq m(^{-3})</td>
</tr>
<tr>
<td>HPA standard detector</td>
<td>90 days</td>
<td>&lt;200 Bq m(^{-3})</td>
<td>(\geq 200) Bq m(^{-3})</td>
</tr>
</tbody>
</table>

detectors were high enough to require a long-term measurement, the follow-up measurement would already be under way.

Reporting of screening results is not as straightforward as for the standard detectors. The HPA makes it clear before screening detectors are issued to householders that results are indicative only, unless they are particularly high or low. Reporting indicative results is a problem that is also encountered in relation to activated charcoal detectors. The NRPB (2001) advised on how to report the results of measurements made using charcoal detectors, which are normally exposed in homes for 4–7 days. The NRPB advised that if the result of such a measurement is less than 75 Bq m\(^{-3}\) it is reasonably certain that the annual average radon concentration is below the Action Level. If the result is greater than 75 Bq m\(^{-3}\) then a long-term measurement is required. Because the HPA short-term detectors measure over a longer period than charcoal detectors, a higher threshold for remeasurement would appear to be justified, and a value of 100 Bq m\(^{-3}\) was chosen for this study. It was decided to introduce an upper threshold, above which householders would be advised that it was reasonably certain that the radon concentration was above the Action Level. The values chosen for the upper threshold are 400 Bq m\(^{-3}\) for the HPA 14 day detector and 500 Bq m\(^{-3}\) for charcoal detectors. The values are shown in Table 1. The validity of the thresholds for 14 day detectors is tested below.

When HPA short-term measurement results are reported to householders, no numerical result is given if the value falls in the ‘uncertain’ band of 100–400 Bq m\(^{-3}\), and the householder is required to wait for the result of the long-term test before receiving a result.

2. The HPA 3 month radon detector

The HPA passive radon detector contains a solid-state nuclear track detecting element housed in casing made of polypropylene loaded with 25% carbon to prevent electrostatic charges from affecting the performance of the detector (see figure 1). The detector is the NRPB/SSI type detector, 56 mm in diameter and 28 mm high. The detecting elements are made of poly allyl diglycol carbonate (PADC or CR-39). The detector is exposed to radon and then the detecting element is chemically etched in 5 M aqueous sodium hydroxide at 81 °C for 18 h to reveal alpha radiation damage tracks. Detectors are placed in Gepe 35 mm slide mounts and scanned with a Nikon LS2000 slide scanner using its automated slide feeder. Etched tracks are counted using in-house software. Etched track sensitivity using the HPA track counting system (mean ± standard deviation for standard PADC sheets that pass quality assurance criteria, Miles et al 2004) is 2.70 ± 0.17 tracks cm\(^{-2}\) kBq\(^{-1}\) m\(^{-3}\) h\(^{-1}\), \(n = 2217\). Mean track background for these sheets is 44 ± 19 tracks cm\(^{-2}\). Full details of the production and processing of the HPA area radon detectors are given by Ibrahimi and Miles (2008).
HPA 3 month detectors are validated under the UK validation scheme for passive radon detectors (Miles and Howarth 2000). To ensure that the detectors meet the requirements for validation, they are subject to stringent quality control checks. However, checks that are intended for detectors which are exposed in homes for 3 months are not necessarily appropriate for detectors exposed for shorter periods. In particular, the criterion applied for determining the minimum detectable exposure for a 3 month measurement is not appropriate for a 2 week measurement. For standard detectors, sheets of PADC are deemed to fail the background quality criterion if the standard deviation (in the form of equivalent radon exposure) is greater than 15 kBq m\(^{-3}\) h. The minimum detectable exposure is commonly taken to be twice the standard deviation on background. The rejection criterion used by the HPA is equivalent to a minimum detectable radon concentration of 14 Bq m\(^{-3}\) for an exposure of 90 days, below the UK average radon concentration in homes of 20 Bq m\(^{-3}\) (Wrixon et al 1988), and well below the UK radon Action Level of 200 Bq m\(^{-3}\).

When passive radon detectors are exposed for many months, account must be taken of changes in the detector material that could affect sensitivity. It has been shown (Hardcastle and Miles 1996) that when PADC is exposed to air, its radon sensitivity gradually changes (referred to as ageing), and the size of etched alpha particle tracks depends on the elapsed time between the track being laid down and it being etched out (referred to as fading). When detectors are exposed for longer than 3 months, corrections to the results are made for these effects.

3. The HPA 14 day screening detector

If the rejection criterion used for detector material destined for 3 month measurements (reject if standard deviation on background tracks, in the form of equivalent radon exposure, is greater than 15 kBq m\(^{-3}\) h) was applied to detectors exposed for 14 days, the minimum detectable radon concentration would be 90 Bq m\(^{-3}\), which would be unacceptably high. It was therefore necessary to adopt a substantially lower rejection criterion for the standard deviation on background in order to use these detectors for screening purposes. For screening detectors, sheets of PADC are deemed to fail the background quality criterion if the standard deviation (in the form of equivalent radon exposure) is greater than 3 kBq m\(^{-3}\) h, equivalent to a minimum detectable radon concentration of 18 Bq m\(^{-3}\).

Although the rejection criterion for 3 month detectors is a standard deviation of 15 kBq m\(^{-3}\) h, the mean value found for sheets that meet this criterion is considerably lower.
An etched track detector for short-term screening measurements of radon at 4.5 kBq m$^{-3}$ h ($n = 2214$). Experiments were carried out to determine whether this figure could be reduced further for the screening service by taking additional measures during handling of the PADC sheets. These measures were:

- increasing ventilation in the laboratory if the radon concentration was at or above 20 Bq m$^{-3}$,
- engraving and treating the PADC in the minimum time possible,
- using freshly prepared antistatic solution for the treatment of the PADC before issue,
- wearing disposable laboratory gloves when handling the PADC,
- storing the PADC in a radon-free atmosphere for at least 24 h before engraving,
- storing the casings in a radon-free atmosphere for at least 24 h before use,
- sweeping the assembly/disassembly area and detector reader before use,
- minimising the time the detectors are exposed to transient radon in the laboratory and during posting to and from the customer.

Ideally, each of these measures would be tested separately to determine which was most effective. However, that would entail a long and laborious testing programme. Since the measures are all relatively cheap and easy to implement, all measures were tested together. It was found that these measures reduced the mean of the background standard deviation from 4.5 kBq m$^{-3}$ h ($n = 2214$) to 2.0 kBq m$^{-3}$ h ($n = 11$). The difference between the values was not statistically significant given the small number of PADC sheets used for the screening detectors.

For the screening detectors, the effects of ageing and fading of the detector material during exposure were re-examined. The findings confirmed the previous conclusion, that there was insignificant ageing and fading during short exposures. It was therefore decided that no storage of calibration and background detectors in air was required, and no ageing and fading corrections should be applied to the screening detectors.

An assessment of transient radon exposure during postal transfer of radon detectors was also undertaken. Detectors were prepared in standard paper padded envelopes in the laboratory and kept in radon-free nitrogen boxes until the postal service vehicle arrived at the laboratory. The detectors were then entered into the postal system using second class stamps (typically 2–3 day delivery) and sent to some 10 volunteer addresses around the UK. The volunteers had been pre-warned about the experiment. On receipt of the envelopes, the volunteers posted them back to the laboratory the same day in second class stamped envelopes. The experiment was undertaken once during the week and once including a weekend. The postal transit exposure periods averaged 3.8 days. Track densities (mean tracks cm$^{-2}$ $\pm$ standard error) on the transit detectors were compared with retained controls; transit (33.8 $\pm$ 1.4), controls (31.6 $\pm$ 3.4). Results were insignificantly different and corresponded to a mean radon concentration of 9 Bq m$^{-3}$ for the transit detectors, compared with a mean outdoor concentration of 4 Bq m$^{-3}$. The results were unsurprising considering post is transferred between vehicles and large (open warehouse-like) postal sorting offices. The results demonstrated there is insignificant transit radon exposure to passive detectors sent through the normal UK postal system.

The HPA began offering a screening service in April 2005. The service includes four detectors for a typical UK home, two of which are returned after 14 days exposure, and the other two after 90 days exposure. Over the period April 2005–September 2007, householders purchased 125 sets of screening and standard detectors compared with 2833 sets of standard detectors for homes. In addition to these purchases by householders, HPA carries out much larger numbers of measurements to identify homes above the Action Level in high radon areas, funded by the Department of Health and devolved governments. Thus the screening service is only a small part of the total indoor radon measurement service offered by HPA and most
customers find the 90 day exposure period acceptable for their circumstances. Since short-term detectors are always supplied to the householder together with long-term detectors, it was decided that all four detection elements should be made from sheets of PADC selected for use as screening detectors, in case householders returned the wrong detectors first.

4. Correcting results to estimated annual mean concentration

4.1. Using seasonal correction factors

Results of 3 month measurements are corrected to the estimated annual mean radon concentration before they are reported to householders. Such a correction requires knowledge of the typical pattern of seasonal variation of indoor radon. The results of the UK national survey of radon in homes were analysed to determine the mean seasonal variation in indoor radon concentration (Wrixon et al 1988). Another determination of the seasonal variation of radon concentration in UK homes was based on the results of indoor radon measurements made in southwest England for an epidemiological survey (Pinel et al 1995). The results of these two determinations of seasonal variation showed a very similar pattern. The HPA applies a seasonal correction factor based on the results given by Wrixon et al (1988) when reporting results of 3 month measurements. The correction factors are given by Miles and Howarth (2000) and used by laboratories validated for long-term radon measurements in UK homes.

4.2. Using temperature correction factors

It has been shown (Miles 1998) that the seasonal variations in mean indoor radon concentrations correlate with outdoor temperatures. This can be understood in terms of the indoor underpressure, which is determined by the indoor/outdoor temperature difference, and draws radon into buildings along with soil air. When radon measurements are made over periods of months, then any short-term fluctuations in outdoor temperature will not have a large effect on the measured radon concentration. However, when measurements are made over 2 weeks, the measurement period could coincide with a spell of unseasonal weather. Applying a correction based on the typical seasonal variation could result in an unrealistic estimate of the annual mean radon concentration in such cases. For this reason, it was decided that short-term radon results should be corrected on the basis of outdoor temperatures during each measurement, rather than on the typical pattern of seasonal variation.

Outdoor temperatures at various UK locations are provided on the UK Meteorological Office website (www.metoffice.gov.uk). Temperature data from this website were used to correct individual measurement results to estimated annual mean radon concentration. Correction was made using a formula based on the relationship between temperature and radon concentration given by Miles (1998) (equation (1); derivation of the equation is described in the original paper (Miles 1998)):

\[
\text{Annual mean radon concentration} = (C - 4) \times \left( \frac{1}{(1.645 - 0.063t) + 4} \right).
\]

(1)

Here radon concentrations are in Bq m\(^{-3}\); \(C\) is the measured indoor radon concentration, a single value derived from a combination of occupancy-weighted living room and bedroom measured concentrations, and \(t\) is the mean outdoor temperature in the region of measurement during the period of measurement, in degree Celsius.

The reason for subtracting 4 from the measured concentration and adding it back to the annual mean radon concentration is that the mean outdoor radon concentration in the UK is 4 Bq m\(^{-3}\) (Wrixon et al 1988), and this contribution to the indoor radon concentration is not affected by the indoor/outdoor temperature difference.
5. Results

Up to September 2007, 411 short-term and standard (long-term) radon measurement results were available from 110 houses. Some householders required more than four detectors because of the layout of their homes, some did not return all their detectors, and the measurement periods were not always as originally intended. After eliminating those households whose short measurement period was more than 1 month, those whose long measurement period was shorter than 2 months, and those with fewer than four results, results from 59 houses were left for analysis. Their estimated annual mean radon concentrations ranged from 0 to 2000 Bq m$^{-3}$.

A comparison of the results of short-term and long-term measurements is shown in figure 2. On average, the long-term measurement results were 85% of the short-term results, with a standard deviation of 42%. The reason for the long-term results being lower is not clear. One possibility is that householders consciously or unconsciously alter their habits to reduce radon concentrations during a short-term test, but not over the longer term. Another possibility is that the temperature corrections to estimate annual mean concentration were not appropriate for all homes. It is recognised that not all homes show the same pattern of variation in radon concentration as a result of changes in outdoor temperature, a minority being more influenced by wind speed and direction than by temperature (Miles 2001).

To explore the second possibility, correction of results by the seasonal correction factors was compared with correction by applying temperature corrections. It was expected that applying temperature corrections to short-term measurements would provide a more accurate estimate of long-term mean concentration than applying seasonal correction factors. However, it was found that there was no significant difference between the results corrected by the different methods. This subject will be explored in more detail in a subsequent study, which will include measurements of radon made in 100 UK homes over a 2 year period.
All of the homes with a short-term radon result less than 170 Bq m\(^{-3}\) had a final estimated annual mean radon concentration below the radon Action Level of 200 Bq m\(^{-3}\), and all of those with a short-term radon result more than 300 Bq m\(^{-3}\) had a final estimated annual mean radon concentration above the Action Level. The screening detectors therefore were more accurate in predicting whether or not a home was above or below the radon Action Level than assumed in table 1, which provides a margin of a factor of 2 above and below the Action Level. The results show that a factor of 1.5 would have been sufficient. However, this is based on a relatively small sample of homes, so the HPA will continue for the present to use a margin of a factor of 2.0 (that is, lower and upper thresholds of 100 and 400 Bq m\(^{-3}\)) when advising householders on the probability of homes being above or below the Action Level following an HPA screening test.

6. Conclusions

The HPA encourages UK householders who wish to measure radon in their homes to take standard (long-term) measurements wherever possible using an HPA validated laboratory. Since introducing a service providing 14 day screening measurements, HPA has found that 4% of householders opted for the screening measurement. It was found that the result of the 14 day measurements, corrected for outdoor temperature at the time of measurement, always gave correct predictions of whether the home was above or below the Action Level, except where the screening result was within a factor of 1.5 of the Action Level.

Temperature correction has been shown to be a viable alternative method for estimating annual mean radon concentration from a short-term radon measurement compared with seasonal correction factors.

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