Article

Title: Interpreting short and medium exposure etched-track radon measurements to determine whether an action level could be exceeded

Creators: Denman, A. R., Crockett, R. G. M., Groves-Kirkby, C. J. and Phillips, P. S.

DOI: 10.1016/j.jenvrad.2016.06.004

Example citation: Denman, A. R., Crockett, R. G. M., Groves-Kirkby, C. J. and Phillips, P. S. (2016) Interpreting short and medium exposure etched-track radon measurements to determine whether an action level could be exceeded. *Journal of Environmental Radioactivity.* **162-163**, pp. 279-284. 0265-931X.

1. Introduction

Radon is a naturally occurring radioactive gas with a variable geographic distribution. It can migrate from underlying rock, entering and accumulating in buildings. There are several isotopes of radon; the most common is radon-222, with a half-life of 3.8 days. A second isotope, radon-220, often known as thoron, is also found in the environment with a concentration on average one tenth that of radon-222. Thoron has a half-life of 54.5 seconds, and makes a small contribution to the dose received by occupants. Radon has been shown to be the second most significant risk factor for lung cancer after tobacco smoking (AGIR, 2009), and as a result, many national governments have established Action Levels for both domestic housing and workplaces, above which action should be taken to reduce radon levels. The risk from radon is proportional to the lifetime cumulative exposure to radon (AGIR, 2009), and Action Levels have therefore been established in terms of annual average radon levels. In the United Kingdom (UK), the current Action Levels are 200 $Bq.m^{-3}$ for dwellings (O'Riordan, 1990) and 400 $Bq.m^{-3}$ for workplaces (IRR, 1999). For domestic housing, the Action Level relates to the annual average radon level, but the UK legislation for workplaces (IRR, 1999) specifies the Action Level as the winter maximum. However, there is a current proposal in the European Union (EU, 2014), based on the latest ICRP guidance (ICRP, 2014), to adopt an Action Level for the annual average radon level of 300 $Bq.m^{-3}$ for both houses and the workplace.

Radon levels in buildings are, however, widely variable with a diurnal variation – usually much higher at night – and with other variability related, for example, to the external weather and occupancy patterns. As a result, measurements with short term exposures may not be a good estimate of the annual average radon level. Traditionally, in the UK and many other countries, etched-track radon dosimeters have been used with three-month exposures, and corresponding appropriate measurement protocols have been established. However, there is a demand for shorter term exposures, particularly for house sales. In a project funded by the UK Department for Environment Food & Rural Affairs (DEFRA), Phillips et al. (2003) evaluated the usefulness of 1-week and 1-month measurements compared to 3-months, and in subsequent work (Groves-Kirkby et al., 2006) suggested when such exposures could be used and proposed measurement protocols for each. Crockett et al. (2006) have subsequently shown that a lunar bi-weekly tidal cycle also influences radon variation, and recommended that a 2-week exposure is preferable to a 1–week one.

One of the most significant patterns of radon level variation in domestic housing is seasonal, with levels higher in winter than summer. Wrixon et al. (1988) therefore proposed the use of Seasonal Correction Factors (SCFs) which they developed from a large series of aggregated measurements in domestic properties, and for many years these have been used in the UK to correct term radon measurements in both domestic housing and the workplace. However, using the data from the original DEFRA study, Denman et al. (2007a) developed SCFs with lower seasonal variation, and commented on the applicability of using seasonal corrections. Recently, Miles et al. (2012, corrected 2014) have recommended the use of revised national SCFs for the UK, which are closely aligned to those of Denman et al. (2007a).

In addition to diurnal and seasonal variations, a number of studies have shown variations in the average radon level year-on-year, with coefficients of variation of 14% or above, as noted by Bochicchio et al. (2009), which are considered to be primarily due to meteorological variations, while some regions may have significantly different seasonal corrections due to underlying geology (Burke and Murphy, 2011).

Etched-track detectors are now used widely by industry for domestic radon level assessments, and, whilst 3-month exposures remain the preferred option, a wide variety of exposure times are used in practice, including 6-weeks, 2-months, and 4-months to suit clients. There is therefore a need for comprehensive guidance over a wider range of exposure periods. This paper reworks the analysis of the original data, and also compares that with the results from the analysis of an extended dataset for 4 houses over 4 years (Crockett et al., 2015), to extend the analysis to other exposure periods, to review and comment on the appropriateness of making seasonal corrections, and to provide appropriate guidance on the interpretation of results and use of seasonal corrections.

2. Methods

The measurement methodology has been described in detail by Phillips et al. (2003), and Groves-Kirkby et al. (2006). 1400 etched-track detectors from two different suppliers, 600 activated-charcoal detectors and 50 reusable electrets were used in a total of 37 dwellings around Northamptonshire, a county in the English Midlands of the UK.

During the year April 2002 – March 2003, etched-track detectors were placed in each dwelling for up to four consecutive 3-month exposures and, simultaneously, for twelve consecutive 1-month exposures. In addition, 1-week measurements using simultaneously-exposed etched-track, activated-charcoal and electret detectors were conducted at approximately 1-month intervals. The 1-week exposures were managed to ensure that detector exposure was 168±2 h, with 1-month exposures similarly managed to ensure exposure was 672±2 h. Following this, measurements were continued for a further three years in a subset of 4 of these dwellings using electret detectors exposed for 1-week periods (the extended electret series).

Detectors were placed according to the UK National Radiological Protection Board (NRPB) protocol (Wrixon et al., 1988), which uses two detectors, one placed in the main living room (generally at ground level) and one in the main bedroom (usually on the first-floor). The protocol calculates a weighted average of the two readings, the bedroom being assigned a weighting of 0.55, the living room 0.45. The weights reflect the usual configuration of UK houses which have two floors, with bedrooms on the upper floor, the usual pattern of occupancy with bedrooms occupied at night, and the usual radon variation where levels are higher at night, and are lower in upper storeys. These weightings have been reviewed in occupancy studies by Briggs et al. (2003), and shown to be appropriate as an estimate of radon exposure of occupants.

For this paper, the etched-track data were re-analysed from the raw data upwards for the 32 houses (from the dataset of 37) for which annual radon levels can be calculated from 3-month measurements, to compare 1-week, 1-month, 3-month to annual results. The 1-week, 1-month, 3-month data were either (a) uncorrected or (b) seasonally corrected using the SCFs of Miles et al. (2012, corrected 2014) or (c) seasonally corrected using SCFs calculated from the 1-month etched-track data, using an updated version (Crockett et al. 2016) of the method described in Denman et al. (2007a).

The ratios between the 1-week, 1-month and 3-month values to annual values were calculated for the uncorrected and both seasonally corrected data-sets noted in the previous paragraph. These provide distributions for the ranges of values that would be expected if using track-etch detectors for these periods to estimate the annual concentrations. From these distributions a confidence interval around the Action Level was estimated according to the null hypothesis that the actual measurement is not systematically different to the Action level (i.e. ratio to Action Level is 1).

In this case, it is a straightforward confidence interval on the distribution of ratios with mode equal to 1, but the confidence interval itself is a range of values not significantly distinguishable from the Action Level,

i.e. an equivocal range, at the desired level of confidence. It is the values outside the interval, in the tails of the probability distribution, which give definitive results for practical use in the field:
i) values below the lower confidence limit represent annual radon concentrations below the Action Level (no remediation necessary);
ii) values above the upper confidence limit represent annual radon concentrations above the Action Level (remediation necessary);
iii) values in the equivocal range (i.e. between the confidence limits) have varying degrees of chance of indicating an annual level which is above the Action Level and therefore repeat measurements are indicated.

In this study, the standard 95% confidence interval was selected (i.e. lower and upper limits at cumulative probability 2.5% and 97.5% respectively), as this level is generally used in scientific literature. Table 1 shows this methodology applied to the domestic Action Level of 200 Bq.m^{-3} for 1-week, 1-month and 3-month ratios and interpolated to other periods using non-linear least-squares regression.

3. Results

The probability histogram and distribution of the ratio of each one-week measurement to the corresponding annual average (for the same location) is shown in Figure 1. There were 212 ratios of uncorrected 1-week measurements to annual levels, from the 32 houses for which an annual level was derived from 3-month measurements, and the ratios are closely lognormally distributed. Figure 1 shows that a 1-week measurement can vary by up to *ca*. 4 times bigger or smaller than the annual average at 95% confidence illustrating the inherent variability of short-term measurements compared to a longer exposure made during the same period in the same room of a property.

For each measurement duration, Table 1 shows the regions of 95% confidence that an uncorrected measurement will indicate whether the annual average is above or below the Action Level. Thus, a 1-week result below 56 Bq.m^{-3} will be indicative that the annual average will be below 200 Bq.m^{-3} with over 95% confidence, and that no remediation is recommended; similarly it is only above 720 Bq.m^{-3} that there is over 95% confidence that the annual average is definitely over 200 Bq.m^{-3} and remediation is recommended. In the equivocal range of 56 to 720 Bq.m^{-3}, for the 1-week measurement, there are varying degrees of probability that the annual average could be below the Action Level. In contrast, a measurement with an exposure length of 3 months has an equivocal range of 113 to 355 Bq.m^{-3}. Therefore, if a 1-week measurement has a result within the equivocal range, then a retest, preferably with a longer measurement period, should be used to determine whether the annual average radon level is above (or below) the Action Level with more certainty.

The extended electret series, with four years of measurement, showed that, normalising and combining the results for 4 houses, the annual calendar year average radon level has a standard deviation of 8.6%.

The SCFs derived from the etched-track dataset are shown in Table 2.

4. Discussion

a. Accuracy of Short-term exposures

In the field, there are many reasons why measurements of radon levels should be as short as possible. The analysis presented above allows the development of protocols so that measurements of radon with a wide range of exposure times can be used. Because of the variability of radon levels over the day, week and season, and the need to assess health risk from the long term average radon level, shorter exposures are inherently less indicative of long-term risk than longer exposures, as exemplified in Table 1 and Figure 1. Table 1 shows that at shorter exposures there is a wider range of values where results fall in the range where there is a likelihood that the long term average radon level could exceed the Action Level and therefore a repeat would be required. To reduce uncertainty, repeat measurements should be done with longer exposures to improve the likelihood of a definitive result. However, as Groves-Kirkby et al. (2006) suggested, a short-term measurement has value as a screening tool, particularly in low to moderate radon-potential areas where the majority of short-term measurements will be below the lower confidence limit, because radon levels in groups of houses in the same locality are found to follow a log-normal distribution, and the majority of houses will be found to have radon levels definitely below the Action Level, even using short exposures.

b. Use of Seasonal Correction Factors

The question arises as to whether SCFs should be applied, and if so, which - those of Miles et al. (2012, corrected 2014) or those calculated from the etched-track data (Table 2). Table 3 shows results from a recalculation of the equivocal ranges of each measurement period after application of SCFs, using the SCF sets reported by Miles et al., (2012, corrected 2014) and derived on a local basis as part of this reanalysis of the original dataset, respectively.

Despite the apparent logic of applying a seasonal correction, the impact of using seasonal correction for radon measurements on the equivocal range of our dataset is modest, as can be seen by examining Tables 1 and 3. Comparing the 95% confidence intervals for the uncorrected data (Table 2) to the corrected data (Table 3) shows:

i) the confidence intervals for the data corrected using the Miles et al. revised UK-national SCFs are wider than for the uncorrected data at all measurement durations;

ii) the confidence intervals for the data corrected using the locally-derived SCFs are wider than for the uncorrected data for measurement durations below 4 weeks and only narrower at both limits for measurement durations of 6 weeks or more.

This demonstrates that even with the locally-derived SCFs, calculated specifically from the reanalysed dataset, the equivocal range was reduced only for measurement durations of 6 weeks or more. Furthermore, this also demonstrates that using the new national SCFs recommended by Miles et al. (2012, corrected 2014) widened the equivocal range at all exposure durations, and therefore slightly reduced the accuracy of the measurements. This somewhat surprising result must reflect the underlying heterogeneity of the variation in radon levels in different domestic house designs, on different underlying rocks, and differing meteorological factors. The moderate impact of SCFs is in keeping with and extends the analysis of Denman et al. (2007a), and is directly comparable with the work of Krewski et al. (2005), who studied Canadian houses using 6-month measurements, showing that the use of a locally calculated SCF enabled them to distinguish which homes were above or below an Action Level of 150 $Bq.m^{-3}$ with an accuracy of around 85% to 90%. However, with measurement durations of less than a month, Krewski et al. (2005) noted that the natural variability of the measurement far exceeds any correction by a SCF and such corrections are consequently of no added value. Miles et al. (2012, 2014) noted that, in their UK dataset, restricting 3-month measurements to spring and autumn (seasons when their and other SCFs are generally closest to 1, between the smallest values in winter and the largest values in summer) improved accuracy more than doing 3-month measurements throughout the year and applying their SCFs.

The locally-derived SCFs presented in Table 2 are comparable with the revised values published by Miles et al. (2012, corrected 2014), and both SCF-sets show less seasonal variation than the original values of Wrixon et al. (1998). Pinel et al. (1995) in their study of 2057 dwellings in South West England suggested the seasonal correction they found was consistent with adoption of the Wrixon SCFs, but suggested that due to the varying geology in the UK there may be areas where regional, rather than national, SCFs should be developed. UKCCSI (2000) assessed 5678 dwellings in UK, divided the results into 9 regions, with between 429 and 860 houses in each region. The SCFs for 8 of the 9 regions were consistent, but the results for Trent showed a different phase, and they concluded that using regional SCFs in their analysis was appropriate. However, there is wide variability of radon levels and different patterns of radon levels in individual homes, which have been shown in many papers, and which have been attributed to differences such as house design, double-glazing, insulation and ventilation (Denman et al., 2007a; Wrixon et al., 1988; Denman et al., 2007b). As a result, any dataset for developing SCFs at a regional level would need to be large. It may be that the SCFs developed by Wrixon et al. (1998) were in houses with higher radon levels, if the variation of seasonal variability with radon level found by Miles et al. (2012, corrected 2014) nationally and Denman et al. (2007a) locally in a small number of houses is universal. The methodology of Wrixon et al. (1998), Pinel et al. (1995) and UKCCSI (2000) used a single 6-month exposure in a large number of houses, and mathematically deriving SCFs by forcing the data to fit a sinusoidal annual variation, while Miles et al. (2012, corrected 2014) and this study made multiple sequential measurements in a smaller number of dwellings.

It should be noted that the locally-derived SCFs in this paper are from houses which are all in Northamptonshire, whereas Miles et al. (2012, corrected2014) derived their SCFs as national values, from a dataset of 91 houses, where up to 20 homes were in each of 5 different regions of the United Kingdom. Miles et al. (2012, corrected 2014) did not detect any significant difference between regions in their dataset, in contrast to the larger dataset studied by the UKCC Investigators (2000). Moreover, with regard to these locally-derived SCFs, it should also be noted that despite geographical proximity of the 32 houses in Northamptonshire from which the re-analysed track-etch data were obtained, for the 17 houses having at least six 1-month measurements, six had monthly data which correlated negatively (i.e. opposite phase in the annual cycle) with the annual sinusoidal model derived from the data to calculate the local SCFs. Furthermore, for the remaining 11 houses which correlated positively, that annual sinusoidal model only explained on average 27.4% (maximum 50%) of the variance. Thus, even applying the locally-derived SCFs, calculated specifically from the data, would only at best correct for half the variance in exposure measurements, and for those houses with negative correlations applying the SCFs would tend to mis-correct rather than correct.

In another study, four different houses from the original 37-house dataset were monitored using electrets, measured at 1-week intervals, for a total of four years, the first year of which coincided with the period of the etched-track measurements reported herein (Denman et al., 2007a). Two sets of SCFs were derived from that electret dataset, one 'standard' set using an annual sinusoidal model, as used by Wrixon et al. (1988), Pinel et al. (1995) and Miles et al. (2012, corrected 2014), and another 'improved' set using an annual sinusoid plus second harmonic model to better correspond to annual cycles observed in meteorological data (Crockett et al., 2015). The two modelled annual cycles reported by Crockett et al. (2015) only explained 21.2% of the variance (standard) and 24.6% of the variance (improved), the improved model representing an improvement of 15.9% (3.4 percentage points) over the standard. Thus, even the improved model, and the SCFs derived from it, still only explains a minority of the variance. Therefore it is not surprising that the use of any SCF has a only modest effect on the accuracy of results, and in some cases can worsen the analysis.

The year-on-year variability of our electret dataset, where the coefficient of variation in four buildings is 50%, is comparable to the five-year series of Italian buildings presented by Bochicchio et al. (2009), where the coefficient of variation in 76 buildings was 14%. Therefore, although the locally derived SCFs, shown in Table 3, are best for correcting our dataset, they may not be as appropriate to correct other results from other datasets measured at different times. Therefore, the SCF dataset selected for use to correct measurement data must be chosen carefully.

c. Measurements in the Workplace

Radon levels in workplaces also show seasonal variation and domestic SCFs can also be applied to workplace measurements (Denman, 2008). This is done because no comprehensive study of seasonal variation in workplaces has been made. Indeed, studies of individual buildings suggest that rooms with air conditioning can have little or no seasonal variation (Marley et al. 1998), while rooms in a central area of a large building may have negligible, or inverted, seasonal variation. In such cases, it may be necessary to conduct repeat measurements at different times of the year, and interpret the results without SCF correction. Finally, occupancy and people flow can affect radon levels. For example, a busy reception area will have very low radon levels by day, when the external doors are always opening, so that the risk to staff and the public when the building is in use will be much lower than expected from the normal diurnal variation of radon levels (Denman et al. 1999).

5. Conclusions

This paper presents revised Seasonal Correction Factors and equivocal ranges for etched track detectors for a comprehensive selection of exposure periods used in practice. It is recommended that these new and more comprehensive values for Equivocal Ranges are adopted in the UK.

Seasonal correction should only be made to exposures of at least one month duration because short-term variations in weather or occupancy, for example, would render the corrections from either (a) the application of longer-term correction factors to short-term measurements or (b) application of short-term correction factors even more susceptible to errors arising from variance unexplained by multi-annual, multi-regional annual models. Use of locally derived SCFs would be better but to develop these would require a large dataset of local radon measurements and so is generally impracticable: within that, even if the data were available, accounting for year-on-year short-term weather variations would be highly impracticable.

Moreover, the analysis in this paper shows that the dominant variability in radon measurements is due to daily and other short-term factors, which are difficult to quantify and vary from house to house. There is also a variation year-on-year. Seasonal correction at best makes only a modest improvement, if any, in certainty, and then only at longer exposures. Therefore use of SCFs in interpreting routine and commercial radon measurements has only marginal value, and is not critical to the interpretation of results. What is more important is to compare a radon measurement to the equivocal range of that exposure duration to determine whether the result is definitive or needs to be repeated with a longer exposure.

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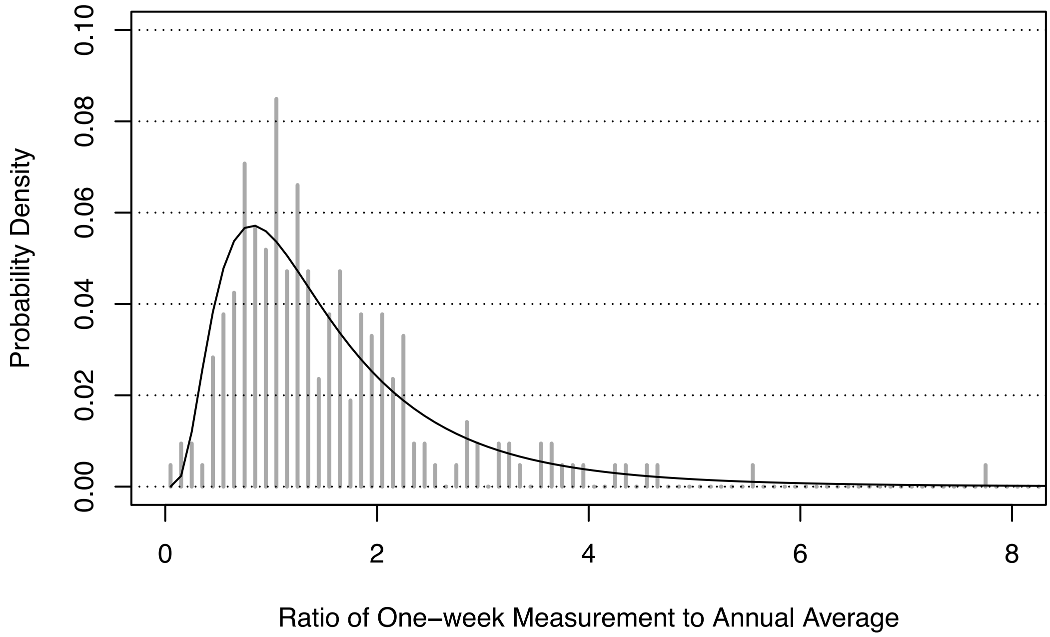

Figure 1. Probability distribution of ratios of uncorrected 1-week measurements to annual values for etched-track detectors.

Table 1. Interpolated 95% Confidence Limits for uncorrected measurements compared to the Domestic Action Level for a range of exposure times using etched-track radon detectors.

Duration	Uncorrected Radon Exposure, $Bq.m^{-3}$	
	Lower Confidence Limit	Upper Confidence Limit
	(below this there is more than 95% confidence the annual average will be below the Domestic Action Level)	(above this there is more than 95% confidence the annual average will be above the Domestic Action Level)
1 week	56	720
2 weeks	61	660
3 weeks	65	610
4 weeks (1 month)	71	570
6 weeks	80	500
8 week (2 months)	90	446
3 months	113	355
6 months	157	255
12 months	191	208