The Suitability of Short-term Measurements of Radon in the Built Environment

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Abstract. Although domestic and workplace radon concentration levels often show marked diurnal/short-term variation, overall health risk is determined by the long-term average level, and many national protocols advocate the use of long exposure periods, usually three months, to assess long-term risk. Simple passive measurement techniques, e.g. track-etch, activated charcoal and electret, can, however, provide reasonably accurate determinations with exposures as short as one week, and there is pressure from users and stakeholders for assessments within this time period. We report evaluation of the effectiveness of one-week, one-month and three-month exposures over a period of one year in a designated Radon Affected Area in the United Kingdom (UK). Although short-term exposures did not compromise measurement accuracy, short-term radon variability rendered one-week measurements less reliable in predicting annual average radon levels via the conventional methodology. Analysis permitted estimation of the maximum and minimum short-term measured domestic radon concentrations at which there was 95% probability of the predicted annual average being below or above the UK Action Level of 200 Bq·m^{-3} respectively. Between these limits, the short-term result is equivocal, requiring repetition, and the 'equivocal range' for one-week measurements is significantly wider than for three-month exposures. In any geographical area, domestic radon concentrations are distributed lognormally, with many properties having low average levels; a small number exhibit excessive levels, and this distribution must be considered when defining exposures for a radon measurement programme. In low-radon areas, where 1% of houses might exceed the Action Level, a one-week assessment will find that fewer outcomes are equivocal. For high-radon areas, with 20% or more houses over the Action Level, more than 50% of one-week outcomes will be equivocal, requiring repeats. The results of this work will be presented, together with a suggested policy for the use of short-term and long-term measurements in different areas and for chosen Action Levels.

KEYWORDS: radon; short-term measurement; equivocal range; action level;

1 Introduction

Radon is a naturally-occurring radioactive noble gas, having variable distribution in the geological environment as a decay product of uranium found, in differing degrees, in a wide range of rocks and soils, and in building materials incorporating or manufactured from these materials. Emanation and migration of radon in rocks and soils are controlled by the distribution and localisation of precursor radionuclides in mineral grains and their coatings, together with water content, rock fragmentation and soil stratification. As soil characteristics are influenced by changes in meteorological conditions, temporal variations of soil-gas radon concentration are widely observed [1]. Although radon dissipates rapidly once in outdoor air, it can concentrate in the built environment, where it contributes around 50% to the average background radiation dose received by the United Kingdom (UK) population [2]. For UK dwellings, the mean radon level is approximately 20 Bq·m^{-3}, compared to 4 Bq·m^{-3} in outside air [3], but levels up to 17,000 Bq·m^{-3} have been found in homes in the West of England [4].

Of the three naturally occurring isotopes of radon, ^{222}Rn is the most significant, its relatively long half-life ($t_{1/2}$ = 3.8 days) enabling it to migrate significant distances within the geological environment before decaying. ^{222}Rn decays by α-emission to ^{218}Po and thence to ^{214}Po, both α-emitters, the final decay product being the stable lead isotope ^{206}Pb. These heavy-metal daughter-products are highly toxic and are readily adsorbed onto atmospheric particles, posing a significant health hazard. Inhalation of ^{222}Rn, and its α-emitting progeny ^{218}Po and ^{214}Po, is believed [5] to provide the majority of the radiation dose received by the respiratory system, and it is estimated that the annual mortality from exposure to radon in buildings represents 9% of all deaths from lung-cancer, and 2% of all cancer deaths, in Europe [6]. Since total annual UK lung-cancer mortality is between 30,000 and 35,000 [7], between 1,800 and 2,100 deaths annually may be attributable to radon and its progeny.

The principal contributors to indoor radon concentrations in UK dwellings are soil-gas emanating from the ground beneath the dwelling [8], and the materials from which the dwelling is constructed [9,10,11]. Further small contributions include the atmospheric background, with a mean population-weighted level of 4 $Bq \cdot m^{-3}$ [3], household water supplies, particularly those derived from wells and boreholes [12], and domestic gas supplies [13]. Entry of radon into a dwelling from the soil-gas is influenced by a number of factors [14]. These include the radon concentration in the soil-gas itself, soil moisture content and ground permeability, and environmental and meteorological conditions in the vicinity of the dwelling [15], together with the nature of the physical entry routes into the dwelling. Overall, the ultimate driving influences are the absolute pressure difference between the radon source and the earth's surface, and the under-pressure caused by temperature differences between the dwelling interior and the external atmosphere, the 'stack effect' [16]. In a recent study by our group, atmospheric pressure was identified as determining the general long-term trend in radon levels whilst water vapour pressure has a shorter-term influence [17].

Indoor radon levels are subject to a number of variations. In addition to a well-defined daily cycle, with night-time levels greater than those experienced in daytime [16], other longer cycles are evident, related to occupancy [18], meteorological conditions [19] and seasonal factors [20], with levels generally higher in winter than summer. As lung cancer risk increases with increasing total radon exposure, the preferred measure of this risk is the long-term average radon level. The current UK recommendation specifies three-month measurements together with the application of a Seasonal Correction Factor (SCF) [20]. In some circumstances, however, particularly during the house-sale process or when confirming that safety measures in new homes are satisfactory, a measurement extending over three months is impractical or inappropriate. The question then arises as to whether short-term measurements, although probably less reliable, have sufficient value to be of use.

We present here detailed consideration of the viability of short-term measurements, highlighting issues relating to detectors and protocols. Following a description of the project methodology, results are presented from a year-long study of radon levels in homes in Northamptonshire utilising a number of types of radon detector [21,22]. The implications of the results are discussed and recommendations arising from them, particularly the value and reliability of a short-term testing protocol, are made.

2 Methodology

To relate short-term to long-term exposure results, dose-integrating detectors were placed immediately alongside two Durridge RAD-7 systems measuring radon levels at hourly intervals [23]. These were operated in three properties for extended periods spanning the full year of the project, and had been calibrated prior to commencement of the study. To ensure reliable correlation, short-term exposures of detectors were carried out in the immediate vicinity of the RAD-7 systems.

2.1 Radon Detector Selection

Dose-integrating radon detectors were procured from suppliers who had submitted detectors to the UK National Radiological Protection Board (NRPB) Inter-Comparison of Passive Radon Detectors [24]. The final detector inventory comprised 1400 Track-Etch detectors [25] from two different suppliers, 600 Activated Charcoal detectors [26] and 50 Electrets [27], reusable devices that were deployed for a total of nearly 1000 exposures. In all, over 2,000 exposures were made. Best practice was employed at all times in respect of detector handling and analysis, the majority of devices being placed and collected by trained technical staff, ensuring data rigour and resulting in a return rate close to unity.

2.2 Property Selection

34 unremediated dwellings, known to have moderately high radon levels in a high-radon area around Northampton, UK, and comprising a mix of house age and type, were monitored during the period April 2002 to May 2003. Of these, 20 were monitored for a full year; the remaining properties were monitored for periods of nine months (four properties), six months (six properties) or three months (four properties). In addition, one-week measurements were made in all properties at six to eight week intervals, using co-located sets of Track-Etch, Activated Charcoal and Electret detectors exposed

simultaneously. In three properties, further comparisons were made with the RAD-7 systems over periods of up to six months.

Northamptonshire, a predominantly rural county in the English Midlands, is situated largely on Jurassic (200 million years old) bedrock [28,29], comprising two distinct series, the Lias clays and the Oolites (limestone and ironstone). The regions of highest radon production are associated with the Northampton Sand Ironstone (which contains significant amounts of phosphorus and associated uranium underlain with phosphorus-rich pebbles); the Upper Lincolnshire Limestone; and the glacial sands and gravels associated with these horizons. In addition, Northamptonshire soils are relatively permeable, permitting significant soil-gas movement. The county was declared a radon Affected Area in 1992 [30] and has an estimated average 6.3% of homes above the UK domestic Action Level [31]. The majority of the dwellings studied were situated on the Northampton Sand Ironstone [28,29].

2.3 Detector Management

Detectors were exposed according to the NRPB protocol [3]. This protocol uses two detectors, one placed in the main living room (generally downstairs) and one in the main bedroom (usually upstairs), care being taken to avoid areas of high relative humidity, e.g. kitchens or bathrooms. The protocol calculates a weighted average of the two readings, the bedroom being assigned weighting of 0.55, the living room 0.45, reflecting relative occupancies. A Seasonal Correction Factor [20] is then applied, depending on the start-month of the exposure. Within each three-month period, each home had:

- one three-month (90-day) Track-Etch exposure
- three consecutive one-month (30-day) Track-Etch exposures
- several one-week (7-day), Track-Etch, Activated Charcoal and Electret exposures

with detectors placed in both the living room and the main bedroom in each case.

3 Results

3.1 Reference Technology

Figure 1 shows typical short-term radon concentration variability reported by the RAD-7 systems, showing the diurnal order-of-magnitude range typically experienced.

Figure 1: Typical Short-Term Radon Concentration Variability, as Monitored Using RAD-7 System.

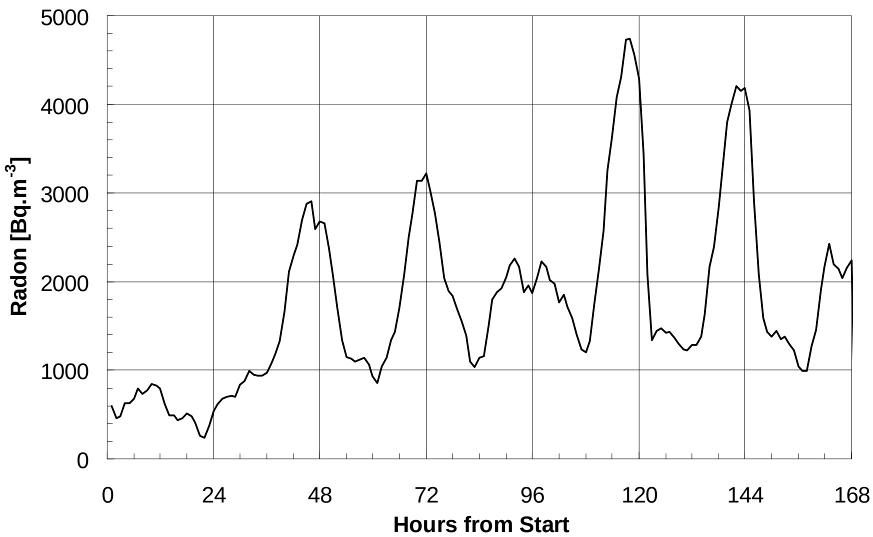


Figure 2 similarly shows typical mean weekly radon concentrations derived from RAD-7 monitoring in three properties, normalized to the overall mean for each property to enable comparison.

Figure 2: Weekly Mean Radon Levels in Three Properties Determined Using RAD-7 Systems. Results Normalised to Mean Value for Each Property

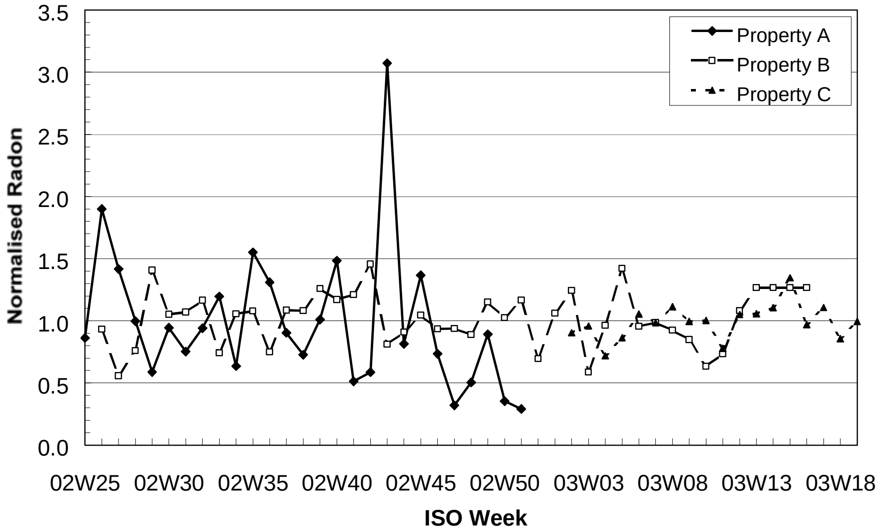
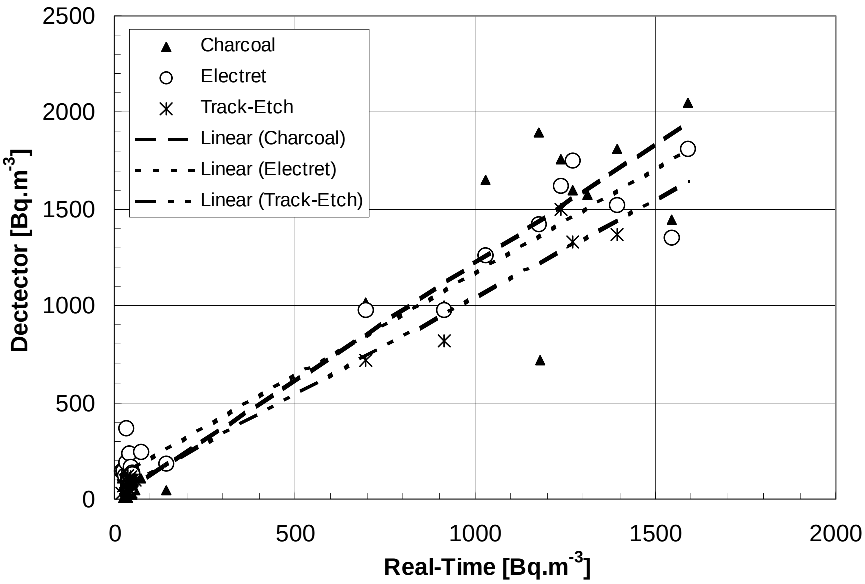


Figure 3 shows the results from one-week exposures, plotted against the average radon levels determined from RAD-7 measurements in the respective properties over the periods corresponding to the short-term exposures, while Table 1 summarizes linear regression parameters from these plots, together with comparable data from one-month and three-month exposures.

Figure 3: Radon Levels from One-Week Exposures in Four Classes of Detectors Vs. Mean Real-Time Levels Determined by RAD-7 Measurement for the Corresponding Exposure Periods.



Analysis of the one-week regression parameters leads to the following conclusions:

- Track-Etch detectors represent time-averaged real-time radon extremely well (gradient = 1.01), exhibiting extremely good linearity (correlation coefficient = 0.99) with moderate background offset (35 Bq·m^{-3}).

- Electret detectors represent time-averaged real-time radon relatively well (gradient = 0.97), with good linearity (gradient = 1.07) but have significant background offset (105 Bq·m^{-3}).

- Activated Charcoal detectors have the smallest background offset, 1.5 Bq·m^{-3}, with good linearity (correlation coefficient = 0.98) but the gradient of 1.22 indicates that these detectors respond 'faster' to radon than the other detectors. It was originally concluded that this discrepancy was due to the fact that Activated Charcoal measures the activity of γ-emitting progeny, rather than radon itself. Subsequent discussion with the supplier confirmed, however, that a "margin of error" correction, equal to +22.2%, had been included in the processing protocol provided by the detector manufacturer. Once this is taken into account, the regression slope for charcoal detectors against time-averaged radon determinations reduces to essentially unity, with a background of 1.24 Bq·m^{-3}.

Table 1: One-Week Regression Parameters

	Track-Etch *one-week*	Charcoal *one-week*	Electret *one-week*	Track-Etch *one-month*	Track-Etch *three-month*
Slope	1.01	1.22	1.07	0.93	1.00
Intercept	35.6	1.52	104.8	4.3	1.35
Correlation Coefficient	0.99	0.96	0.98	0.99	1.00

3.2 One-Week (7 day) Measurements

On the basis of the foregoing results, it was concluded that the activated charcoal detector, with its good linearity and almost negligible background offset, represented the best option for relating short-term (i.e. one week) and long-term measurements statistically. Results from activated charcoal detectors were therefore used as reference for assessing results from other short-term detectors in the majority of properties, where limited availability of RAD-7 systems precluded real-time monitoring.

All sites showed strong week-on-week variability. Using one-week Activated Charcoal data from each property as reference, the accuracy with which these were represented by Track-Etch and Electret detectors was explored. Results are shown in Figure 4, for Track-Etch detectors, and in Figure 5 for Electrets.

Figure 4: Radon Levels Reported from Track-Etch Exposures vs. Radon Levels Reported from Simultaneous One-Week Activated Charcoal Exposures

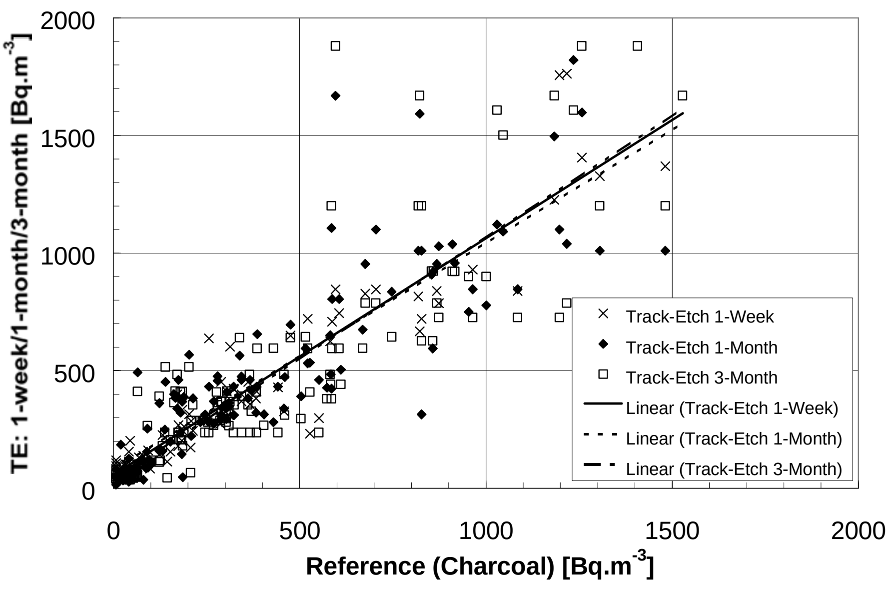
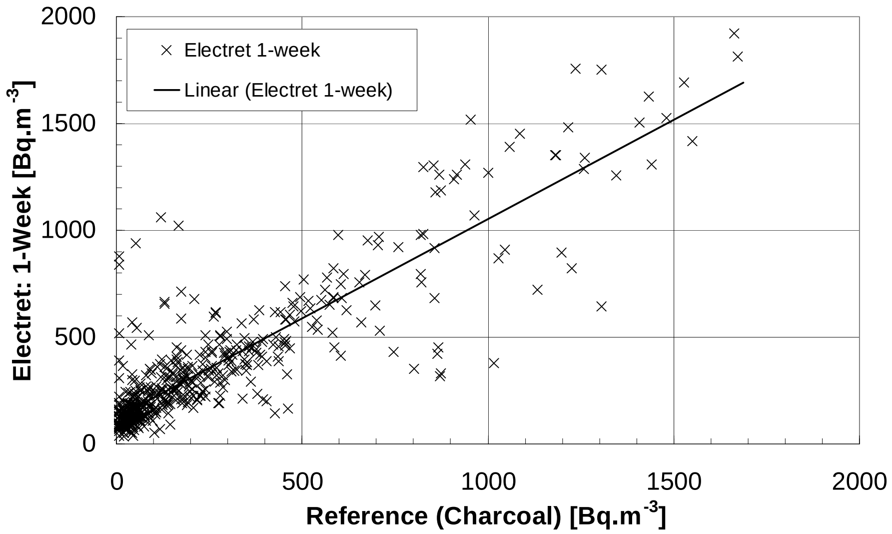


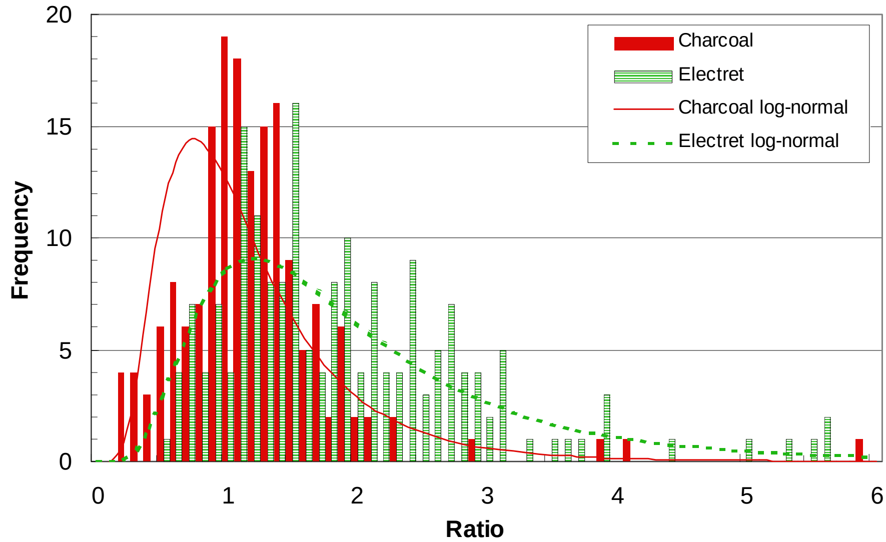
Figure 5: Radon Levels Reported from One-Week Electret Exposures *Vs.* Radon Levels Reported from Simultaneous One-Week Activated Charcoal Exposures



3.3 Estimation Of Mean Radon Levels From One-Week, One-Month And Three-Month Measurements

For each property and exposure period, the ratios of one-week and one-month measurements to the corresponding three-month measurements were calculated, giving results for one-week and one-month Track-Etch, one-week Electret, and one-week Activated Charcoal, all vs. three-month Track-Etch. Figure 6 plots the distribution of ratios of Activated Charcoal and Electret one-week measurements to the corresponding three-month Track-Etch measurements, together with lognormal fits to these data and demonstrates the wide variability of short-term radon levels. Similar plots were obtained for the one-week and one-month Track-Etch detectors.

Figure 6: One-Week/Three-Month ratios – Activated Charcoal and Electret vs. Track-Etch Three-Month



Statistical analysis was applied to derive the probability that one-week or one-month radon levels were within 5%, 10% and 20% of the three-month radon level, the results being summarised in Table 2. Derived from this analysis, Table 3 indicates the threshold levels above/below which there can be 95% confidence that the indicated annual level is greater/less than the Action Level of 200 Bq·m^{-3}.

Table 2: Probabilities that One-Week and One-Month Outcomes Represent Three-Month Track-Etch Outcomes

Required Accuracy	Charcoal *one-week*	Electret *one-week*	Track-Etch *one-week*	Track-Etch *one-month*
5%	6.6%	4.9%	5.7%	11.1%
10%	13.2%	9.9%	11.4%	22.0%
20%	26.5%	19.9%	22.8%	42.1%

Table 3: 95% Threshold Confidence Limits

95% Confidence Level	Charcoal *one-week*	Electret *one-week*	Track-Etch *one-week*	Track-Etch *one-month*	NRPB Advice *three-month*
Lower [Bq·m^{-3}]	68	59	75	109	130
Upper [Bq·m^{-3}]	522	667	518	478	300

4 Discussion

4.1 Action Level Indicators

All detector systems exhibit good linearity with mean radon level during exposure and all appear intrinsically suitable for use in Domestic and Workplace applications. Short-Term (i.e. one-week) exposures are possible, but the results have much greater variability, almost entirely due to the wide variation in radon levels due to climatic and other factors. Thus a higher proportion of one-week exposures will be equivocal than of one-month or three-month exposures, necessitating repeat exposures. As indicated in table 3, statistical analysis confirmed that for individual one-week Track-Etch, Activated Charcoal and Electret measurement outcomes less than 75, 68 or 59 Bq·m^{-3} respectively, the annual average is guaranteed (95% confidence) to be below the UK domestic Action Level (200 Bq·m^{-3}). This is in good agreement with the NRPB recommendation [32] that "if a well-conducted charcoal measurement yields a result of 75 Bq·m^{-3} or less, it can be taken as very likely that the true annual average does not exceed the Action Level of 200 Bq·m^{-3}. Similarly, the upper level is set at the point where there is 95% confidence of exceeding the 200 Bq·m^{-3} Action Level.

Using the known percentage of homes with radon concentrations exceeding the Action Level in the counties of Cornwall, Northamptonshire and Buckinghamshire (areas of the UK with high, moderate and low numbers respectively of properties with radon levels above the Action Level [31]), calculations were made to determine the proportion of measurements which would result in clear indications that radon levels were above and below the Action Level, and how many results which will be equivocal. Results are summarized in Table 4. Outside the indicated ranges, short-term radon concentrations derived from the various detector technologies and exposures can be regarded as definitive (95% confidence) indicators of mean annual levels below or above the Action Level of 200 Bq·m^{-3}. Results falling between these bounds must be regarded as equivocal, necessitating a repeat determination for resolution.

It is evident that one-week measurements are noticeably more useful in areas with low and medium numbers of properties with radon levels in excess of the Action Level, where the majority of results will be normal. In an area, such as Cornwall, with a high proportion of properties with radon concentrations in excess of the Action Level, the majority of one-week results will be equivocal, with only around 5% of results being high enough to be definitely abnormal. The improved accuracy offered by three-month exposures in this situation is a significant benefit. One-week exposures would be suitable for newly-constructed houses with radon precautions where low radon levels are expected.

Table 4: Expected Proportion of Results for Each Exposure Methodology in High, Medium and Low Radon Counties

Locality: % above Action Level	Relative to Action Level	Track-Etch *one-week*	Track-Etch *one-month*	Track-Etch *three-month*	Electret *one-week*	Charcoal *one-week*	NRPB *three-month*
Cornwall:	Below	36.2%	54.3%	55.4%	30.2%	35.5%	61.3%
23.3%	Equivocal	56.2%	40.3%	35.1%	66.3%	60.0%	25.9%
High	Above	4.6%	5.4%	9.5%	3.5%	4.50%	12.8%
Northamptonshire:	Below	71.4%	81.7%	82.6%	63.3%	68.20%	85.9%
6.99%	Equivocal	27.7%	17.0%	15.2%	36.0%	30.9%	10.9%
Medium	Above	0.9%	1.4%	2.2%	0.7%	0.9%	2.6%
Buckinghamshire:	Below	85.9%	93.5%	93.5%	78.4%	83.1%	95.9%
1.19%	Equivocal	14.1%	6.3%	6.3%	21.6%	16.9%	3.8%
Low	Above	0.0%	0.2%	0.2%	0.0%	0.0%	0.3%

4.2 Reproducibility

In evaluating the performance of any method of radon measurement, it is critically important to use some form of primary standard. Although the present study was essentially comparative, based largely on single-exposure detectors procured from a number of validated suppliers, one element, namely the two RAD-7 systems deployed throughout the study, had been calibrated immediately prior to the study, and were therefore considered to be reliable secondary standards. While the possibility is acknowledged that even a perfect set of comparative measurements obtained using two methods might simply result from the two methods being equally biased, in practice this is unlikely, and the correlations found here are believed to be real.

4.3 Perturbing Influences

During the course of the study, short-term measurements, particularly of one-week duration, were identified as being potential perturbed by tidal effects associated with Earth-Tides and Ocean Tidal Loading, and recommendations were made regarding the timing of 7-day measurements relative to the fundamental 14-day (Spring to Neap) tidal period [33,34]. Although these effects will have the effect of increasing the variance associated with the detector responses, the effect will be the same for all detectors, with overall variance remaining attributable to differences in detector response. These effects only affect one-week measurements; any measurement period which is an integer multiple of the two-weekly tidal cycle will average out any such effects.

5 Conclusions

In order to identify the most applicable technology for short-term domestic radon measurements, comparative assessments were undertaken of track-etch, electret and activated charcoal detectors. Thirty-four unremediated dwellings in a high-radon area were monitored using track-etch detectors exposed for 1-month and 3-month periods. In parallel, 1-week measurements were made at 1-month intervals, using co-located track-etch, charcoal and electret detectors exposed simultaneously, while three homes were also monitored by continuous-sampling detectors at hourly intervals over extended periods. Calibration of dose-integrating devices against each other and against recently-calibrated secondary-standard continuous-monitoring systems confirmed good responsivity and linearity. Although track-etch, charcoal and electret devices are suitable in principle for one-week measurements, zero-exposure offset and natural radon variability cause many one-week results to be equivocal, necessitating repetition of the measurement. One-week exposures can be reliable indicators in low-radon areas or for new properties, but in high-radon areas, the use of three-month exposures is indicated. This analysis also established confidence limits for short-term measurements.

The suggested measurement protocol for radon in UK is as shown in Table 5, using Table 3 for determining when results are equivocal.

Table 5: Suggested UK Protocol for domestic radon measurements

Area	Initial Test	Repeat If equivocal
New Homes in Radon Affected Areas < 5% houses over Action Level	one-week	one-week
> 5 % and < 10% houses over Action Level	one-week	three-month
> 10% over Action Level	three-month	three-month

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