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Radon in Workplace Basements

An analysis of PHE measurement results and recommendations on when to test

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Abstract

Radon is a recognised lung carcinogen. Regulations exist in the UK that limit the exposure to radon at work and require employers to take action if levels exceed certain thresholds. As radon levels in individual buildings cannot be predicted, PHE offers a routine measurement service, which has been in operation for around 30 years.

The main source of radon is from the ground. As basements have more ground contact than other parts of a building, and often limited ventilation, there is an increased potential for high radon levels to occur. This effect has been demonstrated repeatedly in workplaces of many types. Both PHE and the Health and Safety Executive advise employers to test routinely occupied basement workplaces for radon, irrespective of geographical location, and to test ground floor workplace premises located in radon Affected Areas as part of the employers' requirements to assess health and safety risks to their employees.

This report uses the pre-mitigation radon results in basements of around 3500 workplaces that have been measured with passive monitors as part of the PHE routine measurement service. The dataset has been analysed with respect to the nature of work undertaken by the employer and by the radon potential of the workplace address. Statistical tests run to assess agreement with lognormality (the distribution typically demonstrated by radon datasets) showed that the data could be used to refine advice to employers on measuring radon in workplace basements.

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This report from the PHE Centre for Radiation, Chemical and Environmental Hazards reflects understanding and evaluation of the current scientific evidence as presented and referenced in this document.

Executive Summary

Radon is a recognised lung carcinogen. Regulations to control exposure to radon at work have been in force in the UK since 1985 and PHE (and its predecessor organisations, the Health Protection Agency, HPA, and National Radiological Protection Board, NRPB) offers a routine measurement service to employers that enables them to fulfil their duty of care. The main source of radon is from the ground. Rocks and soils contain minute amounts of uranium and radium, which decay radioactively into radon gas. Pressure-driven flow can draw this radon-laden air into rooms with ground contact. Basements have proportionally large areas of ground contact, thus increasing the probability of having high radon levels. In addition, basements often have limited ventilation, which limits exchange or dilution with outside air. Consequently, not only is the highest radon level within a building frequently found in basements but the potential of a result exceeding the regulatory threshold is significantly higher than in rooms on the ground floor. PHE and the Health and Safety Executive advise employers to test routinely occupied basement workplaces for radon, irrespective of geographical location, and to test ground floor workplace premises located in radon Affected Areas.

This report presents analyses of the routine measurement service results from basements in around 3500 workplaces. Owing to the responsive nature of this service, the dataset was inhomogeneous and was not representative of all basement workplaces in the UK. The large number of results, however, enabled multiple subsets to be produced of sufficient size to give good indications of the distributions. The basements were categorised by radon potential (based on the delivery point of the workplace) and by occupational sector based on the nature of the work undertaken by the organisation. The effect of using seasonal corrections was investigated along with the effect of compensating for the outdoor air concentration on the distribution of results. The subdivided datasets mostly showed very good agreement with lognormality and this has been used to estimate the percentage of various basement types that may exceed various radon level thresholds. In the light of these analyses, the advice to employers on measuring radon in workplace basements has been reviewed.

Contents

1 Introduction

Radon is a recognised lung carcinogen to which human exposure should be limited. Regulations exist in the UK that limit the exposure to radon at work and require employers to take action if levels exceed certain thresholds. The probability of finding high radon levels in a workplace depends on several factors including its location, structure and usage. The main source of radon in buildings is from the ground. Rocks and soils contain minute amounts of uranium and radium, which decay radioactively into radon gas. Building surfaces in contact with the ground provide an ingress route into room air through construction joints and settlement cracks by pressure-driven flow; increasing the number and area of these surfaces increases the potential for radon ingress. Basements are therefore likely to have higher radon concentrations than other rooms.

Noticeably high radon levels in workplace basements have been observed in the UK since the 1980s. Early mapping exercises of workplace radon levels often produced higher radon potentials in workplaces than predicted from maps of radon in homes (Dixon and Gooding, 1992). Subsequent analysis (Dixon and Gooding, 1995; Gooding, 1996) showed that this increased radon potential was largely as a consequence of the highest radon level in a workplace (which is used to trigger action) being in a basement, whereas ground floor radon levels were similar to those in dwellings. Basements were therefore identified as needing particular attention.

Radon exposure and control for workplaces is covered by the Ionising Radiations Regulations 1999 (HSE, 1999a). The IRR99 are deemed to apply if the average radon gas concentration measured over a 3-month period exceeds 400 Bq m^{-3}, when a mid-winter seasonal correction has been applied. PHE and the Health and Safety Executive (HSE) advise that initial radon monitoring should include all basements with an occupancy of more than 1 hour per week (approximately 50 hours per year), irrespective of the radon potential of the workplace implied from the radon Affected Area* status (Miles et al, 2007), and all ground floor workplaces in radon Affected Areas (HSE, 2015).

This report looks at the distribution of radon levels in basements in more detail. The aims are to:

- **a** Assess the distribution of radon levels in workplace basements by workplace type and Affected Area status
- **b** Assess whether the current guidance on testing in basements is still appropriate and proportionate
- **c** Consider alternative proposals for testing based on occupancy or Affected Area status
- **d** Identify areas of uncertainty and the need for further investigations

* Any 25 metre square of the Ordnance Survey Grid with at least 1% of present or future homes above the domestic action level (200 Bq m^{-3} annual average radon concentration).

2 Background

2.1 Basements

A basement is a room or storey with at least one wall interfacing with the ground or a storey whose floor is at least 1.2 metre below ground level (TIBC, 2011). The walls can range in construction from standard building materials to native rock. This can cover a range of situations:

a Full basements have all walls below ground floor level

b Partial basements have walls only partly submerged and there may be windows at high level

c Semi-basements have at least one wall fully open to the air, may have external windows and doors, and are typically embedded in a hillside

The ventilation, temperature control and damp prevention in basements influence and are often linked to their use. This may be no different from a normal room above ground, have a special purpose such as a beer cellar, or be limited to storage. The frequency and duration of occupancy are linked to both usage and environment; low occupancy should not be assumed as the norm.

2.2 Regulations and application

The IRR99 apply to:

> '… any work (other than a practice) carried out in an atmosphere containing radon 222 gas at a concentration in air, averaged over any 24 hour period, exceeding 400 Bq m^{-3} except where the concentration of the short-lived daughters of radon 222 in air averaged over any 8 hour working period does not exceed 6.24×10^{-7} J m^{-3}.'

As radon monitors for workplaces are normally in place for a period of 3 months, some interpretation is used when determining whether the IRR99 apply in specific circumstances. In practice (and by agreement with the HSE), if the results from any of the passive monitors in the workplace are greater than 400 Bq m^{-3}, when seasonally corrected to 1 month starting January (the 'worst case'), the employer is advised that the IRR99 are likely to apply. If any of the results exceed 400 Bq m^{-3} without the seasonal correction being applied, then the advice is unequivocal: the IRR99 apply without the need for further interpretation.

The impetus to monitor is provided by the Management of Health and Safety at Work Regulations 1999 (HSE, 1999b), which require a 'suitable and sufficient' assessment of workplace risks. Radon is a hazard; the risk depends on the level to which a person is exposed and the duration of that exposure. Workplaces that are located in radon Affected Areas (Miles et al, 2007) should therefore undertake monitoring unless, for instance, the working environment is largely open to the air or has no significant ground contact (such as car washes or buildings on stilts). No monitoring is required in workplace buildings that are unoccupied as the IRR99 apply to the people at work, not the building.

Once information became available that radon levels in basements were generally higher than in ground floor rooms, some employers focused on monitoring these areas, including those that were accessible but unused. In addition, employers with workplaces in non-Affected Areas started to monitor basements only. To provide guidance on what constituted an ‘occupied basement’, a figure of 1 hour per week was established with the HSE. This value was chosen for two reasons: it implied greater occupancy than just occasional access (for instance to read a meter); and a radon level of 5000 Bq m^{-3} (which was considered to be exceptional) for 50 hours would yield an annual dose of 1 mSv, the public dose limit*.

Subsequently, an analysis was made of the radon levels in bank basements to assess the impact of the advice on when to test. This workplace type was chosen as providing a high degree of uniformity, with the advantage that some of the banking industry had undertaken radon monitoring nationwide regardless of radon potential. Separating the basement results into non-Affected and Affected Areas, the distributions were shown to be broadly lognormal, although slightly skewed towards higher results (Gooding, 2009). In Affected Areas, almost 2% of bank basements exceeded 5000 Bq m^{-3}. In non-Affected Areas, the corresponding figure was around 0.1%. The conclusion was that the occupancy threshold of 1 hour per week could be revised upwards for non-Affected Areas, whereas radon monitoring should be considered for all accessible basements in Affected Areas. However, further analysis to include other occupational sectors was indicated and the advice to employers on when to test workplace basements was not changed.

3 Analysis

3.1 Sample selection

The PHE national radon database contains radon gas passive monitor results for both homes and workplaces and the datasets for analysis were extracted from this source. Initially, all workplace buildings where a basement environment was clearly identified were separated and flagged, for instance ‘basement’, ‘cellar’ and ‘underfloor’. This subset was cleaned to remove missing or uncertain results (such as very short measurement periods), additional radon sources (such as geological sample stores) and all post-mitigation results. The radon potential of each workplace address was added, acknowledging the uncertainties when applying this criterion to large buildings. One consequence of having the radon potential available at the level of 25 metre grid squares is that an accurate, current address is required for each workplace. Owing to company closures, postcode changes or ambiguities in the address, not all workplaces could be assigned a radon potential. Thus the total number of records for a particular workplace type is greater than the sum of the Affected and non-Affected Area datasets.

For each workplace the highest result of the initial set of measurements in the basement was used for the analysis. The results were also grouped according to workplace type (retail, industrial, etc). The final dataset comprised approximately 3500 records; 27 subsets were analysed and are listed in Table 1.

* The public dose limit is included in the IRR99 approved code of practice (HSE, 2000); the dosimetry is defined in European Council Directive 96/29/EURATOM (EC, 1996). The equilibrium factor, F, is assumed to be 0.5.

Table 1: Data subsets for analysis by workplace type and radon potential

	Affected Area status, number of records		
Workplace type(s)	**All**	**Affected Area**	**Non-Affected Area**
All buildings	3539	1679	1780
All non-banks	2193	1274	860
Banks	1346	405	920
Education	348	198	128
Healthcare	172	89	77
Industrial	223	113	106
Miscellaneous	392	278	110
Offices	686	405	266
Retail	344	176	163

3.2 Statistical analysis

Radon measurement distributions in houses and workplaces are approximately lognormal (Gunby et al, 1993). This has also been demonstrated for basements (Gooding, 2009). The data subsets shown in Table 1 were tested for lognormality using the Ryan-Joiner method provided by the MiniTab statistical package, which tests for correlation and regression between the data and a lognormal distribution. Other tests are available that have different sensitivities to outliers at the tails of the distribution; a feature that has been observed previously with radon levels in basements (Gooding, 2009) and houses (Daraktchieva et al, 2014). A less outlier-sensitive test was chosen as the objective was to determine whether lognormality was a sufficiently good approximation to be useful over a wide range of radon concentrations to assess the proportion of results above a threshold.

Each of the data subsets was assessed for its lognormality for both the results ‘as measured’ and ‘winter-corrected’. The lognormality in datasets of homes has been improved by removing the additive effect of the outside air concentration (Gunby et al, 1993), which is approximately 4 Bq m^{-3} in the UK (Wrixon et al, 1988). Such an adjustment is justified in basements as, in order to have adequate ventilation, they are not isolated from outside air. The tests for lognormality were rerun after having subtracted 4 Bq m^{-3} from each result. Box and whisker diagrams were used to identify or confirm outliers noted from the graphs obtained from the lognormality assessments.

4 Results

A comparison of all the results from the lognormality tests was made to determine which had the best agreement with lognormality, and would be most suitable for assessing the recommendations on when to test a basement. When the sample corresponds to a lognormal distribution the points on the plot are close to the straight line and the ‘correlation coefficient’ (RJ value) is close to unity; the critical value depends on the number of data points, N, and is approximately 0.987 when N is 100 and approximately 0.998 when N is 400 (Ryan and Joiner, 1976). Marked deviations and a smaller RJ value indicate that the sample is not from a lognormal distribution, for instance discontinuities can indicate a bimodal or multimodal distribution, or outliers at the ends indicate non-normal tails in the distribution. The p-value shows the strength of evidence in rejecting the (null) hypothesis of the sample being from a lognormal distribution, as described in Table 2 (Hooper, 2015).

Thus in the following probability plots the datasets corresponding most closely to the lognormal distribution have p-values greater than 0.100. The effects on the p-value and RJ value from applying a seasonal correction and by making an adjustment for the outside air concentration (subtracting 4 Bq m^{-3}) are illustrated in Figure 1. Any negative radon concentrations calculated when the 4 Bq m^{-3} adjustment is made are rejected, which accounts for the small differences in the number of data points, N. Further refinements (and improvements of fit to the lognormal) could be made to some of the distributions if very high or low outliers were removed.

In addition, for Figure 1 and Figures 4 to 11 inclusive, all non-Affected Area results have been shown as blue circles and all Affected Area results shown as red squares. The blue and red lines are the corresponding best fitting lognormal distributions. The lower text box shows the geometric mean (GM) in Bq m^{-3}, the geometric standard deviation (GSD), the number of results plotted for each category, the RJ value and the p-value; the upper row corresponds to the non-Affected Area values and the lower row to the Affected Area values.

The GMs and GSDs have been used to estimate the percentage of workplaces exceeding three concentration thresholds: 400, 1000 and 5000 Bq m^{-3}, which are shown as value markers in Figure 1 and Figures 4 to 11 inclusive. The rationale for these thresholds is discussed in Section 5.3. As the winter-corrected results that had been adjusted for outside air consistently produced the best agreement with the lognormal distribution, these have been identified as most appropriate for the purposes of this report and the resulting estimated percentages are illustrated in Figure 2.

Table 2: Interpretation of p-value

p-value	Interpretation
$p > 0.100$	No evidence against the null hypothesis. The sample appears to be consistent with the null hypothesis
$0.050 < p < 0.100$	Weak evidence against the null hypothesis in favour of the alternative
$0.010 < p < 0.050$	Moderate evidence against the null hypothesis in favour of the alternative
$0.001 < p < 0.010$	Strong evidence against the null hypothesis in favour of the alternative
$p < 0.001$	Very strong evidence against the null hypothesis in favour of the alternative

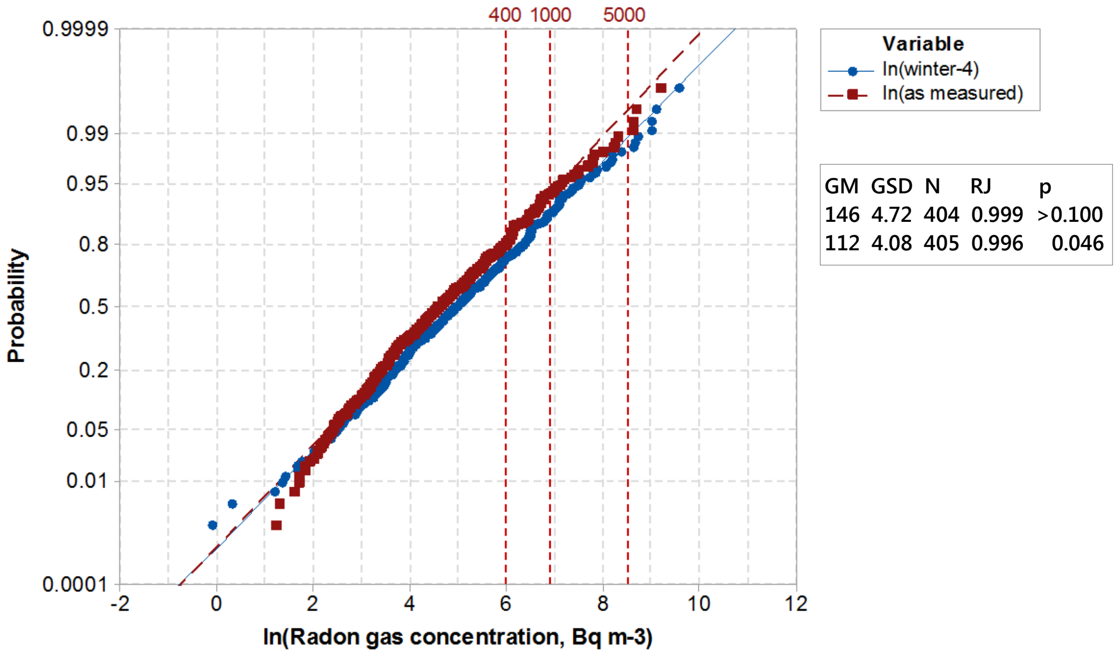

Figure 1: Probability (normality) plot of bank basements in Affected Areas: as measured results, no outside air adjustment; winter-corrected results with outside air adjustment

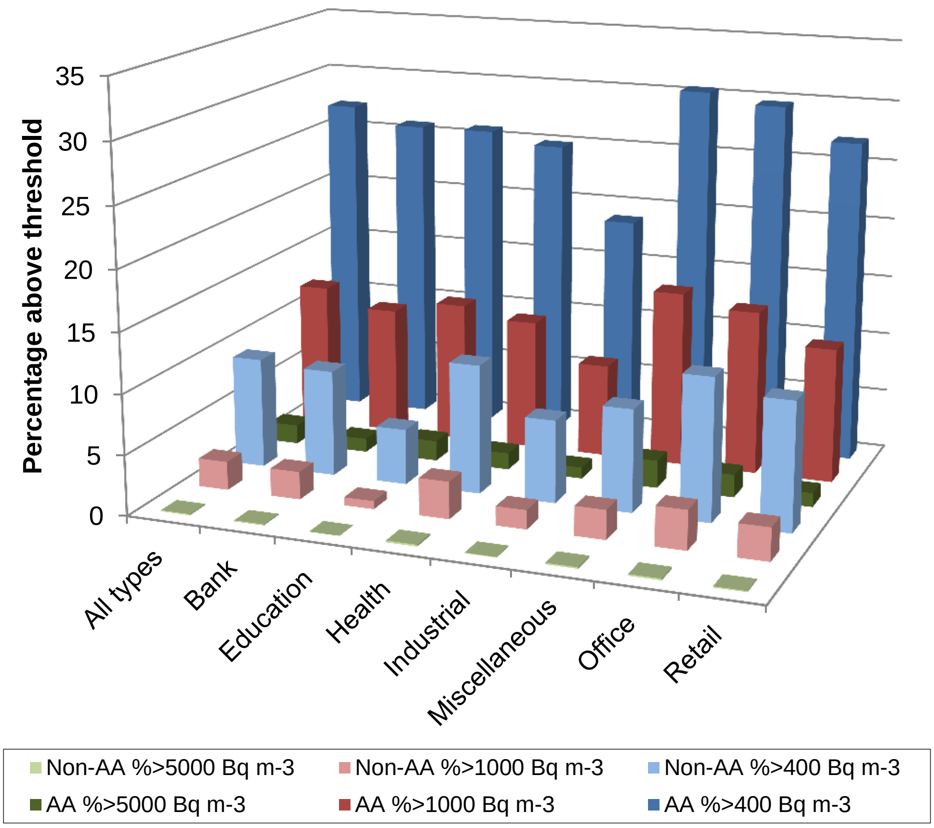

Figure 2: Estimated percentages of workplaces exceeding concentration thresholds, winter-corrected results with outside air adjustment

Table 3: Means and standard deviations of radon concentrations in various workplace basements

		As measured (Bq m^{-3})						Winter maximum (Bq m^{-3})					
Name	**Records**	**GM**	**GSD**	**AM**	**SD**	**(-4) GM**	**(-4) GSD**	**GM**	**GSD**	**AM**	**SD**	**(-4) GM**	**(-4) GSD**
All types all areas	3539	72	4.16	277	1916	64	4.75	103	4.36	404	2243	94	4.85
All types Affected Areas	1679	107	4.56	446	2744	98	5.10	157	4.70	647	3173	147	5.17
All types non-Affected Areas	1780	50	3.43	123	377	43	4.01	69	3.61	185	634	62	4.07
Bank all areas	1346	64	3.75	185	542	56	4.44	88	3.96	277	873	79	4.55
Bank Affected Areas	405	112	4.08	326	790	102	4.56	157	4.29	492	1221	146	4.72
Bank non-Affected Areas	920	50	3.33	123	376	42	4.07	67	3.51	184	655	59	4.14
Education all areas	348	70	4.40	337	1898	63	5.06	99	4.42	462	2486	93	4.79
Education Affected Areas	198	101	4.95	530	2500	92	5.68	142	4.94	722	3272	131	5.56
Education non-Affected Areas	128	41	2.99	71	87	35	3.59	60	3.04	106	129	56	3.21
Health all areas	172	69	3.92	190	381	60	4.65	105	4.11	291	555	93	4.88
Health Affected Areas	89	92	4.21	242	383	85	4.62	144	4.37	390	653	130	5.26
Health non-Affected Areas	77	52	3.50	140	387	42	4.59	75	3.65	190	416	65	4.31
Industrial all areas	223	51	4.65	575	6654	47	5.00	71	4.56	666	7122	68	4.86
Industrial Affected Areas	113	62	5.29	1046	9342	60	5.47	89	5.30	1198	9996	87	5.61
Industrial non-Affected Areas	106	41	3.94	91	121	37	4.33	56	3.72	118	159	52	3.98
Miscellaneous all areas	392	86	4.70	369	1105	77	5.42	132	4.91	562	1616	119	5.67
Miscellaneous Affected Areas	278	116	4.89	479	1284	103	5.68	180	5.01	733	1880	167	5.50
Miscellaneous non-Affected Areas	110	42	3.21	103	295	36	3.67	60	3.37	145	351	50	4.59
Office all areas	686	89	4.43	290	772	82	4.74	129	4.70	455	1318	122	4.88
Office Affected Areas	405	120	4.47	384	888	110	5.01	177	4.69	603	1528	166	5.17
Office non-Affected Areas	266	57	3.96	157	552	53	3.93	81	4.24	247	921	78	4.00
Retail all areas	344	80	3.86	2901	1276	71	4.32	119	4.08	449	1747	110	4.42
Retail Affected Areas	176	108	4.29	445	1745	99	4.65	166	4.36	675	2349	157	4.60
Retail non-Affected Areas	163	58	3.16	129	324	50	3.67	83	3.47	212	607	75	3.86

The GMs and GSDs were obtained for each test for both as measured and winter-corrected results and are shown in Table 3. For completeness, the arithmetic means (AMs) and standard deviations (SDs) were calculated for the distributions as measured and winter-corrected.

The distributions of winter-corrected (with 4 Bq m^{-3} subtracted) radon results in Affected Areas (AAs) and non-Affected Areas (non-AAs) for all basements are shown in Figure 3. Value markers have been placed at concentration thresholds of 400, 1000 and 5000 Bq m^{-3}, as before. The distributions are both lognormally distributed over a wide range of results and clearly distinct from each other, with the Affected Area results having both a higher GM and GSD; these are analysed in more detail in Figure 4. A greater proportion of the Affected Area distribution exceeds all three concentration thresholds.

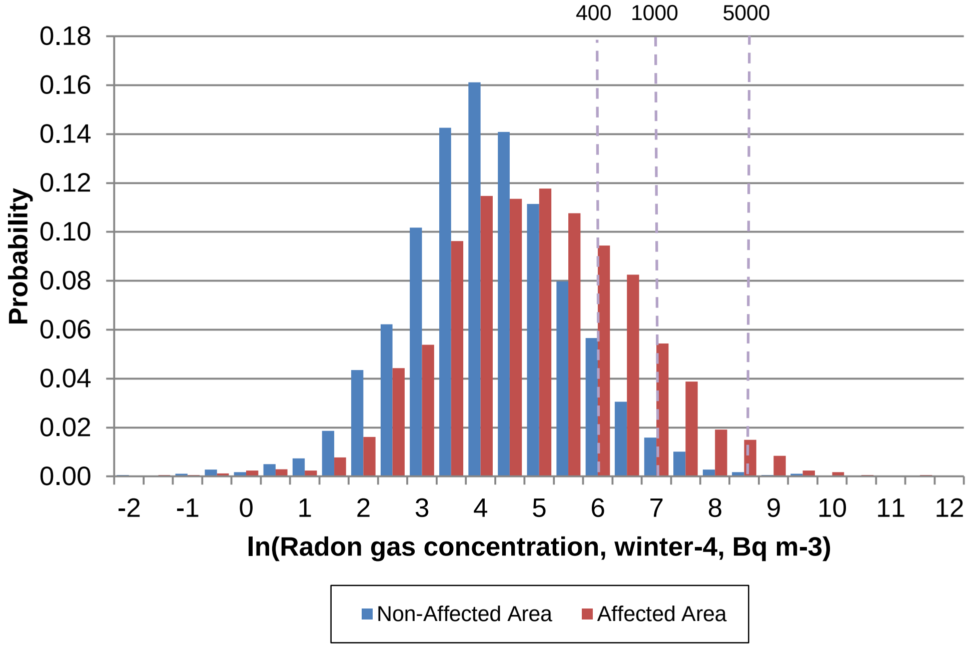

Figure 3: Distribution of radon results for Affected Areas and non-Affected Areas, winter-corrected with outside air adjustment

The probability plots for all the workplace types, showing both Affected Areas and non-Affected Areas, are illustrated in Figures 4 to 11 inclusive. The scales on both axes have been kept similar for all figures to enable direct visual comparisons between the different types of workplaces. The value markers and statistics shown in the text boxes have been described earlier in this section.

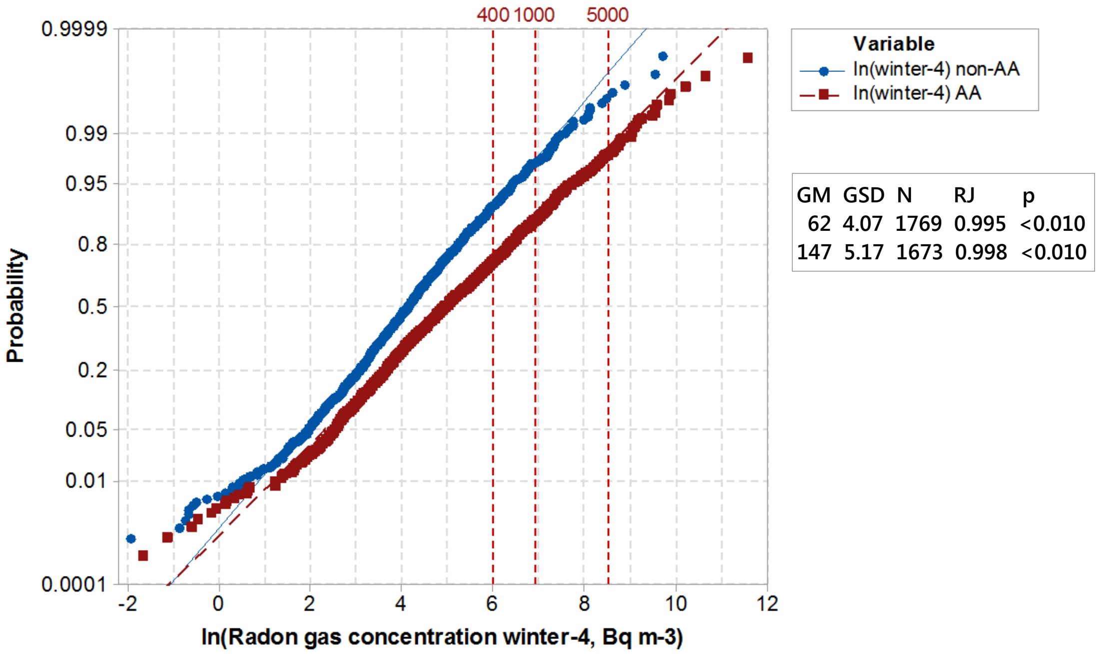

Figure 4: Probability plot of all basements, winter-corrected results with outside air adjustment

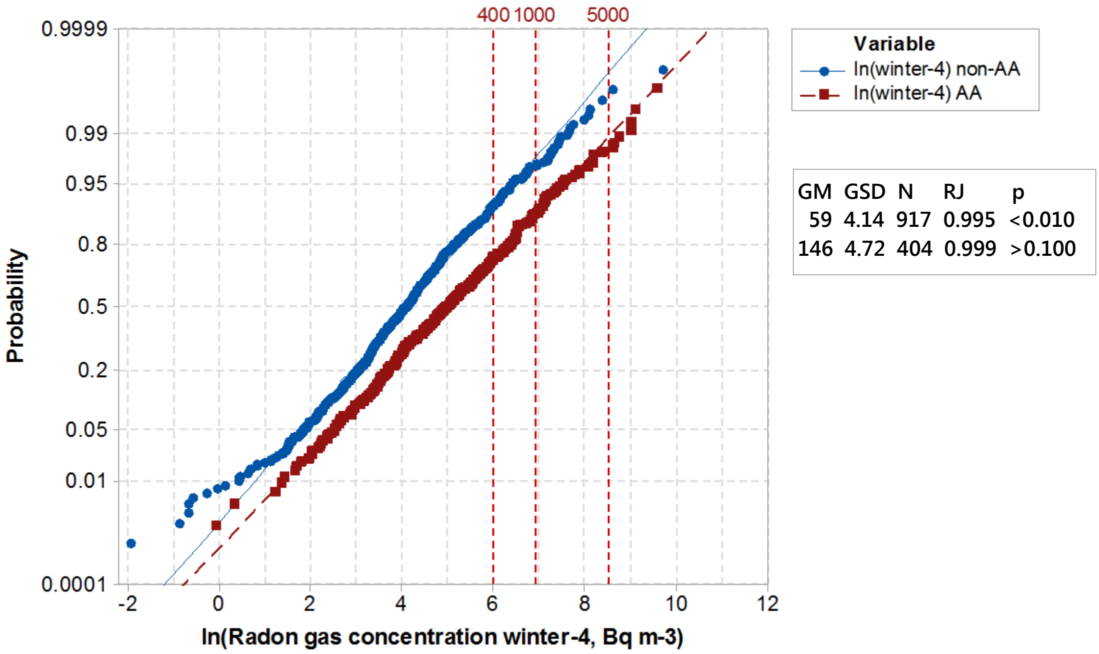

Figure 5: Probability plot of bank basements, winter-corrected results with outside air adjustment

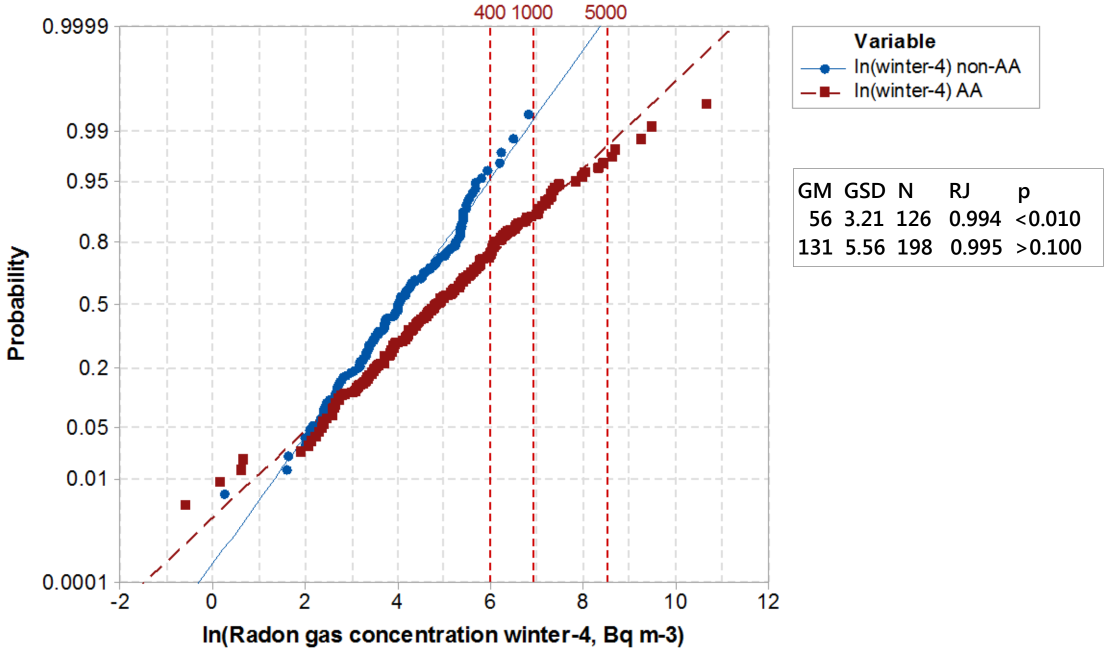

Figure 6: Probability plot of educational property basements, winter-corrected results with outside air adjustment

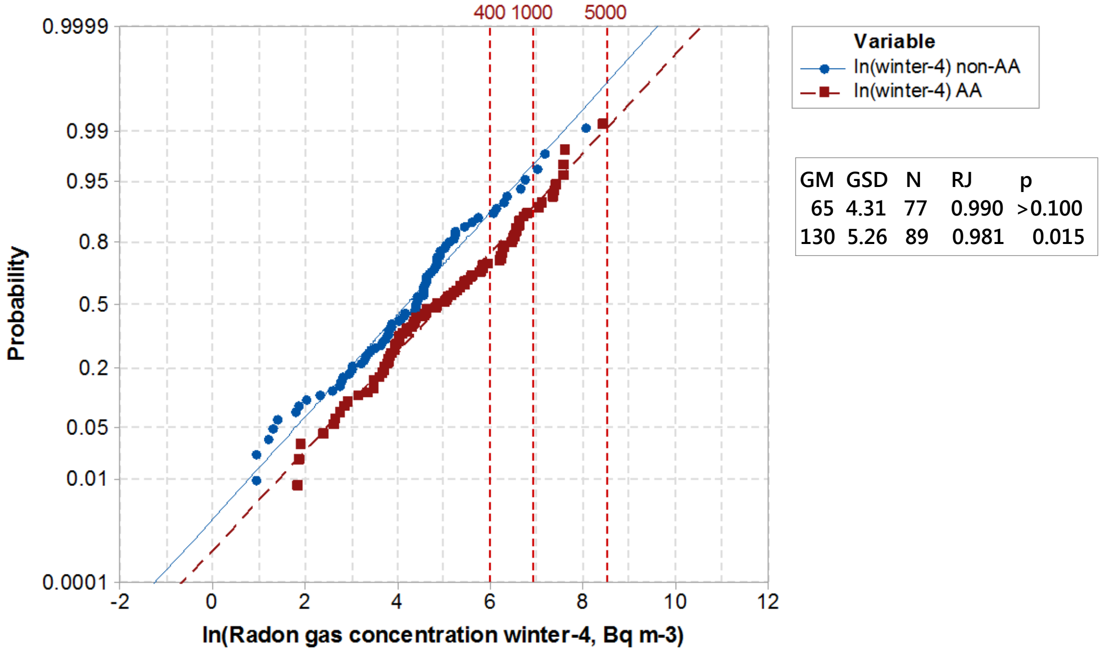

Figure 7: Probability plot of healthcare property basements, winter-corrected results with outside air adjustment

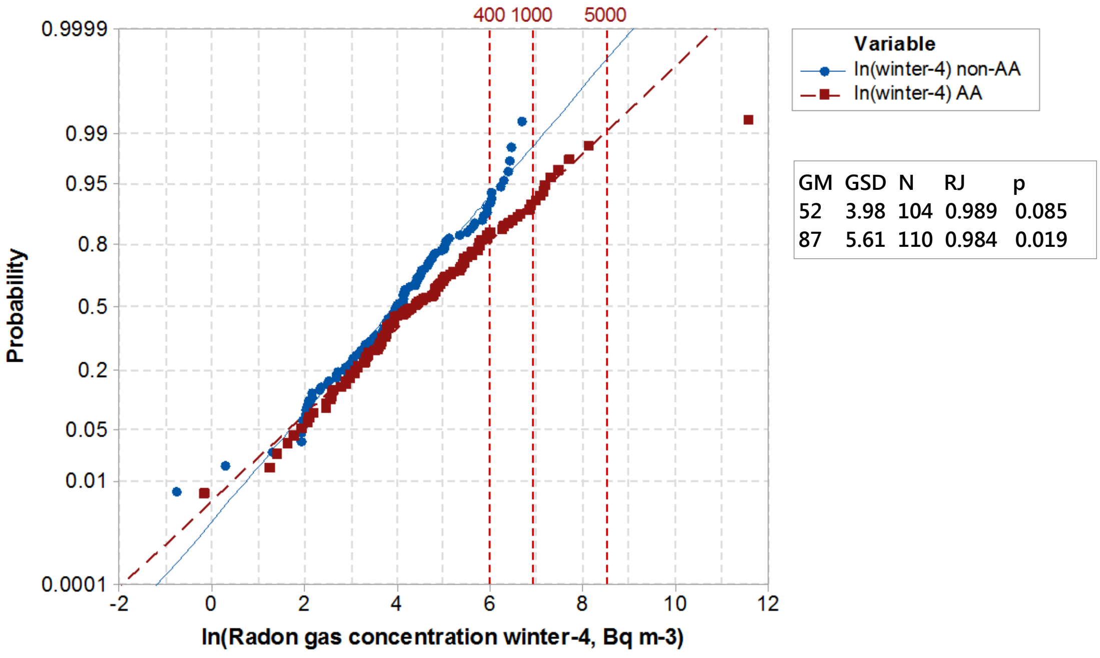

Figure 8: Probability plot of industrial property basements, winter-corrected results with outside air adjustment

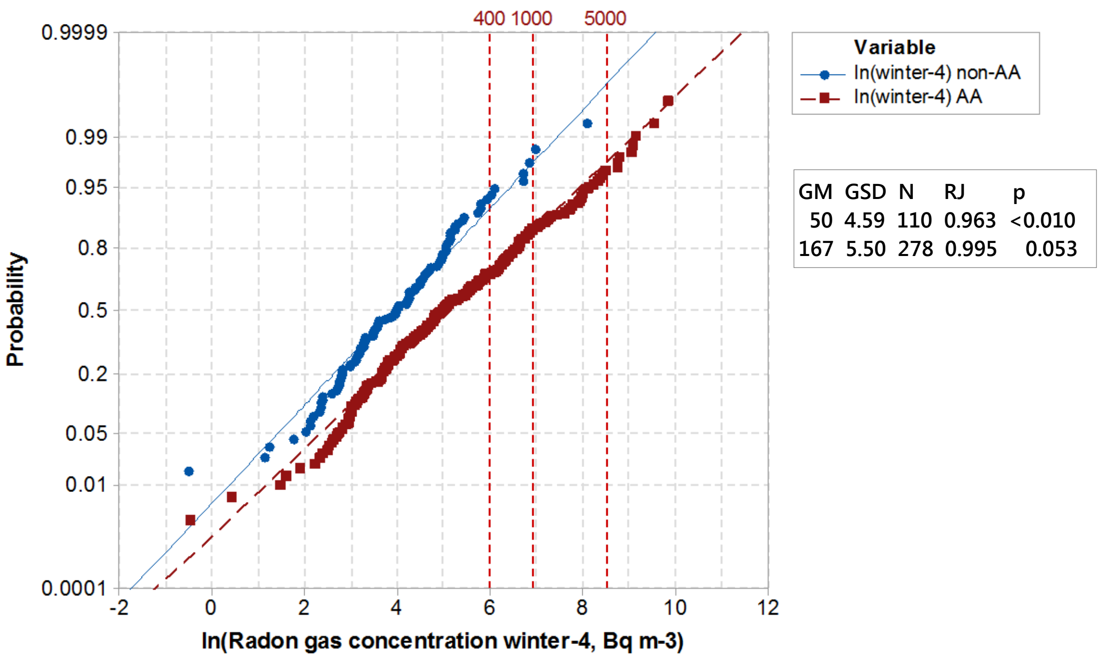

Figure 9: Probability plot of miscellaneous property basements, winter-corrected results with outside air adjustment

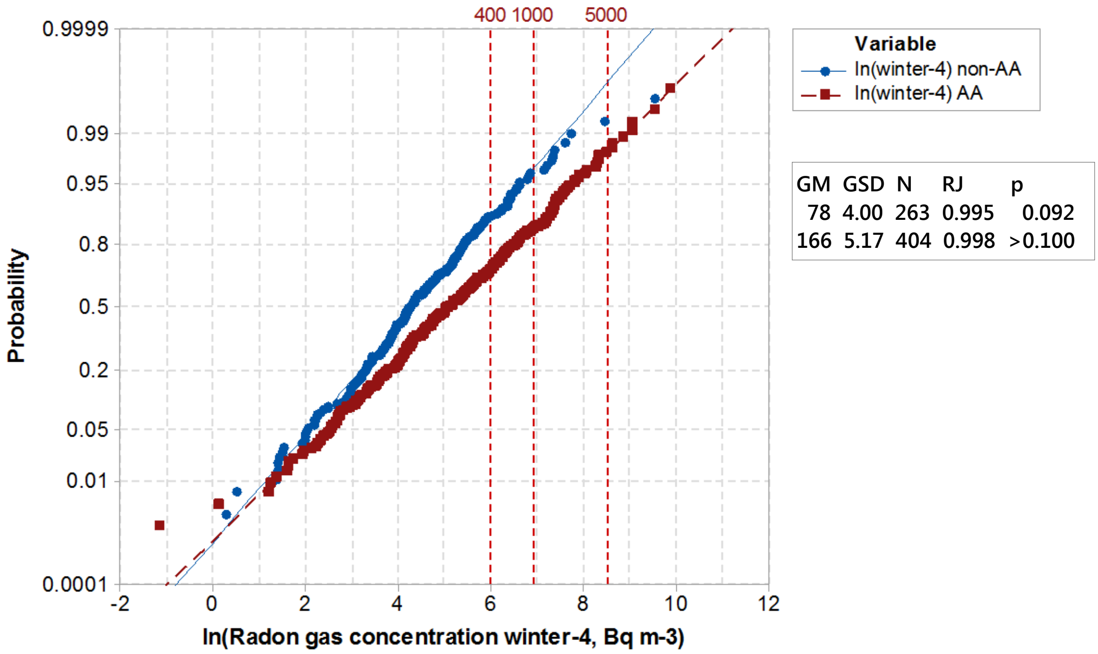

Figure 10: Probability plot of office property basements, winter-corrected results with outside air adjustment

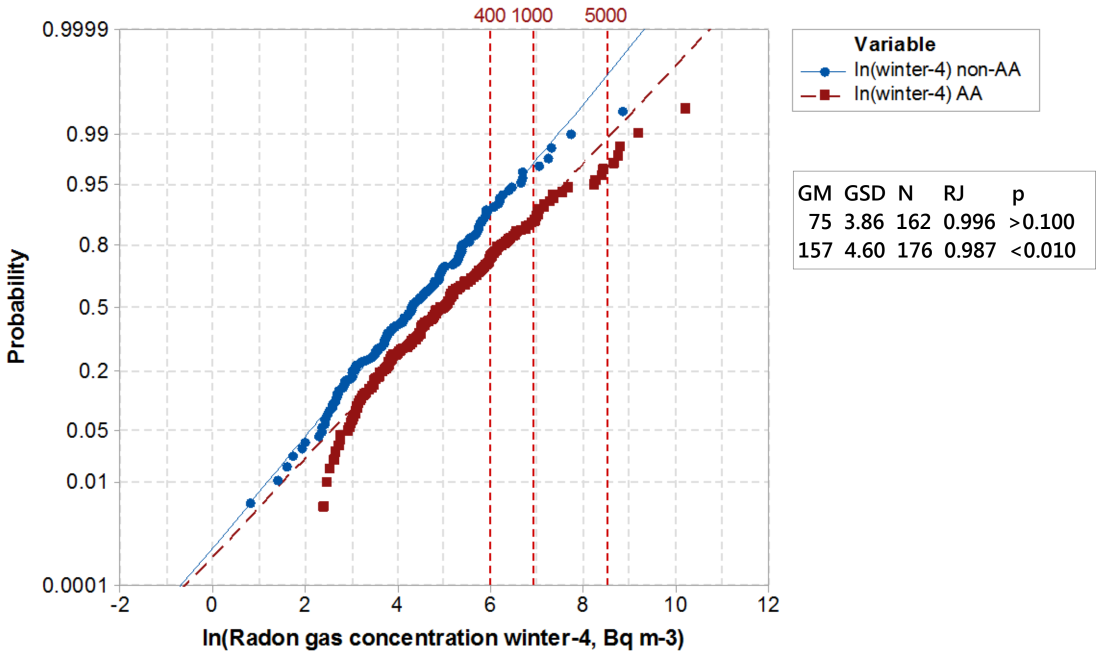

Figure 11: Probability plot of retail property basements, winter-corrected results with outside air adjustment

5 Discussion

5.1 Lognormality

The tests for lognormality showed that this is a reasonable assumption to make for radon results in basements. Lognormality is generally improved if at least three of the following conditions are met:

a The dataset is stratified according to workplace type and radon potential

b The results are seasonally corrected (to winter)

c An adjustment of 4 Bq m^{-3} is made to compensate for the radon concentration in outside air

d In some cases, a small number of outliers at the high and/or low ends are removed – high outliers are more likely in Affected Areas datasets

Given the uncertainties over the seasonal variations (see Section 5.2), the improvements in lognormality shown by seasonally correcting the results were surprisingly strong.

The tests also highlighted predictable issues, for instance where a range of workplace types was included in a single mixed group. The miscellaneous category of basements includes public house cellars and other workplaces not identified separately. The discontinuities shown in Figure 9 suggest the superposition of more than one distribution. Even in this case, however, a lognormality test could be passed by removing two low outliers.

For the favoured dataset (winter-corrected with outside air adjustment), the effect of outliers was investigated further. Both high and low outliers produced a more S-shaped curve in the probability plots, which was straightened with their removal and thus improved the goodness of fit. Removing low outliers increased the GM and decreased the GSD; removing high outliers decreased both the GM and GSD. As all the concentration thresholds were higher than the GM, the removal of outliers reduced the percentage of workplaces that were estimated to exceed these values. However, this was not sufficient in any case to materially alter the conclusions of the analysis or the subsequent recommendations.

5.2 Seasonal effects

Radon measurements are routinely corrected to the mid-winter result to estimate the worst-case radon level in the workplace. The seasonal correction factors are set out in the PHE validation scheme (Howarth and Miles, 2008) and are based on long-term measurements in above ground buildings. It is unclear if the same seasonality applies to basements and the seasonal variations in radon levels in basements are hard to assess from the dataset. Although 396 workplaces had recorded at least two pre-mitigation radon results in their basements, the following factors were identified that prevented meaningful analysis of the seasonal variations:

a The same location was not monitored each time

b The measurements were often widely spaced in time, for instance in successive years or with breaks of several years

- **c** Monitoring started in the same month or season each time
- **d** A significant and sustained reduction in radon level indicated mitigation work not previously notified
- **e** The type and occupancy of the basement were not recorded – they cannot be inferred from the recorded position – and ‘cellar’ can describe a range of environments

Owing to the limited availability of repeated measurements in basements, drawing conclusions on the applicability of standard seasonal corrections is not possible. In practice, this does not cause problems with the application of the IRR99 as employers should continue monitoring locations with high or ambiguous radon levels until seasonal patterns are established and appropriate radon controls implemented. It can be seen, however, that seasonally corrected datasets have better lognormality scores than those with uncorrected as measured results. To address this unresolved issue – over which challenges are frequently made – a programme of measurements in basements in order to collect seasonal information would be needed.

5.3 Thresholds

A radon Affected Area for homes (and, by inference, for workplaces as well) is defined as an area where at least 1% of present or future homes exceed the domestic action level (Miles et al, 2007). There are further gradations indicating a greater potential for a home to exceed the action level, which also correspond to higher average radon levels. The 1% threshold therefore indicates where it is appropriate to focus attention when considering the need for radon measurements, with the higher percentage thresholds used, for example, to help rank properties when assigning priorities during measurement programmes or the need for preventive measures in new build.

Estimates of the percentage of workplace basements that exceed the various thresholds within each occupational group were calculated from the geometric statistical values (winter-corrected radon level with outside air adjustment) and are shown in Figure 2. In addition to 400 Bq m^{-3}, two further threshold values were chosen. The radon concentrations of 1000 and 5000 Bq m^{-3} correspond to an estimated dose of 1 mSv from 250 or 50 hours’ exposure, respectively, under the current dosimetry (EC, 1996). In practical terms, this can be described as an hour per day or an hour per week over the working year.

The percentages of basements exceeding the concentration thresholds for all workplace types (total dataset, with no allowance made for the relative proportions of the different workplace types) are shown in Table 4. As for Figure 2, the winter-corrected radon levels with an outside air adjustment have been used. The dataset for radon concentrations exceeding 5000 Bq m^{-3} has been split as the distribution deviates noticeably from the lognormal above this level.

The analysis shows that workplace basements in all areas are prone to high radon concentrations. Even in non-Affected Areas approximately 9% of basements exceed the IRR99 concentration threshold of 400 Bq m^{-3}. This confirms that basements should be considered as special cases for monitoring and not limited to those workplaces in Affected Areas. However, since many basements are not worked in full-time, the occupancy of the basement should then be taken into account by the employer when considering whether radon testing is required.

Table 4: Percentages of all basements exceeding concentration thresholds (winter-corrected radon levels with outside air adjustment)

Affected Area status	Concentration threshold			
	Assuming lognormal distribution			From actual values
	% > 400 Bq m^{-3}	% > 1000 Bq m^{-3}	% > 5000 Bq m^{-3}	% > 5000 Bq m^{-3}
All areas	18.0	6.7	0.6	1.1
Affected Areas	27.2	12.2	1.6	2.0
Non-Affected Areas	9.2	2.4	0.1	0.3

Affected and non-Affected Areas show significant differences in the percentages of workplace basements exceeding the selected concentration thresholds, with those in Affected Areas having a distribution that is shifted to higher concentrations. Since there is a clear difference between Affected and non-Affected Areas, it is therefore appropriate to consider them separately.

At the highest selected threshold concentration, the distribution deviates from the lognormal and a greater proportion of workplaces exceeds 5000 Bq m^{-3} than is predicted. This is more significant for the non-Affected Areas. Such an effect has also been observed for radon levels in dwellings where the number of homes with very high levels has been greater than predicted (Daraktchieva et al, 2014). At radon levels of 1000 Bq m^{-3} it is therefore appropriate to use the statistics from the lognormal distribution to investigate monitoring criteria, but the more cautious observed distribution should be used at 5000 Bq m^{-3}.

5.4 Radon testing considerations

The recommended minimum annual occupancy threshold for testing in basements is currently 50 hours. Given the clear differences between radon levels in the basements of workplaces in Affected and non-Affected Areas (but similarities between workplace types), the occupancy threshold may be considered in terms of proportionality with other radon testing advice. The current recommendation on when to test in basements was based upon the estimated annual dose. As radon dosimetry is not a fixed entity, comparisons can be made using the product of the concentration threshold, the probability of exceeding such a threshold and the exposure time. This produces an alternative parameter (probabilistic integrated exposure, PIE) that is independent of changes in dosimetry or assumptions about the aerosol characteristics and equilibrium factor.

For example, the probability threshold for an Affected Area is 1%. The annual exposure time may be taken as 2000 hours in regulations (HSE, 2000) but may be closer to 1600 hours once holidays and a more typical working week are taken into account (ONS, 2016). The concentration threshold is 400 Bq m^{-3}. Thus:

$$400 \times 0.01 \times 2000 = 8000 \text{ Bq m}^{-3} \text{ h} \quad (1)$$

$$400 \times 0.01 \times 1600 = 6400 \text{ Bq m}^{-3} \text{ h} \quad (2)$$

Currently, the 50 hour minimum annual occupancy threshold (using the actual values for all basements from Table 4) gives:

$$\text{Affected Areas: } 5000 \times 0.02 \times 50 = 5000 \text{ Bq m}^{-3} \text{ h} \quad (3)$$

$$\text{Non-Affected Areas: } 5000 \times 0.003 \times 50 = 750 \text{ Bq m}^{-3} \text{ h} \quad (4)$$

For Affected Areas this is quite consistent with normal workplaces above ground, but is far more restrictive for non-Affected Areas. To provide the same measure of PIE (5000 Bq m^{-3} h) in non-Affected Areas, a minimum occupancy threshold would be approximately 330 hours (5000 x 0.003 x 330 = 4950 Bq m^{-3} h).

Thus there are three values of PIE (5000, 6400 and 8000 Bq m^{-3} h) that represent a broadly consistent range above which workplace radon monitoring is expected. The resulting minimum occupancy thresholds are shown in Table 5 in relation to two concentrations (1000 and 5000 Bq m^{-3}) on the radon distributions.

Table 5: Minimum annual occupancy thresholds

		Affected Area status			
		Affected Area		Non-Affected Area	
Concentration threshold (Bq m^{-3})	Probabilistic integrated exposure threshold (Bq m^{-3} h)	% exceeding concentration threshold	Minimum annual occupancy threshold (h)	% exceeding concentration threshold	Minimum annual occupancy threshold (h)
1000	5000	12.2	41	2.4	210
1000	6400	12.2	53	2.4	269
1000	8000	12.2	66	2.4	333
5000	5000	2.0	50	0.3	333
5000	6400	2.0	64	0.3	427
5000	8000	2.0	80	0.3	533

On the basis of PIE, clearly the minimum annual occupancy threshold for basements in non-Affected Areas is significantly higher (range 210–533 hours) than that for basements in Affected Areas (41–80 hours).

Radon gas concentrations do not remain constant. Seasonal and diurnal variations can be expected to reduce the average radon concentration during the working day to around half that indicated by the winter-corrected value (Gooding and Dixon, 2005). This means that the radon concentration to which an employee is exposed is usually less than the winter-corrected value and that the dose received is correspondingly reduced. Therefore as the winter-corrected radon concentrations have been used in these calculations, the exposure to employees is likely to be lower.

5.5 Reviewing advice on when to test

The current guidance from the HSE is that basement workplaces should be measured if they are occupied for at least 50 hours per year (1 hour per week), which is clear and unambiguous. No knowledge of the radon potential is required, although this has become easier to obtain since the online search service was launched (PHE, 2015). This analysis suggests that the current guidance on when to test basements in workplaces should be reviewed. The guidance would be more consistent (and proportionate with other advice on radon) if it were to be separated and adjusted for Affected and non-Affected Areas.

5.5.1 Affected Areas

It can be seen from Table 5 that the minimum annual occupancy threshold of 50 hours for basements in Affected Areas remains a pragmatic way of evaluating whether radon testing should be carried out. It is within the range of minimum annual occupancy thresholds and can be described simply as ‘1 hour per week’.

5.5.2 Non-Affected Areas

The distribution shown in Figure 3 and subsequent analyses show that radon levels in non-Affected Areas are systematically lower than those in Affected Areas. For non-Affected Areas, Table 5 indicates that a higher occupancy threshold is appropriate. A value of 250 hours is within but towards the bottom of the range of minimum annual occupancy thresholds. Adopting this criterion for non-Affected Areas would reflect the observed radon levels (in addition to the lower risk of a high radon level), be consistent with current recommendations for Affected Areas, and be pragmatic. It can be described in simple terms as ‘1 hour per day’.

This decision process is illustrated in Figure 12.

5.6 Other rooms in workplace buildings

The above discussion considers only the exposure to radon in basement workplaces. The radon levels in rooms on the ground floor may also require action, as previous work has shown that radon levels in the basements are not a good predictor of the radon levels in other storeys (Gooding, 1994). The advice that employers should test ground floor workplace premises located in Affected Areas is unchanged.

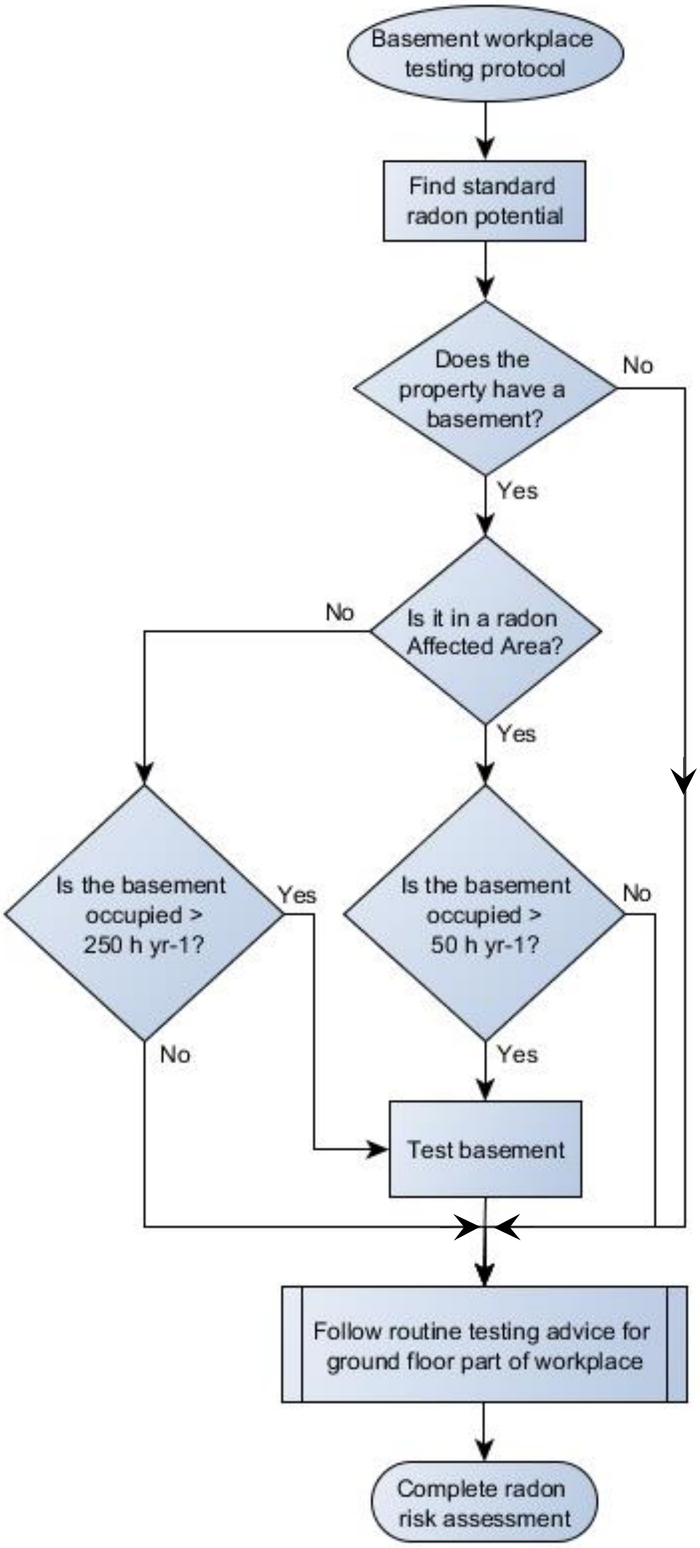

Figure 12: Radon measurement decision process

6 Conclusions

In addition to the well-established practice of monitoring the ground floor rooms of workplaces in Affected Areas, the following conclusions have been drawn from this analysis of radon levels in workplace basements:

- **a** Radon monitoring should be considered in workplace basements irrespective of the radon Affected Area status of the workplace location
- **b** The distribution of radon levels in workplace basements can be described in most cases as lognormal
- **c** Tests of lognormality are more likely to be passed if results are separated by workplace type and radon potential, winter-corrected and with a 4 Bq m^{-3} adjustment made for outdoor air
- **d** In order to be proportionate with monitoring radon levels in ground floor workplaces, the minimum occupancy threshold should be 50 hours per year (1 hour per week) for basement workplaces in Affected Areas and 250 hours per year (1 hour per day) for non-Affected Areas
- **e** There are insufficient results to draw meaningful conclusions about the seasonality of radon levels in workplace basements, and further work on this area should be considered
- **f** Work to increase the awareness of the increased radon potential of basements in all areas should continue

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