

Factors Influencing Upstairs and Downstairs Radon Levels in Two-Storey Dwellings

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Abstract

Environmental radon exposure of residents of two-storey domestic premises is generally estimated on the basis of the measured radon concentrations in, and the relative occupancies of, the principal living-room and bed-room, assuming 45% and 55% occupancy of these two locations respectively. In practice, however, significant case-to-case variability exists, both in the relative periods that individuals spend in the upstairs and downstairs rooms of two-storey homes, and in the relative radon levels in these two areas. Moreover, while it is assumed that radon levels in upper storeys of multi-storey homes will be intrinsically lower than at ground level, this is not always the case, since radon exhalation from the materials from which the house is constructed may contribute significantly to indoor levels. While studies on radon level variability in the individual units in apartment blocks have been reported, the situation in two-storey low-rise dwellings appears not to have been considered. To investigate this, detailed extended measurements of radon concentrations were made in a set of thirty-four homes situated in areas of Northamptonshire known to exhibit high radon levels and declared a radon Affected Area by the United Kingdom (UK) National Radiological Protection Board (NRPB) in 1992. All homes were of typical UK construction of brick/block/stone walls under a pitched tile/slate roof. Approximately 50% of the sample were detached houses, the remainder being semi-detached (duplex) or terraced (row-house). Around 25% of the sample possessed cellars, while 12% were single-storey dwellings. In two-storey homes, all monitored bedrooms were on the upper floor.

Distribution of the ratios of bedroom/living-room radon levels in individual properties was left-skewed (mean 0.67, median 0.73, range 0.05 - 1.05). The mean is consistent with the outcome of early NRPB studies in England, while the variability depends principally on the characteristics of the property, and not on seasonal factors. Ratios in single-storey homes clustered around 1.0, indicating that house design, rather than lifestyle, is the dominant factor in determining bedroom radon levels. Homes with higher mean annual radon levels showed lower bedroom/living-room ratios, supporting our proposal that radon emanation from building materials comprises a significant component of the overall level.

1 Introduction

Environmental radon exposure of residents of two-storey domestic premises is generally estimated on the basis of the measured radon concentrations in, and the relative occupancies of, the principal living-room and bedroom, assuming 45% and 55% occupancy of these two locations respectively [1]. In practice, however,

significant case-to-case variability exists, both in the relative periods that individuals spend in the upstairs and downstairs rooms of two-storey homes, and in the average radon concentrations found in these two areas. Although not considered in our studies to date, the growing popularity of three-storey homes in new residential developments, together with the increased incidence of home-working, with home offices often located in otherwise unused bedroom space, results in significant numbers of individuals experiencing radon exposures in their homes not readily quantifiable using the accepted methodology.

The principal contributors to indoor radon concentrations in UK dwellings are soil-gas emanating from the ground beneath the dwelling, and the materials from which the dwelling is constructed, with further small or negligible contributions arising from the atmospheric background ($4 \text{ Bq}\cdot\text{m}^{-3}$ [1]), water supplies and gas supplies. Entry of radon into a dwelling from the soil-gas is influenced by radon concentration in the soil-gas, soil moisture content, weather, ground permeability, entry routes into the dwelling, and under-pressure caused by temperature differences between the dwelling interior and the external atmosphere [2]. Entry from constructional materials depends largely on the intrinsic radium activity of the materials in question [3], their permeability to radon gas [4] and the barrier effects, if any, of surface treatments such as paint and wall-coverings [5]. Since percolation of soil-gas radon from lower to upper storeys proceeds by gaseous diffusion modified by radioactive decay ($t_{1/2}$ of the order of 3.6 days), the local radon concentration at any level of a multi-storey building can be modelled as a monotonically-decreasing function of the distance from the ground, augmented by a constant, not necessarily negligible, contribution from radon emanating from the walls and ceilings. While it is generally assumed that radon levels in the upper levels of a multi-storey home will be intrinsically lower than at ground level, this is not always the case, with radon exhalation from the materials from which the house is constructed, together with ventilation arrangements, significantly affecting the radon concentration distribution within the dwelling.

While studies on radon level variability in the individual units in apartment blocks have been reported [6, 7], the situation in low-rise, two-storey, dwellings appears not to have been addressed rigorously. Early studies by the UK National Radiological Protection Board (NRPB), since 2005 the Radiation Protection Department of the Health Protection Agency (RPD-HPA), indicated that mean first-floor radon concentrations were of the order of 69% of the corresponding ground-floor concentrations and that this ratio was maintained throughout the year despite significant seasonal variation [1]. Subsequent detailed multivariate analysis of this and additional data [8] confirmed the influence of floor-level of the rooms investigated. Similar behaviour was reported from a study of radon concentrations in first and second floor apartment dwellings in two regions of Northern Italy, with overall radon concentrations equivalent to between 0.64 and 0.83 of the corresponding ground-floor figures being found [7]. Comparison of radon concentrations in ground-floors and cellars in 83 Belgian homes showed a logarithmic linear correlation coefficient of +0.68, and found a corresponding correlation coefficient of +0.76 between first-floor and ground-floor radon concentrations in 55 homes [9]. Additional data from other Belgian studies was compatible with these relationships. Finally, in a study of over 5,000 Italian dwellings [10], distributed across all regions of the country, the mean radon level was shown to decrease monotonically from basement to upper storeys, although it

should be noted that these results were essentially uncorrelated, with detectors placed on only one storey of any particular building.

In contrast to this accumulated evidence in favour of systematic variation in radon concentration with height above the ground, radon concentrations in basements in homes in Fort Collins, Colorado, were reported to be about two times higher than ground-floor concentrations [11], but there was no apparent reduction in concentration levels above the ground floor. Similar results were reported from both the New Jersey-New York area [12] and from Quebec [13].

To investigate these issues further, data collected from a set of homes in Northamptonshire, UK, was analysed in detail, in order to study the variation in bedroom and living-room radon and to attempt to identify causative factors. Northamptonshire, a predominantly rural county in the English Midlands, with a number of medium-sized conurbations, is situated largely on Jurassic bedrock (around 200 million years old) [14]. 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 [15]. In addition, Northamptonshire soils are relatively permeable, permitting significant soil-gas movement. The County has an estimated average of 6.3% of homes above the UK domestic Action Level of $200 \text{ Bq}\cdot\text{m}^{-3}$ [16] and has consequently been declared a radon Affected Area by NRPB [17].

2 Method

A set of 34 unremediated domestic dwellings of mixed age and type, situated on a common geology (Northampton Sand [14]) in a high radon area around Northampton, UK, and known to have moderately high radon levels, were monitored using Track-Etch detectors during the period April 2002 to May 2003 [18, 19]. Of these, 20 were monitored for four consecutive 3-month periods and simultaneously for twelve consecutive 1-month periods; the remainder for periods of nine months (four properties), six months (six properties) or three months (four properties). In addition, 1-week measurements were made in all homes at approximately 1-month intervals, using co-located sets of Track-Etch, Activated Charcoal and Electret detectors exposed simultaneously. In three homes, further comparisons were made with continuous monitoring techniques over periods of up to six months. No structural changes were undertaken in any of the homes under investigation during the monitoring period.

3 Results

3.1 Individual Radon Measurements

Detailed results of the distribution of individual radon measurements obtained from the different detector technologies have been reported elsewhere [18]. Overall, the results were found to follow an approximate lognormal relationship.

3.2 Upstairs Downstairs Ratio

Using the paired data sets for upstairs and downstairs radon concentration resulting from each exposure, ratios of bedroom to living-room radon concentrations were calculated for each exposure. Figure 1 shows the distribution

of results obtained from 28-day Track-Etch detector exposures, together with the best-fit Gaussian distribution matching the data. Similar results obtained were obtained from the other technologies investigated.

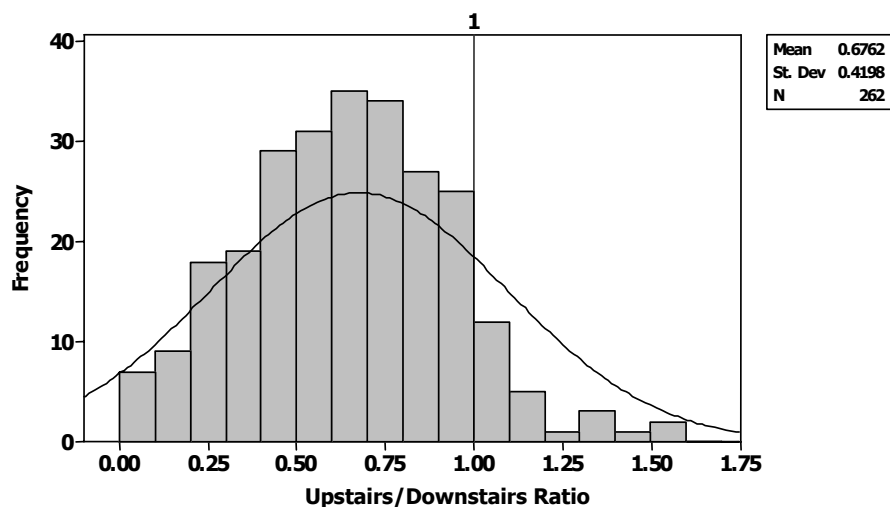


Figure 1: Distribution of Bedroom/Living-Room radon concentration ratio for all 28-day Track-Etch exposures.

4 Analysis of Results

4.1 Correlation between Living Room and Bedroom

Based on these analyses, Table 1 summarises the statistics underlying the various sets of results. With the exception of the 7-day electret exposures, all exposure scenarios result in mean upstairs/downstairs ratios in the region of 0.6 - 0.7, with standard deviations in the range 0.3 - 0.5. Results from electret exposures are significantly anomalous, with a mean of 0.97 and a standard deviation of 2.1.

Table 1: Upstairs/Downstairs Ratio - Statistical Analysis of Results

Exposure Scenario	No. of Samples	Mean	Standard Deviation
90-day Track-Etch	91	0.6192	0.2876
28-day Track-Etch	262	0.6762	0.4198
7-day Track-Etch	190	0.7558	0.3790
7-day Charcoal	243	0.6118	0.4722
7-day Electret	276	0.9694	2.083

Although some variability is evident, the clustering of the mean values in the range 0.6 - 0.7 is comparable with the mean of 0.66 derived by NRPB during the early studies of radon levels in the UK [1].

4.2 Influence of House Type

Figure 2 plots pairwise-correlated bedroom and living-room radon concentration results from 28-day Track-Etch exposures in all properties, the results being presented on log-log axes for convenience of viewing. Table 2 summarises the regression analysis outcomes for the various exposure scenarios. In this representation, the regression slope quantifies the power relationship between the

bedroom radon concentration and the living-room concentration, while the intercept transforms to a multiplying factor.

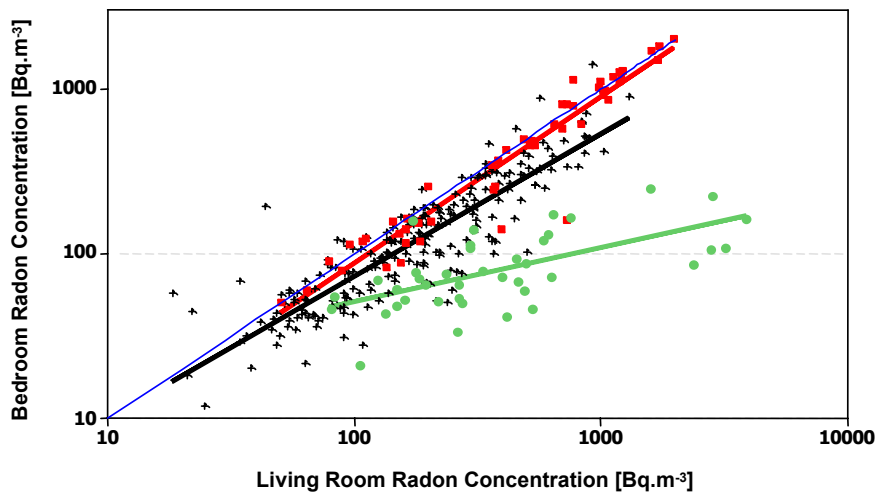


Figure 2: Mean bedroom radon concentration vs. mean living-room radon concentration for all 28-day Track-Etch exposures.
Crosses: 2-storey houses Squares: bungalows
Circles: 2-storey houses 7, 10, 22,33

Table 2: Influence of House Type on Regression Parameters for Bedroom/Living Room Radon Concentrations

Period	Type	House Type	Log-Log Axes Regression	Slope	Intercept
90-day	Track-Etch	Bungalow	$\log(y) = -0.1306 + 1.044\log(x)$	+ 1.044	-0.1306
28-day	Track-Etch	Bungalow	$\log(y) = -0.0901 + 1.015\log(x)$	+ 1.105	-0.0901
7-day	Track-Etch	Bungalow	$\log(y) = -0.2706 + 1.074\log(x)$	+ 1.074	-0.2706
7-day	Charcoal	Bungalow	$\log(y) = -0.1095 + 1.036\log(x)$	+ 1.036	-0.1095
7-day	Electret	Bungalow	$\log(y) = -0.0972 + 1.032\log(x)$	+ 1.032	-0.0972
90-day	Track-Etch	Multi-storey	$\log(y) = 0.1041 + 0.8705\log(x)$	+ 0.8705	0.1041
28-day	Track-Etch	Multi-storey	$\log(y) = 0.1237 + 0.8671\log(x)$	+ 0.8671	0.1237
7-day	Track-Etch	Multi-storey	$\log(y) = 0.1521 + 0.8704\log(x)$	+ 0.8704	0.1521
7-day	Charcoal	Multi-storey	$\log(y) = -0.04314 + 0.9082\log(x)$	+ 0.9082	-0.04314
7-day	Electret	Multi-storey	$\log(y) = 0.8587 + 0.5905\log(x)$	+ 0.5905	0.8587
90-day	Track-Etch	7, 10, 22, 33	$\log(y) = 0.6067 + 0.4787\log(x)$	+ 0.4787	0.6067
28-day	Track-Etch	7, 10, 22, 33	$\log(y) = 1.049 + 0.3284\log(x)$	+ 0.3284	1.049
7-day	Track-Etch	7, 10, 22, 33	$\log(y) = 0.7763 + 0.5415\log(x)$	+ 0.5415	0.7763
7-day	Charcoal	7, 10, 22, 33	$\log(y) = -0.8550 + 1.016\log(x)$	+ 1.016	-0.8550
7-day	Electret	7, 10, 22, 33	$\log(y) = 1.301 + 0.3105\log(x)$	+ 0.3105	1.301

Overall, and generally independently of exposure scenario, the results reflect the presence of three distinct classes of dwelling:

- Bungalows, single-storey dwellings in which both living-room and bedroom are situated on the ground floor, with regression slopes in the range 1.0 - 1.1, the bedroom and living room radon concentrations being essentially equal.
- Two-storey houses, in which the living-room and bedroom are generally on the lower and upper storeys respectively, with regression slopes in the range 0.8 - 0.9 and in which the bedroom radon concentration is typically 0.6 - 0.7 of the living-room concentration.

- A small anomalous set of four houses, with regression slopes generally in the range 0.3 - 0.5 (charcoal, $m = 1.0$) and in which the bedroom radon concentration is significantly lower than the living-room concentration. This group includes two of the stone-built dwellings.

4.3 Influence of Construction Materials

Although the influence of building materials on indoor radon concentrations is recognised [20], little data has been identified as quantitatively representing the structural contribution to domestic radon in the UK. Gunby et al. [8] noted the changing fashions in building materials in the UK, particularly the decline in the use of stone from 33% of construction in the 19th century and earlier to just 2% in the post-1976 era. Over the same period, brick construction rose from 58% to 84%, while the use of concrete fluctuated between 0% and 11%, reaching a peak in the "prefab" era of the post-World War 2 period. Similar changes can be observed in materials used for flooring, with concrete, either solid or suspended, replacing suspended wooden flooring in new construction, particularly since the middle of the last century, and in the increased use of plasterboard for internal partitioning. Recent studies have identified both concrete [21] and gypsum-based plasterboard [22] as significant radon-emitters.

Applying multiple regression on a set of seventeen parameters potentially influencing indoor radon concentration, Gunby et al. [8] showed that the nature of the building materials used for both the walls and the floors in the rooms in which radon measurements were made were significant. Using brick walls as a basis for comparison, concrete walls increase the structural radon contribution by 20% and stone walls by 72%; in contrast, wooden walls reduce the structural radon to 57% of the value associated with brick walls. Although this work acknowledged that building materials may account for 20 - 50% of the radon in an average UK dwelling, it concluded that interference to this contribution from structural factors also affecting soil-radon ingress precluded its reliable isolation.

A figure of $20 \text{ Bq}\cdot\text{m}^{-3}$ has recently been suggested [23] for the contribution from building materials to indoor radon concentration in a typical Belgian house of clay-brick/mortar/concrete/wood construction. Porstendorfer [24] reported ordinary building materials to be the dominant radon sources in German dwellings with indoor radon concentrations up to about $50 \text{ Bq}\cdot\text{m}^{-3}$, while a more recent report [25] suggests that the figure for homes in Germany falls within the range $10 - 70 \text{ Bq}\cdot\text{m}^{-3}$. These figures are not incompatible with the lowest figures found here, indicating that even in geographical areas of negligible radon potential, houses constructed from "inappropriate" materials can contain significant radon concentrations.

Of the 34 houses in the present study, 4 were constructed of stone (3 with wooden floors), the remainder being of either brick or brick/ block construction. Among the brick and brick/block categories, 12 houses (40.0%) had wooden floors, 13 (43.3%) concrete floors, the remainder (16.7%) having mixed wood/concrete flooring. Figure 3 shows the variation of mean bedroom radon concentrations with mean living room levels for 28-day Track-Etch exposures in two-storey houses, indicating the difference in behaviours exhibited by houses with concrete and wooden floors, the latter in conjunction with stone and brick walls. Again, comparable results were obtained for other detector types and exposure regimes.

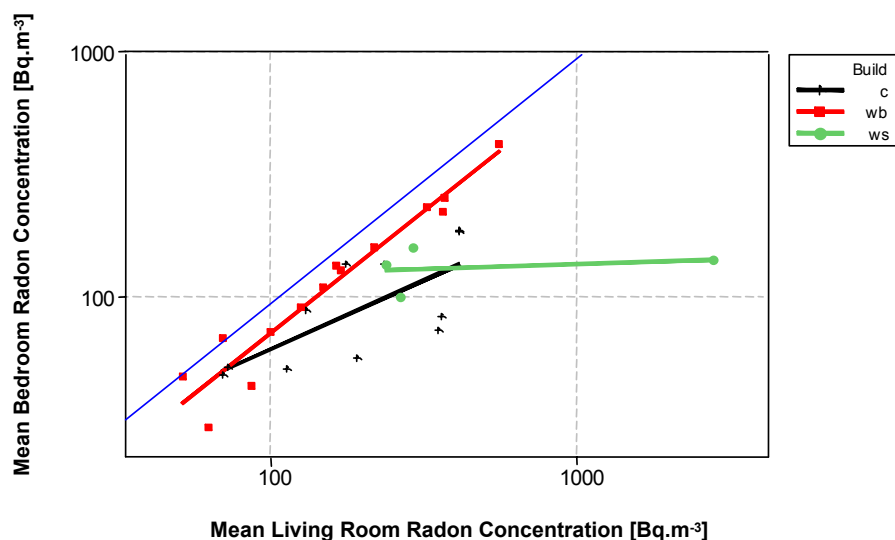


Figure 3: Mean bedroom radon concentration vs. mean living-room radon concentration for all multi-storey 28-day Track-Etch exposures.
wb: wood floor, brick walls c: concrete floor
ws: wood floor, stone walls

Table 3 summarises the regression parameters (log-log axes) of the relationships between mean bedroom and living-room radon concentrations for the principal combinations of wall and floor materials found in two-storey houses. These results are quantitatively comparable with those of Zhu et al. [9], derived from a study of 55 homes in southern Belgium, shown in the final row of the table. For homes with brick walls and wooden floors, the relationship is essentially linear, the slope of the log-log relationship being not significantly different from unity. In all other cases, the less than unity slope implies a sub-linear power relationship between ground-floor and first floor radon.

Table 3: Influence of Floor and Wall Materials on Regression Parameters for Bedroom/Living Room Radon Concentrations

Floor (wall)	Exposure/Type	Log-Log Axes Regression			Slope	Intercept
Concrete	90-day Track-Etch	$\log(y) =$	0.7385	+	0.5148	0.7385
			0.5148 $\log(x)$			
Concrete	28-day Track-Etch	$\log(y) =$	0.6838	+	0.5614	0.6838
			0.5614 $\log(x)$			
Concrete	7-day Charcoal	$\log(y) =$	0.2514	+	0.6971	0.2514
			0.6975 $\log(x)$			
Wood (stone)	90-day Track-Etch	$\log(y) =$	1.800	+	0.1186	1.800
			0.1186 $\log(x)$			
Wood (stone)	28-day Track-Etch	$\log(y) =$	2.023	+	0.0407	2.023
			0.0407 $\log(x)$			
Wood (stone)	7-day Charcoal	$\log(y) =$	1.010	+	0.4753	1.010
			0.4753 $\log(x)$			
Wood (brick)	90-day Track-Etch	$\log(y) =$	-0.1185	+	0.9930	-0.1185
			0.9930 $\log(x)$			
Wood (brick)	28-day Track-Etch	$\log(y) =$	-0.1135	+	0.9969	-0.1135
			0.9969 $\log(x)$			
Wood (brick)	7-day Charcoal	$\log(y) =$	-0.2985	+	1.065	-0.2985
			1.065 $\log(x)$			
[Belgium] [9]	4-day Charcoal	$\log(y) =$	1.192	+	0.667	1.192
			0.667 $\log(x)$			

4.4 Variation Between Houses

Figure 4 plots the variability in Upstairs/Downstairs ratio for each property in the study, using colour/shading to identify three relatively well-defined groups of properties.

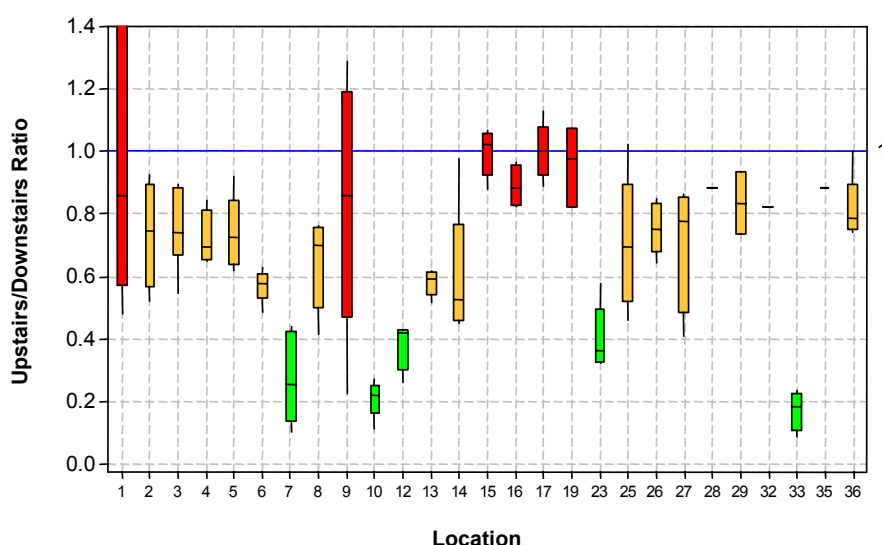


Figure 4: Variability in Upstairs/Downstairs ratio for 28-day measurements in each property

Yellow/light: two-storey
 anomalous two-storey
 Red/dark: single-storey (bungalow)
 Green/medium:

Although Figure 4 confirms that the majority of houses studied have u/d ratios of around 0.7, two anomalous groups can be identified. Firstly, it is apparent that a small set of five houses have characteristic very low bedroom radon levels when compared to living room levels. Secondly, four of those houses with boxes crossing $y = 1.0$ are bungalows (100% of single-storey homes in the study), suggesting that differences between bedroom and living room radon levels may be due to elevation above ground level as opposed to occupancy factors. Finally, as the box-plot indicates, the distributions of ratios about the mean do not follow a set pattern, with some left-skewed, some right-skewed and others symmetric.

4.5 Variation with Radon Level

Figure 5 plots bedroom radon levels as a function of living room levels on logarithmic axes, with house type as parameter.

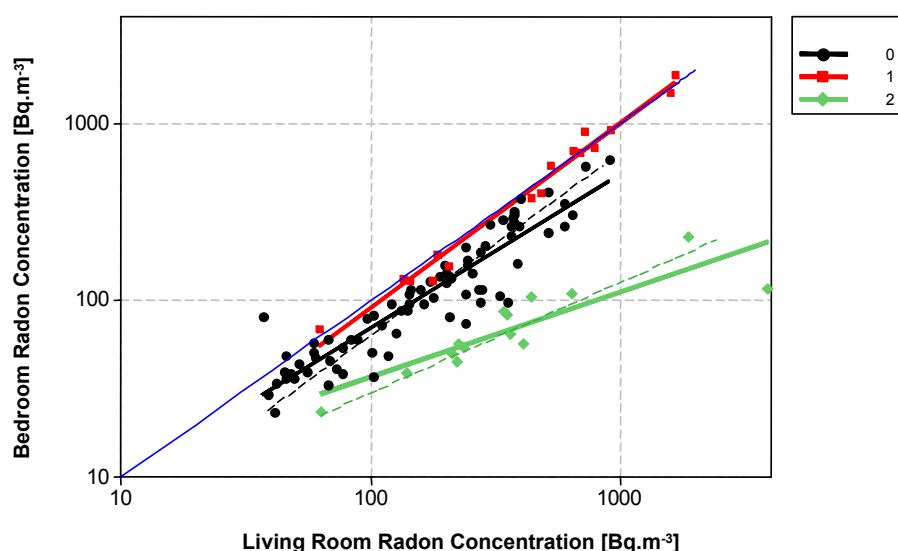


Figure 5: Variation of bedroom radon levels with living room levels with house type as parameter.

The plot enables three classes of home to be distinguished:

- Bungalows [1], exhibit bedroom radon levels essentially identical to living room levels, with a slope of unity in this representation.
- Two-storey homes [0] in which bedroom radon concentration is typically less than the living-room concentration. The slope of the relationship is close to, but slightly less than, unity, and is offset slightly below the bungalow plot.
- A small subset of two-storey homes [2] in which bedroom levels increase at a much lower rate than living room levels. It is possible that some behavioural or structural characteristic differentiates these locations from the other multi-storey homes [0].

These results are consistent with a model whereby radon emanating from building materials plays a significant role, discussed elsewhere in this Conference [26].

Due to the small number of data points, analysis by house parameters does not produce a great deal in the way of results. There are a few hints that certain parameters such as building materials, postcode and temperature may influence the upstairs/downstairs ratio, however there is insufficient independent information to be able to model these parameters with sufficient numbers of degrees of freedom.

5 Conclusions

Overall, the distributions of upstairs/downstairs ratio are generally skewed, with almost all houses exhibiting values <1.0. Mean upstairs/downstairs ratios are in the range 0.6 - 0.75, and are generally significantly different from 1.0. The right-hand tails of the distributions at least partially constrained at unity, although properties have been identified in which the mean bedroom radon concentration is greater than the living-room value.

In single-storey homes, the upstairs/downstairs ratio is distributed around a value of 1.0. This distribution may be Gaussian, but the sample is too small to verify this. The observed distributions are almost certainly not representative of the housing stock as a whole, as the 34 houses investigated were selected to meet particular criteria [18].

Results from certain combinations of detectors and exposure periods provide evidence of a secondary peak around 0.2-0.3, suggesting that the bedrooms in question are well insulated from the associated living rooms.

Upstairs/downstairs ratios are especially sensitive to detector response offsets, and there will be an inherent tendency for lower recorded levels to return higher ratios. This is especially apparent for the 7-day charcoal detectors used during the study, for which radon concentrations less than $20 \text{ Bq}\cdot\text{m}^{-3}$ are reported as $20 \text{ Bq}\cdot\text{m}^{-3}$.

6 Acknowledgements

We are grateful to those members of staff at the University of Northampton and at Northampton General Hospital who participated in the study reported here and who agreed to have their houses tested over an extended period. The work reported here forms part of a study supported by the UK Department of Environment, Food and Rural Affairs (DEFRA) under Contract EPG 1/4/72/RW 8/17/64.

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