Radon Remediation of a Two-Storey UK Dwelling by Active Sub-Slab Depressurization: Observations on Hourly Radon Concentration Variations

A.R. Denman*[a], C.C. Allison[b], C.J. Groves-Kirkby[b], P.S. Phillips[c], R. Tornberg[d]

[a] School of Health, University of Northampton, Northampton NN2 7AL, UK

[b] Medical Physics Department, Northampton General Hospital, Northampton NN1 5BD, UK

[c] School of Applied Sciences, University of Northampton, Northampton NN2 7AL, UK

[d] Radon Centres Ltd., Moulton, Northampton NN3 7TG, UK

Abstract. Radon concentration levels in a two-storey detached single-family dwelling in Northamptonshire, UK, were monitored at hourly intervals throughout a 5-week period during which sub-slab depressurisation remediation measures, including an active sump system, were installed. Remediation of the property was accomplished successfully, with the mean radon levels upstairs and downstairs greatly reduced and the prominent diurnal variability in radon levels present prior to remediation almost completely removed. Following remediation, upstairs and downstairs radon concentrations were 32% and 16% of their pre-remediation values respectively. The mean downstairs radon concentration was lower than that upstairs, with pre-and post-remediation values of the upstairs/downstairs concentration ratio, $R_{U/D}$, of 0.93 and 1.76 respectively. Cross-correlation between upstairs and downstairs radon concentration time-series indicates a time-lag of the order of 1 hour or less, suggesting that diffusion of soil-derived radon from downstairs to upstairs either occurs within that time frame or forms a relatively insignificant contribution to the upstairs radon level. Cross-correlation between radon concentration time-series and the corresponding time-series for local atmospheric parameters demonstrated correlation between radon concentrations and internal/external pressure-difference prior to remediation. This correlation disappears following remediation, confirming the effectiveness of the remediation procedure in mitigating radon ingress from the ground via the stack-effect. Overall, these observations provide further evidence that radon emanation from building materials makes a not insignificant contribution to radon concentration levels within the building. Furthermore, since this component remains essentially unaffected by sub-slab depressurisation, its proportional contribution to the total radon levels in the home increases following remediation, leading to the conclusion that where remediation by sub-slab depressurisation has been effective, and also in areas of low soil-gas radon, upstairs radon levels may be dominated by radon exhalation from the walls of the dwelling.

KEYWORDS: radon; domestic; remediation; building materials.

1. Introduction

1.1 Environmental Radon Gas

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 $Bq\cdot m^{-3}$, compared to 4 $Bq\cdot m^{-3}$ in outside air [3], but levels up to 17,000 $Bq\cdot m^{-3}$ 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, and

---

[*] Presenting author, E-mail: tony.denman@northampton.ac.uk

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. 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], it is suggested that between 1,800 and 2,100 deaths annually are attributable to radon and its progeny.

1.2 Remediation against Domestic Radon

Responding to the health threat posed by radon in domestic properties, the UK Health Protection Agency (HPA) established an Action Level of 200 $\mathrm{Bq{\cdot}m^{-3}}$ for domestic properties and designated Radon Affected Areas, geographical entities where more than 1% of the housing stock is predicted to have radon concentrations in excess of the Action Level [8]. Within these areas, householders are strongly encouraged to take remediatory action. In existing homes, the methods adopted to reduce radon levels rely on two key processes, dilution and/or pressure change, achieved principally by the installation of a pressure-modifying sump, often in conjunction with an extraction fan. The preferred approach for new-build houses is by installation of a radon-proof membrane across the entire footprint of the house, with cavity trays protecting the walls [9]. In higher-risk areas, this is supplemented with natural under-floor ventilation, in the case of suspended flooring, or by construction of a passive sump below the level of the ground-floor, in the case of ground-bearing concrete flooring. In either case, if the completed house is found to have an elevated radon level, these measures can be reinforced with a mechanical fan to provide enhanced sub-slab depressurisation.

1.3 Radon in Two-Storey Dwellings

The principal contributors to indoor radon concentrations in UK dwellings are soil-gas emanating from the ground beneath the dwelling [10], and the materials from which the dwelling is constructed [11,12,13]. Further small contributions include the atmospheric background, with a mean population-weighted level of 4 $\mathrm{Bq{\cdot}m^{-3}}$ [3], household water supplies, particularly those derived from wells and boreholes [14], and domestic gas supplies [15]. Entry of radon into a dwelling from the soil-gas is influenced by a number of factors [16]. 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 [17], 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' [18]. 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 [19].

Radon emanation from constructional materials depends largely on their intrinsic radium activity [11], their bulk permeability to radon gas [20] and the barrier effects of any surface treatments such as paint and wall-coverings [21], the most significant parameters being the effective diffusion range, the effective surface area for emission [22] and the superficial structure [23]. As with soil-gas, radon concentration levels attributable to building materials can vary significantly from house to house and from area to area and, in extreme cases, has been identified as contributing up to 85% of the total radon input [24]. Unlike soil-gas radon, however, radon emanating from walls and ceilings cannot be significantly reduced by sub-slab depressurisation.

Despite considerable ongoing interest into the health effects of domestic radon, few studies have explored the distribution of radon within the single-occupancy multi-storey dwellings characteristic of Europe and North America. Kies et al. [25] reported bedroom/living room concentration ratios ($R_{U/D}$) in multi-storey houses in the Grand Duchy of Luxembourg to be lognormally distributed with an arithmetic mean of 0.59, and cited similar results from France and Belgium (original sources currently inaccessible), while a sample of 452 homes in the Netherlands showed mean $R_{U/D}$ ratio around 0.9 [24]. Early UK studies indicated a mean value for $R_{U/D}$ of the order of 0.6, this value being maintained throughout the year despite significant seasonal variation in absolute radon concentrations [4]. Subsequent detailed multivariate analysis of this and further data [26] confirmed the qualitative influence of the level above ground-floor of the rooms investigated but did not analyse the potential variability in detail. As part of our ongoing study of the factors affecting domestic radon concentrations [12,13], we recently analysed radon concentration measurements carried out in 34 homes in the Northamptonshire radon Affected Area. These studies demonstrated substantial variability in $R_{U/D}$, suggesting that a not insignificant contribution to mean annual radon concentration in UK dwellings can be attributed to sources other than soil gas, with emanation from constructional materials identified as a potential contributor. As part of this study, the opportunity was recently taken to perform detailed continuous monitoring of radon concentration levels in a house scheduled for remediation by sub-slab depressurisation, the results from which are presented here.

2. Method

2.1 Experimental Site

During a 5-week period spanning April - May 2006, access was available to a 4-bedroomed two-storey detached residential property in Brixworth, Northamptonshire. Northamptonshire, a predominantly rural county in the English Midlands, is situated largely on Jurassic bedrock (200 million years old) [27], 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 [28] and has an estimated average 6.3% of homes above the UK domestic Action Level [29].

The property is located on a housing development constructed around 1994, and therefore subject to the radon protection provisions mandated by the UK Building Regulations from 1992 onwards [9], in that its foundations incorporated a protective membrane and a sump. We recently demonstrated, however, that a significant proportion of the properties in this development exhibited elevated radon levels, indicative of failure of the radon-protective measures [30]. Post-construction radon concentrations in this particular house showed radon concentrations exceeding the Action Level of 200 $Bq \cdot m^{-3}$. The householders therefore decided to implement the final stage of remediation, namely installation of an extraction fan coupled to the sump in order to enhance the sub-slab depressurisation. In the course of this process, the original sump could not actually be located, and a new sump was constructed in accordance with UK Radon Council best practice. This installation was carried out approximately midway through the 5-week period, during which simultaneous radon concentration measurements were made on two floors at hourly intervals.

2.2 Equipment, Calibration and Data Collection

Two types of continuously operating radon monitor were available, a Radhome-P radon monitor with counting resolution typically 65 $Bq \cdot m^{-3} \cdot (count.hour^{-1})^{-1}$ over 60-minute sampling periods and an Alphaguard system with significantly higher sensitivity. The Radhome-P was located in the ground-floor living-room, while the Alphaguard was placed upstairs in the principal bedroom. Following the measurements in the house, the two detectors were operated for two weeks side-by-side in a basement room known to exhibit relatively high mean radon concentrations. This confirmed that numerical results from the two systems were in agreement to better than 0.2%. In addition to radon concentration, the Alphaguard is capable of measuring local ambient temperature, barometric pressure and relative humidity. These parameters were measured in the upstairs bedroom throughout the investigation. External temperature and barometric pressure measurements were made at the Pitsford Hall Weather Station (COL Station No. 91012), situated 10 km north of Northampton and 5 km south of the experimental site at Brixworth, and published on the station web-site [31].

3. Results and Discussion

3.1 Remediation Effectiveness

Fig. 1 reports the complete time-series of the upstairs and downstairs radon concentrations recorded/averaged over 60-minute intervals. The vertical lines define the specific day of remediation, 14th April 2006. The plots confirm qualitatively the effectiveness of the mitigation process, both upstairs and downstairs radon concentration levels being greatly reduced following installation of the pump. Time-correlation between downstairs and upstairs data series is generally good, with peaks and troughs occurring at the same epoch, although excursions in the Alphaguard (upstairs) data are generally smaller in magnitude than for the Radhome data (downstairs).

Figure 1: Radon concentration time-series:
Heavy line: Upstairs - Alphaguard: Light line: Downstairs - Radhome
Vertical lines span the date of remediation

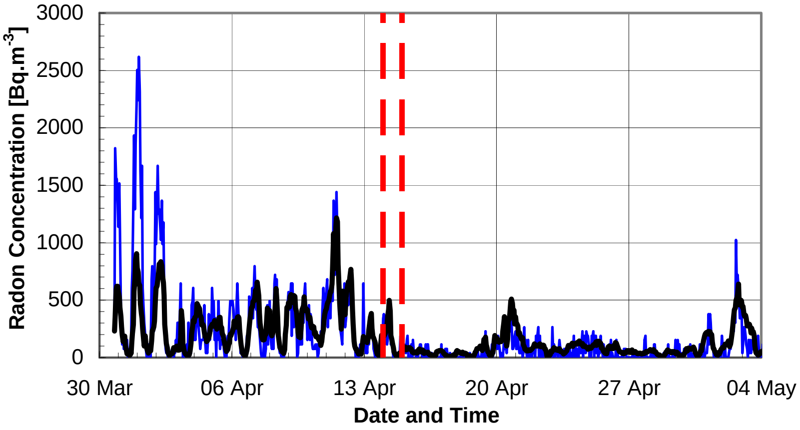
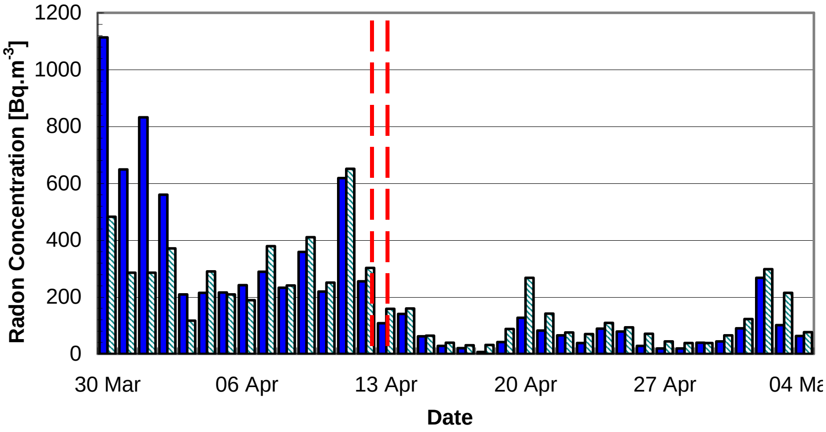


Fig. 2 compares the mean daily upstairs and downstairs radon concentrations throughout the period under study, the two vertical lines encompassing the day of mitigation, as previously, and provides clear evidence of the qualitative efficiency of the remediation process. Over the two-week period following remediation, the mean downstairs radon concentration was reduced to 18% of its pre-remediation value, the corresponding upstairs concentration being 33% of its pre-remediation value.

Figure 2: Mean daily radon concentrations
Solid bars: Downstairs (Radhome) Hatched bars: Upstairs (Alphaguard)
Vertical lines span the date of remediation



Although remediation has reduced the amount of radon entering the house from the ground, Fig. 2 shows that radon concentration levels upstairs are frequently higher than those downstairs, and that remediation has resulted in the downstairs radon levels being significantly decreased compared to those upstairs. This is demonstrated quantitatively in Table 1, which summarises the distribution of days for which the downstairs radon concentration was greater than the upstairs concentration, and vice versa, for the periods before and after the remediation. Prior to remediation, the mean ratio of upstairs to downstairs radon concentrations, $R_{U/D}$, was 0.81, somewhat higher than the range 0.6 - 0.7 typically reported for two-storey domestic dwellings in the UK [13]. Following remediation, however, the ratio increased to 1.51, substantially divergent from the normal range of values for this parameter.

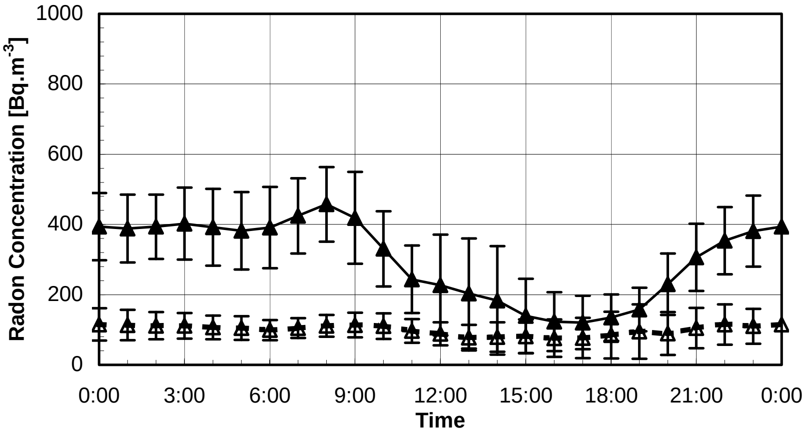
Table 1: Distribution of Relative Upstairs and Downstairs Radon Concentration Levels Before and After Remediation

	Days	Downstairs > Upstairs	%	Upstairs > Downstairs	%
Before Remediation	14	7	50.0%	7	50.0%
After Remediation	21	1	4.8%	20	95.2%

3.2 Diurnal Variation

Fig. 3 plots the averaged daily variation of upstairs radon concentrations for the periods before and after remediation, while Fig. 4 shows the corresponding behaviour downstairs. The error bars represent the 95% confidence intervals, the difference between upstairs and downstairs results reflecting the differing data resolution levels achievable with the Radhome and Alphaguard systems.

Figure 3: Pre-and post-remediation mean diurnal variation of upstairs radon concentration
Solid line/solid triangles: pre-remediation Dashed line/open triangles: post-remediation
Error bars show 95% Confidence Intervals

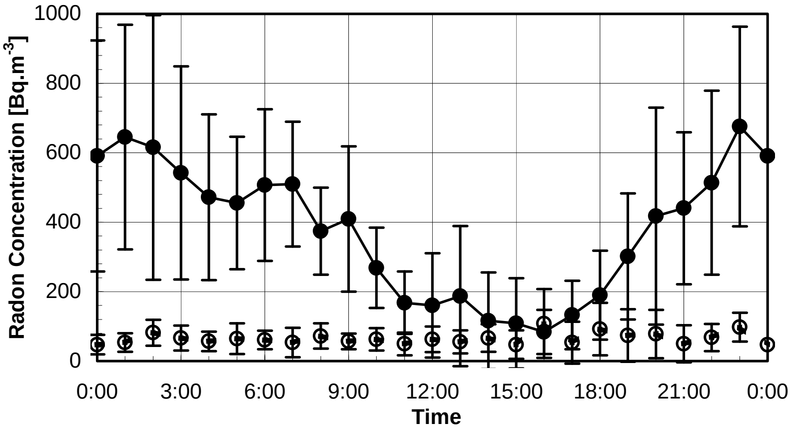


Prior to remediation, significant diurnal variability is evident upstairs and downstairs. Radon concentration upstairs exhibits a well-defined minimum around 150 Bq·m^{-3}, in late afternoon (16:00 hrs) and increases consistently until about midnight. A mean level of around 400 Bq·m^{-3}, twice the UK domestic Action Level, is then maintained from late evening until the morning, with a minor peak in the early hours of the morning (at around 02:00 hrs). Comparable behaviour is observed downstairs, although the night-time level is more variable, declining persistently from its maximum around 600 Bq·m^{-3} (three times the Action Level) from midnight onwards, the daytime minimum being around 100 Bq·m^{-3}. Following remediation, diurnal variation effectively disappears throughout the dwelling, with mean upstairs and downstairs values of around 100 Bq·m^{-3} and 65 Bq·m^{-3} respectively. As indicated in Table 2, the post-remediation downstairs radon concentration is 18% of the pre-remediation level, the corresponding upstairs ratio being nearly twice this, 33%, indicating that the upstairs reduction is not simply a scaling of the downstairs behaviour.

Table 2: Remediation Effectiveness - Mean Daily Upstairs and Downstairs Radon Concentrations (Bq.m^{-3}) and $R_{U/D}$ Ratio Before and After Remediation, with After/Before Ratio ($R_{A/B}$)

	Before Remediation [Bq·m^{-3}]	After Remediation [Bq·m^{-3}]	$R_{A/B}$
Upstairs	299.06(95% C.I. 45.58)	99.00(95% C.I. 5.54)	0.331
Downstairs	370.14.17(95% C.I. 75.98)	65.71(95% C.I. 6.47)	0.178
$R_{U/D}$	0.81	1.51	
Long-term Weighted Mean	331.05	84.02	

Figure 4: Pre-and post-remediation mean diurnal variation of downstairs radon concentration
Solid line/solid triangles: pre-remediation Dashed line/open triangles: post-remediation
Error bars show 95% Confidence Intervals



3.3 Correlations Between Upstairs and Downstairs

Upstairs and downstairs radon concentration levels in the pre-remediation period exhibit significant periodicity, with indications of temporal correlation, reflected qualitatively as a relatively well-defined lag period between the radon levels downstairs and upstairs. This is believed to be due principally to the effects of radon diffusing around the house, in particular from the ground to the upstairs. Fig. 5 analyses this more formally, showing the outcome of mathematical cross-correlation between the upstairs and downstairs radon concentration time-series presented in Fig. 1. The plot indicates a near-perfect classical cross-correlation pattern, with a maximum correlation coefficient of the order of 0.8 occurring at a time-lag of approximately 1 hour, indicative of the time taken for radon entering the dwelling from the ground to percolate to the upper storey. Secondary maxima are offset approximately ±24 hours, implying a cyclical trend with approximately daily periodicity.

Figure 5: Cross correlation between downstairs and upstairs radon time-series for full study period.

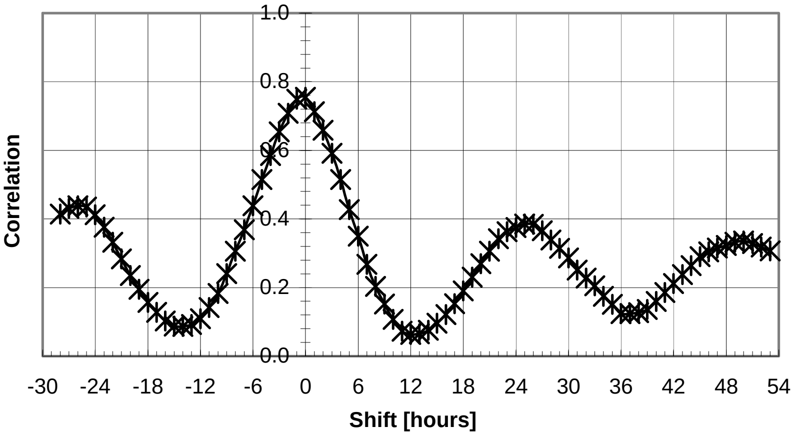
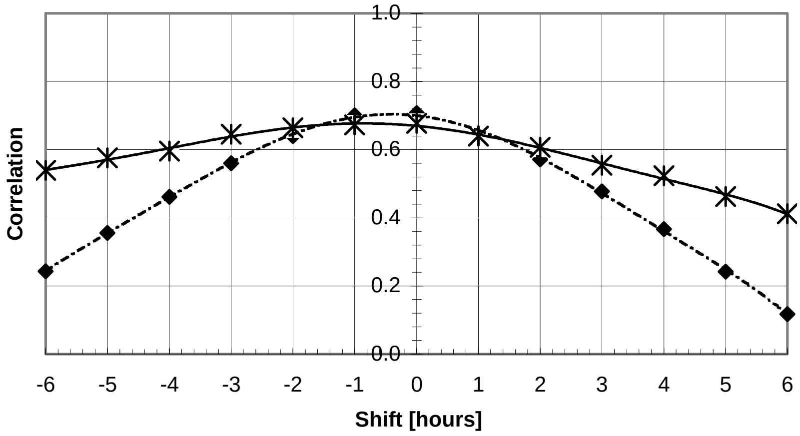


Fig. 6 details the cross-correlation maximum for the periods prior to and following remediation. The 1-hour resolution imposed by the sampling/integration period of the radon-monitoring equipment hampers precise determination of the location of the correlation maximum. However, both plots indicate a lag period of around an hour, the post-remediation lag being slightly greater than that in the pre-remediation period. Moreover, the reduced variation in post-remediation correlation coefficient over the timescale under consideration confirms the reduced diurnal variability observed experimentally. In the absence of any internal reconfiguration to the building, remediation would not be expected to influence this time-lag period; the figure confirms this.

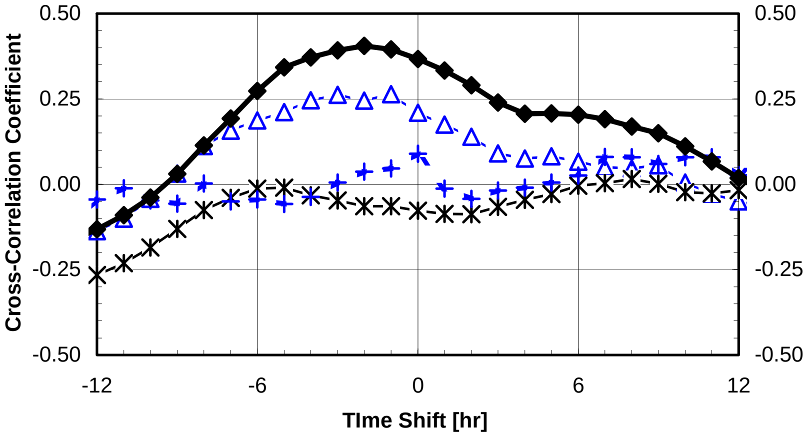
Figure 6: Cross-correlation between upstairs and downstairs radon time-series
Dashed line/diamonds: pre-remediation period
Solid line/crosses: post-remediation period



3.4 Correlation with Environmental Conditions

Since pressure difference between the interior and exterior of a house is widely acknowledged as the principal driving force for radon entering by soil-gas advection, the difference in time-synchronised internal and external barometric pressure was explored as a potential indicator of the pressure difference driving radon ingress. Fig. 7 shows the results of cross-correlation between hourly upstairs and downstairs radon concentrations and the corresponding hourly pressure differential. Note particularly: (i) the relative lack of correlation between radon and pressure differential following remediation; (ii) the marked positive correlation between both upstairs and downstairs pre-remediation radon concentrations and pressure differential, peaking at a time-shift of around 2 hours, suggesting that radon levels within the dwelling respond to changes in pressure differential on this time-scale.

Figure 7: Cross-correlation between radon and pressure-difference time-series:
Diamonds: Upstairs, pre-remediation. Triangles: Downstairs, pre-remediation
Stars: Upstairs, post-remediation Crosses: Downstairs, post-remediation



4. Discussion

4.1 Remediation Effectiveness

The observation that upstairs radon concentrations are consistently higher than those downstairs following remediation raises issues relating to the effectiveness of current processes and procedures for remediation. While it is apparent that radon ingress from the ground has been effectively inhibited by sub-slab depressurisation, the observation of consistently higher levels upstairs than downstairs requires the presence of an alternative source of radon not susceptible to the remediation process. Recent analysis of upstairs/downstairs radon concentration ratios ($R_{U/D}$) in a series of 34 homes in Northamptonshire demonstrated significant and consistent differences between single-storey ($R_{U/D}$ = 1) and two-storey ($R_{U/D}$ = 0.67) homes, [12,], suggesting that the total indoor radon concentration within a dwelling could be represented by two principal components [30], radon entering the house entrained in the soil-gas and radon generated by the building materials of the house.

Although building materials can contribute a significant fraction of the overall radon level [12], the sub-slab depressurisation and impermeable barrier mitigation approaches intrinsically only attenuate radon originating from the ground [32]. This is believed to be responsible for the anomalous behaviour observed in the present case. In addition, the effective reduction of ground-floor radon concentrations following remediation, coupled with consistently higher upstairs radon concentrations, implies that if radon liberated from the walls is the dominant contributor to total radon following successful remediation by sub-slab depressurisation, than more radon is being liberated from the walls upstairs than from those downstairs. The house under investigation here contains an integrated garage, physically insulated from the remainder of the dwelling. With a correspondingly larger surface floor area and more, and generally smaller, rooms upstairs than downstairs, the total internal wall area upstairs is greater than that downstairs, providing a larger surface area from which the radon can be emitted, leading to elevated radon concentrations in the upstairs of the house.

4.2 Diurnal Variability

The observed diurnal periodicity in pre-remediation radon concentrations is as expected. Radon levels in dwellings subject to soil-gas advection in a temperate climate are at their highest during the night, due to the generally decreased ventilation and the increased internal/external temperature differential. As this temperature differential increases, the corresponding pressure differential increases proportionally, resulting in correspondingly increased flow of radon into the house from the sub-soil. The opposite effect occurs during the day. The specific times of minimum and maximum levels depend on the domestic routine of the residents, for example when they go to work, when windows and doors are opened and at what time they go to bed. In contrast, however, a dwelling in which soil-gas radon advection has been suppressed, either by careful design and construction or by post-construction remediation, would not be expected to exhibit this diurnal variability, as there would be no significant source of radon capable of responding to 'stack-effect' and related pressure differences; this appears to be the case in the present situation.

4.3 Radon Sources and their Contribution to Total Exposure

The relatively strong (0.3 - 0.4) correlation between radon concentration and pressure difference in both storeys of the dwelling in the pre-remediation period confirms the role of soil-gas advection in defining internal radon concentrations during this period, while the observed lag (approx. 2 hours) is in agreement with observations in a single-storey Finnish house [33]. The effective disappearance of this correlation following remediation confirms the effectiveness of the process in eliminating soil-gas advection as a radon ingress mechanism, which in turn indicates that other factors, a prime candidate being radon emission from construction materials, are contributing to the overall radon environment.

Although the influence of building materials on indoor radon concentrations is recognised [34], little data has been identified as quantitatively representing the structural contribution to domestic radon in the UK. Applying multiple regression on a set of seventeen parameters potentially influencing indoor radon concentration, Gunby et al. [26] showed that building materials may be responsible for 20 – 50% of the radon in an average UK dwelling, but concluded that interference to this contribution from structural factors also affecting soil-radon ingress precluded its reliable isolation. A level of 20 $Bq\cdot m^{-3}$ has been suggested [35] as the contribution from building materials to indoor radon concentration in a typical Belgian house of clay-brick/mortar/concrete/wood construction. Ordinary building materials have been reported [36] to be the dominant radon sources in German dwellings having indoor radon concentrations up to about 50 $Bq\cdot m^{-3}$, a more recent report [37] suggesting that the figure for homes in Germany falls within the range 10 - 70 $Bq\cdot m^{-3}$. In the Netherlands, radon exhalation from building materials has been identified as generating 70% of the 30 $Bq\cdot m^{-3}$ national average radon concentration, with just 15% originating from the soil [24]. Radon concentrations in the range 20 to 40 $Bq \cdot m^{-3}$, equivalent to between 0.64 and 0.83 of the corresponding ground-floor figures, have been reported in first and second floor apartment dwellings in two regions of Northern Italy [23]. Our own studies in Northamptonshire [30] suggest that a contribution to the total radon concentration in the range 20 - 50 $Bq \cdot m^{-3}$ might be expected from the materials typical of UK domestic construction.

5. Conclusions

Radon concentration levels in a two-storey detached single-family dwelling in Northamptonshire, UK, were monitored throughout a 5-week period, midway through which sub-slab depressurisation remediation measures were installed. Remediation was successful, with upstairs and downstairs radon concentrations reduced to 33% and 18% of their pre-remediation levels respectively. Following remediation, the mean downstairs radon concentration was lower than that upstairs, with pre-and post-remediation values of the upstairs/downstairs concentration ratio, $R_{U/D}$, of 0.81 and 1.51 respectively. Although the achieved reduction of the downstairs radon concentration to 18% of its pre-remediation level confirms that radon ingress into the dwelling by advection from the ground has been effectively inhibited by sub-slab depressurisation, the presence of residual radon both downstairs and, more importantly, at a higher level upstairs, indicates that other processes contribute to the overall radon concentration levels, supporting the suggestion that radon emanating from the structure of the house contributes significantly to the overall exposure. Further support for this hypothesis is offered by the well-defined cross-correlation between both upstairs and downstairs radon concentration time-series and internal/external pressure difference for the pre-remediation period, confirming the dependence. Following remediation, this correlation is absent, demonstrating that radon and barometric pressure difference are no longer interdependent. Cross correlation between upstairs and downstairs radon concentration time-series indicates a time-lag of the order of 1 hour or less, suggesting that diffusion of soil-derived radon from downstairs to upstairs either occurs within that time frame or forms a relatively insignificant contribution to the upstairs radon level. In the absence of any internal reconfiguration to the building, remediation would not be expected to influence this time-lag period, the correlation data confirming that this is the case.

These observations provide further evidence that domestic radon concentrations are not necessarily determined solely by soil-gas advection, and corroborate the suggestion that upstairs radon levels, in particular, may dominated by radon exhalation from the walls of the dwelling. If this is true, a number of health implications arise. Firstly, sub-slab depressurisation on its own can never reduce domestic radon concentrations below a baseline level defined by emanation from the structure of the building itself. Secondly, since the protocol for calculating mean annual radon exposure in the UK assumes higher occupancy upstairs (55%) than downstairs (45%), it may be necessary to consider introduction of enhanced ventilation and/or the application of anti-radon barriers to the walls, and possibly the ceilings, in order to reduce internal radon concentrations to acceptable levels, especially upstairs.

6. References

[1] NEZNAL, M. et al. Short-term temporal variations of soil gas radon concentration and comparison of measurement techniques. Rad. Prot. Dosim. 108 (2004) 55.

[2] WATSON, S. et al. Ionising radiation exposure of the UK population: 2005 review. HPA-RPD Report RPD-001. Didcot: Health Protection Agency (2005).

[3] WRIXON, A. et al. Natural radiation exposure in UK dwellings. National Radiological Protection Board Report R190. Didcot: NRPB (1988).

[4] NATIONAL RADIOLOGICAL PROTECTION BOARD. High radon houses found in Cornwall. Environmental Radon Newsletter, No. 40 (2004).

[5] DARBY, S et al. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. Brit. Med. J. 330 (2005) 223.

[6] DARBY, S. et al. Radon – a likely carcinogen at all exposures. Ann. Oncology 12 (2001) 1341.

[7] DEPARTMENT OF HEALTH. Dataset HSQ14DT2: Deaths, 2001 Registrations: deaths by age, sex and underlying cause. http://www.statistics.gov.uk. 3rd March 2005

[8] O'RIORDAN, M. Human exposure to radon in homes: recommendations for the practical application of the Board's statement. Docs. NRPB 1 (1990) 17.

[9] SCIVYER, C. Radon: guidance on protective measures for new buildings. Garston: BRE Press (2007).
[10] ÅKERBLOM, G., ANDERSSON, P., CLAVENSJO, B. Soil gas radon - a source for indoor radon daughters. Rad. Prot. Dosim. 7 (1984) 49.
[11] BOSSEW, P. The radon emanation power of building materials, soils and rocks. Appl. Rad. Isotop. 59 (2003) 389.
[12] DENMAN, A. et al. Factors influencing upstairs and downstairs radon levels in two-storey dwellings. In: 2nd European I.R.P.A. Congress on Radiation Protection, Paris, France (2006).
[13] DENMAN, A. et al. Health implications of radon distribution in living rooms and bedrooms in UK dwellings - a case study in Northamptonshire. Environ. Internat. 33 (2007) 999.
[14] KENDALL, G. Controls on radioactivity in water supplies in England and Wales, with especial reference to radon. J. Radiol. Prot. 24 (2004) 409.
[15] DIXON, D. Radon exposures from the use of natural gas in buildings. Rad. Prot. Dosim. 97 (2001) 259.
[16] ARVELA, H., WINQVIST, K. A model for indoor radon variations. Envir. Internat. 15 (1989) 1.
[17] SINGH, K. et al. Variation of radon (222Rn) progeny concentrations in outdoor air as a function of time, temperature and relative humidity. Rad. Meas. 39 (2005) 213.
[18] EATON, R., SCOTT, A. Understanding radon transport into houses. Rad. Prot. Dosim. 7 (1984) 251.
[19] MARLEY, F. Investigation of the influences of atmospheric conditions on the variability of radon and radon progeny in buildings. Atmos. Environ. 35 (2001) 5347.
[20] KELLER, G., HOFFMANN, B., FEIGENSPAN,, T Radon permeability and radon exhalation of building materials. Sci. Tot. Environ. 272 (2001) 85.
[21] HO, T. Radon Survey in eleven newly developed estates in Hong Kong. Hong Kong Papers in Design and Development 1 (1998) 57.
[22] ABU-JARED, F., FREMLIN, J. BULL, R. A study of radon emitted from building materials using plastic a-track detectors. Phys. Med. Biol. 25 (1980) 683.
[23] CARRERA, G. at al. Natural radioactivity and radon exhalation in stony materials. J. Environ. Radioact. 34 (1997) 149.
[24] STOOP, P. et al. Results of the second Dutch national survey on radon in dwellings. RIVM 610058006. Bilthoven, NL: Rijksinstituut voor Volksgezondheid en Mileu (1998).
[25] KIES, A. et al. Radon survey in the Grand-Duchy of Luxembourg - indoor measurements related to house features, soil, geology and environment. Environ. Internat. 22 (1996) S80.
[26] GUNBY, J.A. et al. Factors affecting indoor radon concentrations in the United Kingdom. Health Phys. 64 (1993) 2.
[27] HAINS, B., HORTON, A. British Regional Geology - Central England. London: HMSO (1969).
[28] MILES, J., GREEN, B., LOMAS, P. Radon affected areas: Derbyshire, Northamptonshire and Somerset. Docs. NRPB 3 (1992) 17.
[29] GREEN, B. et al. Radon Atlas of England and Wales. NRPB Report W26, Didcot: NRPB (2002).
[30] GROVES-KIRKBY, C. et al. Radon mitigation in domestic properties and its health implications- a comparison between during-construction and post-construction radon reduction. Envir. Internat. 32 (2005) 435.
[31] PITSFORD HALL WEATHER STATION; www.Brixworth.demon.co.uk (accessed Nov 2007)
[32] NAISMITH, S., MILES, J., SCIVYER, C. The influence of house characteristics on the effectiveness of radon remedial measures. Health Phys. 75 (1998) 410.
[33] KESKIKURU, T. et al. Variation of radon entry rate into two detached houses. Atmos. Environ. 34 (2000) 4819.
[34] EUROPEAN COMMISSION. Radiological protection principles concerning the natural radioactivity of building materials. Brussels: Dir.-Gen., Environment (1999).
[35] PARIDAENS, J., DE SAINT-GEORGES, L., VANMARCKE, H. Mitigation of a radon-rich Belgian dwelling using active sub-slab depressurisation. J. Environ. Radioact. 79 (2005) 25.
[36] POSTENDORFER, J. Properties and behaviour of radon and thoron and their decay products in the air. J. Aerosol Sci. 25 (1994) 219.
[37] ETTENHUBER, E. et al. Principles for the control of exposures to radon in dwellings – concept for a national radon programme in Germany. 7th Int. Symp. Soc. Rad. Prot. Cardiff, U.K. (2005).