Influence of Environmental Factors on Indoor Radon Concentration Levels in the Basement and Ground Floor of a Building - A Case Study

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Abstract

A series of experiments was conducted to measure indoor radon concentrations variations and observe any correlations with indoor and outdoor atmospheric parameters for over a period of one year. Indoor environmental parameters and radon concentrations were measured on an hourly basis in a two-story building both in a laboratory on the well-ventilated ground floor and in the basement below it which had negligible ventilation. The monthly average indoor radon concentration value of 29 ± 21 Bq m⁻³ in the laboratory was below the ICRP recommended limit of 200-300 Bq m⁻³. The monthly normalization factor for that location ranged from 0.5 to 2.0, while the seasonal normalization factor ranged from 0.78 to 2.0. In the unventilated basement, however, the average monthly indoor radon concentration was $1,083 \pm 6$ Bq m⁻³ with little seasonal variation. The basement is only used for storage and thus the elevated radon concentration does not pose a serious health risk. The results indicated that indoor radon levels are higher in the autumn-winter season than in the spring-summer season. Analysis further showed that indoor radon concentrations negatively correlated with indoor humidity (correlation coefficient $R = -0.14$, $p < 0.01$), outdoor temperature (correlation coefficient $R = -0.3$, $p < 0.01$), outdoor dew point temperature (correlation coefficient $R = -0.17$, $p < 0.01$) and outdoor wind speeds (correlation coefficient $R = -0.25$, $p < 0.05$). Radon concentrations correlated positively with outdoor barometric pressure (correlation coefficient $R = 0.35$, $p < 0.01$), indoor-outdoor temperature difference (correlation coefficient $R = 0.32$, $p < 0.05$) and indoor-outdoor barometric pressure difference (correlation coefficient $R = 0.67$, $p < 0.01$). Indoor temperature, indoor barometric pressure and outdoor wind direction showed no clear correlations with indoor radon concentration.

Keywords: Indoor radon; environmental factors; temporal variability; radon monitors; seasonal normalization factor

1. Introduction

Radon is one of the most extensively investigated human carcinogens. Radon and its progeny in the air contribute to human exposure from natural radiation sources (UNSCEAR, 2009). Since people spend so much of time indoors, long-term exposure to elevated radon concentrations has been linked to increased lung cancer risk (Steck, 2009). Some residential case-control radon studies in North America showed a direct association between prolonged radon exposure and lung cancer (Field et al., 2006). Radon may contribute to an estimated 21,800 lung cancer deaths in the United States of America (USA) annually (BEIR, 1999). Furthermore, the health impacts of seriously elevated radon levels, such as measured radon concentration levels exceeding $410,000 \text{ Bq m}^{-3}$ in indoor residential air (Kearfott, 1989), are not open to controversy. In order to evaluate the possible radon hazard to inhabitants of the buildings in the central northern, or midwestern, region of the USA, knowledge about the monthly and seasonal radon concentration variations is desirable.

Meteorological parameters, geology, building materials, building construction type and the degree of ventilation of closed environments are among the important factors affecting the radon in indoor air (Porstendorfer et al., 1994; Espinosa and Gammage, 1998; Baeza et al., 2003; Faheem et al., 2008; Rahman, et al, 2010; Müllerová and Holý, 2010; Rafique et al., 2011a, 2012a, 2012b; Matiullah, et al, 2012; Kropat et al., 2014). Because the relationship between indoor radon and the weather is mediated by regional differences in both building construction and ventilation practices, indoor radon concentrations typically show monthly and seasonal variations that are both significant and geographically variable. Indoor radon concentrations are reportedly more sensitive to meteorological parameters than building characteristics (Steck, 2009). Meteorological parameters including indoor and outdoor environmental variables were thus chosen for the focus of this study of indoor radon in the midwestern USA.

A long-term measurement period will give a much better indication of annual average radon concentration than measurements of shorter duration. Seasonal normalization factors (SNF) and monthly normalization factors (MNF) are numerical multipliers used to convert a short-term radon concentration measurements to estimates of annual average concentrations (S. Rahman et al, 2007; Kozak et al., 2011, Burke and Murphy, 2011). Burke and Murphy (2011) use a formula

of $\frac{3 \sum_{k=1}^{12} m_k}{12 \sum_{i=1}^{i+1} m_k}$ (Where $i = 1, \dots, 12$; $\hat{m}_k$ is the radon level) to calculate the three-month seasonal

correction factors. S. Rahman et al (2007) have used the similar simple ratio calculation methods to

calculate the seasonal correction factor. K. Kozak et al (2011) used a equation of $\frac{GM_Y}{GM_m}$ (where GM_Y is the geometric mean of annual radon concentrations and GM_m is the geometric mean of monthly radon concentrations) to calculate monthly correction factor. In this paper, Burke and Murphy's equation and K. Kozak et al's equation have been used to calculate seasonal and monthly correction factors. The SNF is calculated by dividing the annual arithmetic mean by the arithmetic mean calculated for each short-term period, i.e. the cycle or season, specifically spring, summer, autumn and winter for the SNF or the month for the MNF. Both factors are simple ways of accounting for the impacts of environmental parameters and building ventilation variations on indoor radon concentration.

Radon mapping data reveal not only substantial regional variations but complex indoor radon levels distributions within a single city or town (Burke and Murphy, 2011). In addition, geological characteristics and meteorological parameters likely present synergistic effects on indoor radon levels. The SNF is reported in some locations to be larger than 1.0 in the summer, with the smallest SNF values recorded for the winter-spring season (Kozak et al., 2011). In other highly radon-bearing places the opposite result is encountered, which may be caused by thermally induced subterranean air flow (Sundal et al., 2007).

Outdoor environment variables affecting the magnitude and variation of annual indoor average radon concentrations include indoor-outdoor temperature difference, barometric pressure, humidity, wind speed and direction, and precipitation. Published research on the correlation of indoor radon concentration with specific environmental parameters is not consistent. The irregularity most often observed is seasonal variation. For example, higher radon concentrations are most often observed in dwellings in the cool seasons of the year and lower radon concentrations in the warm periods (Denman et al., 2007). However, the opposite relationship occurs in Alabama homes, with the highest radon levels occurring during the summer (Wilson et al., 1991). The best explanation for this difference is that in locations where temperatures are hotter, homes are tightly sealed and air conditioned during the hottest months, and ventilated during the milder months during which heating is not needed. This is certainly the case in Arizona, with a climate similar to Alabama, where arrangements relating to the cooling of homes have even resulted in markedly elevated radon levels (Kearfott et al., 1992a; Kearfott et al., 1992b).

Detailed relationships between specific environmental parameters and indoor radon concentration have been the subject numerous publications. Porstendorfer et al. (1994), Nazaroff et al. (1988) and Müllerová and Holý (2010) all reported that indoor radon concentrations showed elevation with increasing indoor-outdoor temperature differences. Marley (2001) found that indoor radon was primarily dependent on the three atmospheric variables: barometric pressure, vapor pressure and wind variation. Kitto (2005) observed that diurnal indoor radon levels were heavily influenced by indoor and outdoor temperature differentials, with little correlation to barometric pressure and wind speed. Hubbard et al. (1996) demonstrated an opposite effect, namely indoor radon level was reduced as temperature differences increased because of increased ventilation with outdoor air with lower radon concentrations. Riley et al. (1996) and Nazaroff et al. (1988) reported that wind speed could generate over-pressure with a positive effect on radon entry into structures from soil radon. Jane et al. (2002) reported that rainfall and barometric pressure had little effect on radon concentration. By contrast, it was reported that seasonal rainfall and increased snowfall could cause unexpected high indoor radon concentrations (Mose et al., 1991; Steck, 2009; Francesco et al., 2010). These seemingly disparate findings probably arise because the effects of environmental parameters on indoor radon are very complicated, with some parameters having cross correlations with other parameters with the relationships mediated by regional factors influencing both the weather, construction types, and building ventilation practices.

In the present study, the significance of multiple indoor and outdoor environmental factors on the amount of radon that actually enters and accumulates in two locations within a single two-story building was studied in depth. The primary goals of the present paper were to analyze monthly and seasonal indoor radon variations in a typical building with a basement in a northern latitude climate and to find the possible relationships between indoor radon concentrations and main environmental variables, such as pressure, temperature and relative humidity. It was envisaged that the results of this study would be useful in assessing overall temporal variations in indoor radon behavior in this specific region while contributing to an overall understanding of the relationships between environmental parameters and radon.

2. Description of study location and building

The building is located on a suburban university campus in the north central, or midwestern, USA. The town is located at north latitude 42°16' and west longitude 83°43'. It experiences a typically midwestern humid continental climate, influenced by the Great Lakes. There are four

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4 distinct seasons. Winters (November-March) are cold (average temperature of -0.1°C) with
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6 moderate to heavy snowfall, while summers (June-August) are very warm (average temperature of
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8 21.6°C) and humid. Spring (April-May) and autumn (September-October) are short but mild and
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10 have average temperatures of 12.4°C and 14.5°C , respectively. Precipitation tends to be the heaviest
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12 during the summer months, but is most frequent during winter. Snowfall, which normally occurs
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14 from November to April but occasionally starts in October, averages 147 cm per season. The area
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16 experiences "lake effect weather", primarily in the form of increased cloudiness during late fall and
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18 early winter.

19 The particular building studied has two stories plus a basement, and is constructed from red
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21 brick, concrete, gypsum and lime with some cinder block interior walls. Sandy soil surrounds the
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23 ground contact surfaces. The building's occupied portions are served by a central heating and
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25 cooling supply system, which is used in heating mode for about half the year (November–April).
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27 The primary space studied in this building consisted of a laboratory room with a 5.4 m ceiling,
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29 having several smaller occupied rooms on the second floor immediately above it. The room is
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31 situated directly atop another room, also instrumented for radon, in a completely underground
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33 basement that is unventilated (isolated from the central heating and cooling system) and used for
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35 storage space. There is a central air-conditioning supply system and mechanical ventilation system
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37 providing a typical hourly air change rate of 5 h^{-1} . Fans usually run continuously circulating air in
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39 the building but not the basement room. There are no windows in the laboratory and other windows
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41 throughout the remainder of the building are not opened as a matter of policy.

42 **3. Methods and materials**

43 Indoor radon concentration levels were measured from March 2004 to April 2005. All the
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45 measurements were collected simultaneously on a continuous hourly basis in the laboratory and
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47 basement at the height of 1.5 m using two relatively inexpensive, commercially available
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49 continuous radon monitors (Professional Continuous Radon Monitor, Model 1027, Sun Nuclear
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51 Corporation, Melbourne, FL, USA). The devices, which use diffused-junction photodiode sensors,
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53 were pre-calibrated by the manufacturer and should have measured radon gas concentrations within
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55 25%.

56 Hourly environmental measurements were performed using a roof-mounted residential
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58 quality weather station (Complete Weather Monitor II, Model 7440CS, Davis Instruments Corp.,
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60 Hayward, CA, USA). Commercially available statistical analysis software (SPSS v.12.0 for
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Windows, SPSS Inc., Chicago, IL, USA) was used to analyze the available data. The variables of interest included indoor and outdoor temperature (precision of ± 0.5 °C), wind speed and direction, indoor and outdoor barometric pressure, indoor and outdoor humidity (precision of $\pm 5\%$ indoor, $\pm 3\%$ outdoor) and dew point temperature (precision of ± 2 °C). Annual average indoor radon concentrations may be variable to some degree and can fluctuate considerably around the multi-year mean, so annual averages for this study were calculated based on the average of all data during the measurement period. The SNF and MNF were similarly computed.

4. Results and discussion

4.1 Average and temporal variations of indoor radon concentration

For northern climates, radon concentration was previously reported to typically be highest in the winter and lowest in summer, with the autumn and spring season having indoor radon levels approaching the annual average (Mose et al., 1992). In the present study, similar but not exactly identical trends were observed, as shown by the monthly averages in Fig. 1 and Table 1. As mentioned earlier, spring was defined to include April and May, summer was from June to August, the months of September and October were considered autumn, and the season winter was defined to be from November to March. It is interesting to note that the highest radon concentration was observed for the late autumn season, the month of November, not matching prior reports of the highest levels in winter for the northern portion of the northern hemisphere.

In the unventilated basement, radon concentrations were relative stable with the average value of $1,083 \text{ Bq m}^{-3}$, much higher than those observed in the ventilated laboratory located above it. As can be seen from Fig. 1, there was a tendency for measured radon levels in the summer months to be less than those in the winter months, but there was also a significant month-to-month variation.

The monthly arithmetic means (AM) and arithmetic standard deviations (ASD) of indoor radon concentrations for the two locations within the building are listed in Table 1. The monthly average indoor radon concentrations in autumn-winter season were the highest at $51 \pm 43 \text{ Bq m}^{-3}$, almost twice the annual radon concentration level of $29 \pm 21 \text{ Bq m}^{-3}$. These trends vary only slightly from prior research results at a different location (Mose et al., 1992).

4.2 Correlation between radon concentration and outdoor meteorological parameters

Radon concentration and meteorological parameters are depicted as a function of time in Fig. 2 and Fig. 3. Due to the relationships of radon concentration and meteorological parameters with time, the time factor has been considered using SPSS in the computations of the correlations

between radon levels and meteorological parameters. A close correlation was found between the monthly indoor radon variations several of the environmental parameters in the laboratory, demonstrating that indoor radon concentrations may be strongly affected by both indoor-to-outdoor temperature and pressure differences. Indoor radon concentrations had a negative correlation with indoor relative humidity (correlation coefficient $R=-0.14$, $p<0.01$), especially in the more elevated autumn-winter season, as seen in Fig. 2. Figure 3 clearly illustrates that indoor radon concentrations correlated negatively with outdoor temperature (correlation coefficient $R=-0.3$, $p<0.01$), outdoor dew point temperature (correlation coefficient $R=-0.17$, $p<0.01$) and outdoor wind speeds (correlation coefficient $R=-0.25$, $p<0.05$), but positively correlated with outdoor barometric pressure (correlation coefficient $R=0.35$, $p<0.01$). Indoor-outdoor barometric pressure difference (correlation coefficient $R=0.67$, $p<0.01$) showed a more significant correlation with indoor radon levels than indoor-outdoor temperature differences (correlation coefficient $R=0.32$, $p<0.05$), as shown in Fig. 4. The pressure difference across the building shell caused by temperature difference between outdoor and indoor air was recognized as the dominant means to affect radon entry into the building by other researchers (Müllerová and Holý, 2010).

Extremely high outdoor pressure and low outdoor wind speeds, indoor humidity and outdoor temperature occurred during November 2004, which corresponded to the highest indoor radon levels of the entire year in the laboratory. This is shown in Fig. 5, which also reveals that extremely high indoor radon concentrations appeared under conditions of higher outdoor barometric pressure and lower indoor relative humidity. Outdoor wind speeds had a significant negative correlation with outdoor barometric pressure with a correlation coefficient of -0.25 . Under the special humid continental climate influenced by the Great Lakes in the USA, with much lower indoor humidity and outdoor temperature, outdoor barometric pressure is mainly governed by wind speed, which could generate over-pressure to take a positive effect on radon entry from the soil. Indoor radon concentrations decreased with the increase of outdoor temperature during the spring-summer season, then increased with outdoor temperature dropping during autumn-winter season. This generally agrees with the findings of Steck (2007).

4.3 Seasonal Normalization Factors (SNF) and Monthly Normalization Factors (MNF)

Figure 6 shows that the monthly normalization factor ranged from 0.5 to 2.0, which is slightly different from Burke and Murphy's (2011) reports of a minimum value in summer. The winter-to-summer ratio of radon concentration in the laboratory was been computed to be 1.43,

while seasonal normalization factors in the laboratory were 2.0, 1.2, 0.78, 0.8, respectively, as shown in Fig. 7.

Ventilation rate undoubtedly plays a key role in the SNF and MNF. In autumn and winter seasons, due to the low temperature and restricted ventilation, i.e. stack effect, the buildup of radon in the rooms will be enhanced because of lack of direct ventilation through open windows, increased usage of the heating system, and because hot air rises pulling air from the basement which is in direct contact with the sources of radon on all surfaces except for the ceiling. It is obvious that the laboratory radon concentrations have a lower average level of $29 \pm 21 \text{ Bq m}^{-3}$ with good ventilation, compared to extremely high average indoor radon level of $1,083 \pm 6 \text{ Bq m}^{-3}$ in the basement with no ventilation.

4.4 Uncertainties and sources of variability

The stability, range, temporal response times and accuracy of measurement instruments is one source of uncertainty in the data. Instruments used in this particular work were relatively inexpensive, residential quality devices. Similar limitations exist for the environmental parameter data reported here. Combined, these measurement limitations could have obscured fine temporal transitions and diminished correlation values to some extent.

Even more importantly, weather is quite variable from year to year especially when global climate change may be occurring. Not only is ventilation strongly influenced by the weather, but annually varying energy costs influence not only the usage of both heating and cooling systems but also the cycling of ventilation, such as whether or not continuous air turnover (e.g. fan usage) is maintained for a building. This may produce large variations in the SNF, and to an even greater degree, the MNF. This confounds the overall study of the correlation of radon with environmental parameters.

With other factors maintained equal or accounted for, quantifying the effects of seasons from one location to another is complex, because it is difficult to absolutely distinguish the four seasons separately by months even for a single location. This is particularly true for the typical humid continental climate influenced by the Great Lakes where this study was conducted. The measurement seasons also coincidentally correlate to geological regions, which may introduce a bias in the isolation of seasonal variations. Seasons and geological region effects should be considered together in the future, because it is difficult to separate a “pure” seasonal variability such as in the reports by Bossew et al. (2007). Besides meteorological parameters, building

structures and ventilations systems are both other important factors, mentioned above, that may affect seasonal variation, which need to be studied further.

Perhaps a solution to the problems posed by the usage of MNF and SNF for extrapolating short-term measurements to annual averages, essential for rapidly assessing health risks and the desirability of radon mitigation, is to replace these with factors that relate to measurable environmental parameters. Such could be generally determined for a given geological region and be adapted appropriately for particular housing construction types found in those regions. Short-term measurements would thus consist of indoor radon concentrations, specific environmental parameter measurements, and building type. Appropriate environmental and building type correction factors could then be applied to those. Ideally, such environmentally-based correction factors might be more generally applicable from one geographic location to another. This will require additional research.

5. Conclusions

The present paper reports indoor radon levels and environmental parameters continuously measured on an hourly basis over one year, with the same methodology, equipment and protocols, in a well-ventilated laboratory with an unventilated basement directly below it in a two-story building in midwestern USA.

The maximum values of the indoor radon concentration were observed during the autumn-winter season, whereas the minimum concentration value has been observed in the spring-summer season. The monthly average indoor radon concentration values in the laboratory varied from $14 \pm 12 \text{ Bq m}^{-3}$ to $51 \pm 43 \text{ Bq m}^{-3}$ with an average value of $29 \pm 21 \text{ Bq m}^{-3}$, which was below the ICRP-recommended limit of 200-300 Bq m^{-3} (ICRP, 2009). From the average values calculated, the basement presented a notably high average indoor radon concentration of $1,083 \pm 6 \text{ Bq m}^{-3}$. Fortunately, the basement was not occupied continuously, as it is only used for storage. Unlike the unventilated basement, the ventilated laboratory showed expected monthly and seasonal variation in radon concentration. The variation in indoor radon levels of ventilated laboratory reflects the impacts of ventilation for the particular building type, while the unventilated basement radon levels likely predominantly reflect a constancy of outdoor soil radon levels for the geological location of the building.

Indoor radon concentrations were negatively correlated with outdoor temperature, dew point temperature and wind speeds, but positively correlated with outdoor barometric pressure and

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4 indoor-outdoor temperature and barometric pressure differences. No clear correlations were found
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6 between indoor radon concentrations and the other meteorological parameters included in this
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8 study. Because indoor-outdoor barometric pressure differences appear to be of particular
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10 significance to indoor radon levels for this specific location, it may ultimately serve as a parameter
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12 for a short-term radon measurement correction factor to extrapolate to longer-term measurements
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14 that is based upon more appropriate and directly measurable environmental parameters, rather than
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16 simply the season or month. Future research on the detailed relationship between meteorological
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18 parameters and indoor radon levels, in different building types and locations, is needed in order to
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20 accomplish such a goal.

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Table 1 Monthly indoor radon level (Bq m^{-3}) and Standard Deviation in Lab and Basement

	Laboratory radon (Bq m^{-3})				Basement radon (Bq m^{-3})			
	Mean	SD	Max	Min	Mean	SD	Max	Min
March-2004	30	29	204	0	1084	7	1098	1061
April-2004	14	12	78	0	1080	5	1088	1064
May-2004	14	12	80	0	1081	5	1094	1065
June-2004	15	13	79	0	1078	7	1093	1060
July-2004	26	25	159	0	1080	5	1087	1067
August-2004	34	25	133	0	1080	5	1094	1067
September-2004	31	24	133	0	1083	5	1093	1071
October-2004	42	42	307	0	1086	5	1097	1076
November-2004	51	43	255	0	1090	5	1099	1060
December-2004	34	32	215	0	1086	12	1110	1059
January-2005	30	28	148	0	1085	5	1095	1061
February-2005	32	30	174	0	1082	5	1088	1060
March-2005	24	23	184	0	1082	5	1093	1061
April-2005	16	19	179	0	1081	5	1089	1066

Table 2

Table 2 Seasonal indoor radon concentration in Lab and Basement

Indoor Radon concentration (Bq m ⁻³)													Annual Average Radon Value (Bq m ⁻³)	Winter/Summer ratio
Spring (April-May)			Summer (June-August)			Autumn (September–October)			Winter (November-March)					
Max.	Min	Average ±SD	Max.	Min.	Average ±SD	Max.	Min.	Average ±SD	Max.	Min.	Average ±SD			
Lab	80	0	14±12	159	0	25±23	307	0	37±34	255	0	36±34	29	1.43
Basement	1094	1064	1080±5	1094	1060	1079±6	1097	1071	1084±5	1095	1059	1082±6	1081	1.0