SEASONAL VARIATION IN RADON CONCENTRATION OF 3000 DWELLINGS WITH MODEL COMPARISONS

H. Arvela
Finnish Centre for Radiation and Nuclear Safety
PO Box 14, 00881 Helsinki, Finland

Abstract — Indoor radon concentration of two consecutive half-year measuring periods in 3074 Finnish dwellings were analysed. The periods were the warmest and coldest half-year periods in Finland. The mean of winter/summer concentration ratio in all low-rise residential buildings was 1.28, and in houses with winter concentrations of <50, $50–100$, $100–200$ and >200 Bq.m^{-3}, 0.97, 1.22, 1.34 and 1.55, respectively. The results are in agreement with the results predicted by the model, which takes into account the varying contribution of diffusive and convective radon entry as well as the contribution of stack effect and wind induced air infiltration. The model is a useful tool for estimating the average correction factor for the annual average radon concentration from the two months measurements used in Finland. Typical correction factors vary in the range of 1.0–0.7, depending on the outdoor temperature and on radon concentration level. Model comparison with winter/summer ratios measured in houses with slab on grade suggests an average diffusive radon entry rate of 7 Bq.m^{-3}.h^{-1} and a convective entry rate of 50 Bq.m^{-3}.h^{-1} at an average indoor/outdoor temperature difference of 17 K. The use of a simple averaging of winter/summer ratios for houses with varying radon levels, creates inaccuracy in the information on seasonal variation. Surprisingly, the behaviour of the winter/summer ratio in blocks of flats was very similar to that in low-rise residential buildings. The results support the interpretation that soil air leakage also contributes unexpectedly to the radon concentration in flats.

INTRODUCTION

Indoor radon measurements in low-rise residential houses have shown that in houses with natural ventilation, where the pressure difference driven radon flow from soil is the dominant radon source, winter concentrations are normally higher than summer concentrations. In Finland, a measurement period of two months during the heating period is used for indoor radon measurements in dwellings. Measurements of seasonal variation and model calculations have been used for estimation of the annual average concentration. The measured variation has been in agreement with model predictions, but the small number of houses measured has limited the accuracy of parameter estimates[1–4]. The Finnish Centre for Radiation and Nuclear Safety carried out a study of indoor radon in 1990–91 in 3074 dwellings[5]. Because of the large number of houses and long measurement periods, the study provides new data for studies of seasonal variation. The aim of this study is to present the results concerning the seasonal variation and to compare the results with model predictions. This is also the first Finnish study providing representative information on seasonal variation in blocks of flats.

MATERIALS AND METHODS

Indoor radon measurements

The measurements were carried out in 1990–91 in the dwellings of 3074 persons randomly chosen from the Central Population Register, 2071 of these in low-rise

residential buildings and 903 in blocks of flats. Alpha track detectors[4,6] and two consecutive half-year measuring periods were used. The measuring periods were 22 Nov. 1990–3 May 1991 and 3 May 1991–19 Nov. 1991 (median dates), also approximately the coldest and warmest half year periods in Finland. The median length of the periods was 162 d and 200 d. Thus the periods also covered spring and autumn. However, for simplicity the periods are herein termed winter and summer.

In order to avoid the highest extremes of the winter/summer concentration ratio due to detector inaccuracy, the minimum concentration of radon was set at 15 Bq.m^{-3}. This limitation affected only the concentrations measured in 15 dwellings with floor slabs made of concrete. Taking into account the contribution of radon concentration in outdoor air[7], 5 Bq.m^{-3}, the limitation is well justified.

Air infiltration prediction

The modelling used for the predictions of seasonal variation combines both air infiltration and radon sources to a simple model. At first, Finnish air infiltration models were tested, but then the Lawrence Berkeley Laboratory (LBL) air infiltration model was chosen as it has been tested in moderately cold climates and because it gives a simple analytical basis for calculations[8].

The LBL infiltration model adds in quadrature the infiltration rates due to indoor–outdoor temperature differences (stack effect) and wind speed as follows:

$$Q = ELA \left[(f_{sr} \Delta T^{0.65})^2 + (f_{wr} v)^2 \right]^{1/2} \qquad (1)$$

$$N = QV^{-1} \tag{2}$$

where Q is the total infiltration $(m^3.s^{-1})$, ELA is the effective leakage area (m^2), ΔT is the indoor–outdoor temperature difference (K), f_{sr} is the stack parameter $(m.s^{-1}.K^{-1/2})$, v is the meteorological wind speed at 10 m and f_{wr} is the wind parameter. N is the air exchange rate (h^{-1}) and V the house interior volume (m^3).

The envelope leakage exponent of ΔT in Equation 1 is 0.5 for turbulent air flows and 1.0 for laminar air flows, the effective parameter is in the range of 0.5–0.7. The contribution of flow through vents and non-planned leakage routes to the total air infiltration affects the effective value of this exponent, as described later in this section. Comparison between predicted and measured air flows, made by the LBL give an estimate of 0.65 for the exponent[9]. The comparison implies that the original model, with an exponent of 0.5, overpredicts at low pressures and underpredicts at high pressures. In this study a value of 0.65 for the flow exponent will be used.

In the development of the infiltration model, it is assumed that all significant air flow takes place directly through the shell of the house envelope. Normally Finnish low-rise residential houses have been equipped with exhaust vents, located mostly in the kitchen and bathrooms. Air flow through a vent, Q_v, can be expressed as follows[8]:

$$Q_v = A_v(v^2 + 2gh'\Delta T/T_{out})^{1/2} \tag{3}$$

where A_v is the leakage area of the vent (m^2), v is wind speed at the top of the ventilation stack $(m.s^{-1})$, h' is the height of the stack (above the neutral level), g is the acceleration of gravity $(9.8 \ m.s^{-2})$, ΔT is the indoor-outdoor temperature difference and T_{out} is the outdoor temperature (K).

In Finland, the use of air intake vents in living rooms and bedrooms was uncommon before 1987 when a new building code was instituted[10]. As a rule the new code requires mechanical ventilation. When natural ventilation is chosen air intake vents are required. The air flow through a vent will be balanced only if there is an intake vent of the same air flow. Houses with intake vents are at the present time few in number and hence the air flow through exhaust vents in the Finnish housing stock is, in general, unbalanced. Unbalanced flow adds to the total infiltration in quadrature. The wind and stack effect induced components of the vent flow, Equation 3, are approximately similar physically to the infiltration Equation 1. Therefore, the addition of the unbalanced flow through the vents to the stack and wind induced flows through the house envelope is explicable as alterations in the leakage area as well as the stack and wind parameters of the air infiltration equation.

The fraction of leakage in the floor and ceiling affects both the stack and wind parameters[8]. In houses with slab on grade, the floor leakage is of the order 1 $m^3.h^{-1}$, as estimated in the present study. In such cases the floor

leakage area is, in comparison with the total air infiltration, virtually negligible. However, as a source of indoor radon concentration, this leakage area is significant. The available measured results from the fraction of leakage in the ceiling in Finnish moderately tight houses are 40–60% (pressure tests, vents closed)[11]. Exhaust vents are installed through the ceiling and increase the flow through the ceiling. Based on a study of 60 houses with natural ventilation, the non-planned flow through the envelope is typically 30–60% of the total infiltration[12]. As a result, the overall fraction of leakage in the ceiling is approximately 70–80%. These calculations resulted in a value of 0.08 for the stack parameter and 0.11 for the wind parameter (Equation 1) of the model house presented in Table 1.

Radon concentration prediction

Equations 4–9 give the steady state radon concentration A $(Bq.m^{-3})$ used in model calculations:

Table 1. Physical characteristics of the model house used in the calculations.

Substructure	Slab on grade
Floor area	$100 \ m^2$
No of storeys	1
House height	4 m
House volume, V	$250 \ m^3$
House interior height	2.5 m
Ventilation	Natural
Wall bearing structures	Wooden
Air exchange model parameters[8]	
Leakage area, ELA*	$0.036 \ m^2$
Ceiling leakage area	75% of ELA
Terrain class	3
Wind parameter, f_{wr}	0.11
Stack parameter, f_{sr}	$0.08 \ m.s^{-1}.K^{-1/2}$
Indoor temperature	22 °C
Ventilation rate	$0.40 \ h^{-1}$
Radon concentration and sources	
Average soil gas radon concentration	$30,000 \ Bq.m^{-3}$
Indoor radon concentration, annual average	$170 \ Bq.m^{-3}$
Diffusive radon, volumetric entry rate, S_d	$6 \ Bq.m^{-3}.h^{-1}$
Convective radon entry rate, per unit indoor–outdoor temperature difference**	$2.8 \ Bq.m^{-3}.h^{-1}.K^{-1}$
Convective soil air leakage rate, Q_{sol}**	$0.4 \ m^3.h^{-1}$

*Calculated at outdoor temperature of 0 °C and wind speed of 4.3 $m.s^{-1}$.

**Calculated for the following annual average climatic parameters: outdoor temperature 4.4 °C, wind speed 3.3 $m.s^{-1}$.

$$S_{soil} = A_{soil} Q_{soil} \tag{4}$$

$$Q_{soil} = \Delta P_s R_t^{-1} \tag{5}$$

$$\Delta P_s = \rho_{out} g H_{npl} \Delta T T_{in}^{-1} \tag{6}$$

$$\Delta P_s = P_1 H_{npl} \Delta T (T_{in} T_{out})^{-1} \tag{7}$$

$$A = [A_{soil} F_{soil} \Delta T (T_{in} T_{out})^{-1} + S_d] (\lambda + N)^{-1} V^{-1} + A_{out} \tag{8}$$

$$F_{soil} = P_1 H_{npl} R_t^{-1} \tag{9}$$

The source comprises two components, diffusion from building materials; $S_d(Bq.h^{-1})$ and radon source due to convective flow of soil gas into the house, S_{soil} ($Bq.h^{-1}$). The force driving the convective flow is the pressure differential caused by the indoor–outdoor temperature difference, ΔT (K), this phenomena designated as the stack effect[8]. T_{in} and T_{out} indicate the indoor and outdoor temperatures (K). S_{soil} is proportional to the soil gas radon concentration A_{soil} ($Bq.m^{-3}$) and flow rate of soil gas into the house $Q_{soil}(m^3.h^{-1})$, which in turn is the quotient for the stack pressure difference ΔP_s (Pa) at floor level and the flow resistance R_t ($Pa.h.m^{-3}$). R_t is the total resistance of both floor cracks and soil, to soil gas flow. The stack pressure at floor level is given in Equation 6[8]. In deriving Equation 7 from Equation 6, the density of the outdoor air ρ_{out} was expressed in terms of the air density (1.29 $kg.m^{-3}$) at a temperature of 273 K. The acceleration due to gravity, g, is 9.8 $m.s^{-2}$, thus P_1 has a value of 3450 $Pa.m^{-1}.K$. H_{npl} is the height of the neutral pressure level (m)[8] above floor level. F_{soil} is the leakage parameter and accounts for the total leakage for the soil ($m^3.h^{-1}.K$). λ is the radioactive decay constant of ^{222}Rn, 0.0076 h^{-1}, N being the air exchange rate (h^{-1}) (Equation 2). A_{out} is the outdoor air radon concentration, the annual average being about 5 $Bq.m^{-3(7)}$. The factor $A_{soil} F_{soil}$ $(T_{in} T_{out})^{-1}$ demonstrates the total convective radon entry rate per unit temperature difference.

Equations 10–12 give the quotient for the radon concentration of winter and summer periods, A_W/A_S, as a function of A_W, in the case $N \gg \lambda$ and $T_{inS} = T_{inW}$, solved from Equation 8. The variables are defined above, subscripts W and S referring to winter and summer periods.

$$A_W A_S^{-1} = A_W (K_1 A_W + K_2)^{-1} \tag{10}$$

$$K_1 = T_{outW} \Delta T_S N_W (T_{outS} \Delta T_W N_S)^{-1} \tag{11}$$

$$K_2 = S_D V^{-1} N_S^{-1} [1 - T_{outW} \Delta T_S (T_{outS} \Delta T_W)^{-1}]$$
$$+ (1 - K_1) A_{out} \tag{12}$$

Model house

Table 1 shows the physical characteristics of the model house used in our calculations. The house represents the most common house type in Finland; based on a nationwide study, 50% of the low-rise buildings are of this type, i.e. with slab on grade and single

storey[5]. The average radon concentration of the convective leakage air is given in Table 1, in order to estimate the convective flow rate Q_{soil}. The indoor radon concentration of the model house, 170 $Bq.m^{-3}$, is the average value measured for houses with slab on grade in the nationwide survey[5]. The estimate of the average radon concentration of soil gas convectively flowing into the house, 30,000 $Bq.m^{-3}$, is based on an estimate of the average deep soil radon concentration of 50,000 $Bq.m^{-3}$. This concentration was multiplied by an approximate factor of 0.6, which displays the ratio of leakage air radon concentration to the deep soil radon concentration. The estimate of the deep soil concentration, 50,000 $Bq.m^{-3}$, is calculated on the basis of the average ^{238}U concentration of the Finnish moraines[13], 41 $Bq.kg^{-1}$, with an average emanation coefficient of 0.2[14] and a soil porosity of 0.3.

For low-rise residential houses with wooden wall structures and slab on grade, both diffusion through the concrete slab and from the slab material should be considered as diffusive entry mechanisms. The exhalation rate through a typical uncovered floor slab in Finnish houses with a thickness of 6 cm would be 70 $Bq.m^{-2}.h^{-1(15)}$, when the soil air radon concentration below the slab is 30,000 $Bq.m^{-3}$. The corresponding effective diffusion coefficient was 3.8×10^{-8} $m^2.s^{-1}$ (porosity 0.17, density 2.18)[15]. This is in agreement with recent results on diffusion through floor slabs[16], the effective diffusion coefficient (product of pore diffusion coefficient and porosity) for a slab with a similar porosity being about 2×10^{-8} $m^2.s^{-1}$.

The cover material of the slab has a most important role in exhalation. Vinyl coverings with a thickness of 2 mm and a diffusion constant of $10^{-10} - 10^{-11}$ $m^2.s^{-1(15)}$, when used, reduce the exhalation rate by more than 90%. Vinyl coverings, especially those with felt backing, permit horizontal diffusion between the concrete slab and floor covering, which in turn increases the radon entry rate. For wood floors the reduction is much lower than for plastic coverings. Both vinyl coverings and wood floors are used in Finland, vinyl coverings being most common. The exhalation rate from an uncovered slab itself is of the order 5 $Bq.m^{-2}.h^{-1(15,17)}$. As cover material reduces exhalation remarkably, this contribution is, therefore, low in comparison with exhalation through the slab. In this study, a rough approximation of 15 $Bq.m^{-2}.h^{-1}$ for the average diffusive entry rate from a floor slab in Finnish low-rise houses has been used (30% wood floors with a reduction of 50%, 70% vinyl coverings with a reduction of 95%).

The average air exchange rate, 0.40 h^{-1}, as well as the mean indoor temperature, 22°C, of the model house was adopted from a study of 60 houses with natural ventilation in the capital area[12,18]. The air exchange study was taken during the heating season and the leakage area of the model house, 0.036 m^2, was calculated (Equations 1 and 2) utilising the air exchange rate of 0.40 h^{-1} and the mean climatic parameters of the

measurement period (Nov. 1988–Apr. 1989); temperature 0 °C and wind speed 4.3 m.s^{-1}.

RESULTS

Table 2 presents the results for winter and summer periods and the annual average concentration. For flats the results have been presented for houses with concrete as the building material, as it is the main building material in 90% of the blocks of flats studied. The average winter concentrations in low-rise houses and concrete flats were 171 and 78 Bq.m^{-3}, the corresponding summer concentrations being 133 and 74 Bq.m^{-3}. Figure 1 demonstrates the distribution of the winter/summer concentration ratio for 2071 low-rise houses and for 903 blocks of flats, with means of 1.28 and 1.20. Figure 2 illustrates the annual average concentration in low-rise houses as a function of winter period concentration.

Table 3 gives the winter/summer concentration ratio as well as the ratio of annual average over the winter radon concentration. These ratios can be used to estimate the annual average from measurements made during one season only, summer or winter. The concentration ratios are presented for concentration groups <50, 50–100, 100–200 and >200 Bq.m^{-3}. In both low-rise residential houses and flats, the winter/summer concentration ratio increases with increasing radon concentration. This is also clearly seen in Figures 3 and 4.

In order to obtain a homogenous study material single family houses of the model house type, i.e. with slab on grade, one floor, natural ventilation and wood frame have been studied. Figure 3 shows the measured winter/summer concentration ratio for 439 houses as

well as results of model prediction. Variation in the winter/summer concentration ratio is quite high, the standard deviation in single groups being 30–40%. The low values of the ratio are clearly concentrated in the 0–100 Bq.m^{-3} winter radon concentration range.

Model predictions
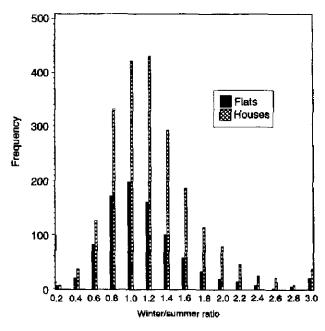
The average outdoor temperature of the half-year

Figure 1. Distribution of winter/summer radon concentration ratio, based on two half-year measurements in 2071 houses and 903 flats.

Table 2. Winter, summer and annual average radon concentration for the 3074 dwellings studied, based on two consecutive half-year measurements.

	N	Winter		Summer		Annual av.	
		mean	gmean	mean	gmean	mean	gmean
Low-rise buildings							
wooden frame	1645	158	103	125	87	139	96
concrete frame	253	224	122	164	109	181	117
All*	2171	171	107	133	91	149	100
Blocks of flats, concrete							
ground floor, no cellar	31	198	121	224	115	212	122
ground floor, with cellar	64	84	70	74	64	78	68
ground floor all	99	119	83	122	77	121	82
upper floors	563	71	62	65	57	68	61
All concrete flats*	674	78	65	74	60	76	64
All flats*	903	90	64	76	59	82	63

*Includes dwellings with insufficient questionnaire data for classification.

36

study periods were -2.6 °C (winter) and $+10$ °C (summer). The average wind speeds for the periods were 3.1 m.s^{-1} and 3.3 m.s^{-1} respectively. The temperatures and wind speeds from Tampere airport, centrally located in Southern Finland, were used. The minimum monthly average temperature occurred in February, -8.0 °C, and the maximum in July, 17.1 °C. The monthly average wind speed in Tampere is quite even throughout the year, 2.5–4.2 m.s^{-1}. The mean temperature during the study was 4.4 °C, which is close to the long term (1961–1980) annual average temperature in Tampere, 3.8 °C. Using the parameters of Table 1, the calculated average air exchange rates (Equations 1 and 2) of the model house were, in the winter period 0.40 h^{-1}, in the summer period 0.28 h^{-1} and during the whole study period 0.33 h^{-1}.

Figure 5 illustrates the results for the model house presented in Table 1 as well as for a similar house with varying diffusion source strengths and air exchange rates. The air exchange rates utilised in Figures 5, 6 and 3 were calculated for the average outdoor temperature and wind speed of the winter period, given above. The air exchange rate and diffusion source strength affect the steepness of the curve. High diffusion source strengths and low air exchange rates produce a flatter curve. Increasing air exchange rate and decreasing diffusion source force the curve to rise rapidly. Parameters with similar diffusion source strength to air exchange rate ratio yield approximately similar curves. At high values of the winter radon concentration A_W, where the contribution of diffusion is of minor importance, the quotient of winter and summer concentrations approaches the value of K_1^{-1} (Equation 10). The climate
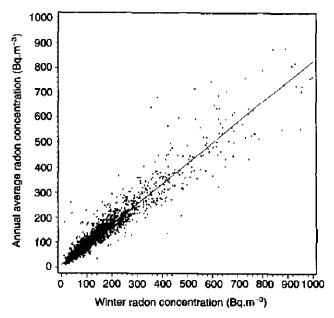

Figure 2. The annual average radon concentration A_A in 2142 low-rise houses as a function of radon concentration of the half-year winter measurement A_W. The line represents the linear regression equation fitted to the point. $A_A = 12 + 0.82 A_W$.

is considerably colder in Northern Finland than in Southern Finland. However, the predicted winter/summer ratios are very similar to those presented in Figure 5, even when the climatic conditions of Northern Finland (differences less than 15%) or of the south coast (differences less than 7%) were used.

The relative contribution of the stack effect and wind induced infiltration to the total infiltration affect the winter/summer ratio, this is shown in Figures 6 and 3. High values of stack parameter decrease the winter/summer ratio, whereas high values of wind parameter increase the ratio. The parameter values utilised in Figure 3 represent the average values of the parameters presented in Table 1 and realistic combinations of the parameters producing high and low winter/summer ratios.

Comparison with the measured results supports the value chosen, 6 Bq.m^{-3}.h^{-1} for the volumetric diffusion source strength of the model house. The statistical significance of the variations in the winter/summer ratio results of Figure 3 were tested using the following procedure. First, Equation 10 was rewritten into the form presented in Figure 6. Second, a linear regression analysis was performed for the variables A_S/A_W and A_W^{-1} using the data of Figure 3. Figure 7 giving the results. The analysis gave statistically significant ($p < 0.0001$) values for coefficients K_1 and K_2. By substituting K_2, as well as the temperature and air exchange values given above, into Equation 12, one gets a value of 1720 Bq.h^{-1} for the diffusion source strength S_D, the corresponding volumetric entry rate being 7 Bq.m^{-3}.h^{-1}. This is in good agreement with the value of 1500 Bq.h^{-1} used in Figure 4.

The average convective radon entry rate, $A_{soil}F_{soil}$ $(T_{in}T_{out})^{-1}$, and the average flow rate of soil gas into the house (Q_{soil}) were calculated using the average outdoor temperature and wind speed of the total study period and the annual average indoor radon concentration of the slab on grade houses in this study, 170 Bq.m$^{-3(5)}$. These parameters and the results are given in Table 1. The average convective radon entry rate was 706 Bq.h^{-1}.K^{-1}, the volumetric entry rate being 2.8 Bq.m^{-3}.h^{-1}.K^{-1}. This produces a source strength comparable with the diffusion source strength of 6 Bq.m^{-3}.h^{-1} at a temperature difference of 2 K. The corresponding volumetric convective radon entry rate at the average annual indoor–outdoor temperature difference of 17.6 K is 50 Bq.m^{-3}.h^{-1}. Utilising the soil air radon concentration of 30,000 Bq.m^{-3}, the corresponding flow rate of the soil gas into the house is 0.4 m^3.h^{-1}.

DISCUSSION

Low-rise residential houses

The model used herein provides a good physical basis for comparisons between the predictions and the measured results. The model is a simplification of the

phenomena affecting radon entry and air exchange. The model calculations are based on a single compartment model. In the houses, however, the sources, transport of radon, as well as air infiltration may differ from room to room.

The differences in ventilation practices during the two measuring periods is one of the factors strongly affecting the winter/summer ratio. The lowest value of 0.04 was measured in a house where the supply and exhaust ventilation system was operating only during the winter period. In addition, in this unusual case, the measurement room was equipped only with an air intake duct, the outlet ducts being in other rooms. In a study carried out during the heating season in the capital area[12], in 52% of the dwellings ventilation through open windows was a daily habit. In 15% of the cases such airing was done more than twice a day. The duration of each venti-

lation was less than 2 min, 2–10 min, 10–30 min or more than 30 min in 5%, 41%, 34% or 20% of the dwellings respectively. The average air exchange rate in the category with the lowest open window ventilation (less than once per week) was 0.44 h^{-1} and in the highest category (more than twice per day) 0.56 h^{-1}. Based on the average short ventilation durations and on the rather low differences in ventilation rates between categories, ventilation through an open window does not greatly decrease radon concentration during the heating season. On the other hand, summer ventilation through an open window is an important factor in increasing the winter/summer ratio, this effect not being taken into account in the model of this study. In the present study, with half-year measuring periods, the contribution of hot summer periods with active window ventilation is, however, relatively low.

Table 3. Winter/summer and annual average/winter radon concentration ratios for the 3074 dwellings studied, based on two consecutive half-year measurements.

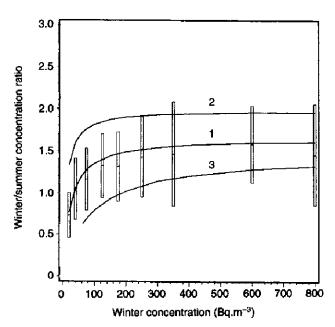|	N	Winter/summer ratio		Annual av./winter ratio	
		mean	gmean	mean	gmean
Low-rise houses					
winter conc. <50	415	0.97	0.90	1.13	1.08
winter conc. 50–100	681	1.22	1.14	0.96	0.94
winter conc. 100–200	599	1.34	1.26	0.91	0.90
winter conc. >200	476	1.55	1.42	0.86	0.85
Houses with					
wooden frame	1645	1.29	1.19	0.95	0.93
concrete frame	253	1.23	1.12	0.99	0.96
All houses	2171	1.28	1.17	0.96	0.93
Blocks of flats, concrete					
First floor, no cellar					
winter conc. <50	7	0.72	0.70	1.27	1.26
winter conc. 50–100	7	1.20	1.16	0.95	0.94
winter conc. >100	17	1.36	1.19	0.98	0.94
All	31	1.18	1.05	1.03	1.01
First floor with cellar					
winter conc. <50	21	0.94	0.87	1.13	1.10
winter conc. 50–100	26	1.23	1.17	0.94	0.93
winter conc. >100	17	1.56	1.28	0.95	0.92
All	64	1.22	1.09	1.00	0.98
Upper floors					
winter conc. <50	194	0.93	0.88	1.15	1.10
winter conc. 50–100	277	1.23	1.15	0.96	0.94
winter conc. >100	92	1.55	1.41	0.87	0.86
All	563	1.18	1.08	1.01	0.98
All concrete flats*	674	1.18	1.08	1.01	0.98
All flats*	903	1.20	1.08	1.01	0.98

*Includes dwellings with insufficient questionnaire data for classification.

Our previous studies[2,3] yielded measured winter/summer ratios similar to the present results. In the first of these studies, the periods of measurement were the coldest and warmest two month periods. Therefore, the winter/summer ratios at high radon concentrations were higher than in the current study which utilised a half-year period of measurement.

Soil air flows may also affect seasonal variation, amplifying, especially on eskers, the indoor concentrations either in winter or in summer[2,19,20]. Because of these flows, the winter/summer ratio may vary over a range of 0.1–1.0. The effect of building soil and relative position on esker in this study material calls for further analysis. However, the number of houses on steeply formed eskers where subterranean air flows can have a significant contribution, is, at maximum, only a few per cent.

Blocks of flats

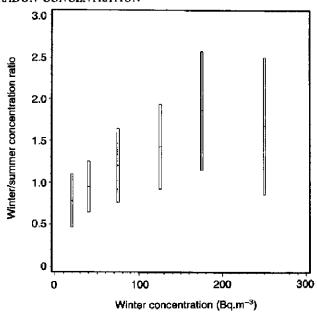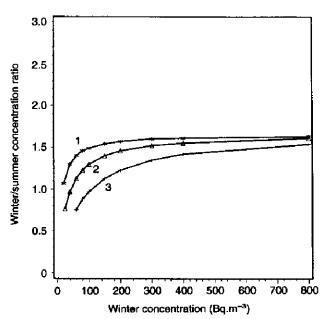The concentrations are highest in ground floor dwell-

Figure 4. Measured winter/summer radon concentration ratio as a function of winter concentration in 728 flats above the ground floor, based on two consecutive half-year measurements. The bar shows the mean radon concentration and the standard deviation of the ratios measured.
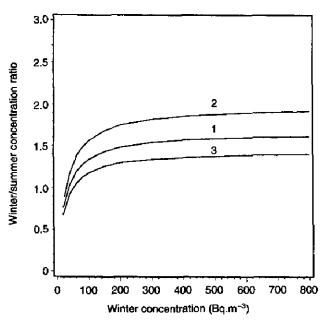
Curve	S_D (Bq.h^{-1})	N (h^{-1})	f_{sr} (m.s^{-1}.K$^{-1/2}$)	f_{wr}
1	1500	0.40	0.08	0.11
2	750	0.80	0.04	0.12
3	3000	0.20	0.12	0.06

Figure 3. Measured and model predicted winter/summer radon concentration ratio as a function of winter concentration in 439 low-rise residential houses with wooden frame and slab on grade. The bar shows the mean radon concentration and the standard deviation of the ratios measured. The average outdoor temperatures and calculated air exchange rate of the half-year periods were in winter −2.6 °C and 0.4 h^{-1} and in summer 10.0 °C and 0.28 h^{-1}. Curve 1 represents the average parameter values of diffusion source strength S_D, air exchange rate N as well as stack parameter f_{sr} and wind parameter f_{wr}. Curves 2 and 3 represent the parameter values which give low and high winter/summer ratios, respectively.

Curve	$S_D = 1500$ Bq.h^{-1}	N = 0.3 h^{-1}
	N (h^{-1}):	S_D (Bq.h^{-1}):
1	1.0	500
2	0.3	1500
3	0.1	4500

Figure 5. Calculated winter/summer concentration ratio of two half-year periods in the model house with varying diffusion source strengths and varying air exchange rates.

39

ings with no cellar, because these flats are in direct ground contact. Both the geometric and the arithmetic means are higher in these dwellings than in single family houses. In blocks of flats with a cellar, the cellar protects the ground floor flats from direct soil air flow, and, therefore, the concentrations are close to those of the upper floors. In most houses, however, there are no ground floor apartments, because the ground floor includes storage space, sauna, technical rooms and garages. This way of building decreases effectively the number of flats with direct ground contact, which is only about 5% of the total number of flats[5].

In the case of flats above the ground floor, it is generally assumed that the radon source is diffusion from building materials. If diffusion were the only source, the winter/summer concentration ratio should not be dependent on radon concentration level. Surprisingly, the results from the flats are similar to those from low-rise residential buildings. This can be explained through the influence of soil air flow also into block apartments. Other evidence for this result will be introduced below.

Diffusion of radon from concrete used in Finnish flats has been studied through measurements of radium concentration of concrete ballast material and radon exhalation from Finnish concrete samples[17]. The arithmetic

mean of exhalation rate was 15 $Bq.m^{-2}.h^{-1}$. The samples used in the exhalation studies were not surface treated. Using a surface (radon emitting) to volume ratio of 1.33, in the case of flats, and an average decreasing factor of 20% for the effect of painting, floor covers and wallpapers[21-23], the level of source strength per unit volume is 16 $Bq.m^{-3}.h^{-1}$. The studies on the effect of wall coverings show a large variation, with the reduction factor of 20% being an estimate of the minimum reduction, based on References 21-23. The volumetric source strength of 16 $Bq.m^{-3}.h^{-1}$ can be compared to source strength results based on simultaneous indoor radon and air infiltration measurements in Finnish flats. The arithmetic and geometric means of these studies are clearly higher, 35 and 27 $Bq.m^{-3}.h^{-1}$[17], a later more extensive study yields the same values[19]. These studies were made in the capital area, and the mean values can be regarded as representative even for the whole country. This comparison, therefore, supports the view about unexpected soil air contribution to radon concentrations in flats.

The analysis of the log-normal cumulative frequency distribution of the radon concentrations of the material of this study also demonstrate that one reason for the convexity of the distribution is the marked contribution of radon coming directly from the ground[24]. If the
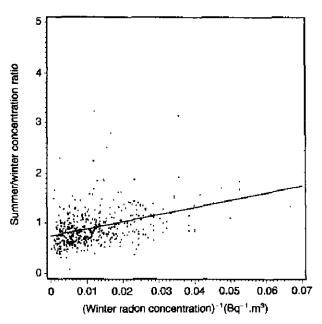

Figure 6. Calculated winter/summer radon concentration ratio in the model house with varying stack parameter f_{sr} and wind parameter f_{wr}. Curve 1 represents the average parameter values of stack parameter f_{sr} and wind parameter f_{wr}. Curves 2 and 3 represent the parameter values which give low and high winter/summer ratios, respectively. In all cases the diffusion source strength is 1500 $Bq.h^{-1}$ and the air exchange rate is 0.40 h^{-1}.

Curve	f_{sr} (m.s^{-1}.K$^{-1/2}$)	f_{wr}
1	0.08	0.11
2	0.04	0.12
3	0.12	0.06

Figure 7. Summer/winter concentration ratio (A_S A_W^{-1}) of two half-year measurements as a function of the inverse of the winter concentration (A_W^{-1}), in 439 houses with slab on grade and wooden frame. The line represents the linear regression equation fitted to the points.

$$A_S/A_W = K_1 + K_2 A_W^{-1}$$

$$K_1 = 0.75 \pm 0.05,$$

$$K_2 = 14.5 \pm 3.4$$

results for ground floor flats are omitted, the distribution for flats becomes much straighter although still not completely so.

Potential entry routes for radon rich soil air are stairwells and various shafts built for ventilation pipes, water pipes, sewer pipes etc. Air leakage from the shafts has been studied very rarely; in one block of flats studied the leakage from the shafts contributed up to 30% of the total air infiltration into the flats on certain floors[25]. In those cases where the shafts are in direct contact with permeable sub-foundation ground, radon concentration of the leakage air may be high. This hypothesis remains to be ascertained through measurements, nonetheless observations of shaft leakages in flats with radon concentration exceeding 400 Bq.m^{-3} have already been made in Finland.

Seasonal correction factor

Table 3 also gives a calculation of the factor by which the measured winter concentration should be multiplied in order to get the measured annual mean. This ratio of annual average concentration to winter concentration for low-rise residential buildings was on average 0.96. If the winter period of measurement lasts only two months in the coldest part of the winter, the ratio of annual to winter radon concentration, is somewhat smaller than demonstrated by the results of this study. Table 4 shows this factor calculated for the model house and for different average outdoor temperatures during the measurement.

The results give a correction factor of about 0.8 for getting the annual average from the half-year winter concentration of 500 Bq.m^{-3}. Figure 2 demonstrates that

Table 4. Correction factor for the annual average indoor radon concentration for different outdoor temperatures during the measurement period and for varying winter concentrations.

Outdoor temperature (°C)	Correction factor for annual average radon concentration					
	Measured radon concentration (Bq.m^{-3})					
	50	100	150	200	400	800
+10	1.10	1.19	1.22	1.24	1.26	1.27
+5	1.02	1.02	1.02	1.02	1.02	1.01
0	0.97	0.92	0.90	0.89	0.88	0.87
−5	0.94	0.85	0.82	0.81	0.78	0.77
−10	0.91	0.80	0.76	0.74	0.71	0.70
−15	0.88	0.76	0.71	0.69	0.66	0.64
−20	0.86	0.72	0.68	0.65	0.62	0.60

The factor was calculated for a typical Finnish low-rise house with natural ventilation and a diffusion source strength of 6 Bq.m^{-3}.h^{-1}, an annual average temperature of + 3.8 °C and an air exchange rate of 0.40 h^{-1} (calculated at outdoor temperature of 0 °C and wind speed of 4.3 m.s^{-1}).

using this factor, 85% of houses exceeding the measured annual average of 400 Bq.m^{-3} would be included. On the other hand, 7% of the 107 houses chosen, exceeding the winter concentration of 500 Bq.m^{-3}, did not exceed the measured annual average of 400 Bq.m^{-3}. Thus, the predictive power of the half-year winter measurement is high.

CONCLUSION

The physical behaviour of the diffusive radon entry into buildings, pressure difference driven air flow from soil and air infiltration explain the seasonal behaviour of indoor radon concentration. In the cold Nordic climate, the ventilation through open windows generally does not contribute markedly to total air infiltration. Therefore model predictions which do not take open windows into account are, nevertheless, in good agreement with the measured results. Discrepancy between the single compartment model and occurrence of radon in real dwellings as well as the variation in summertime ventilation through windows are the factors most affecting the difference between measured and predicted results.

The following four observations support the interpretation that soil gas radon makes a considerable contribution to radon concentrations in flats. However, the leakage routes and the magnitude of the contribution remain to be determined in further studies. The observations are:

(1) Exhalation measurements of concrete samples give lower source strength estimates than direct source strength measurements in flats.

(2) The winter/summer ratios in ground floor flats with ground contact were similar to those in flats without ground contact.

(3) The winter/summer ratios in flats were similar to those in low-rise residential houses. In low-rise houses, high soil gas entry rate in winter clearly affects the ratios.

(4) The convexity of the cumulative distribution of the radon concentrations in flats can be to some degree explained by the radon coming directly from ground.

In Finland, the range of the total diffusive radon entry rate from building materials and from soil is not broad, and the variation in radon transported by soil gas flow is the main reason for variations in indoor radon concentration. In countries with relatively higher contributions from building materials, the winter/summer ratios should be lower.

The model is a useful tool for estimating the average correction factor for the annual average radon concentration from the two months measurements used in Finland. Typical correction factors vary in the range of 1.0–0.7, depending on the outdoor temperature and on radon concentration level. The mean of the winter/summer

ratio was 1.28 in low-rise residential houses. However, in winter concentration groups of <50, 50–100, 100–200 and >200 Bq.m^{-3}, the ratios were 0.97, 1.22, 1.34 and 1.55 respectively. Using a simple average of winter/summer ratios for houses with varying radon levels, without consideration of the radon concentration due to different radon sources, causes inaccuracy in the information on seasonal variation.

REFERENCES

1. Arvela, H. and Winqvist, K. *Influence of Source Type and Air Exchange on Variations of Indoor Radon Concentration.* STUK-A51 (Finnish Centre for Radiation and Nuclear Safety, Helsinki) (1986).

2. Arvela, H., Voutilainen, A., Mäkeläinen, I., Castrén, O. and Winqvist, K. *Comparison of Predicted and Measured Variations of Indoor Radon Concentration.* Radiat. Prot. Dosim. **24**(1), 231–235 (1988).

3. Arvela, H. and Winqvist, K. *A Model for Indoor Radon Variations.* Environ. Int. **15**, 239–246 (1989).

4. Castrén, O., Arvela, H., Mäkeläinen, I. and Voutilainen, A. *Indoor Radon Survey in Finland: Methodology and Applications.* Radiat. Prot. Dosim. **45**(1), 413–418 (1992).

5. Arvela, H., Mäkeläinen, I. and Castrén, O. *Residential Radon Survey in Finland.* STUK-A108 (Finnish Centre for Radiation and Nuclear Safety, Helsinki) (in Finnish, abstract only in English) (1993).

6. Mäkeläinen, I. *Experiences with Track Etch Detectors for Radon Measurements.* Nucl. Tracks **12**, 717–720 (1986).

7. Finnish Meteorological Institute. *Observations of Radioactivity 1982* (Finnish Meteorological Institute, Helsinki) (1984).

8. Sherman, M. H. and Grimsrud, D. T. *Measurement of Infiltration using Fan Pressurization and Weather Data.* LBL-10852 (Lawrence Berkeley Laboratory, University of California) (1980).

9. Sherman, M. H. and Modera, M. P. *Comparison of Measured and Predicted Infiltration using the LBL Infiltration Model.* LBL-17001 (Lawrence Berkeley Laboratory, California) (1984).

10. Ministry of Environment. *Indoor Climate and Ventilation.* Building Code D2 (Helsinki) (1987).

11. Saarnio, P. *Calculation Model for Air-tightness and Natural Ventilation of Buildings.* Report 242 (Technical Research Centre of Finland, Espoo) (1983).

12. Ruotsalainen, R., Rönnberg, R., Säteri, J., Majanen, A., Seppänen, O. and Jaakkola, V. *Indoor Climate and the Performance of Ventilation in Finnish Residences.* Indoor Air **2**(3), 137–145 (1992).

13. Koljonen, T. (Ed.) *The Geochemical Atlas of Finland, Part 2: Till* (Geological Survey of Finland, Espoo) (1992).

14. Markkanen, M. and Arvela, H. *Radon Emanation from Finnish Soils.* Radiat. Prot. Dosim. **45**(1), 269–272 (1992).

15. Kronqvist, P. *Developing a Method to Measure Diffusion of Radon through Building Materials.* Master's thesis, Helsinki University of Technology, Espoo (in Finnish, abstract only in England) (1989).

16. Rogers, V. C., Nielson, K. K., Holt, R. B. and Snoddy, R. *Radon Diffusion Coefficients for Residential Concretes.* Health Phys. **67**(3), 261–265 (1994).

17. Mustonen, R. *Natural Radioactivity in and Radon Exhalation from Finnish Building Materials.* Health Phys. **46**(6), 1195–1203 (1984).

18. Arvela, H. *Radon Study in 250 Finnish Houses with Different Ventilation Systems.* In: Proc. 5th Int. Conf. on Indoor Air Quality and Climate, Toronto, Canada (1990).

19. Arvela, H., Voutilainen, A., Honkamaa, T. and Rosenberg, A. *High Indoor Radon Variations and the Thermal Behaviour of Eskers.* Health Phys. **67**(3), 253–259 (1994).

20. Hutri, K.-L. and Mäkeläinen, I. *Indoor Radon in Houses built on Gravel and Sand Deposits in Southern Finland.* Bull. Geol. Soc. Finland **65**(1), 49–58 (1993).

21. Petterson, H. *Radon Exhalation from Building Materials.* SP-RAPP 1982:32. Statens Provningsanstalt and University of Lund, Bôrås (in Swedish) (1982).

22. Yu, K.N. *The Effects of Typical Covering Materials on the Radon Exhalation Rate from Concrete Surfaces.* Radiat. Prot. Dosim. **48**(4), 367–370 (1993).

23. Tso, M. W., Ng, C. and Leung, J. K. C. *Radon Release from Building Materials in Hong Kong.* Health Phys. **67**(4), 378–384 (1994).

24. Castrén, O. *Radon Reduction Potential of Finnish Dwellings.* Radiat. Prot. Dosim. **56**(1–4), 375–378 (1994).

25. Heikkinen, J., Korkala, T., Luoma, M. and Salomaa, H. *Fault Operations and Susceptibility to Disturbing Factors of Ventilation Systems.* Research Notes 737 (Technical Research Centre of Finland, Espoo) (In Finnish. Abstract only in English.) (1987).