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ABSTRACT

The model relates radon concentration to source strength and its variations, air exchange rate and meteorological factors. Two types of sources have been studied. The pressure difference dependent source is made up of radon transported with soil pore air and driven by pressure difference due to the stack effect. The constant source is made up of radon transported by diffusion from building materials or from soil. The air exchange rate depends exponentially on indoor-outdoor temperature difference and linearly on wind speed. These two inputs have been summed in quadrature.

In a house with a constant source radon concentration decreases when the air exchange rate increases due to the increasing temperature difference, whereas the pressure difference dependent source causes an increasing concentration. This is due to the fact that the effect of the source strength increase is stronger than the decreasing effect of air exchange on concentration.

The winter-summer concentration ratio depends on the combination of the two types of source. A pure pressure dependent source leads to the winter-summer ratio of 2 - 3.5 (winter -5 °C , summer +15 °C, wind speed 3 m/s). A strong contribution of a constant source is needed to cause a summer concentration higher than the winter concentration.

The model is in agreement with the winter-summer concentration ratios measured. This ratio increases with the

increasing winter concentration. The measured ratio was near 1.0 for houses with winter concentration of 200 Bq m^{-3} or less and near 2.0 with concentration of 1000 Bq m^{-3}.

In a house with a constant source, the diurnal maximum occurs in the afternoon, while in houses with a pressure difference dependent source the time of maximum is early in the morning.

1. INTRODUCTION

We have measured wintertime indoor radon concentrations several times higher than summertime concentrations[7]. Likewise diurnal variation may be conciderable. Wide temperature variations, with up to 50 °C indoor-outdoor temperature difference in the Nordic countries are obviously one special reason for these variations. Results measured in Finland show that the radon flowing from soil into buildings is the most important source of radon[1]. In order to be able to understand and to make good use of results measured we have developed a model which relates radon concentration to source strength and its variations, air exchange rate and meteorological factors.

2. MODEL

2.1 Stack effect

The stack effect is caused by a difference in temperature between the air inside and the air outside the building. The density of the warmer air inside is lower. The pressure difference can be represented by the following equations[4]:

$$\Delta P = \rho g H \frac{\Delta T}{T} (b_o - b) \qquad (2.1)$$

$$\Delta P = P_s (b_o - b) \qquad (2.2)$$

$$P_s = \rho g H \frac{\Delta T}{T} \qquad (2.3)$$

ΔP is the stack pressure at height b (Pa)

P_s is the stack pressure

b is the dimensionless height , b= h/H when h is the height in m and H is the inside height of the building (m)

b_o	is the dimensionless height of the neutral plane
ρ	is the density of outdoor air
ΔT	is the indoor-outdoor temperature difference (°K)
T	is the inside temperature (295 °K)
g	is the gravitation constant (9.8 m/s^2)

The neutral level is the height at which the inside and outside pressures are equal. Infiltration through the walls occurs on the area between the floor and neutral level and exfiltration occurs above the neutral level. The stack effect also forces the radon rich air below the floor to flow into the building.

2.2 Sources

The flow through joints, holes and cracks in the foundation is the most important mechanism of radon entry from soil into buildings. The driving force for this flow is the pressure difference across the leakage paths. Diffusion through porous building materials or holes in the construction may also be conciderable.

The source comprises two components S_c and S_s. S_c is the constant source which is not affected by the pressure difference across the construction. The transport of radon from S_c occurs by diffusion, the radon source being in the building elements or in the subjacent ground from where it is diffused through the building elements or leakage paths.

S_s is the part of the source which flows from the soil with the pore air driven by pressure difference across the construction and may be represented by the equations:

$$S_s = A_s \; Q_s \qquad (2.4)$$

$$Q_s = F_s \; \Delta T \; T \; / \; T_{out} \qquad (2.5)$$

A_s is the radon concentration of the leakage air (Bq/m^3)

Q_s is the flow rate of soil air into the building, ($m^3\ h^{-1}$)

F_s is the leakage parameter ($m^3\ h^{-1}\ °C^{-1}$)

T_{out} is the outdoor temperature (°K)

It is assumed that the pressure difference dependent flow is laminar and depends linearly on the pressure difference.

Wind may also contribute to the source. On one side of the building wind may increase the pressure difference driving radon from the soil into the building while on the other side the pressure difference may decrease. In this study we disregard the effect of wind on the source and take into account only the decreasing effect of wind on radon concentration. This decrease is caused by increased air exchange.

The leakage parameter F_s accounts for the total leakage area. The relationship between the crack geometry and flow rate will not be studied in this work.

2.2 Air infiltration

The only effects decreasing the indoor radon concentration are air exchange and radioactive decay. Because of the long half life of radon, 3.82 d, the air exchange is the most important. The radon flow from the building due to an air exchange rate N (in air changes h^{-1}) can be written:

$$S_{out} = A\ Q_{out} \qquad (2.6)$$

$$Q_{out} = N\ V \qquad (2.7)$$

S_{out} is the radon flow rate from the building ($Bq\ h^{-1}$)

A is the radon concentration of indoor air ($Bq\ m^{-3}$)

Q_{out} is the air exfiltration rate ($m^3\ h^{-1}$)
V is the inside volume of the building, 270 m^3 below

The radon concentration of exchange air flowing into the building is expected to be negligible.

The Lawrence Berkeley Laboratory (LBL) air infiltration model was chosen for this study because of its rather simple analytical form and because there are good comparisons of measured and predicted results[4,5]. The comparison sites have been selected to represent wide variability in climate, house construction and infiltration rates. Thus the model has been reasonably well tested in conditions comparable with Scandinavian conditions. The model is based on physical simplifications of many effects that enter into the process of air infiltration. In this work a good agreement between measured and predicted infiltration rates is not needed, the model provides a good physical basis for studies on factors affecting indoor radon concentrations.

For weather-driven infiltration there are two independent driving forces: wind and temperature difference caused by the stack effect which is presented in chapter 2.1 . The wind-induced and stack-induced infiltration cannot be simply added together. In the LBL-model the two have been combined in quadrature, because flow is proportional to the square-root of the pressure. Equations 2.8 and 2.9 represents the total infiltration Q . The stack-induced and wind-induced flow rates Q_s and Q_w are represented by equations 2.10-2.15.

$$Q = \left(Q_w^2 + Q_s^2 \right)^{1/2} \qquad (2.8)$$

$$Q = L_o \left((f_{sr} \sqrt{\Delta T}\ )^2 + (f_{wr}\ v)^2 \right)^{1/2} \qquad (2.9)$$

$$Q_s = L_o\ f_s \sqrt{g\ H \frac{\Delta T}{T}} \qquad (2.10)$$

$$Q_s = L_o\ f_{sr} \sqrt{\Delta T} \qquad (2.11)$$

$$f_s = 1/3\ (1 + R/2)\ (\ 1- X^2(2-R)^{-2}\ )^{3/2} \quad (2.12)$$

$$f_{sr} = f_s \sqrt{g\ H\ /T} \quad (2.13)$$

$$Q_w = L_o\ f_{wr}\ v \quad (2.14)$$

$$f_w = C\ (1 - R)^{1/3}\ f_T \quad (2.15)$$

$$f_T = \frac{a_w\ (H_w/10)^{\gamma_w}}{a_t\ (H_t/10)^{\gamma_t}} \quad (2.16)$$

L_o is the total leakage area of the building (m^2) It is the sum of floor, wall and ceiling leakage areas L_f, L_w and L_c.

f_s is the dimensionless stack parameter

f_{sr} is the reduced stack parameter ($m\ s^{-1}\ {}^{\circ}K^{-1/2}$)

f_{wr} is the dimensionless reduced wind parameter

R is the ratio of ceiling and floor leakage area $(L_c + L_f)/L_o$

X is the leakage distribution parameter, $(L_c - L_f)/L_o$

$H_{w,t}$ are the height of the house and the weather measurement tower (m)

$a_{w,t}$ $\gamma_{w,t}$ are terrain parameters for the building (w) and the weather tower (t) respectively, given for standard terrain classes in Table 1

C is the generalized shielding coefficient. The coefficient for five degrees of obstruction around the building is given in Table 2

v is the weather tower wind speed (m/s)

f_T is the terrain factor which converts measured wind speed into effective wind speed

Figure 1 shows the air exchange rate for different temperature difference values as a function of the wind speed. Obviously the effect of temperature variations on the exchange rate is higher when the wind speed is low. The

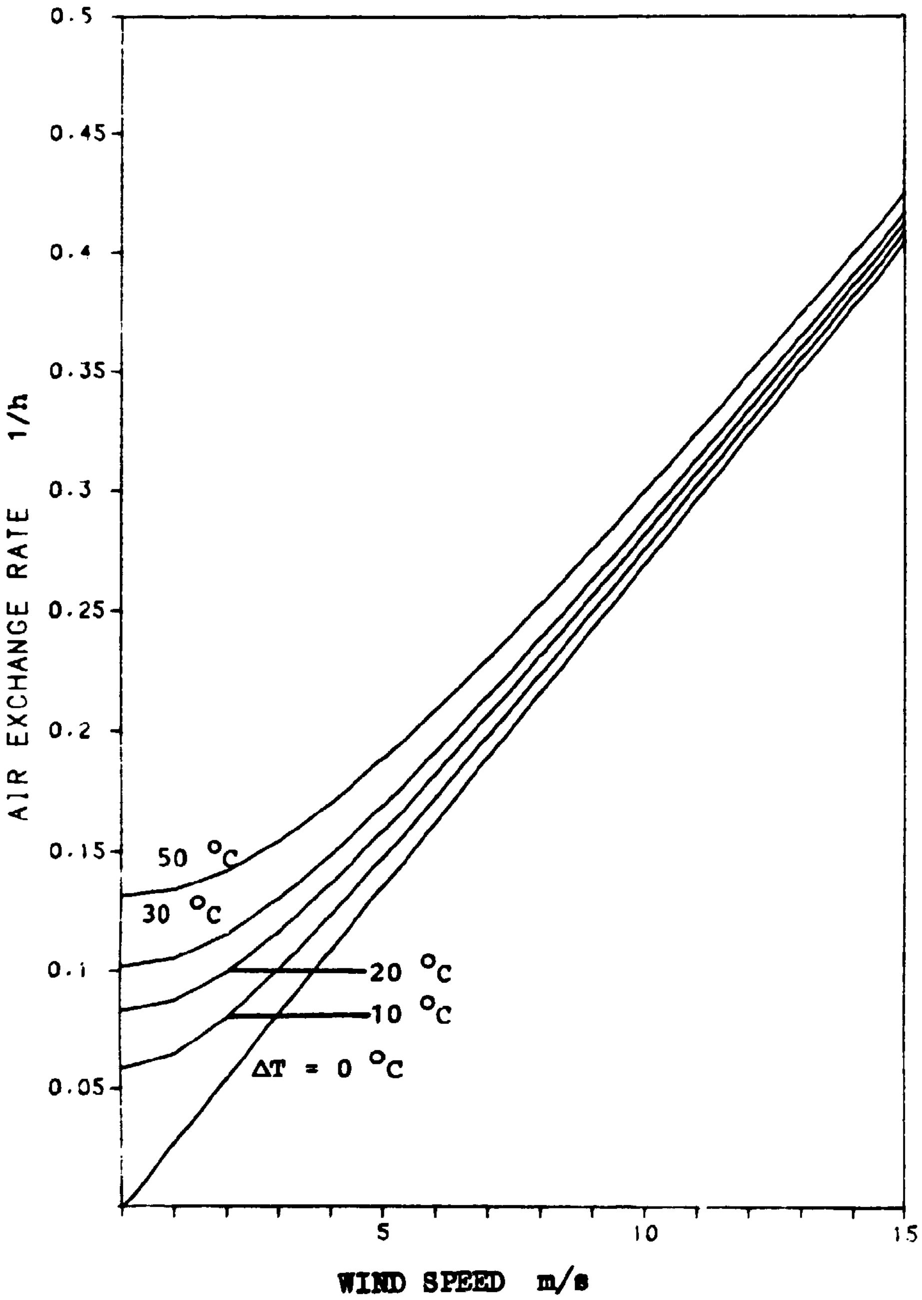

Figure 1
Dependence of air exchange on temperature difference and wind speed , the LBL-model.

values for L_o, f_{sr} and f_{wr} used are 150 cm^2, 0.11 and 0.16.

2.3 Equation

The source terms and concentration decrease by both ventilation and radioactive decay can be combined in a differential equation as follows:

$$dA/dt = -\lambda A - N A + V^{-1} (S_c + S_s) \qquad (2.17)$$

In a constant situation the solution of the equation can be written:

$$A = \frac{A_s \ F_s \ \Delta T \ T \ / \ T_{out} \ + S_c}{(\lambda + N) \ V} \qquad (2.18)$$

For exchange rates $N > 0.1 \ h^{-1}$ the effect of λ is very small and the concentration is inversely proportional to the exchange rate.

For a general situation with varying temperature difference and wind speed a Fortran 5 coded computer program TALOMA was developed for the solution .

2.4 Temperature variations

The maximum temperature occurs during the afternoon usually between 14 and 17 p.m. . In Southern Finland the maximum occurs in winter about 2 h and in summer about 3 h after the time of highest sun position[3]. The diurnal minimum occurs in autumn and winter just before sunrise and in the other seasons just after sunrise. The variations are smaller during cloudy periods than during sunny periods.

Figure 2 shows the average daily temperature variation[3] in January and June in Tampere, which represents a typical non-coastal area in Southern Finland

Figure 3 shows the annual temperature variation[2] in Tampere. Below the months from November to March are called wintertime and months from June to August are called summertime. The average winter and summer temperatures in Tampere are -5.1 °C and +15.1 °C.

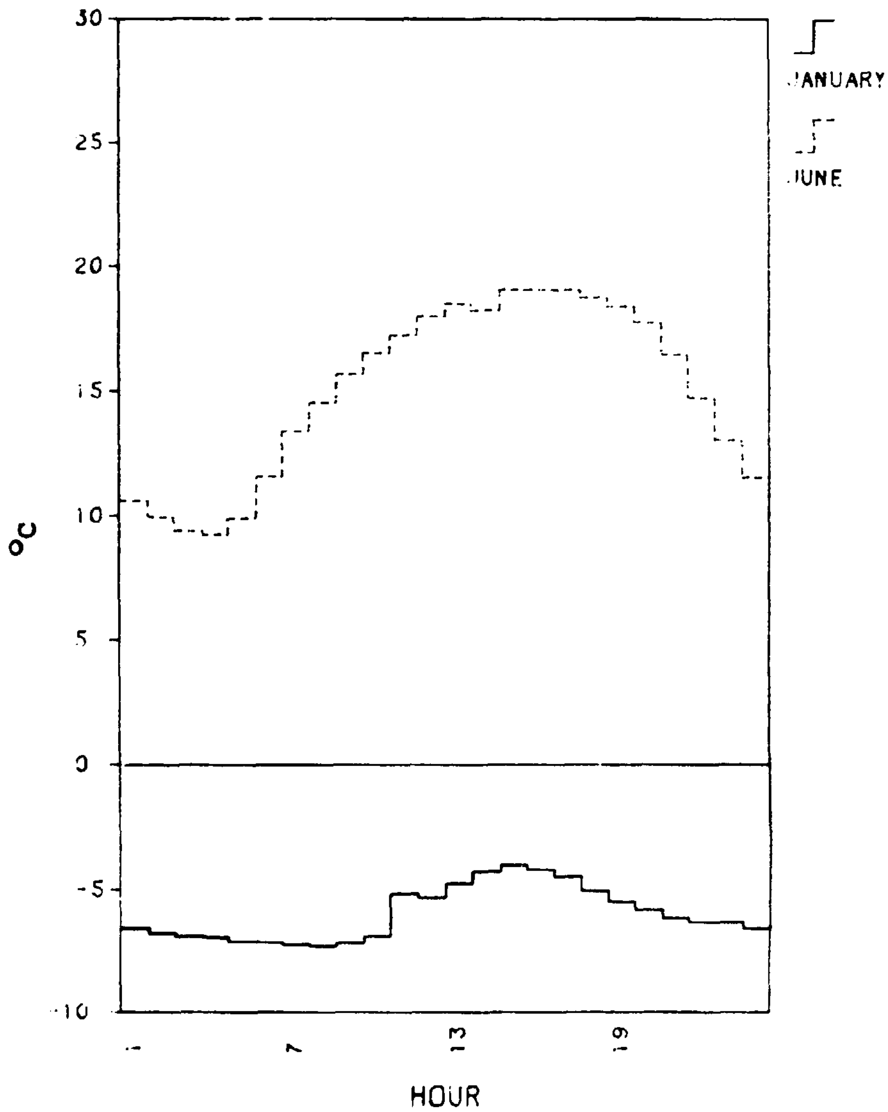

Figure 2
Average diurnal variation of temperature , Tampere.

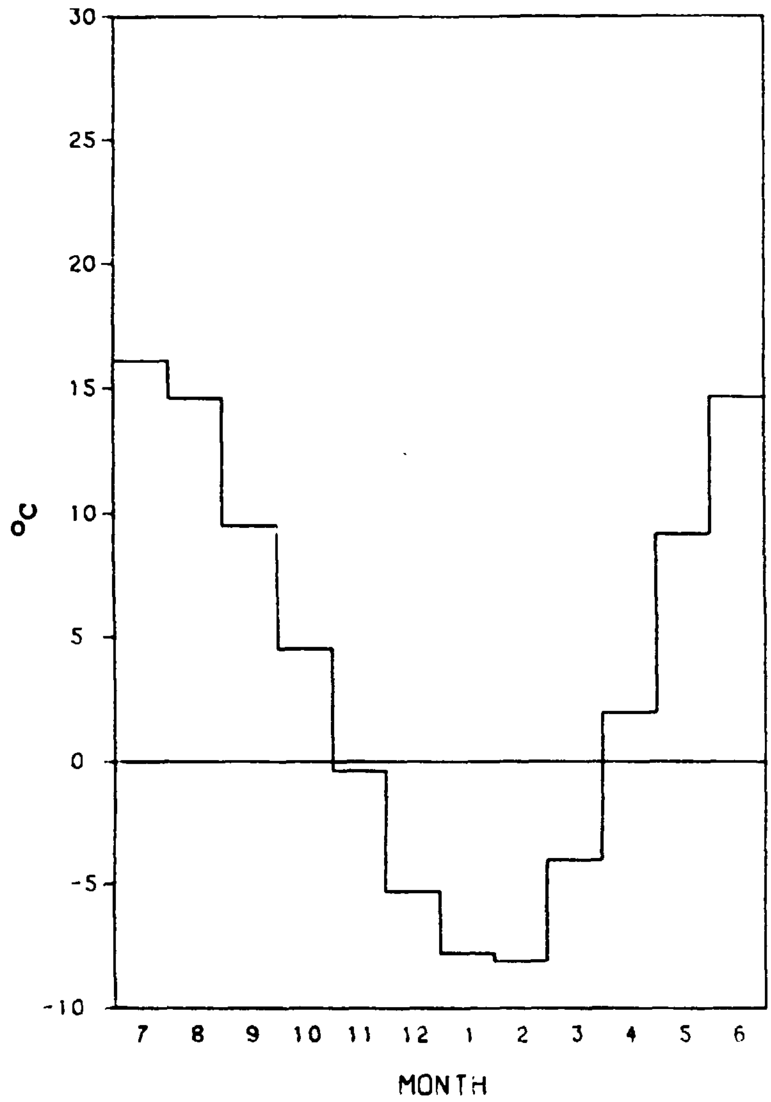

Figure 3

Annual variation of temperature , Tampere.

3. RESULTS AND DISCUSSION

3.1 Air infiltration parameters

In the air exchange measurements of reference 5, different buildings were selected to represent wide variability in climate, house contruction and measured infiltration rates. Ten of these buildings were built on one level. For these buildings the stack parameter was on the average 0.11 (variation 0.09 - 0.12). Five of the one level houses belonged to shielding class 3. The average reduced wind parameter for these was 0.16 (0.14 - 0.18), the terrain factor being 0.76 (0.62 - 0.85).

In the following calculations the air infiltration model parameters f_{sr} and f_{wr} were chosen to be 0.11 and 0.16 representing an average one level house in shielding class 3. Radon concentrations have been calculated for three different air exchange rates with leakage areas of 150, 300 and 750 cm^2. The corresponding air exchange rates with temperature difference of 10 °C and wind speed of 3 m/s are 0.12, 0.24 and 0.60 h^{-1}. The exchange rates with zero wind speed are respectively 0.07, 0.14 and 0.35 h^{-1}.

The relation between the stack parameter and parameters R, X and b_0 is described in reference 4. The equations for the stack parameter in chapter 2.2 are given here to give the reader a good view of the model. In this work we aim to find the relationship between different factors affecting radon concentration and no detailed evaluation of leakage parameters is needed.

3.2 Constant situation

Figure 4 shows the dependence of concentration on indoor-outdoor temperature difference in a constant situation

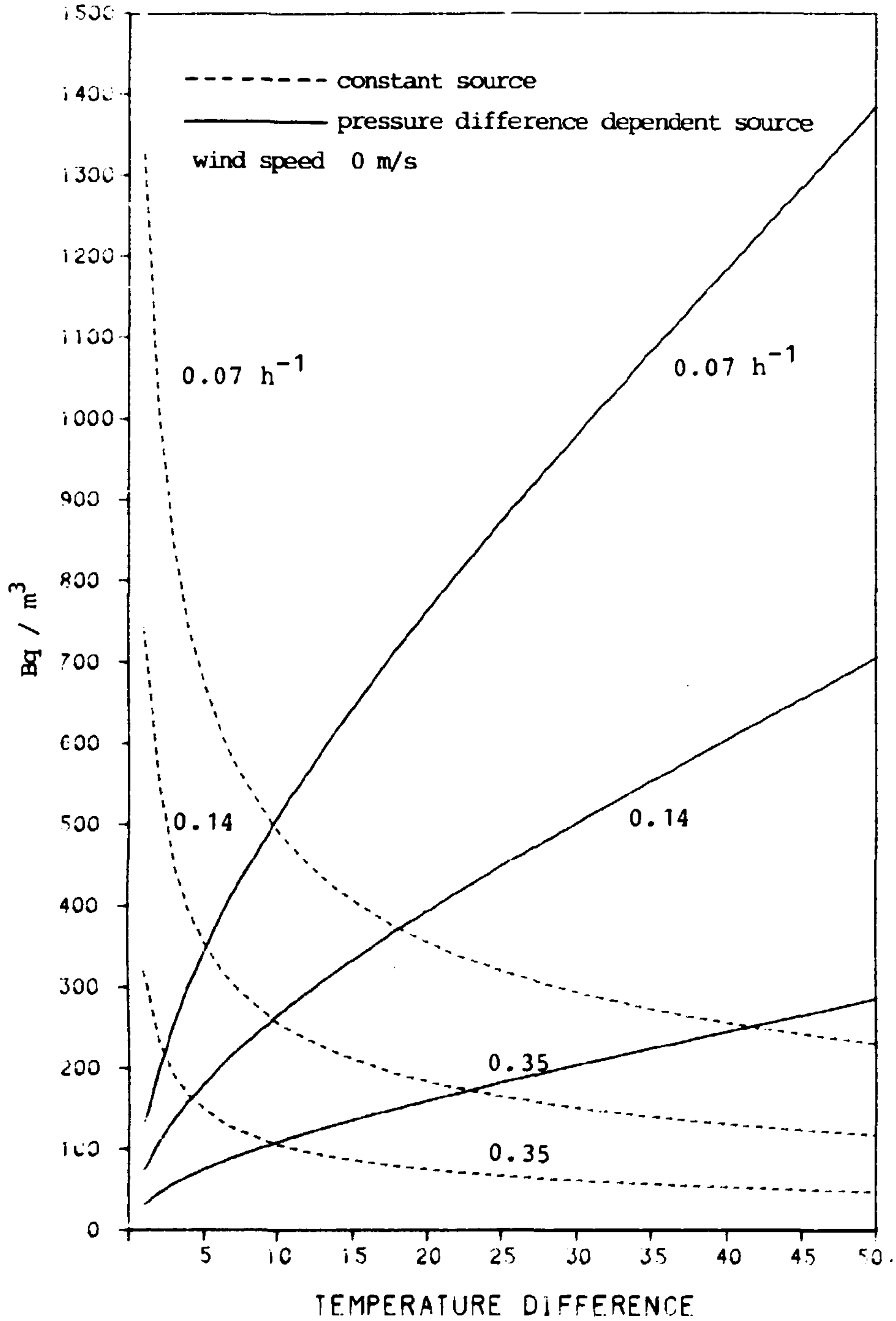

Figure 4

Dependence of radon concentration on indoor outdoor temperature difference in houses with a pure pressure difference dependent or constant source. Air exchange rates at $\Delta T = 10\ °C$ 0.07, 0.14 and 0.35 h^{-1} .

for a house with a constant source of 10000 Bq h^{-1} and a house with a pure pressure difference dependent source of 0.01 m^3 h^{-1}, calculated using equation 2.18. The concentration of the flow is 100000 Bq m^{-3}, hence the source strength at ΔT of 10 °C is also 10000 Bq h^{-1}. Figure 4 shows the dependence for different air exchange rates. Exchange rates of 0.07, 0.14 and 0.35 h^{-1} with ΔT of 10 °C and zero wind speed have been used.

In a house with a constant source, radon concentration decreases when the ventilation rate increases due to the increasing temperature difference, whereas the pressure difference dependent source causes an increasing concentration. This can be explained by the fact that the increase of the source strength is stronger than the decrease of concentration through the air exchange, see equations 2.18, 2.7 and 2.9.

Figure 5 shows the influence of wind. The curve for the constant source, with the average wind speed in Finland of 3 m/s, shows less variation with the temperature difference than the curve for the other source type. The relative effect of wind on concentrations is the same, but for a house with a constant source the absolute decrease of concentration is much higher.

In Finnish detached houses, the source of radon is usually a combination of pressure difference dependent and constant source. Figure 6 shows the radon concentration for different combinations of the two types of sources. In the cases where the pressure difference dependent source is dominant, the constant source has a noticable effect on concentration at low values of temperature difference. This effect is greatly reduced by wind.

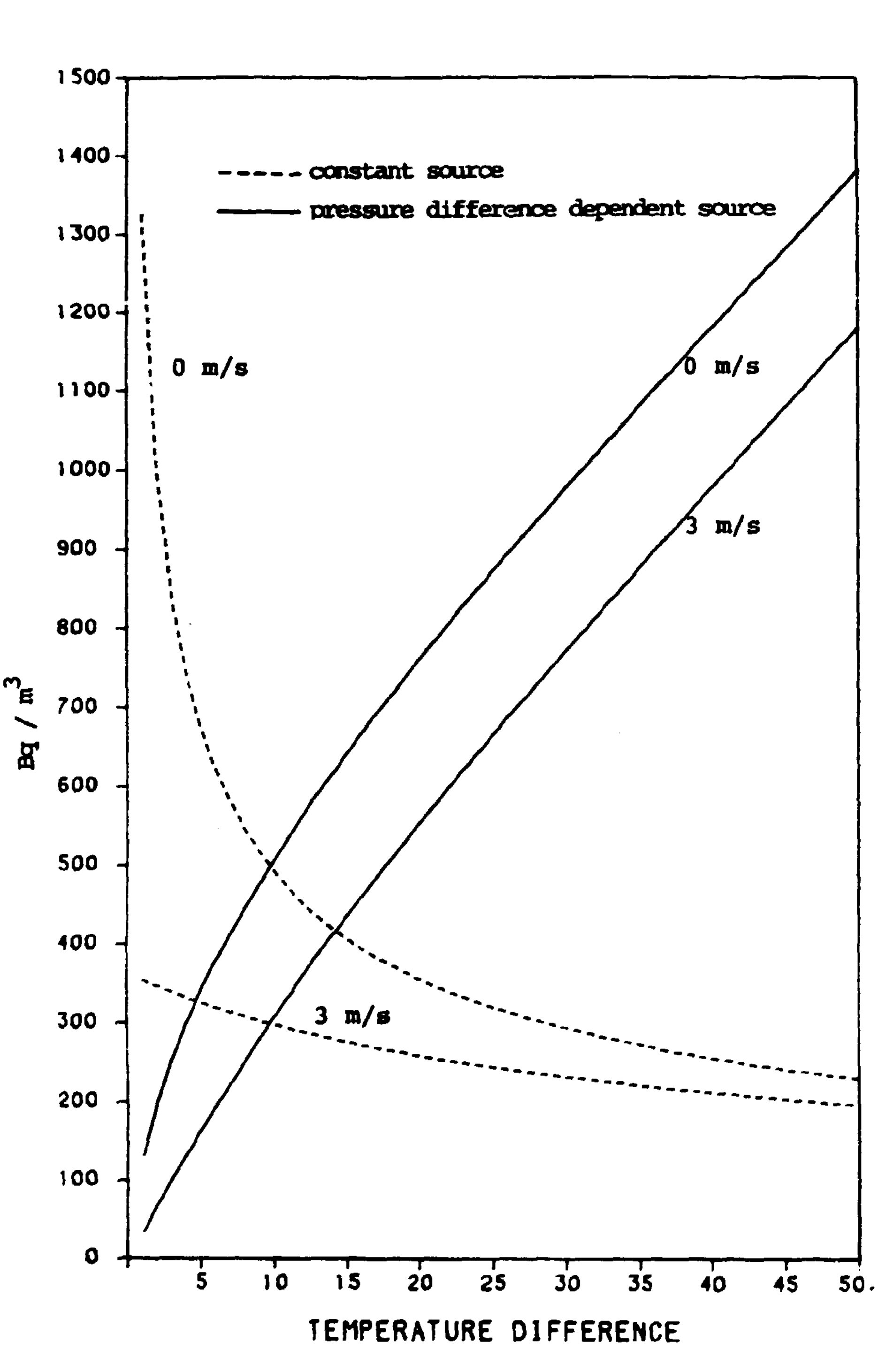

Figure 5
Effect of wind on radon concentration for different types of sources . Air exchange rates 0.07 h^{-1} (v = 0 m/s) and 0.12 h^{-1} (v = 3 m/s) at ΔT= 10 °C.

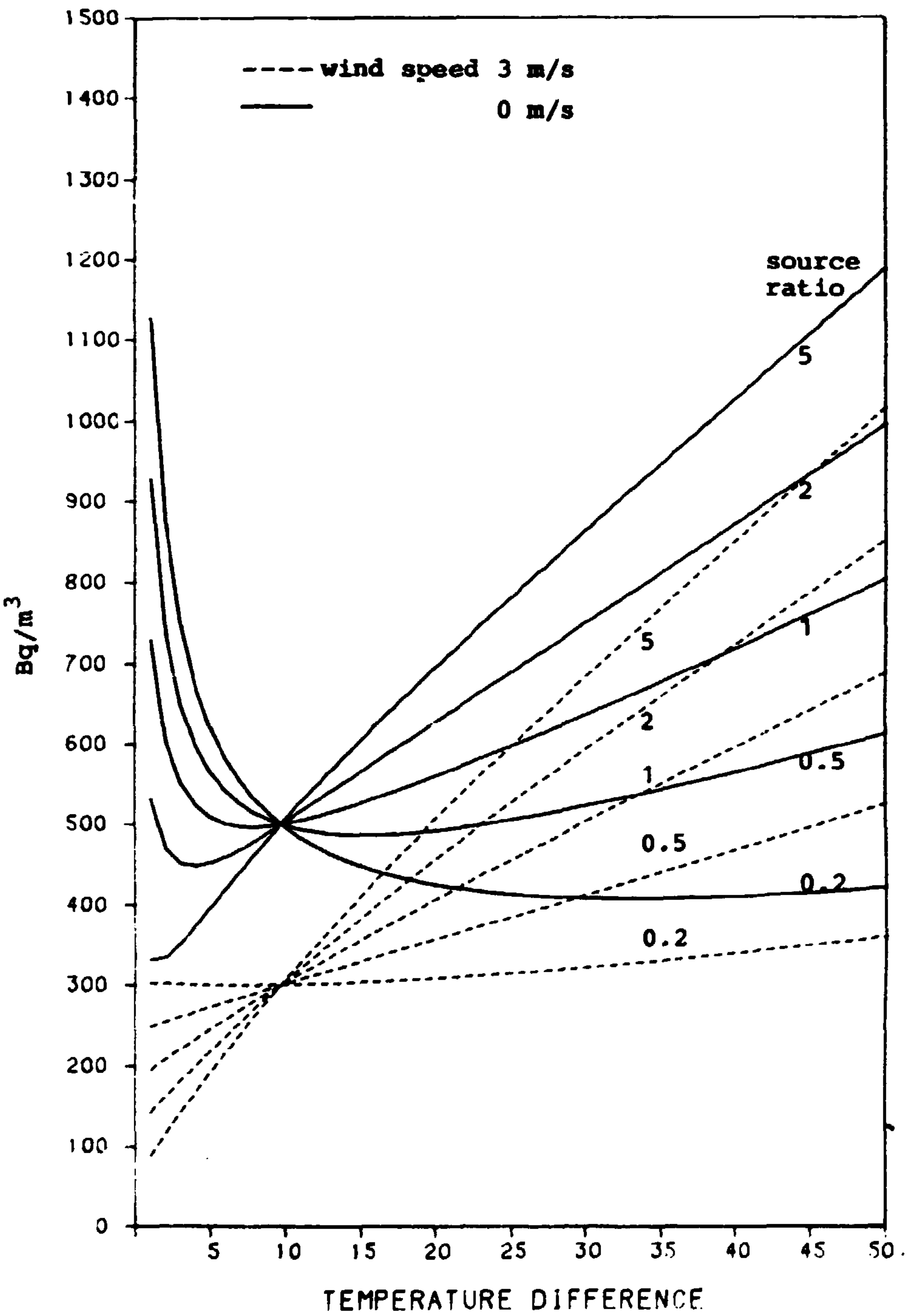

Figure 6

Dependence of radon concentration on temperature difference for different source combinations. The source strength ratio , pressure difference dependent / constant source, at ΔT of 10 °C is given for the combinations.

3.3 Annual variation

The equation 2.18 has been used to evaluate the annual variation of indoor concentration in Finnish houses. The annual temperature variation used in the calculation is presented in figure 3 . Figure 7 gives the annual variation and the effect of wind. Wind reduces the annual variation much more in houses with a constant source than in houses with a pressure difference dependent source.

Figure 8 shows the annual variation in houses with different combination of sources. A strong input of a constant source is needed to make the summer concentration higher than the winter concentration.

3.4 Calculations of the winter-summer ratio

The average (1961-1980) temperature difference during the wintertime (November - March) in Tampere is 27.1 °C and during the summertime (June-August) 6.9 °C. The average wind speeds are 3.4 and 3.1 m/s . The winter and summer concentrations have been calculated using these values and equation 2.18.

Figure 9 gives the winter and summer concentration as a function of pressure dependent source strength for different constant sources. The quotient of winter and summer concentrations is presented in figure 10. The winter-summer ratio increases with increasing pressure dependent source input, the value at 2000 Bq m^{-3} being from 2 to 3 for usual constant source strengths. The level of the constant source in a Finnish detached house with a volume of 270 m^{-3} is normally from 1000 to 4000 Bq h^{-1} . The ratio increases more rapidly towards its maximum value when the input of constant source is low.

Figure 11 gives the winter-summer ratio for different

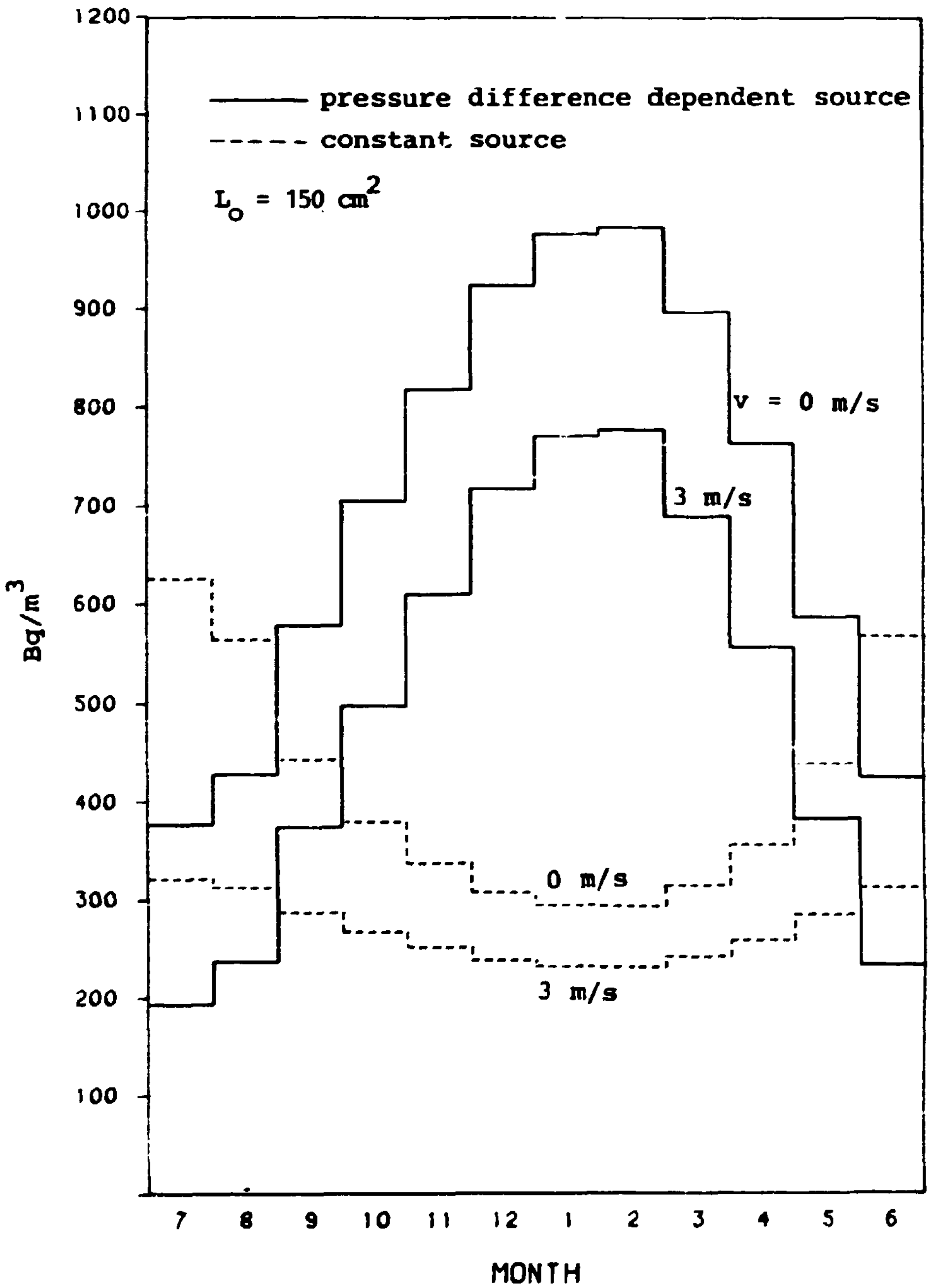

Figure 7
Annual variation of radon concentration for different types of sources. The effect of wind is also shown.

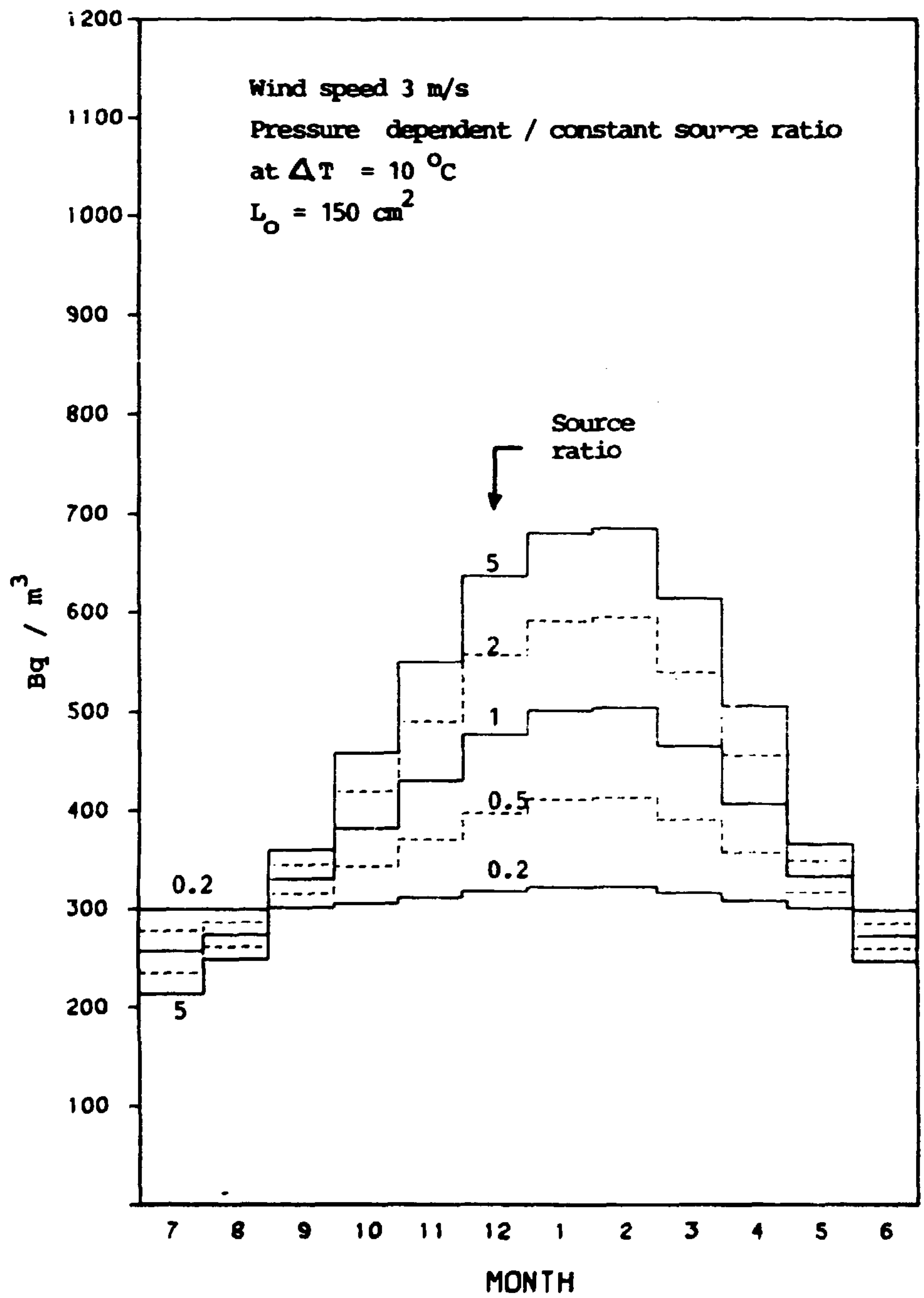

Figure 8
Annual variation for houses with different combinations of sources. Wind speed is 3 m/s.

combinations of sources. In a windless situation, the constant source must be twice the pressure dependent source at ΔT of 10 °C for winter-summer ratio of 1.0. With wind speed of 3 m/s the corresponding factor is about five.

Because of the nonlinear dependence of the radon concentration on the weather parameters, the distribution of wind speed and daily temperature variation should be taken into account when calculating accurately the concentrations. The use of average temperature and wind values causes an error of less than 15 % to the winter-summer ratio.

The calculated winter-summer ratio is rather sensitive to the summer temperature difference value used. Figure 12 shows the curve for ΔT of 4.9 °C when the value for the winter temperature difference is unchanged.

3.5 Measurements of the annual variation

The annual variation of indoor radon concentration has been studied in about 250 detached houses in the Southern Finland [7]. In every house a measurement has been done during winter- and summertime. As dosemeter bare Kodak LR-115 films have been used.

Figure 10 gives measured annual variations as a winter-summer ratio as a function of winter concentration. Each of the points represents measurements in at least 20 houses. The results were collected in concentration groups. The measurement period was 1-2 months and not exactly the same as the periods used in calculations. When comparing calculated and measured values it should be noted that the weather conditions during measurement periods differ from the average conditions used for the calculations. The seasonal variations[6] of soil gas radon concentrations may also affect the results.

Ventilation through open windows is noticable in summertime during warm periods. This is difficult to evaluate numerically and it increases the difference between measured and calculated winter-summer ratios.

Comparison of the measured and calculated results show obvious agreement. In summertime the concentration is higher in houses with low concentration values caused by a rather low constant source from building materials. The highest value of the ratio measured, 3.85 , represents the winter concentration of 1200 - 2000 Bq m^{-3} . The corresponding summer concentrations varied more than in the other summer measurements increasing the inaccuracy of the winter-summer ratio.

More accurate measurements are being carried out with a better dosemeter system based on Makrofol film in a closed plastic cup with filtered air inlets.

3.6 Effect of daily temperature variation

Figure 13 gives the variation of indoor radon concentration when the temperature has a sinusoidal variation of ± 5 °C around an average value of + 10 °C . The sinusoidal curve is a good approximation of measured variations, see figure 2.

In a house with a constant source, the maximum occurs in the afternoon when the ventilation is at a minimum, while in houses with a pressure difference dependent source the time of maximum is early in the morning.

The result calculated is in agreement with the long-term measurements made in many Finnish houses. The dominant observation is the maximum in the early morning.

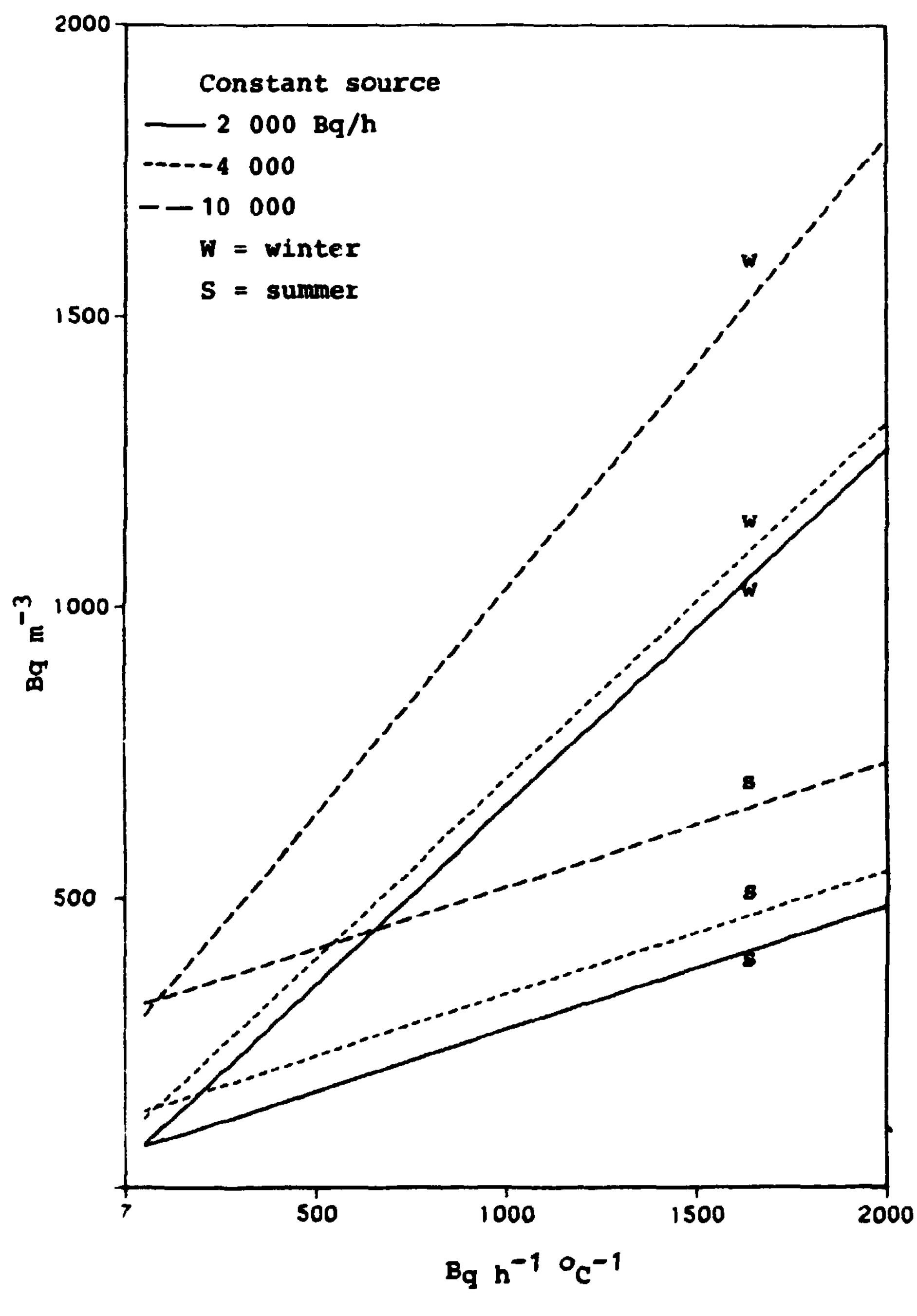

Figure 9
Calculated winter and summer concentrations as a function of pressure difference dependent source strength for different values of constant source.

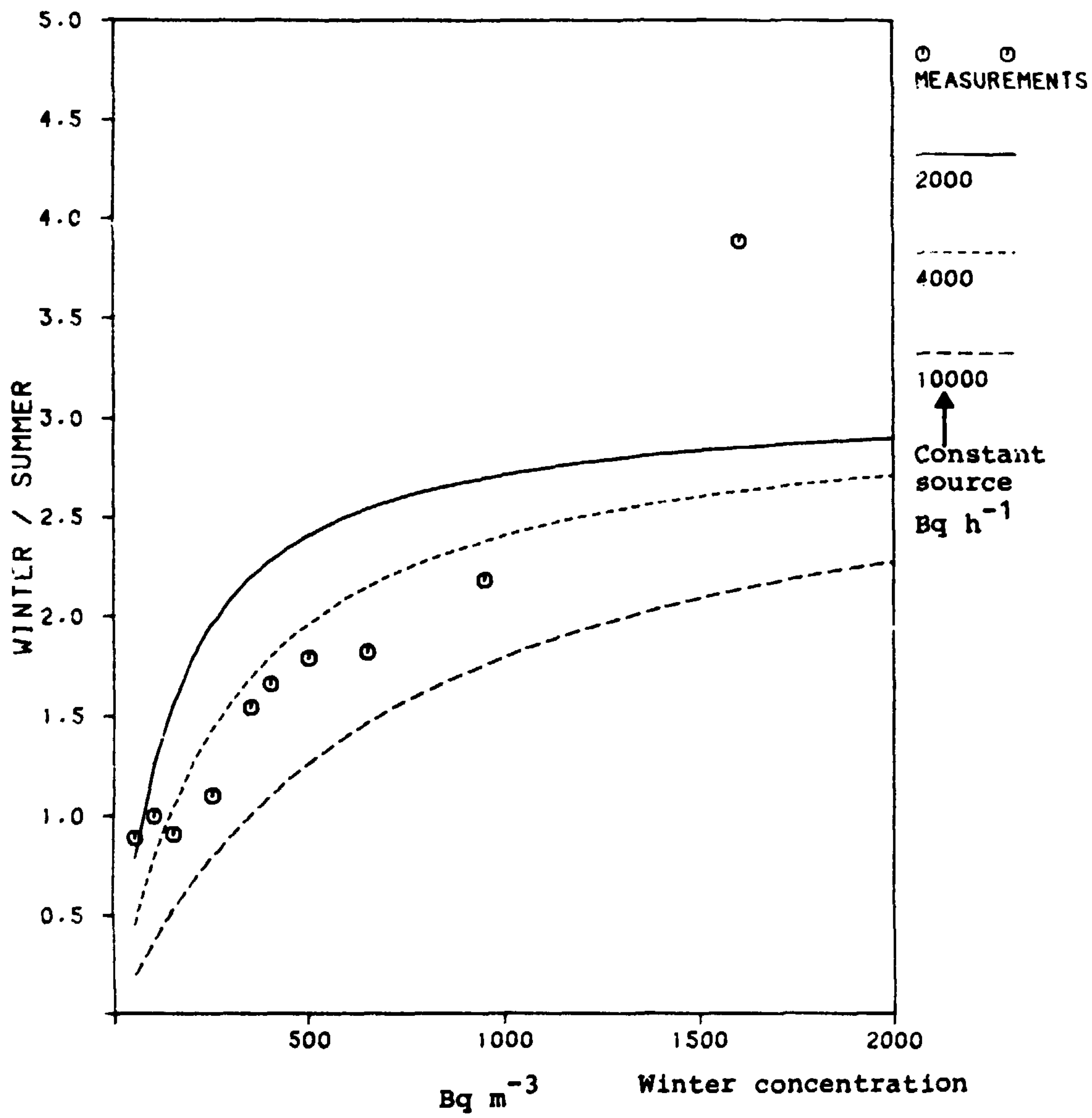

Figure 10
Calculated and measured winter-summer ratio. Curves for different constant sources and varying pressure difference dependent source as a function of winter concentration.

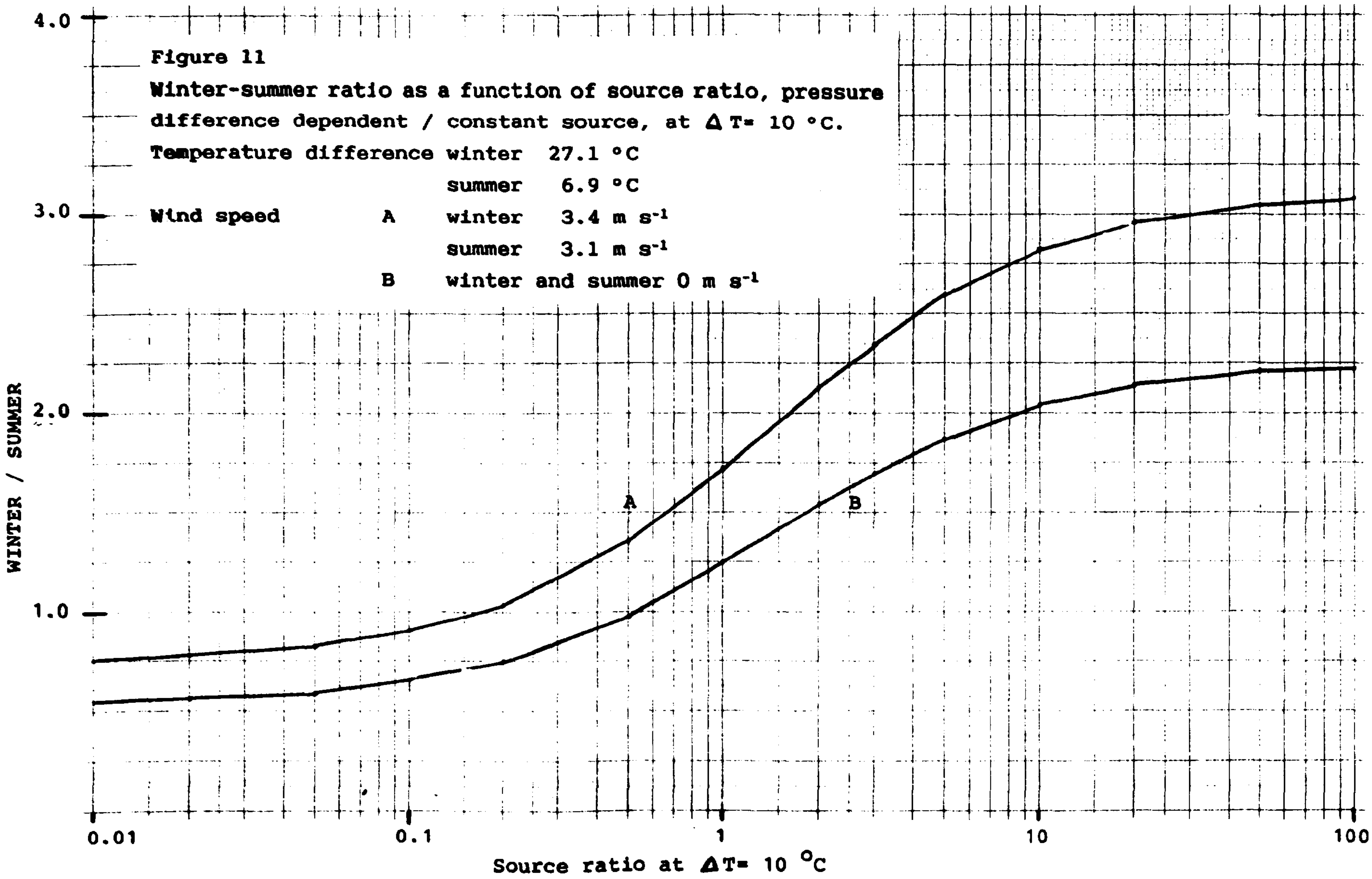

Figure 11
Winter-summer ratio as a function of source ratio, pressure difference dependent / constant source, at ΔT= 10 °C.

Temperature difference		winter	27.1 °C
		summer	6.9 °C
Wind speed	A	winter	3.4 m s^{-1}
		summer	3.1 m s^{-1}
	B	winter and summer	0 m s^{-1}

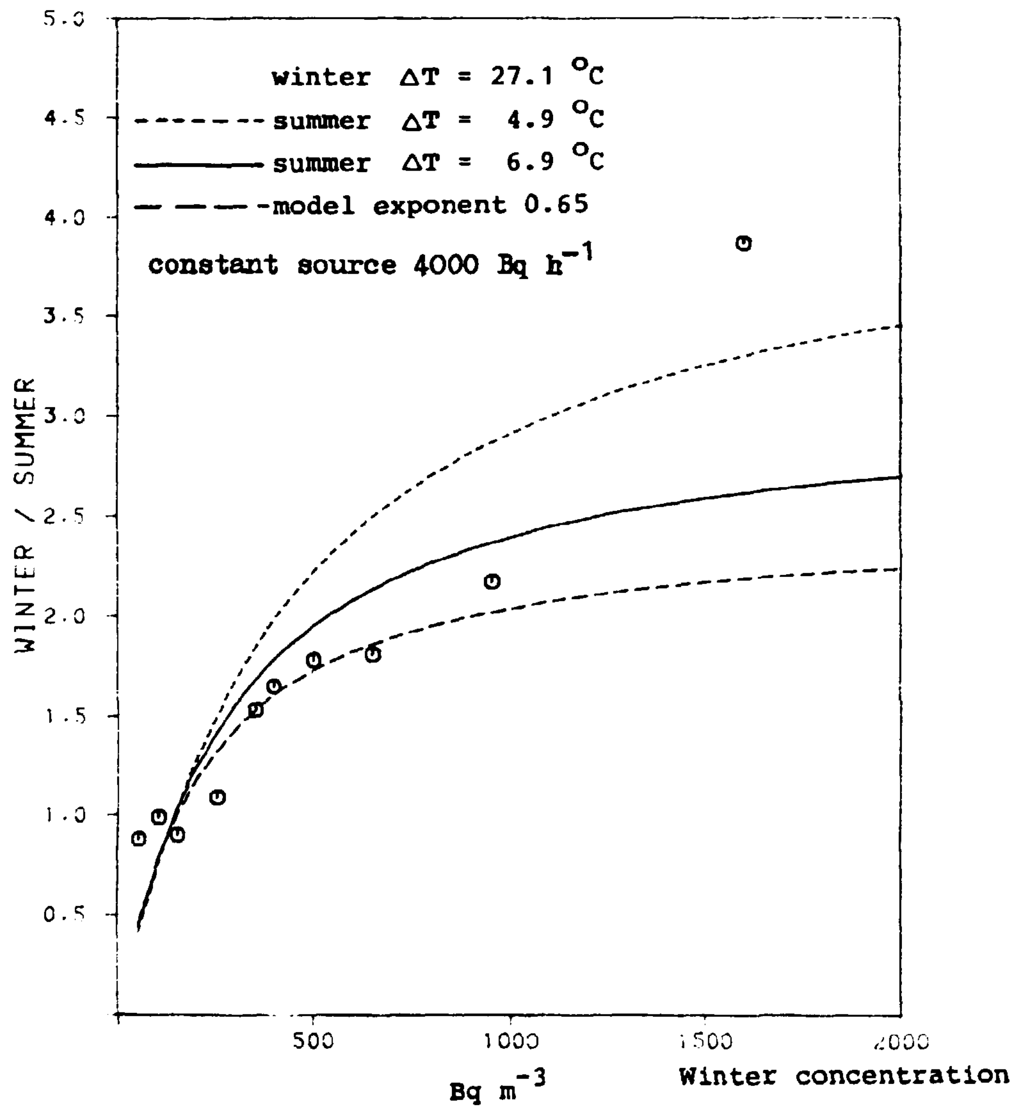

Figure 12
Effect of summertime indoor-outdoor temperature difference and air exchange model on winter-summer ratio.

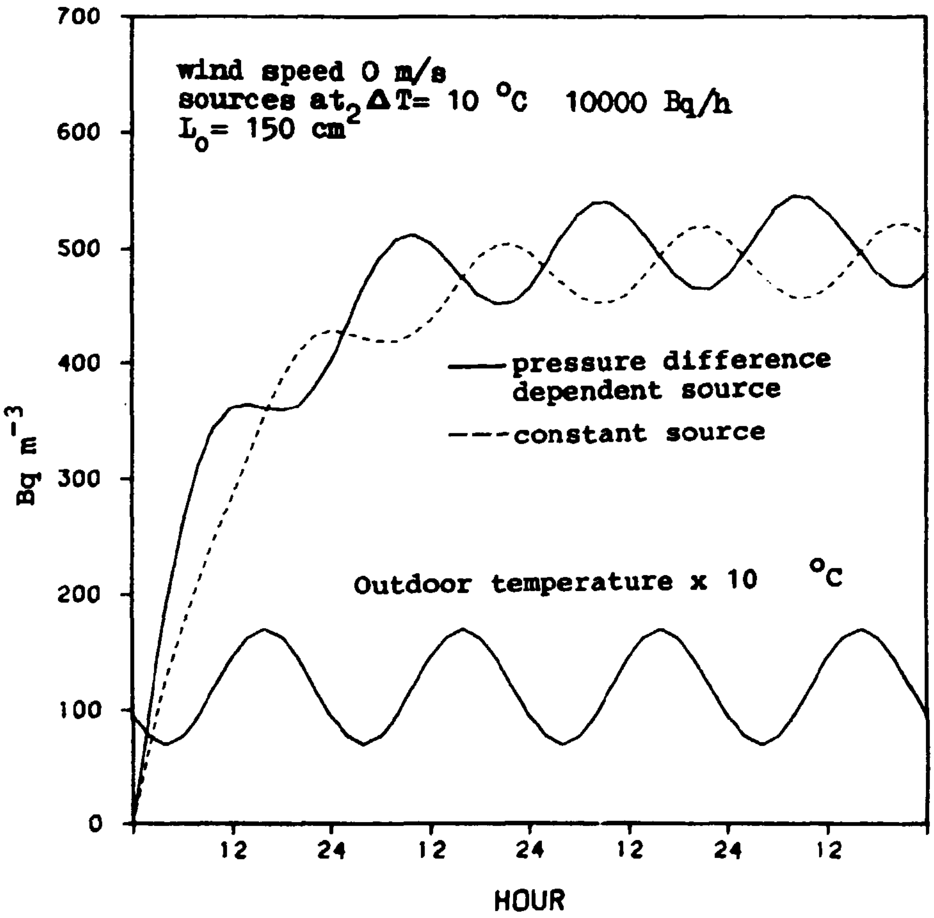

Figure 13

Diurnal variation of indoor radon concentration in a building with a constant or pressure difference dependent radon source and with zero initial concentration.

3.7 Effect of the air exchange model

The factors in the LBL-model affecting most the seasonal and diurnal variation calculated are the exponent of T and the ratio of factors f_{sr} and f_{wr} in equation 2.9. The leakage factor L_0 only changes the level of radon concentration. In Reference 5 measurements and predictions have been compared. As a result the model overpredicts at low pressure values (across the leaks in structure) and underpredicts at high pressures. This is traceable to the fact that the LBL model assumes an exponent of 0.5 for temperature difference and the measured exponent is 0.65 (LBL Mobile Infiltration Test Unit measurement).

The exponential relationship between Δ T and air exchange is a physical simplification of reasonable accuracy. The flow versus pressure behavior of a building more closely resembles turbulent ($Q \sim T^{1/2}$) than laminar ($Q \sim T$) flow. In theory the exponent is near 1.0 only in houses with a very low air exchange rate, being between 0.5 - 0.7 in most houses.

The effect of the exponent can roughly be demonstrated by replacing the exponent 0.5 by 0.65 in equation 2.9. Figure 12 shows the result. The winter-summer ratio decreases by about 20 % at high values of winter concentration.

Taking into account the inaccuracies above, the winter-summer ratio for a Finnish house with a pure pressure difference dependent source is from 2 to 3.5 .

4. CONCLUSION

The model is in agreement with the measured values. The interaction between the stack effect dependent radon source and the air exchange contribute to the observed high winter-summer ratios. To find dwellings with high radon concentrations the radon measurements in Finland have been carried out at least once during wintertime. The model supports the practice chosen.

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Table 1

Terrain parameters for standard terrain classes /4,5/

Class	γ	a	Description
1	0.10	1.3	Ocean or other body of water with at least 5 km of unrestricted expanse.
2	0.15	1.00	Flat terrain with some isolated obstacles.
3	0.20	0.85	Rural areas with low buildings, trees, or other scattered obstacles.
4	0.25	0.67	Urban, industrial or forest areas or other built-up area.
5	0.35	0.47	Center of large city or other heavily built-up area.

Table 2

Generalized shielding coefficients /4,5/

Class	C	Description
1	0.324	No obstructions or local shielding whatsover.
2	0.285	Light local shielding with few obstructions.
3	0.240	Moderate local shielding, some obstructions within two house heights.
4	0.185	Heavy shielding, obstructions around most of perimeter.
5	0.102	Very heavy shielding, large obstruction around perimeter within ten meters.

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