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ANALYSIS OF INDOOR RADON IN DIFFERENT VENTILATION SYSTEMS

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ABSTRACT

The pressure driven flow of radon gas from soil through the permeable floor increased radon levels indoors in the houses with mechanical ventilation systems. The enchanced ventilation increased pressure under a slab, which caused the increased convective flow. We tested several equations that estimate radon levels indoors. Soil radon activity, exhaust air flow, subpressure differences and air tightness were measured for substitution in equations. The calculated and measured radon values agreed well for the natural vantilation and for the mechanical exhaust ventilation. The agreement was not so good for the combined air supply and exhaust system. Our equation was found to be the most widely applicable in estimation of indoor radon level. Both theory and measurements revealed the importance of floor tightness.

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INTRODUCTION

Radon gas enters the house through floor or through walls of a basement driven by positive pressure in soil. The other radon source is exhalation from tap water and building materials. The last mechanism has not been found to cause high radon levels indoors in Finland (1).

In several works (2, 3, 4) the radon level is assumed to depend directly on the strength of radon source and inversely on the air exchange rate. The other mechanism affecting radon level is the pressure difference between indoors and the subslab space. The high pressure difference may enchance radon leakage to indoor air; and the difference usually increases with enchanced air exchange rate. We propose an equation notifying both effects of air exchange.

The aim of the study was to examine the accuracy of estimated indoor radon level based on different equations, in which we substituted the measured values of air exchange and of radon activity in soil.

MATERIALS AND METHODS

Three two-story concrete townhouses are constructed on a slab. They locate on a gravel esker in Eastern Finland. The only difference between the houses is the ventilation system: the first has natural ventilation, the second has mechanical exhaust, and the third has combined air supply and exhaust system. There are in each house six apartments having separate ventilation system so that tenants can regulate ventilation after their will.

Radon levels indoors were measured in December 1987 during a week. The analysis of radioactivity was carried out by using the Lucas cell method (5) with the Pylon AB-5 detector assembly (6). The computer controlled the data collection system that registered the amounts of exhaust air (7). The pressure differences were monitored by a manometer.

Accuracy of the equations for indoor radon, which were presented by Nazaroff et al. (3), D'Ottavio and Dietz (4) and Kokotti et al. (this work), was examined. The measured values of radon in soil, air exchange rate, air tightness and pressure difference changes were employed for practical calculations.

The equations studied are based on the model presented by Bruno in 1983 (2). It takes the influence of air exchange rate n (h^{-1}) into consideration with the equation:

(1) $C = G/nV + C_o$,

where G (Bqh^{-1}) is the total strength of radon source from soil, building materials and water, V (m^3) is the house volume, C and C_o the indoor and outdoor concentrations of radon (Bqm^{-3}), respectively.

Nazaroff et al. described (3) the dependence of indoor radon concentration C (Bqm^{-3}) on air exchange rate n (h^{-1}) by the following equation ignoring the outdoor concentration in addition to decay time constant λ ($0.0076h^{-1}$)

(2) $C = k_f + б_d/n$ and $k_f = б_f/n = f_s C_s$,

where $б_d$ is a diffusive component and $б_f$ a flow component of the radon entry rate per house volume ($Bqm^{-3}h^{-1}$). The sum of these components is the total radon source strength (G) per the house volume (V). Nazaroff et al. assumed that the term k_f is independent on ventilation rate and computed k_f to be 43 ± 1 (Bqm^{-3}) and 220 ± 10 (Bqm^{-3}) for the low and high soil activity, respectively.

The diffusive component o_d of the radon entry is constant, if soil activity is ignored, and its value becomes 2.1 ± 0.2 ($Bqm^{-3}h^{-1}$). We utilized these constants and the measured ventilation rates in the study houses for our calculations.

The most comprehensive model for indoor radon level is given by D'Ottavio and Dietz (4). Their equation also considers the outdoor-indoor temperature difference dT and wind speed u.

(3) $$C = \frac{f_s C_s}{1 + an} + \frac{б_d}{n} + C_o \quad \text{and} \quad a = \frac{0.0729\ dT + 0.0777\ u^{1.5}}{0.0106\ dT + 0.0257\ u^{1.5}}$$

When dT is from 4 to 16 ^oC and u between 1.0 and 3.5 ms^{-1}, a becomes 5.3 ± 1.0. After substituting all known values the equation has the form

(4) $$C = \frac{1.34}{1+5.3n} + \frac{0.06}{n} + 0.3\ (pCi\,l^{-1})$$

We tested this equation after converting it to SI units with the factor of 37.

The equations (5) and (6) are proposed by us. These notify the convection by the leakage air through the slab and the time dependent variation of radon level. During short periods with differences in pressure, in ventilation rate and in air tightness the radon concentration varies as

(5) $$C = (G/(n+\lambda)/V)\ (1-e^{-(n+\lambda)t}) + C_o.$$

The exponential term including the ventilation rate balances the removal of indoor radon only partially, because its effect is smaller than the effect of the first term. In addition the effect of the balancing term decreases with increasing ventilation. At long periods the exponential term becomes near zero. So the equation (5) can be utilized for calculations estimating the limits of radon indoors during short periods with different conditions.

G (Bqh^{-1}) is the total strength of the source due to building materials (G_M), diffusion (G_D), and convection (G_C) from the soil. We assume that the convective flow is not constant and independent on the ventilation rate.

Because the convection depends on pressure difference and air tightness the following equation can be presented:

$$(6) \quad G_C = 0.12\ C_s\ (q_{50}/50^{0.73})\ dp^{0.73},$$

where q_{50} is the flow of leakage air with 50 Pa indoor-outdoor pressure difference, and dp the pressure difference between indoor and soil. The factor 0.12 bases on the experimental study of the air leakage pathways of a house and describes the fraction of the leakage air entrying through the slab as compared to the total amount of leakage air.

RESULTS AND CONCLUSIONS

The measured average indoor radon concentration was 52 Bqm^{-3} in the house with natural ventilation. The measured level agreed fairly with the values obtained from the different equations. The equation by Nazaroff et al. (2) with low soil activity, and the equation (5) presented by us without the effect of convection, were most consistent (Table 1). The overall fit of calculated values is satisfactory, as seen from figure 1.

TABLE 1. THE MEASURED AND CALCULATED RADON CONCENTRATIONS IN THE HOUSE WITH NATURAL VENTILATION

	Radon concentration C (Bqm^{-3})			
	mean	std.dev.	minimum	maximum
The equation:				
Nazaroff et al. (2)				
-low soil activity *	56	1	57	59
-high soil activity	237	1	236	239
D'Ottavio and Dietz (4)				
f_s=0.0020; a=5.3	49	1	47	52
Kokotti et al. (this work)				
-with convection	347	161	92	616
-without convection	56	18	24	85
Measured	52	20	-	-

* Soil activity was measured to be 7 000 Bqm^{-3}.

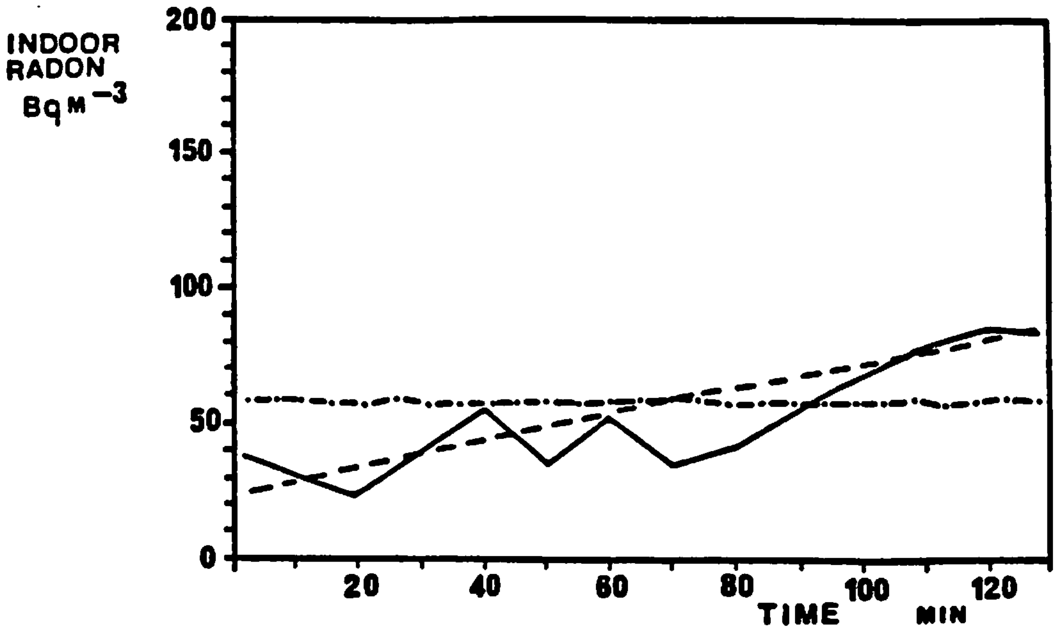

Figure 1. The measured and calculated radon levels in the house with natural ventilation. Lines: measured ———, calculated by the equations: (2) —·—·—·—, (5, 6) – – – –.

The measured and calculated radon values agreed fairly well (Table 2) in the house with combined air supply and exhaust system. At minimum ventilation effectiveness the measured radon level 25 Bqm^{-3} was best predicted by the equation of D'Ottavio and Dietz, which yielded exactly the same result. The equation with low soil activity by Nazaroff et al. and our equation without convection resulted the most accurate value (Table 2). At high ventilation rate notifying of convection in the strength of radon source is needed.

The comparison of the theory with the measurements revealed importance of the convective flow in the house with combined air supply and exhaust ventilation at high ėffectiveness in this case. We found that the indoor radon level increased with the increasing air exchange. This is in contradiction with the generally assumed form of ventilation effect (see eq. 1). We observed however, that the convective flow can be neglected in the natural ventilation, and in the balanced mechanical ventilation at minimum effectiveness. The estimations without any time depences gave rather consistent radon values. The proposed new equation was capable to estimate time variation of radon level, as seen Figures 1 and 2.

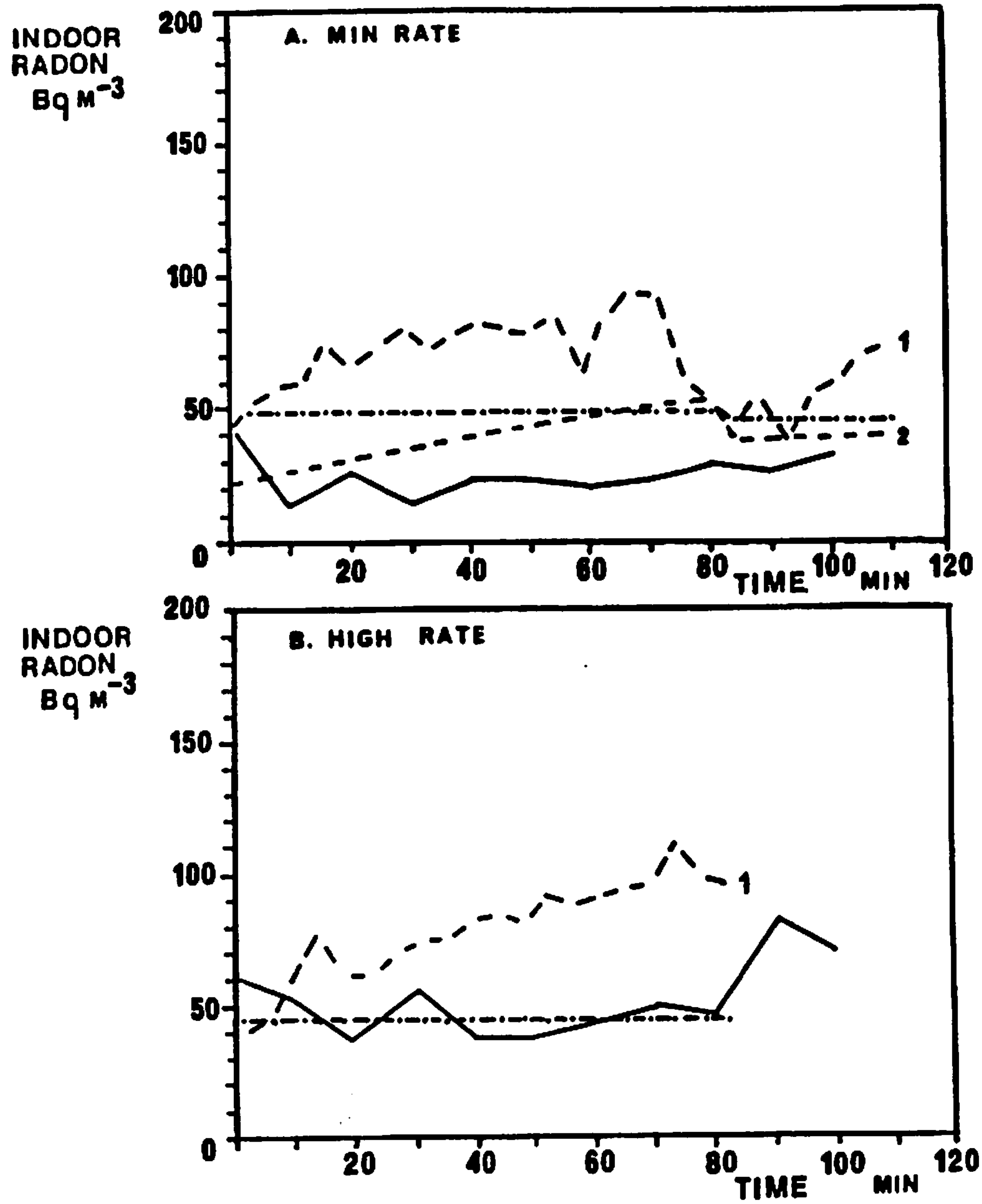

Figure 2. The measured and calculated radon levels in the house with combined air supply and exhaust system at a. minimum and b. high ventilation rate. Lines: measured ———, calculated by the equations: (2) —·—·—, (5, 6) – – – – (1 with convection and 2 without).

TABLE 2. THE MEASURED AND CALCULATED RADON CONCENTRATIONS IN THE HOUSE WITH COMBINED AIR SUPPLY AND EXHAUST SYSTEM AT MINIMUM AND AT HIGH VENTILATION RATE

	Radon concentration C (Bqm^{-3})							
	mean		std.dev.		minimum		maximum	
Ventilation rate	MIN	HIGH	MIN	HIGH	MIN	HIGH	MIN	HIGH
The equation:								
Nazaroff et al. (2)								
-low soil activity *	48	45	2	0	44	45	49	45
-high soil activity	227	224	2	0	224	224	228	224
D'Ottavio and Dietz (4)								
f_s=0.0020 ; a=5.3	25	15	5	0	15	15	28	15
Kokotti et al. (this work)								
-with convection	60	44	22	25	10	3	93	80
-without convection	34	24	13	11	8	2	53	36
Measured	25	53	8	14	-		-	

* Soil activity was measured to be 4 000 Bqm^{-3}.

TABLE 3. THE MEASURED AND CALCULATED RADON CONCENTRATIONS IN THE HOUSE WITH MECHANICAL EXHAUST VENTILATION AT MINIMUM AND AT HIGH VENTILATION RATE

	Radon concentration C (Bqm^{-3})							
	mean		std.dev.		minimum		maximum	
Ventilation rate	MIN	HIGH	MIN	HIGH	MIN	HIGH	MIN	HIGH
The equation:								
Nazaroff et al. (2)								
-low soil activity *	250	47	76	0	117	47	513	47
-high soil activy	430	226	76	0	296	226	693	226
D'Ottavio and Dietz (4)								
f_s=0.0020 ; a=5.3	273	23	82	0	126	22	557	23
Kokotti et al. (this work)								
-with convection	234	279	42	92	161	106	333	430
-without convection	67	45	20	10	32	26	100	58
Measured	267	332	47	42	-		-	

*Soil activity was measured to be 16 000 Bqm^{-3}.

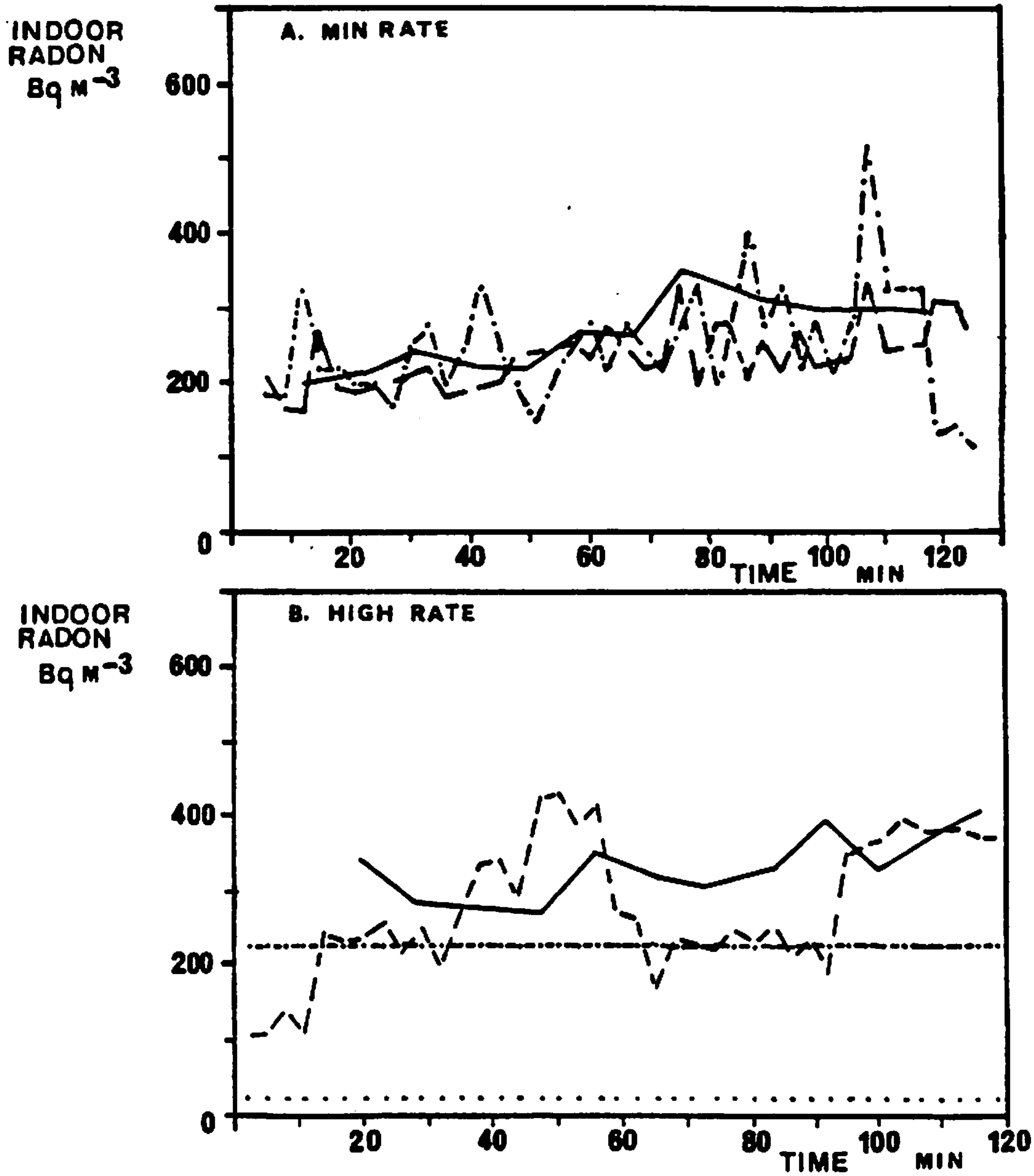

Figure 3. The measured and calculated radon levels in the house with mechanical exhaust ventilation at a. minimum and b. high ventilation rate. Lines: measured ———, calculated by the equations: (2) —·—·— , (5, 6) – – – –, and (4) ·····.

The measured average concentration of indoor radon was 267 Bqm^{-3}, when the mechanical exhaust was set to minimum effectiveness. The equation of Nazaroff et al. yielded the result 250 Bqm^{-3} using the low soil activity. The average radon level obtained by the equation of D'Ottavio and Dietz succeed best in comparison with the measured value (Table 3). Our proposed equation computed slightly lower levels than by others. The overall fit of our calcuted values is, however, satisfactory, as seen in Figure 3.

When the air exchange was set to high effectiveness, the average measured level of radon indoors was 332 Bqm^{-3} (Table 3). The equation proposed by us gave the indoor radon level almost the same as the measured one; and the curves fit well at different times. The other equations yielded about constant values due to high constant ventilation rate (Figure 3). It is assumed that the ventilation effects more on the removal than on the entry of radon, in these equations.

All calculations and measurements proved that radon levels can be predicted rather accurately. In addition we propose that the convection should be notified by the leakage air equation including air tightness and pressure differences. We should not neglect the permeability of the floor or of the walls of a basement, and the convective flow, especially in the house with mechanical ventilation systems. High ventilation rate affects in two ways on the level of radon indoors. It increases both removal and entry of radon gas. The study proved that the concentration of radon increased with the increasing ventilation rate in the houses with mechanical ventilation systems.

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REFERENCES

1. Mustonen, R. Natural radioactivity in and radon exhalation from Finnish building materials. Health Physics. 46:1195-1203, 1984.

2. Bruno, R.C. Sources of indoor radon in houses: A review. Journal of the Air Pollution Control Association. 33:2:105-109, 1983.

3. Nazaroff, W.W., Feustel, H., Nero, A.V., Revzan, K.L., Grimsrud, D.T., Essling, M.A., and Toohey, R.E. Radon transport into a detached one-story house with a basement. Atmospheric Environment. 19:1:31-46, 1985.

4. D'Ottavio, T.W., and Dietz, R.N. Radon transport into a detached one-story house with a basement: Discussions. Atmospheric Environment. 20:5:1065-1067, 1986.

5. Lucas, H.F. Improved low-level alpha-scintillation counter for radon. Rev. Sci. Instrum. 28:680-683, 1957.

6. Vandrish, G., and Lebel, A. Techniques and equipment for residential radon monitoring. Paper presented at 1986 Air Pollution Control Association Conference on Indoor Radon. Philadelphia, PA., February, 1986.

7. Savolainen, T., Raunemaa, T., and Wellman, K. Automatic measurement and data collection system on indoor air study at three small housing flats. In: Proceedings of the 4th International Conference on Indoor Air Quality and Climate. Institute for Water, Soil and Air Hygiene, Berlin. Vol 2: 129-134, 1987.