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Radon and Radon Daughters Indoors, Problems in the Determination of the Annual Average

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Abstract

The annual average of the concentration of radon and radon daughters in indoor air is required both in studies such as determining the collective dose to a population and at comparing with limits. Measurements are often carried out during a time period shorter than a year for practical reasons.

Methods for estimating the uncertainties due to temporal variations in an annual average calculated from measurements carried out during various lenghts of the sampling periods. These methods have been applied to the results from long-term measurements of radon-222 in a few houses. The possibilities to use correction factors in order to get a more adequate annual average have also been studied and some examples have been given.

Keywords (chosen by the author)

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Dwellings

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47

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RADON AND RADON DAUGHTERS INDOORS, PROBLEMS IN THE DETERMINATION OF THE ANNUAL AVERAGE

Gun Astri Swedjemark

A INTRODUCTION

Many measurements of radon and radon daughters are performed in order to calculate an annual average. For practical reasons, these measurements are often carried out during a time period shorter than a year. Earlier, grab samples were the only method available for large scale measurements. For the past few years, simple integrating instruments have been used, the integrating time being different for various instruments.

The aim of this investigation was to study the methods for estimating the uncertainty due to temporal variations in an annual average calculated from measurements carried out during various sampling time periods and to study the practicability of using correction factors in order to obtain a more adequate annual average.

The annual average can be defined in different ways. It can refer to the true exposure of the occupants and it can refer to the house used in a normal way. One aim of measurements may be to calculate the exposure of a population from RnD. Another aim may be to compare the results of the measurements with limits. In this case the house used with normal ventilation ought to be the important object and not the occupants. To obtain reproducible values for comparison with limits, in practical situations some restrictions on the ventilation must be specified for the measuring period also when integrating methods are used.

A measurement during an entire year would not give the correct annual average for the house either. This is due partly to variations in the weather from one year to another, partly to variations in the habits of a family from one year to another or changes of families. When in the following, the "true" annual average is given, it is true according to the temporal variations for this particular family and this particular year.

To get the total uncertainty in the annual average, the uncertainty due to the measuring method should be added to the uncertainties due to the temporal variations. Those differ between the instruments. To avoid complications, statistical methods have been applied to long-term measurements of radon for which the uncertainties due to measuring have been found to be approximately similar for the actual levels.

NOMENCLATURE

Abbreviations used in the text are explained and some definitions are given below.

EER, the equilibrium equivalent concentration of radon.

RADON, ^{222}Rn, the radon isotope in the natural uranium decay series.

RADON DAUGHTERS, the decay products following ^{222}Rn in the natural uranium series.

RnD, short-lived radon daughters.

THORON, ^{220}Rn, the radon isotope in the natural thorium decay series.

THORON DAUGHTERS, the decay products following ^{220}Rn in the thorium series.

Ventilation systems

- FT system, mechanical controlled inlet and outlet air.
- F system, mechanical exhaust air.
- S system, natural draught ventilation.

1 Radon sources

The ground, the building materials and the tap water are possible radon sources for the radon concentration indoors. The radon exhalation rate G depends on what source the radon gas comes from.

When the major radon source is the building materials the radon exhalation rate G varies with sudden drops in the atmospheric pressure as was shown by Mac Laughlin and Jonasen (Mc78) and confirmed by Stranden(St80b). A pressure drop of one millibar gives an increase in the radon concentration by 5 - 10 %. The exhalation rate also varies with pressure increases, temperature and humidity, but usually not as much as with pressure drops in existing dwellings. However, damp concrete may have an exhalation rate higher by a factor of up to 30 than completely dry concrete (Pe82, St83). For ordinary concrete thickness this implies that measurements of the radon concentration in a newly built house should not be made until six months after casting the concrete (Pe82).

However, for existing dwellings in normal use the radon concentration depends to a major extent on the ventilation rate when the dominant radon source is the building materials. The radon exhalation rate G in Eq 5 can then be treated as a constant.

The ground may cause the highest radon concentration indoors. When the ground is the major radon source, the radon exhalation rate varies strongly by the pressure indoors in relation to the air pressure outdoors. An appreciable degree of underpressure indoors causes radon to be sucked from the ground under the building if there is not an airtight layer between the basement and the ground. Added to this are the variations of the radon exhalation from the ground under the house, variations which are not well known. Investigations of the radon flux through the soil, the concrete slab or cracks and into the house (Ed80, La82, La83, He84), measurements of the radon exhalation from various conditions (Li84) and measurements of the radon concentration indoors and in the soil-gas (An83, Ak83) have shown that there are many important parameters. Examples are changes in the atmospheric pressure and changes in the humidity.

The exhalation rate G is therefore very time-dependent and cannot be regarded as even approximately constant.

The tap water is used intermittently in a dwelling and therefore the radon exhalation is not constant when the tap water contains high radon activities. With regular living habits in the dwellings, the average radon exhalation rate G might be regarded as a constant over periods of at least a week.

The outdoor air concentrations of radon and thoron vary from place to place. At the same place the concentrations vary with changes in the atmospheric pressure, the temperature, the humidity, the wind strength, the wind direction etc. However, in most Swedish dwellings the concentration of radon is much higher indoors than outdoors. Therefore, the variations in the outdoor air can be neglected and the radon concentration of the outdoor air, C_{in}, can be treated as a constant in Eq 5. An exception is regions with high radon exhalation from the ground during periods of marked inversion. Israelson et al (Is72, Is82) have investigated the variations of radon and thoron at a place near Uppsala where the radon exhalation from the ground is higher than normal. The radon concentration has varied between 20 Bq m^{-3} and 200 Bq m^{-3} and the thoron concentration between 70 Bq m^{-3} and 200 Bq m^{-3}. It has not yet been investigated if the combination of high radon exhalation from the ground and inversion might be of any significance for the annual dose in the lungs.

The concentration of thoron (^{220}Rn) with its daughters in the indoor air in Sweden is not yet very well known. Because of the short half life, 55 seconds for the thoron-gas, no concentrations of importance have been expected in Swedish dwellings. Nor were high values found in the measurements by Hultqvist (Hu56) in dwellings built before 1946 or in the few measurements made later. However, during the last few years it has been found (Åk83, An83) that the ground is of more importance for the penetration of radon into houses than had previously been expected. No measurements of thoron or its daughters in houses built on ground containing high levels of thorium-232 have yet been carried out.

The thoron gas can not be expected to diffuse through the bottom slab because of its short half life, but it follows with the flow of ground air through holes in the bottom slab, e.g. for water-pipes, power cables etc, or through cracks in the concrete. It is therefore possible that there are dwellings in contact with thorium-rich ground which have high concentrations of thoron and its daughters.

For houses with low RnD concentrations, several workers (St79, Wi79. C180, Gu82) have found potential alpha energies of thoron of 20 to 200 % of the potential alpha energies of radon. These values are of no practical importance for the health effects.

Because of the short half-life of the thoron gas, the concentration indoors does not depend on the air change rate. The half-life of one of the daughters, however, is longer than the half-life of the RnD and the daughter concentration therefore depends on the ventilation rate.

For the case when the dominant radon source is the building materials the radon content of a room is determined by the radon exhalation from building materials and the ventilation rate.

We assume a room with volume V m^3, wall area A m^2, radium content Q Bq m^{-3} in the building material and ventilation rate ℓ m^3h^{-1}. If the effective diffusion coefficient of radon in the building material is D m^2h^{-1}, the wall thickness is h m, λ is the disintegration constant for radon or thoron, ϕ is the net exhalation rate per unit area and $C(\infty)$ is the radon or thoron concentration in the room, the total net exhalation rate into the room is, for steady state:

Eq 1 $$A\phi = A\sqrt{\lambda \cdot D}\left(\frac{Q}{\lambda} - C(\infty)\right)\tanh\sqrt{\frac{\lambda}{D}}\,h$$

The radon influx is, for steady state, balanced by the removal due to radioactive decay and ventilation.
Thus:

Eq 2 $$\frac{A}{V}\sqrt{\lambda D}\left(\frac{Q}{\lambda} - C(\infty)\right)\tanh\sqrt{\frac{\lambda}{D}}\,h = \lambda C(\infty) + \ell(C_o - C_{in})$$

when C_{in} is the radon concentration in the outside air, which gives

Eq 3
$$C(\infty) = \frac{\frac{A}{V}\sqrt{\frac{D}{\lambda}} \cdot Q \tanh \sqrt{\frac{\lambda}{D}}\, h + \ell\, C_{in}}{\lambda + \ell + \frac{A}{V}\sqrt{\lambda \cdot D} \tanh \sqrt{\frac{\lambda}{D}} \cdot h}$$

The term $A/V \sqrt{\lambda D} \tanh \sqrt{\lambda/D}\, h$ in the denominator is normally quite small compared to $\lambda + \ell$ because reported values for the diffusion length $\sqrt{D/\lambda}$ for concrete and bricks are in the range 0.05 - 0.25 m (Jo80, Kr71, St80b, Za83). The ratio A/V in ordinary dwellings is of the order of 1 m^{-1} and this implies that the term is of minor importance.
Thus if

Eq 4
$$G = A \sqrt{\frac{D}{\lambda}} \cdot Q \tanh \sqrt{\frac{\lambda}{D}} \cdot h$$

we get

Eq 5
$$C(\infty) = \frac{G/V + \ell \cdot C_{in}}{\ell + \lambda}$$

When estimating the effects of the ventilation rate on the radon concentration it is thus permissible to ignore the effects of back-diffusion, which makes the calculation of time variations quite simple. Thus after a change in the ventilation rate, resulating in a change in the radon concentration from a steady state value C_o to a new steady state value $C(\infty)$, $C(t)$ is given by

Eq 6
$$C(t) = C(\infty) \left(1 - e^{-(\lambda + \ell)t}\right) + C_o\, e^{-(\lambda + \ell)t}$$

When the change in radon content is due to changes in exhalation rate the situation is more comlicated. Using the diffusion model, such changes can be described formally as changes in the effective diffusion coefficient or in the apparent source strength Q or both. Provided these changes can be described quantitatively, which is normally not the case, the radon concentration as a function of time can be found by solving the diffusion equation

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - \lambda C + Q$$

where x is the depth in the wall.

The solutions of this equation depend on the pertinent boundary conditions and can normally be obtained as the sum of a rapidly converging series of error functions or the like with the arguments $\sqrt{\lambda t}$ and $(nh)/(2\sqrt{Dt}) \pm \sqrt{\lambda t}$ which implies that the time scale for such a change is of the order $1/\lambda$ ($\approx$ 100 h) for thick building elements (i.e. when $\sqrt{\lambda/D}\, h$ is relatively large) and h^2/D for thin elements. This implies that when the wall thickness is more than the diffusion length it can in practice be regarded as an infinitely thick wall from the diffusion point of view.

2 The influence of ventilation

As has been mentioned, variations in the ventilation rates are the primary cause of the variations in the concentration of radon and thoron daughters indoors. The ventilation consists both of the intentional ventilation, when the air goes through the ventilation system, and of the unintentional ventilation, when the air goes through badly sealed walls etc.

The intentional ventilation rate does not change very much with time in houses with regulated mechanical inlet and outlet systems (FT systems). It varies somewhat in houses with mechanical exhaust systems (F systems) and it varies greatly in houses with natural draught ventilation systems (S systems).

The unintentional air changes depend on the airtightness of the house. However, both the S and F ventilation systems are based on inlet of the air through air regulators or air leaking round windows etc. These houses can therefore not be made quite airtight if the ventilation is supposed to work. No dwelling can in reality be made quite airtight but it is possible to reduce air changes to less than 0.1 h^{-1} with modern building techniques.

Consequently, the air change rate can not be treated as a constant during any extended time interval except for houses with FT systems without window airing. Also a dwelling in a multi-family house with F ventilation, where the unintentional air changes are less than in detached houses with a greater outer wall area, the ventilation rate varies, thus varying the radon concentration. This is illustrated in Fig. 1 which shows an attempt to adapt various ventilation rates to a long-term registration made in a closed bedroom in a dwelling in a multi-family house with F ventilation built in the 1960s (House A). The radon exhalation rate was expected to be constant because the building materials were the major radon source and the atmospheric pressure was steady during the measuring period, about 1010 mbar. Therefore, the variations in the radon exhalation can not have contributed to the variations in the radon concentration to any major degree. The air change rates have varied from 0.18 to 0.10 h^{-1} during these rather steady conditions.

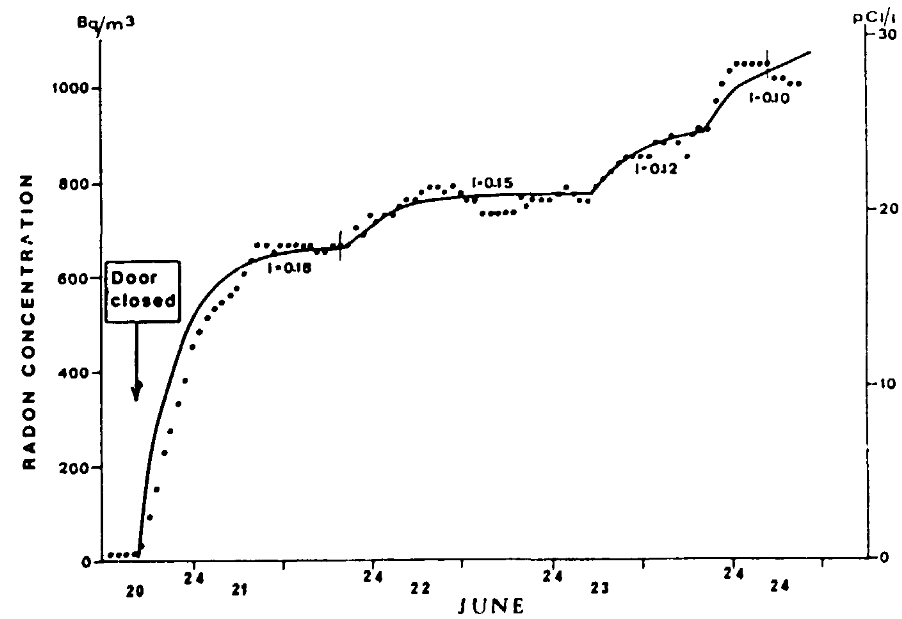


Fig. 1. Long-term registration in a dwelling in a multi-family house (House A) built of aerated concrete based on alum shale and heavy concrete with a mechanical exhaust ventilation system compared with the calculated curve for the given air change rates.

To reach the new steady state level for the radon concentration a long period of time is needed after the air change rate has been decreased or increased. The period of time required depends mainly on the air change rates before the change, ℓ_o, and after the change, ℓ_1. If the radon exhalation rate is assumed to be constant, equations 5 and 6 give:

Eq 7 $$C(t) = C_1 + (C_o - C_1) \cdot e^{-(\ell_1 + \lambda)\, t}$$

Eq 8 $$C_o = \frac{C_{in} + G/V}{\ell_o + \lambda}$$

Eq 9 $$C_1 = \frac{C_{in} + G/V}{\ell_1 + \lambda}$$

where C_0 is the steady state value before the change of the ventilation and C_1 is the steady state value after the change.

When the air change rate is decreased, the time needed to reach the fraction p of C_1 can be derived from Eq 7 giving:

Eq 10 $$t = \frac{1}{\ell_1 + \lambda} \ln \left(\frac{1}{1 - p} \cdot \frac{\ell_o - \ell_1}{\ell_o + \lambda}\right) \qquad \ell_o > \ell_1$$

For p = 0.95 the curves in Fig. 2 are obtained. For small ℓ_1 values the curves approach each other between $\frac{1}{\lambda}$ ln 10 ($\approx$ 303 hours) and $\frac{1}{\lambda}$ ln 20 ($\approx$ 394 hours) for the extreme values of $\ell_o \approx \lambda$ and $\ell_o >> \lambda$ respectively.

When the air change rate is increased, the time needed to reach $C_1 + p\, C_0$ can be shown to be:

Eq 11 $$t = \frac{1}{\ell_1 + \lambda} \ln \frac{1}{p} \frac{\ell_1 - \ell_o}{\ell_1 + \lambda} \qquad \ell_o < \ell_1$$

For p = 0.05, Eq (11) gives the curves in Fig. 3. When $\ell_1 >> \ell_o$, $\ell_1 >> \lambda$ and the curves will coincide.

The air change rates in dwellings in Sweden vary from less than 0.1 h^{-1} to several air changes per hour. For newly built single family houses the air change rates are mostly about 0.3 h^{-1} and in old single family l uses perhaps 1 h^{-1} (En77). The air change rates averaged over a whole year are very time consuming to determine in houses with S ventilation and especially in old houses which may be far from airtight. Energy saving campaigns have been in progress since 1973 and this will tend to decrease the air change rates even in most old single-family houses. In multi-family houses the air change rates average about 0.6 h^{-1}, i.e. they are often higher than in single-family houses (En77).

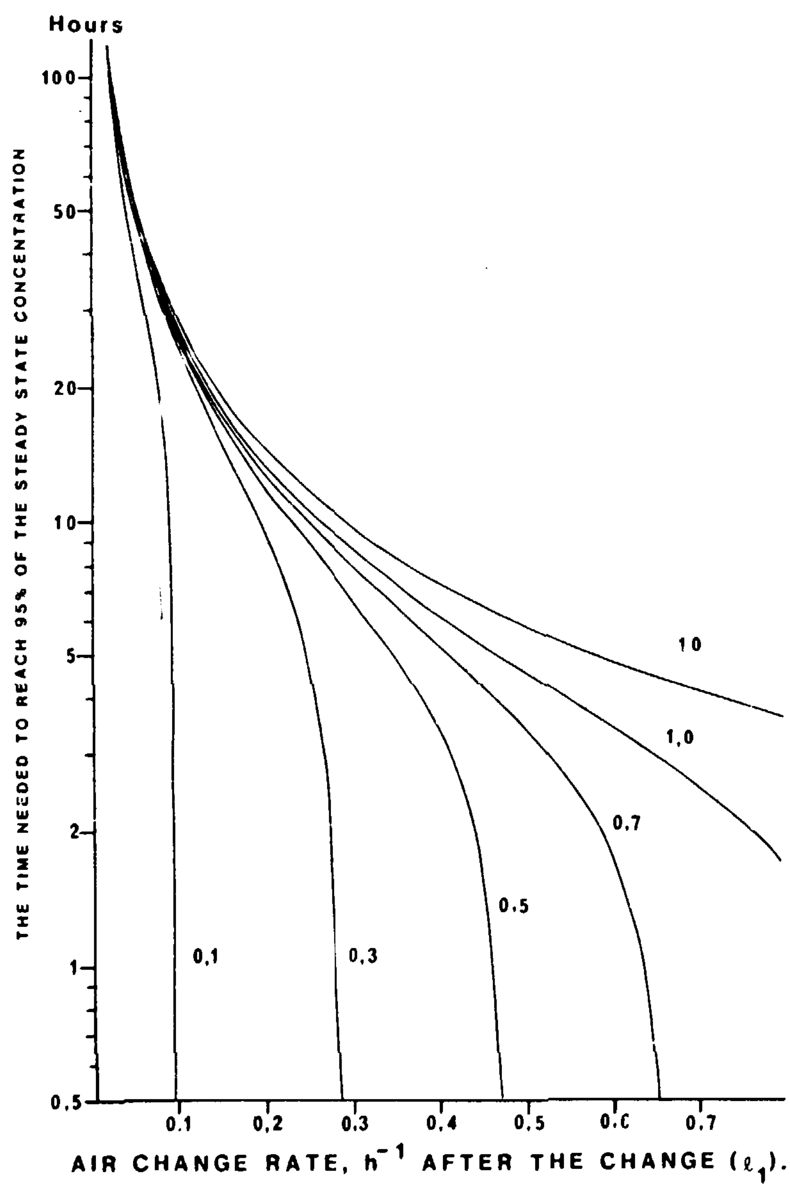


Fig. 2. The time needed to reach 95 % of the steady state concentration of ^{222}Rn when the air change rates have been decreased from ℓ_o to ℓ_1 air changes per hour according to Eq 10. The curves have been calculated for various values of ℓ_o as functions of ℓ_1. They are only valid when the exhalation rate can be regarded as constant.

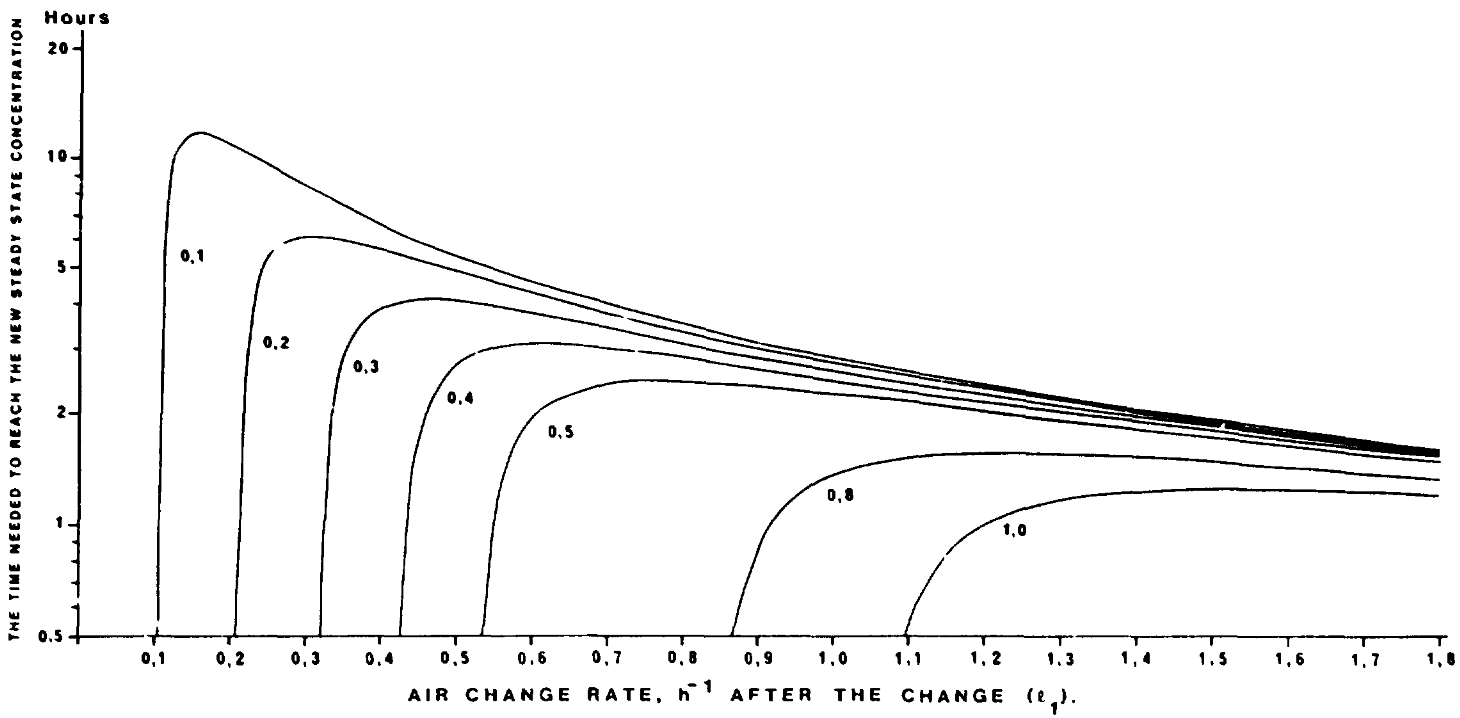


Fig. 3. The time needed to reach the new steady state concentration C_1 + 5 % of the old steady state value C_0, when the air change rates have been increased from ℓ_0 to ℓ_1 according to Eq 11. The curves have been calculated for various values of ℓ_0 as a function of ℓ_1. The curves are only valid when the exhalation rate can be regarded as constant.

C MEASUREMENT METHODS

Long-term registrations have been carried out in 17 dwellings during the last ten years. These measurements have been carried out for various purposes, for example to study the effect of closing doors and windows and of energy-saving measures etc, to seek to understand the highest radon concentrations in dwellings. This material is therefore not homogenous. One of these houses has also been studied during an entire year during ordinary behaviour by the family.

The long-term registrations have been carried out with ion chambers constructed at the Institute. 1.5 litres of air per minute is passed through a specially constructed chamber with a volume of six litres. The radon daughters are largely removed by filtration before the passage through the chamber.

The errors in the estimated radon concentrations are between 8 and 56 Bq/m^3. The instruments were redesigned and long-term registrations carried out after 1977 have smaller errors. The error of the calibration constant is not included but is of no importance in the study of the variations with time.

Some of the radon daughters plate out inside the chamber and it takes about two hours to reach equilibrium after a change in the radon concentration to be measured. A program has been developed to correct for this memory effect.

The readings are made at regular time intervals (normally one hour), ... -3, -2, -1, 0 etc. The corresponding radon levels are ... C_{-3}, C_{-2}, C_{-1}, C_0 etc and the instrument reading at time 0 is D_0.

It is now assumed that the radon concentration in a time interval, -(n+1) to -n varies linearly with time, i.e.

Eq 12 $$C_{-(n+1)+\theta} = C_{-(n+1)} + \left[C_{-n} - C_{-(n+1)}\right]\theta$$

$$0 \leq \theta \leq 1$$

where θ is a time interval.

It is further assumed that the relation between the instrument reading and the radon concentration is:

$$\text{Eq 13} \qquad D_o \cdot \sum \frac{S_i}{\alpha_i} = \int_{-\infty}^{0} C(t) \sum S_i \, e^{\alpha_i t} \, dt$$

where S_i are functions of a combination of the decay constants and counting efficiency.

α_i are the exponents of the exponential functions into which the received decay curve can be divided.

t is the integration time.

For t = θ-(n+1) this relation thus approximates to the sum:

$$\text{Eq 14} \qquad D_o \sum \frac{S_i}{\alpha_i} = \sum_{n=-\infty}^{0} \int_0^1 \left(C_{-(n+1)} + (C_{-n} - C_{-(n+1)})\theta\right) \cdot$$

$$\sum_i S_i \, e^{\alpha_i(\theta-(n+1))} \, d\theta$$

Now:

$$\text{Eq 15} \qquad \int_0^1 (A + B\theta) e^{\alpha(\theta-(n+1))} \, d\theta =$$

$$= e^{-\alpha n} \left[\frac{A}{\alpha} (1 - e^{-\alpha}) + \frac{B}{\alpha^2} (\alpha - 1 + e^{-\alpha})\right]$$

and it is thus found that:

$$\text{Eq 16} \qquad D_o \cdot \sum \frac{S_i}{\alpha_i} = C_{-1} \sum \frac{S_i}{\alpha_i} (1 - e^{-\alpha_i}) + (C_o - C_{-1}) \cdot$$

$$\sum \frac{S_i}{\alpha_i^2} (\alpha_i - 1 + e^{-\alpha_i}) + C_{-2} \sum \frac{S_i}{\alpha_i} (1 - e^{-\alpha_i}) \cdot e^{-\alpha_i} +$$

$$+ (C_{-1} - C_{-2}) \sum \frac{S_i}{\alpha_i} (\alpha_i - 1 - e^{-\alpha_i}) + \ldots\ldots.$$

The constants in Eq 16 have been derived from five long-term registrations during the time period before and after abrupt changes in the radon concentration from a high value to a low. The decay curves (F) found by experiment can be described as

Eq 17 $$\frac{F}{K} = \sum_i \frac{S_i}{\alpha_i} e^{-\alpha_i}$$

where K is the initial radon concentration.
With the exception of the first seconds, the experimental decay curves were rather well described by three terms for which two of the exponents were the disintegration constants for RaB (^{214}Pb) and RaC (^{214}Po).

From Eq 16 and the experimentally received S_i/α_i and α_3, the radon concentration C_n corrected for the memory effect and for time intervals of one hour is derived as

Eq 18 $$C_n = r_o \cdot D_n - r_1 \cdot C_{n-1} - r_2 \cdot C_{n-2} - r_3 \cdot C_{n-3} - r_4 \cdot C_{n-4}$$

The constants r_o to r_4 derived from each measuring series are shown in Table 1. The precision has been found to be about 3 % in the radon concentration using the memory correction. This estimate has been made both from Table 1 and from application to a known increasing curve which gave similar results (Fig 4).

The instantaneous measurements of radon at our institute are made by sampling the air in evacuated 5 litre containers and measuring in an ion chamber (Sn76). The instantaneous measurements of RnD have been made by sucking air through a filter for five minutes. The filter is measured by a zinc sulphide detector and the equilibrium equivalent concentration is calculated using Kusnets´ method (Ku56). The inhabitants are instructed to keep the dwelling closed and not to use the kitchen fan from nine pm on the evening prior to the measurement.

Integrating measurements of radon have been carried out with passive radon monitors containing $CaSO_4$-Dy thermoluminiscence dosemeters (Bu82).

Table 1. The constants in Eq 18 calculated from each of five decay curves.

Nr	r_0	r_1	r_2	r_3	r_4
1	1.557	0.463	0.0765	0.0142	0.00276
2	1.563	0.470	0.0761	0.0140	0.00271
3	1.517	0.430	0.0747	0.0130	0.00253
4	1.421	0.349	0.0581	0.0109	0.00214
5	1.529	0.441	0.0714	0.0131	0.00253
Mean	1.517	0.431	0.0714	0.0130	0.00253
$s/\sqrt{n}$	0.026	0.022	0.0034	0.0006	0.00011
	1.7 %	5.0 %	4.8 %	4.5 %	4.3 %

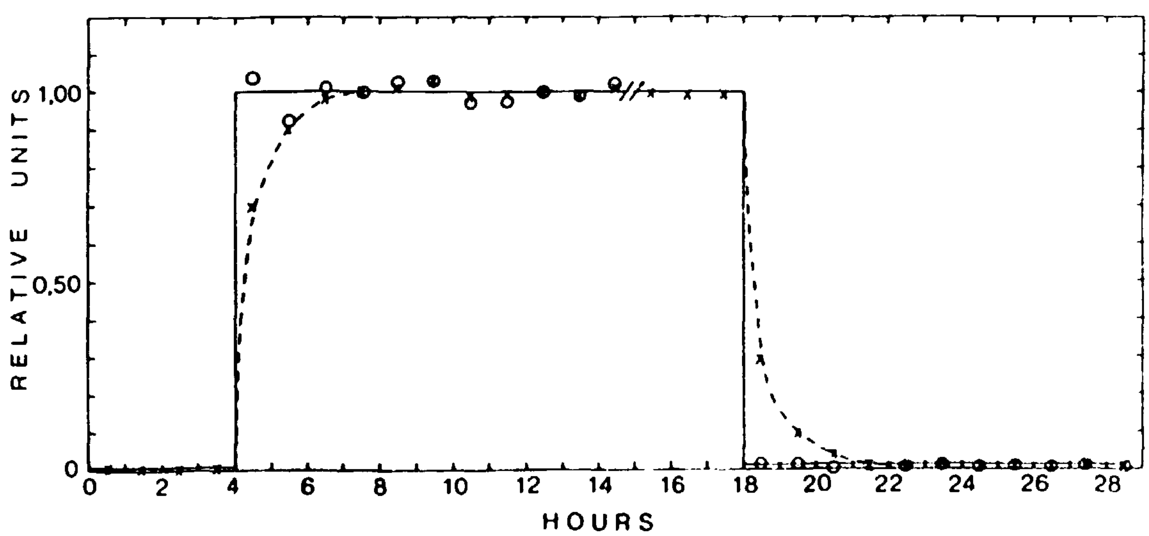


Fig. 4. Illustration of the correction for the memory effect. The ratio has been given between the measured and the "true" radon concentration after the change.

——— the "true" radon concentration,

x the measured radon concentration without correction,

o the measured radon concentration with correction for the memory effect.

D INFLUENCE OF THE WAY OF LIVING

When evaluating the results from instantaneous measurements for estimating the annual averages for groups of dwellings, it is of interest to derive correction factors for various habits, for example airing and opening and closing doors. To do this, something must be known about the reproducibility of the levels for simultaneous conditions in dwellings.

1 Reproducibility at the same adjustments of ducts, windows etc

The radon exhalation rate and the ventilation rate can be expected to be rather constant in dwellings without direct contact with the ground in multi-family houses with mechanical ventilation systems. For such dwellings the radon concentration is changed according to Eq 6 when the air change rates are changed because of changes in the settings of doors, ducts etc. However, even for such a dwelling the air change rate will not be constant for the same positions of doors etc, as shown in Fig 5 and 6, because of the unintentional ventilation. The figures show repeated sequences at the same conditions in each of the two dwellings, both situated in multi-family houses with mechanical exhaust ventilation systems, one of them with a high (house A) and one with a low radon exhalation rate from the building materials (house B). The curves have been normalized to the time for changing the conditions and to the initial radon concentrations. The range of the observed steady state concentrations was from 30 to 50 % of the averages. The same variations have been found in single-family houses on normal ground with exhaust ventilation systems, but only when the ventilation was forced.

When the ventilation conditions are altered by airing, almost reproducible curves are found in mechanically ventilated multi-family houses but also in mechanically ventilated single-family houses. For houses with natural draught ventilation systems, the differences in the temperature outdoors and indoors and the strength and direction of the wind are of decisive importance for the effect of the airing. This is illustrated by the registration shown in Fig 7 (house C).

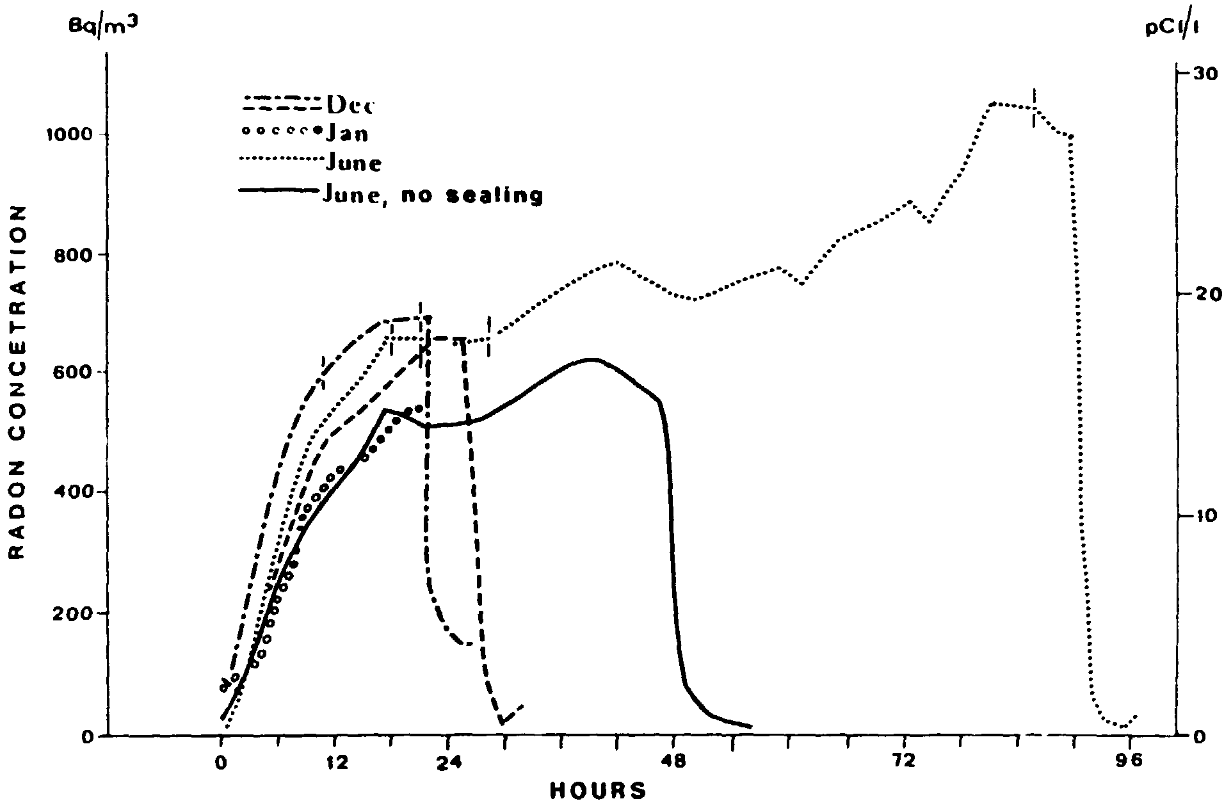


Fig. 5. Repeated sequences under the same conditions in a room in a multi-family house (House A) where the door to the room was closed. The given errors are 1 s.

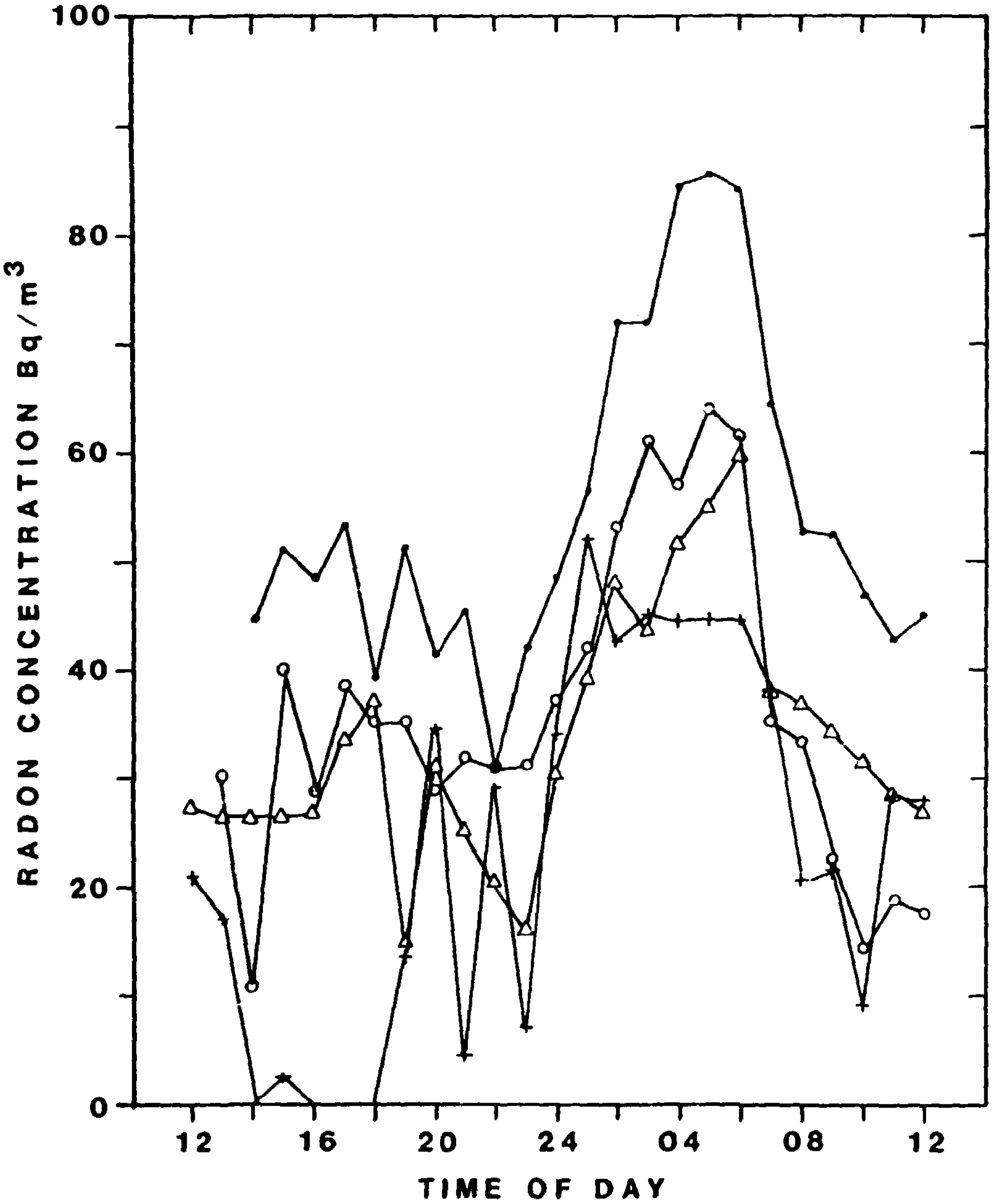


Fig. 6. Repeated sequences under the same conditions in a room in a multi-family house (House B) where the speed of the fans was reduced every night from midnight to 6.00 am.

2 Closed bedrooms

It is of interest to see how the possible exposure of the occupants is influenced by the levels which can occur in a bedroom when the door to the room is kept closed during the night. In Fig 8, the average increase of the radon concentration has been calculated for a room with the door closed for eight hours in relation to the level when the door is kept open for 24 hours a day. These calculations are only relevant when the radon exhalation rate can be treated as approximately constant, that is to say when the only significant radon source is the building materials. The curves do not depend on whether or not the radon exhalation rates are the same in the other rooms in the dwelling. The average increase may be up to 100 % depending on the air change rates in the closed room and the ratios between the steady state values with the door closed and open. If the radon exhalation is the same in the room studied as in the other parts of the dwelling, the average increase can be up to 50 %, assuming that the initial air change rate is not higher than 0.5 per hour.

Measurements in bedrooms in multi-family houses, showed that after closing the door the radon concentration increased by up to 50 %, possibly almost to the steady state value, representing an average increase of up to about 10 % from the values in Fig 8 since the radon exhalation is approximately the same in all the rooms in this house. In bedrooms in which the radon exhalation was higher than in the other parts of the dwelling, the corresponding increases were 170 to 350 %, giving an average increase of up to 70 % from the values in Fig 8.

The radon concentration varies much more with the time in single-family houses, than in multi-family houses, not only when the ground or the tap water is the essential radon source. In one house built of aerated concrete, the concentration in a bedroom increased after closing the bedroom door by up to 400 %. In a wooden house, the corresponding increase was between 50 and 100 %. These results seem to be rather general since they are confirmed by long-term registration in other houses.

When the exhalation of radon is less in the bedroom than in the other parts of the dwelling, a lower radon concentration may be obtained in the room even if the air change rate in the closed room is less than when the door was open. This occurs mostly in bedrooms on the upper

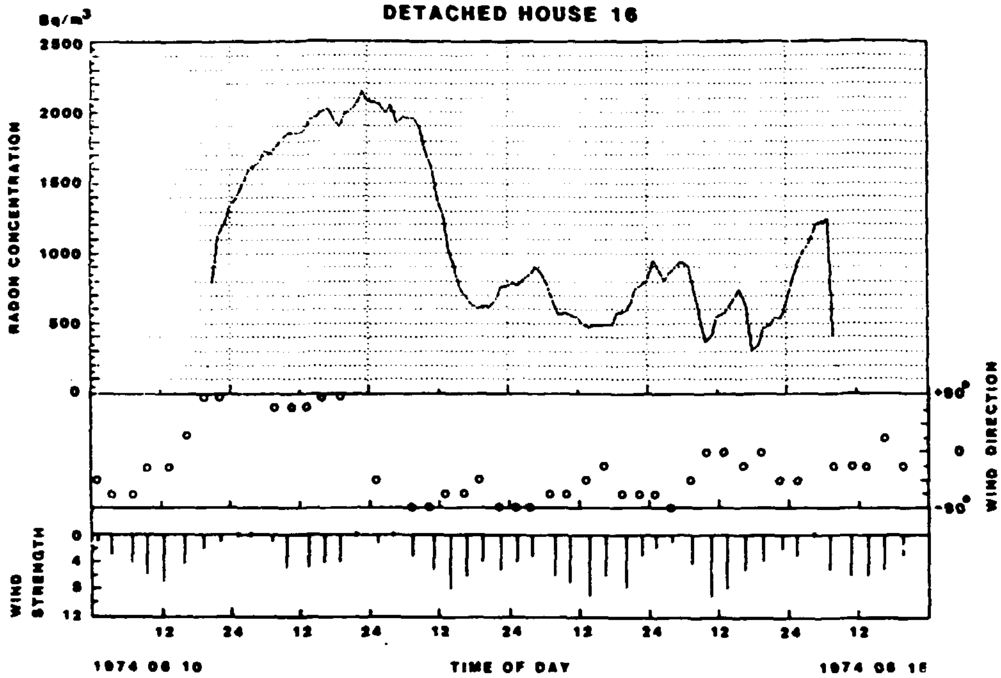


Fig. 7. The radon concentration in a detached house with natural draught ventilation system where the building materials are the major radon source (House C). The door to the room was closed when the measurement was started. The wind direction and strength are marked.

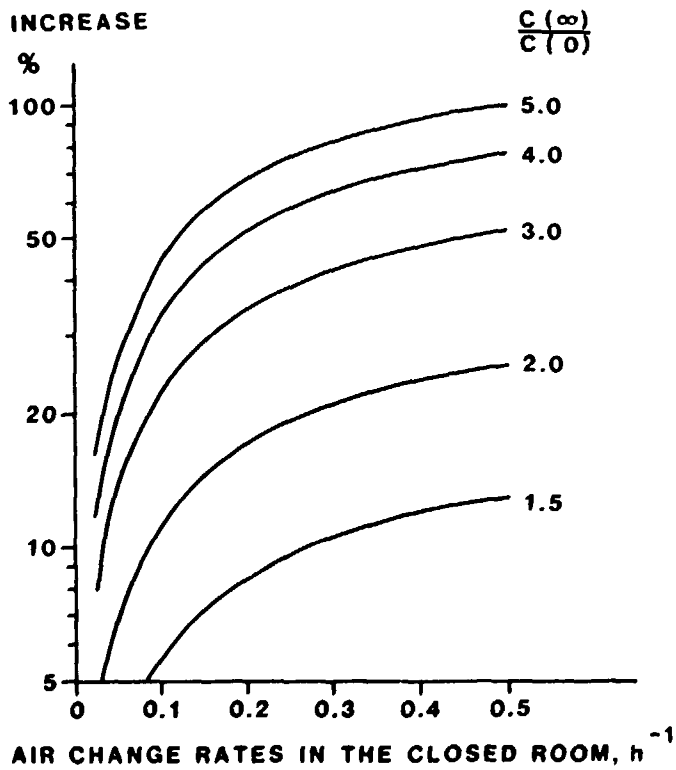


Fig. 8.

The average increase in the radon concentration during 24 hours when the door to a room is kept closed for 8 hours and open for 16 hours in relation to the concentration when the door is kept open for 24 hours a day. The average increase has been calculated for various ratios between the concentration for closed door and that for open door.

floors of single-family houses because they are further from the ground and because the building materials in that part of the house often contain less radon exhalating materials (see the measurements reported in Refs. Er76, Er80 and Sw82).

3 Ventilation ducts

In houses having mechanical exhaust ventilation or natural draught ventilation the inlet air is assumed to enter the house through ventilation ducts or chinks. The effects on the radon concentration have been found to vary between 20 and 700 % of the initial level, depending on the kind of house, the ventilation ducts, climatic conditions etc (Table 2).

The effects of closing the inlet ducts in single-family houses with natural draught ventilation are illustrated by the results of measurements. When the inlet ducts were closed in two houses after being fully open the air change rates decreased by about half from 0.14 to 0.07 and 0.15 to 0.09 air changes per hour (Er76). The ground was the major radon source in this house.

The instantaneous samplings were carried out when the dwellings had been closed for at least 11 hours. Normally, a dwelling is aired once or twice in each 24 hour period, especially when the air change rate is low. Correction factors are therefore needed and these are shown in Fig 9 as a function of the air change rate. These correction factors are based on Eq 5 and 6 and the calculations are described in ref Sw78. As an average for calculating the average radon/radon daughter exposure for Swedish dwellings the correction factor 0.8 has been used.

4 Ventilation fans

It is often the case that the speed of the fans used in multi-family houses is reduced during the night in cold weather to save energy. Sometimes the fans are even stopped during the night. The effect of reducing the speed of the fans is shown in Fig 10 as a function of the air change rate during the night calculated from equations 5 and 6 as the average increase of the radon concentration related to the level when the fan speed is unchanged during the whole 24-hour period. The calculations have been made in the same manner as for the closed bedroom but with the air change rates during the day as parameter. From Fig 10 it can

Table 2. The increase in the radon concentration after closing various types of ventilation ducts for inlet air in different seasons. The door to the rest of the dwelling was closed, with two exeptions marked by [1)]

Dwelling No.	Type of ventilation inlet	Time for the measurement	Radon concentration		
			from Bq m^{-3}	to Bq m^{-3}	fractional increase %
31	Small ventilation duct	March			20
17	Airing panel	June	30	56	90
		Dec	19	150	700
3:3[a)]	Balcony door ajar	March	96	144	50
		April	74	133	80
		March	21[b)]	40[b)]	95[b)]
		April	21[b)]	30[b)]	44[b)]
74	Airing panel	April	19	67	370
63	- " -		22	63	280
74[1)]	Airing panel	April	30	81	280
	- " -		30	52	175
76[1)]	Airing panel	Jan	37	74	100

[a)]Comparison between various dwellings in the same group of houses (Er76).

[b)]RnD

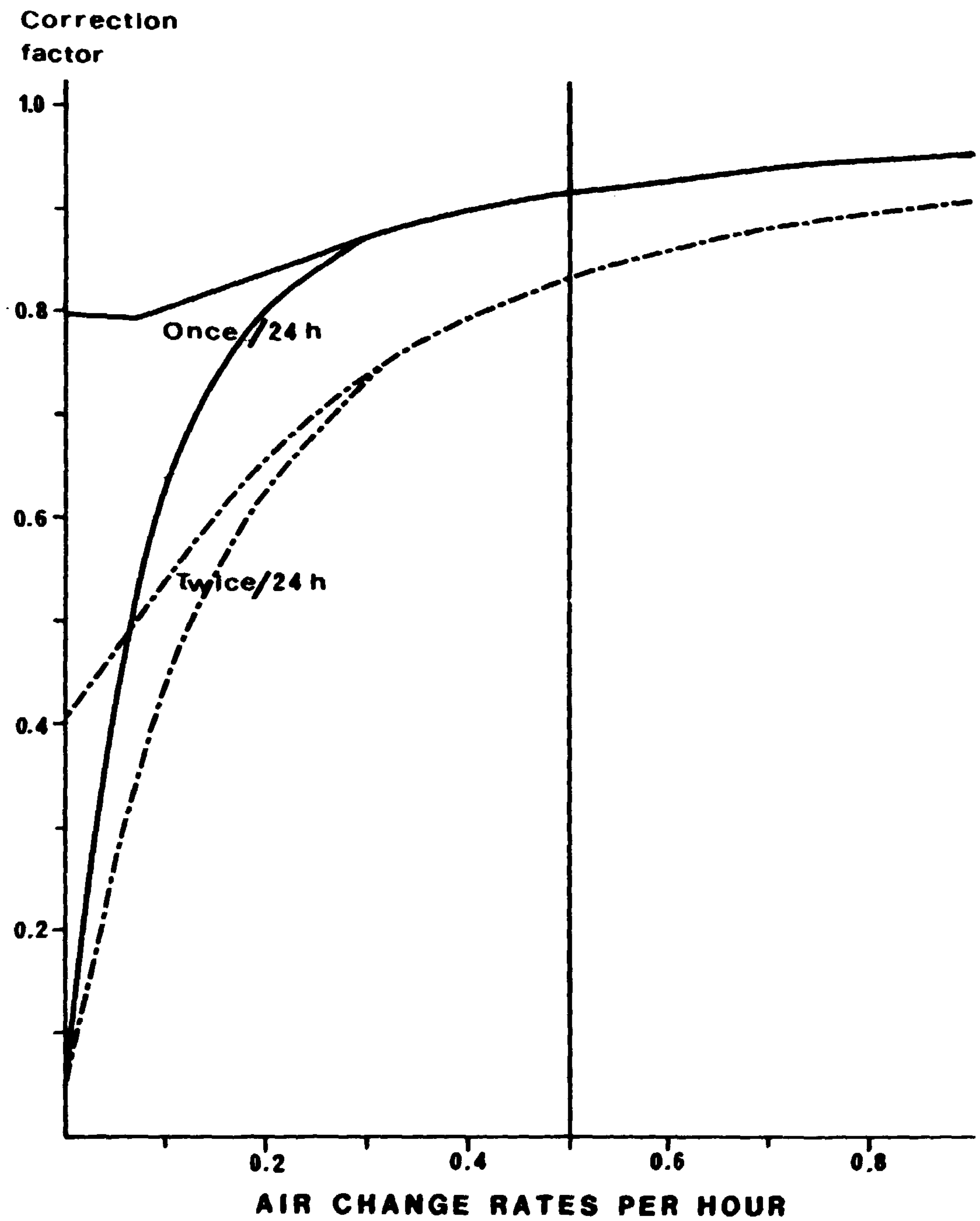


Fig. 9. Correction factors for thorough airing once or twice during each 24 hour period to be used on measured values found:

1) when the house had been closed for about 15 hours (the upper curves).

2) when the house had been closed for so long that the radon concentration had reached the steady state value (the lower curves).

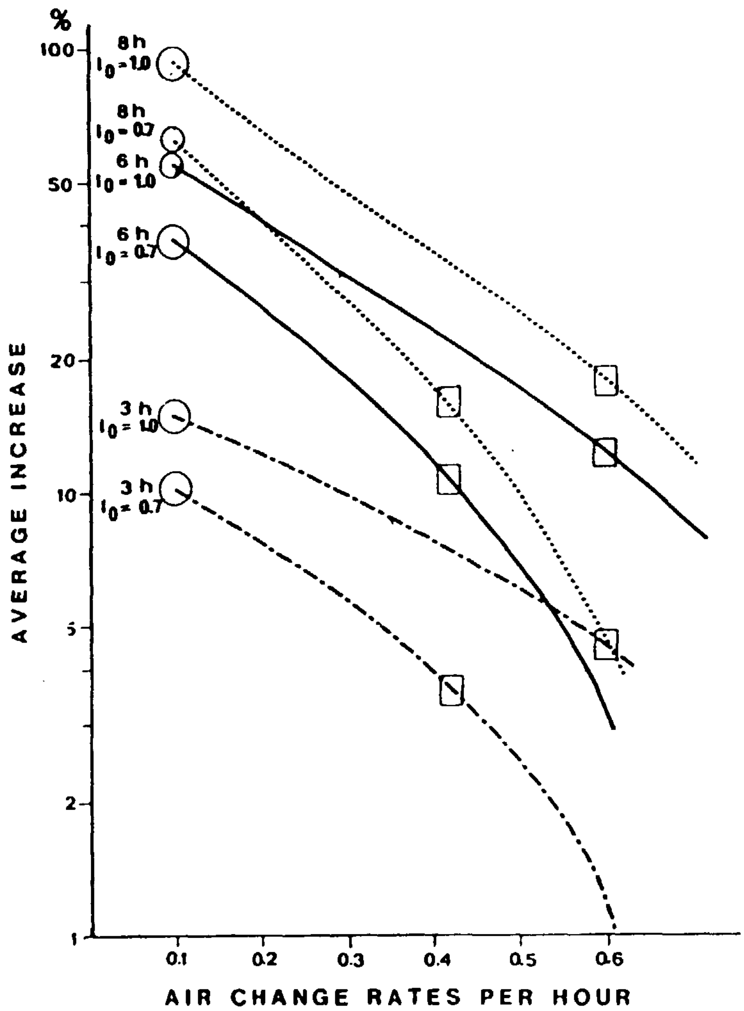


Fig. 10. Relative average increase in the radon concentration during a 24 hour period given by a decrease in the speed of the fans for 8 hours, 6 hours and 3 hours respectively as a function of the air change rate with the lower fan speed.

□ $\ell \approx 0.6\ \ell_o$ corresponds approximately to fans going at half speed.

○ $\ell \approx 0.1\ \ell_o$ corresponds approximately to stopped fans.

be seen that the relative increase in the average radon exposure can be expected to be between 10 and 20 % when the air change rate is decreased to 60 % of the daytime air change rate. Such a decrease often corresponds to a decrease to half in the fan-driven air-flow. The lack of proportionality depends on the unintentional ventilation. When the fans are stopped, the air change rate will not be zero, both because of the unintentional ventilation, and because some natural draught ventilation is always present, although it is less than in houses where the ventilation system is designed for natural draught ventilation. In the calculations for Fig 10 it has therefore been assumed that stopped fans give approximately an air change rate of 0.1 changes per hour. No measurements appear to have been made of the air change rates with stopped fans.

Fig 11 shows a long-term registration from a dwelling in a multi-family house (house B) where the fans were stopped for six hours each night. The average radon concentration increased by a factor of two to a level which might be near the steady state level, because of the results in Fig 2 and because the air change rates in multi-family houses are often greater than 0.7 changes per hour. Consequently, for this dwelling stopping the fans during night resulted in an average increase of 25 % in the radon exposure relative to the exposure without stopping the fans.

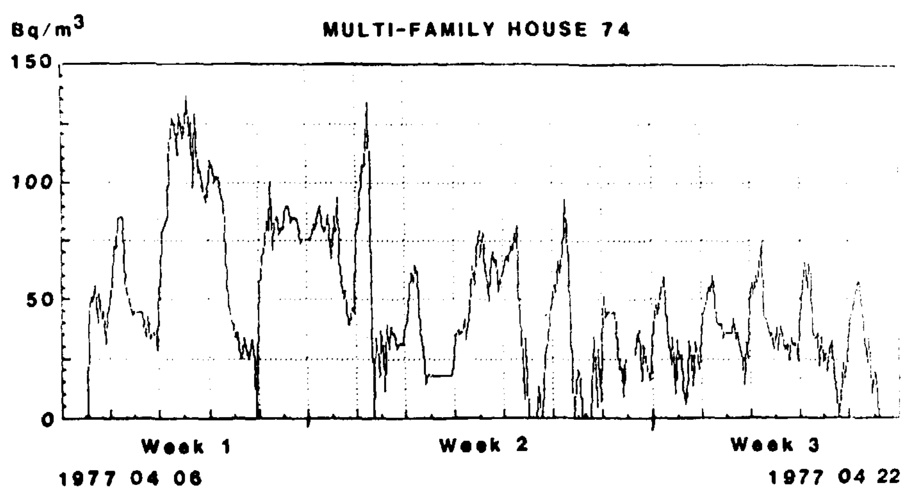


Fig. 11. The radon concentration in a room in a multi-family house with a mechanical exhaust ventilation system (House B). The fans were stopped for six hours each night.

E INSTANTANEOUS MEASUREMENTS

Instantaneous sampling has been and is being carried out for both radon and RnD measurements. The sampling may last from a few minutes for radon sampling up to 20 minutes for RnD sampling. Instantaneous sampling was earlier the only method for large scale measurements and it is still a convenient method in many situations. It is therefore of interest to look at the representativity of an instantaneous measurement with regard to the temporal variations.

Instantaneous sampling by our Institute has only been carried out when the dwelling has been closed for at least 11 hours, by which time steady state levels have generally been reached as was shown in Fig 2. An interesting question is whether or not this approximate steady state level is constant throughout the day. In order to obtain simulated instantaneous measurements with the same requirements regarding ventilation etc as with real instantaneous measurements, calculations have been made from long-term registrations in three houses during periods when the dwellings had been closed for at least 11 hours before a daytime period of 8.00 to 16.00 hours.

The concentration of radon found from long-term registrations has been recalculated as one-hour averages although the instantaneous samplings for radon measurements using evacuated containers usually extended over a period of less than five minutes. The reason for the choice of one-hour averages is the desire to obtain the best possible counting statistics. A comparison between the conditions for true instantaneous sampling of radon in an evacuated container for measurement in an ion chamber with our long-term registration gave the following result. Our evacuated containers contain 5 litres of air and are filled in a few minutes. The long-term registration instrument pumps 1 1/2 litres per minute through an ion chamber. Consequently, an average during a few minutes gives a larger error due to measurement compared with samples taken in the evacuated containers which are measured in a larger ion chamber for at least twenty minutes. A comparison between five-minute averages and one-hour averages has been carried out for one house. A somewhat higher radon concentration (about 5 %) and a larger standard deviation (one per cent unit) were found for the five-minute values than for the one-hour averages.

Calculations have been made of the ratios between the simulated instantaneous measurements and the average concentrations; during the same 24-hour periods, during the same weeks, during the whole measurement periods and, when possible, related to the "true" annual average. The calculations have been made for two single-family houses, one with natural draught ventilation built during the 1950s (house F) and one with mechanical exhaust ventilation built during the 1970s (house E), and in one dwelling in a multi-family house with natural draught ventilation built one hundred years ago (house G). In the single-family houses the occupants were living as usual most of the time. In the multi-family house the occupants were away during the measurement period. When calculating the ratios, a correction factor for airing of 0.8 (Fig 9) has been used when the simulated instantaneous measurements were related to integrated measurements during normal occupancy.

A ratio of approximately 1 was found for the two single-family houses E and F irrespective of the time of day of the measurement (Fig 12). For the old multi-family house with natural draught ventilation, house G, the ratios decrease during the day so that a sample taken in the morning gave a higher value than a sample taken in the afternoon. From an analysis of the weather conditions it was found that the wind strength was higher during the afternoons than during the other times of day and night for more than half of the investigated days, and this seems to be the explanation for the significant decrease in the radon concentration during the day. The wind strength was more than 6 meters per second during 70 % of the measurement period. For the two single-family houses no periodicity of the wind strength was found and less than 10 % of the period had wind strengths higher than 6 meters per second.

Some other single-family houses were investigated in the same way but for shorter periods and nothing was found to contradict the results presented here. One conclusion is that instantaneous sampling should not be made when the wind strength is higher than 6 meter per second when the aim is to estimate the annual average.

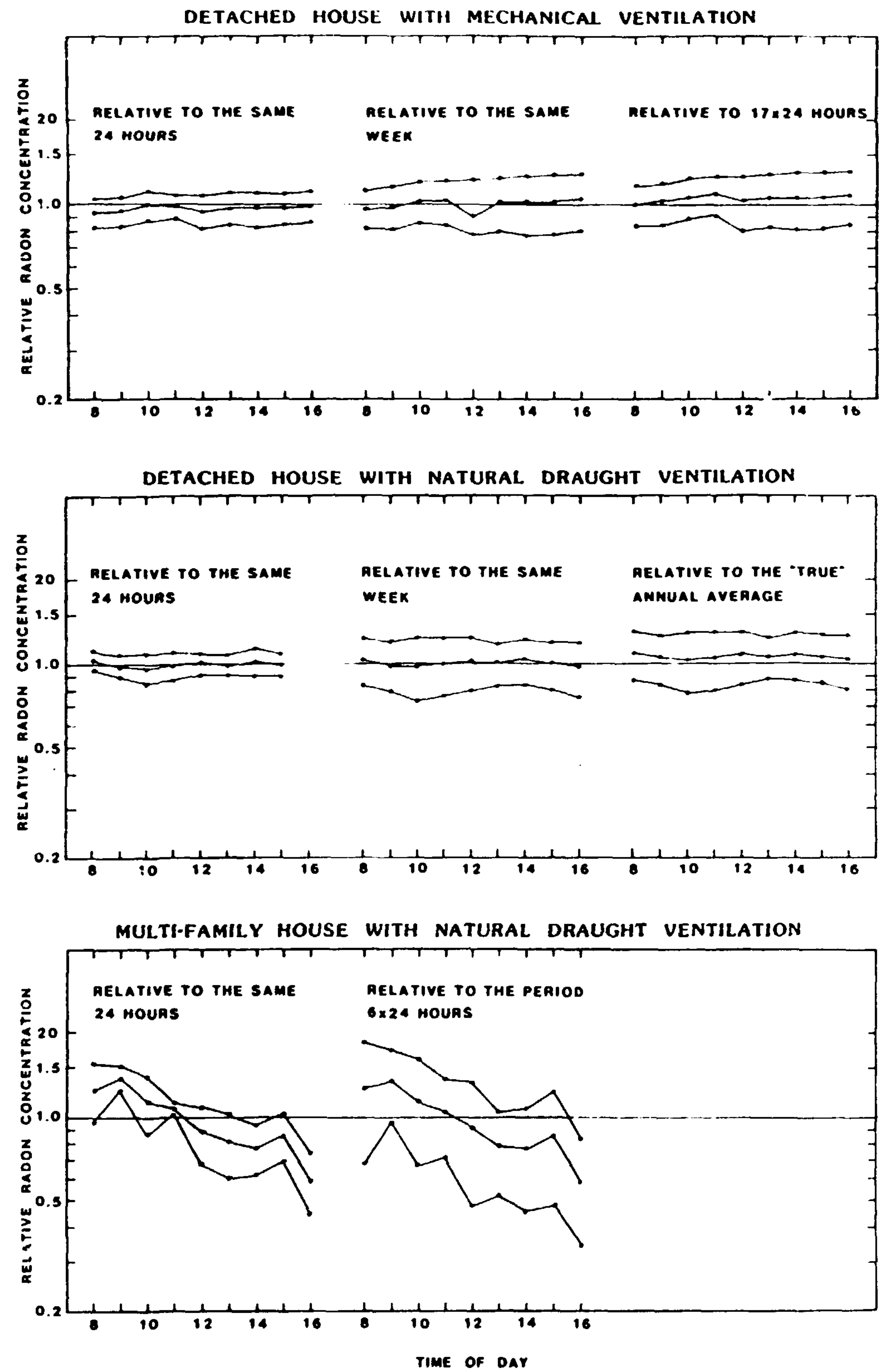


Fig. 12. The ratio between simulated grab samples at various times of day and the average concentrations of radon during different periods (Houses D, E and F).

An increase in the ratios between the simulated instantaneous measurements and the average concentrations during the day may occur when the air change rates are lower than 0.25 per hour. Fig. 2 shows that at such low air change rates the steady state concentration has not been reached after 11 hours. Such low air change rates are not uncommon as averages for entire dwellings in Sweden and are very common in bedrooms with closed doors and windows. The cause of the low air change rates in bedrooms is that they usually have no direct ventilation ducts for exhaust air and often no ducts for supply air. Fig 2 shows that if the door to a bedroom is closed and the air change rate decreases from 0.8 to 0.18 per hour, as illustrated in Fig 1, it will take 15 hours to reach the steady state level. A measurement after 11 hours then gives a value lower than the steady state concentration. However, such a measurement may be useful in the estimation of the annual average because a room occupied by a person is not often closed for more than ten hours, especially since the air may be unpleasant to breath after a long time at such low air change rates. To determine the steady state radon concentration even at very low air change rates, the measurements had to be carried out 18 hours after closing the house. Such a long time with the house closed would have been very impractical for the occupants and would not have given us much more information.

In the statistical analysis of different sampling periods in the next section, simulated grab samples will be compared with integrating measurements.

F INTEGRATING MEASUREMENTS[1)]

Figs. 13a and 13b illustrate the influence of various integrating times during normal occupancy with regard to the time variations for two single-family houses with natural draught ventilation combined with kitchen fans. The averaging periods were from one hour to one week. The largest short-term variations were caused by the fan speed or airing the house by opening windows or door. The dominant radon source was the ground under the house in Fig 13a (house H) and the building materials in the house in Fig 13b (house F). The radon content of the tap water in this house was 1100 - 1600 kBq/m^3 and it can be estimated that this contributes of the order of 100 Bq/m^3 to the radon concentration in the ground-floor air during the heating season. A daily pattern was found for both houses. The time variations are larger for the house in which the ground is the dominant radon source, than in the house with the building materials as the dominant radon source.

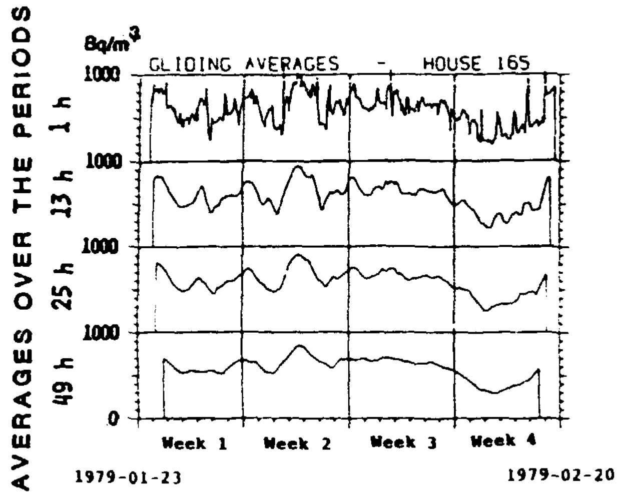
The measurement period was only one month for house H and that is insufficient for statistical calculations. Therefore, only house F, in which the measurements were carried out for an entire year, will be treated statistically below. This house with the building materials as the dominant radon source should be regarded as an example of how a statistical analysis can be carried out.

1 Distribution curves

Fig 14a shows frequency distributions of observed daily means for sampling periods ranging from one day to 162 days containing data from all seasons. The "true" annual average has been used as the mid-point. From this average intervals of 25 Bq/m^3, or 7.3 % of the annual average, have been chosen.

Measurements to determine the annual average in dwellings in Sweden have only been made during the heating season since data from the summer season are difficult to interpret. Therefore, the frequency distribution for the heating season is shown in Fig 14b.

[1)] The same material has been presented in ref Sw84 in condensed form.



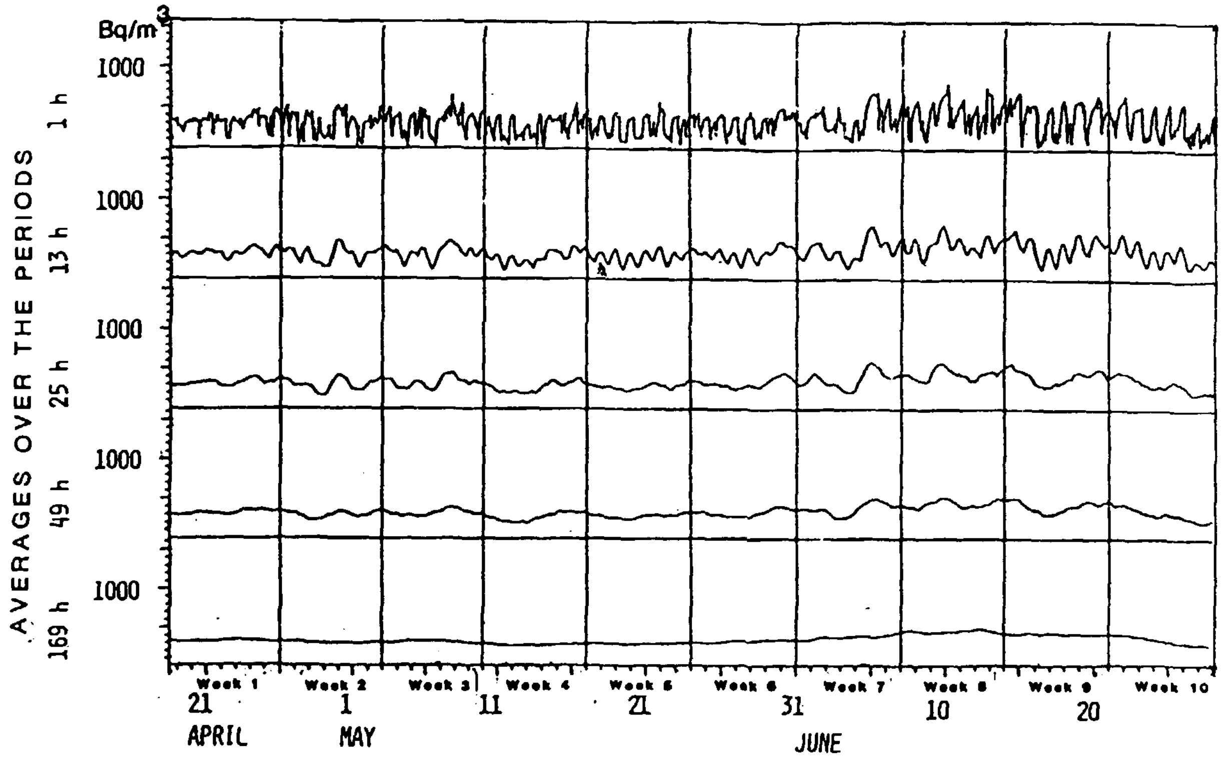


Fig. 13. Gliding averages during different sampling periods.

a) HOUSE H, DOMINANT Rn SOURCE: THE GROUND
House type: detached, wooden, with a cellar of concrete in a rock site, natural draught ventilation system.
Placing of the instrument: a work-room in the cellar, open to the rest of the house.

b) HOUSE F, DOMINANT Rn SOURCE: THE BUILDING MATERIALS
House type: detached, aerated concrete based on alum-shale with a cellar of ordinary concrete in a silt site, natural draught ventilation system, Tap water 1100 Bq/m^3.
Placing of the instrument: the living room, open to the rest of the rooms on the ground floor.

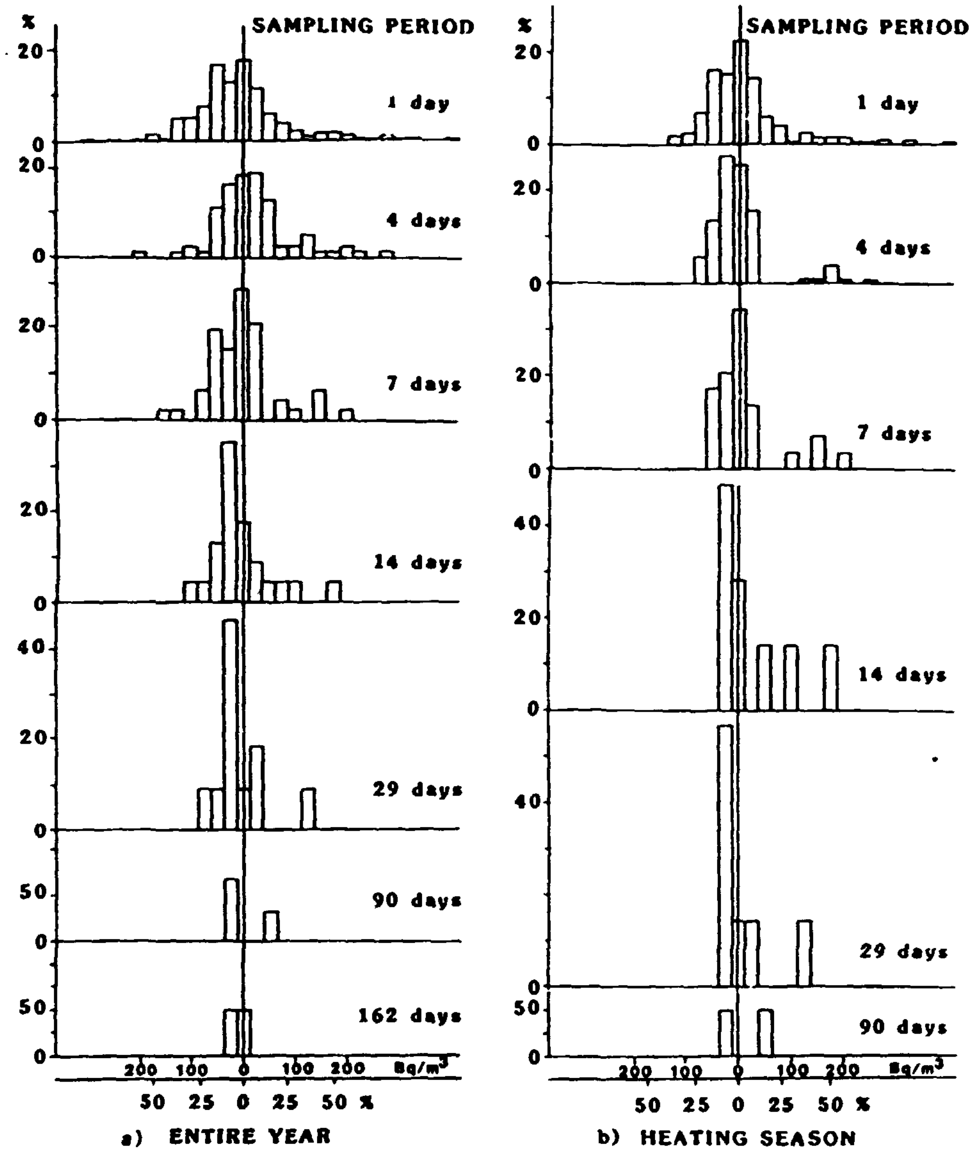


Fig. 14. Frequency distributions for radon concentrations obtained during different sampling periods related to the "true" annual average, 341.50 Bq/m^3 (House F). The intervals are 25 Bq/m^3.

Fig 14a shows that the frequency distributions for all seasons are approximately normal, but with some skewness towards higher values. This tendency is more pronounced for the heating season (Fig 14b) when the summer values (which are low) are excluded, but is not found for the spring and autumn. Consequently, the high values are found during the winter season. One measurement during the entire heating season has given an overestimate of the annual average by 2.5 % compared with the "true" annual average.

The average for the summer period, 316 ± 9 Bq/m^3, (15th of May - 14th of September) differs significantly on the 0.5 % level (t-test) from the average 354 ± 4 Bq/m^3 for the heating season (the rest of the year).

2 Sampling periods

In Fig 15, the standard deviation related to the "true" annual average is plotted for all seasons as a function of the sampling period, from one hour to 108 days. Simulated grab samplings have also been marked on the diagram, e.g. one-hour samples taken under the ventilation conditions required for grab sampling. The requirements in the official method descriptions (SP81) are that the house should be closed for at least 12 hours and that neither the kitchen fan nor the vacuum cleaner should be used during the period. It can be seen in Fig 15 that simulated grab sampling gives an annual average of the same precision as a sampling period of about five days, measured during all seasons without restrictions.

Fig 16 shows the standard deviation together with the extreme dispersions as functions of the sampling period for the heating season. For this season too the simulated grab samples have a precision similar to that of measurements covering about five days. The figure also illustrates the skewness of the frequency distribution.

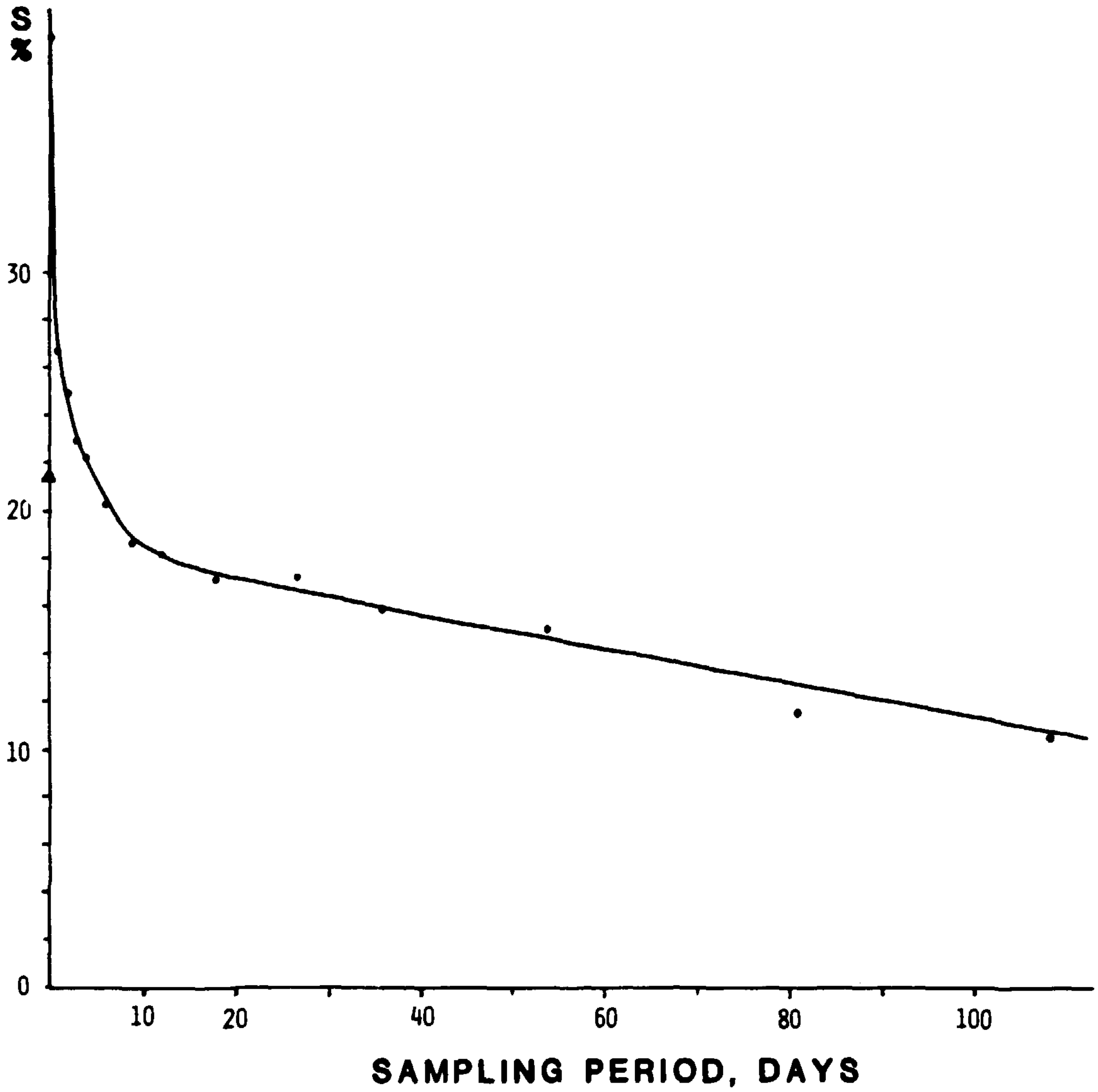


Fig. 15. The standard deviation related to the "true" annual average as a function of the length of the sampling period. All seasons (House F). Δ indicate simulated grab samples.

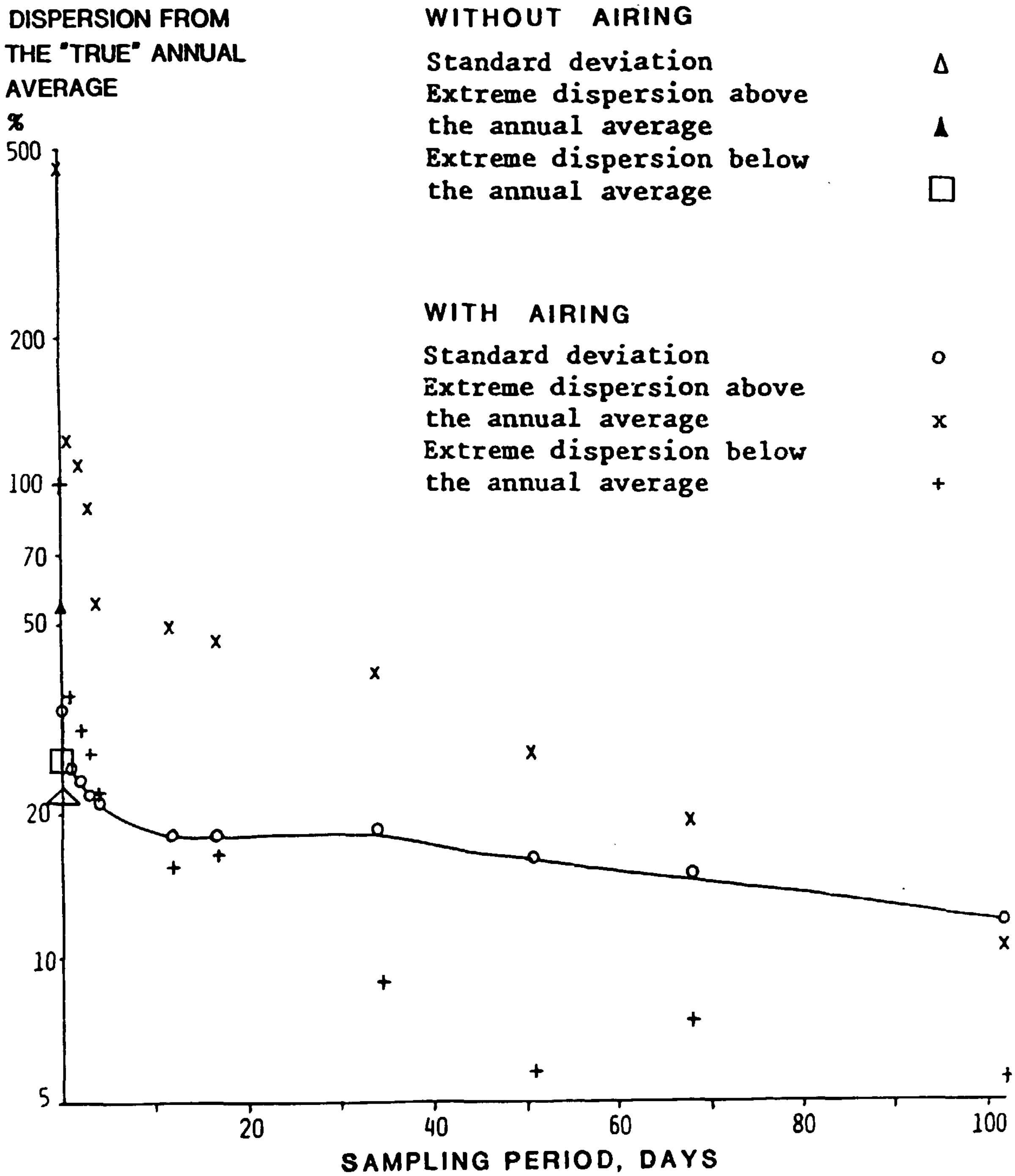


Fig. 16. Dispersions from the "true" annual average obtained as extreme values and standard deviations in house F, the same as Fig. 13b - 15.

3 Comparison between the rooms in a house

Measurements with passive radon monitors with thermoluminiscence dosemeters were made in all rooms in house F, measured during an entire year (Fig 14). The instruments are described in Bu82. The results are summarized in Table 3. The difference between the rooms on the first floor was not significant. The radon concentration in the kitchen was 80 - 90 %, and the concentration in the cellar bedroom was 50 - 60 % of the concentration in the rooms on the first floor. This shows together with gamma measurements that the major radon source seems to be the building materials on the first floor and that the water does not contribute as much as the building materials.

One of the passive radon monitors was placed in the same room as the long-term radon equipment. The results agreed within 5 % for the first measuring period. For the other periods no comparisons have been possible.

Table 3. Radon concentrations in Bq/m^3 measured simultaneously in five places in house F with passive radon monitors using thermoluminiscence dosemeters. The measuring period was two weeks. The long-term registration equipment was placed in the sitting room.

Place	MEASURED PERIOD	
	1981 24/4 - 7/5 Bq/m^3	1981 9/11 - 22/11 Bq/m^3
FIRST FLOOR		
Sitting room	330	360
Bedroom I	330	340
Bedroom II	350	330
Kitchen	300	290
CELLAR		
Bedroom	180	200

G CONCLUSIONS

Table 4 shows the precision of the estimate of the annual average from measurements in house F during the heating season together with examples of methods using various sampling periods. The relative standard deviation varies from 33 % for one-hour measurements without restrictions on the ventilation to 13 % for three-month samplings. The integrating measurement made during the heating season overestimated the annual average to a very small degree in this house.

Table 4. Relative standard deviations from the "true" annual average for different sampling periods (House F).

Sampling period	Relative standard deviation (%)	Examples of sampling methods
Grab samples with restrictions	22	Lucas cells etc
Grab samples without restrictions	33	Lucas cells etc
24 hours	25	Activated charcoal
3 days	22	Activated charcoal
1 week	20	" "
2 weeks	18	Passive Rn monitors with TLD
1 month	18	" " " "
3 months	13	Nuclear track detectors

Measurement during the summer season has not been used in Sweden to check radon daughter concentrations for comparison with limits. Nothing in this study indicates that this policy should be changed. Summer measurements underestimate the concentration in houses with natural draught ventilation systems when the family is at home during the summer months and overestimate it when they are away from home, when this type of ventilation system does not work. Most measurements for comparison with limits are made in detached houses, and most of these have natural draught ventilation systems.

Grab samplings with restrictions on the ventilation, to be used when a quick result is required, are found to be an acceptable method for estimating the annual average for this type of house. Young et al (Yo83) and Prichard et al (Pr82) have come to the same conclusion. One condition is that the wind strength twelve hours before and during the sampling is not higher than about six meters per second.

However, the restrictions on the ventilation usually cause overestimation of the annual average concentration. When the building materials are the dominant radon source, correction factors can be calculated. When the ground is the dominant radon source, the radon exhalation depends to a high degree on several factors besides the ventilation rate. One important example is the difference between the air-pressure inside and outside the house. Correction factors are then much more complicated to calculate.

Even when the building materials are the dominant radon source, only rough correction factors can be calculated. The distributions of the errors of the factors have not been investigated, but the factors are probably in most cases log-normally distributed. Some of the errors may not be stochastic. Despite these uncertainties, an attempt has been made to calculate correction factors.

The average radon concentration during the heating season can be written as

Eq 19 $$\bar{C}_{heat} = C(o) \widetilde{\prod_i} k_i$$

with an estimation of the standard deviation, s, of

Eq 20 $$\frac{s_{heat}}{\bar{C}_{heat}} = \sqrt{\sum_i \left(\frac{s_{k_i}}{k_i}\right)^2 + \left(\frac{s_{C(o)}}{C(o)}\right)^2}$$

where k_i are the correction factors for changing in the ventilation conditions, e.g. for window airing of the dwelling, for closed bedroom, for adjustment of ventilation ducts and for reducing the speed of fans during part of the night. C(o) is the measured radon concentration when a grab sampling method is used.

The correction factors have been calculated for radon, but may be used approximately also for RnD. However, the standard deviation will be larger because the equilibrium factor F is a function of several parameters, one of the most important being the ventilation rate. EER, the equilibrium equivalent concentration of radon, C_e, is calculated from the radon concentration

Eq 21 $$C_e = \tilde{C} \cdot F = C(o)\, F \prod_i k_i$$

with a standard deviation of

Eq 22 $$\frac{s_e}{C_e} = \sqrt{\left(\frac{s}{C}\right)^2 + \left(\frac{s_F}{F}\right)^2}$$

The annual average C_y is lower and the fractional deviation larger than the corrected value for the heating season. An attempt to make a correction may be carried out in the following way. During the summer the windows are assumed to be kept open when the occupants are at home. C(o) is then assumed to be reduced by the factor k_{sum} during 1/4 of the year and the annual average of the EER is estimated to be

Eq 23 $$C_{e,y} = 1/4\ C_e(o)\ k_{sum} + 3/4\ C_{e,heat}$$

Eq 24 $$s_{e,y} = \sqrt{\left(\frac{1}{4} \cdot s_r\right)^2 + \left(\frac{3}{4} \cdot s_{e,heat}\right)^2}$$

where $r = C_e(o) \cdot k_{sum}$

Eq 25 $$\frac{s_r}{r} = \sqrt{\left(\frac{s_{C_e(o)}}{C_e(o)}\right)^2 + \left(\frac{s_{k_{sum}}}{k_{sum}}\right)^2}$$

As an example, equations 19 - 22 are used to calculate the annual concentration in a dwelling in an apartment house with F-ventilation on the following assumptions. The rates of the fans are reduced to half of the normal rate for six hours each night. The radon exhalation is approximately the same in the whole dwelling. The bedroom is used with the door and the window closed each night for eight hours. The dwelling has no ventilation ducts for inlet air and window airing of the dwelling is made once in each 24-hours period. The air change rate is not known. The ratio between the radon concentration in the closed bedroom after eleven to eighteen hours and in the rest of the dwelling, $C(\infty)/C(o)$, is 500 %. The correction factors are then

for window airing	0.8 ± 0.1	(Fig. 9)
for closed bedroom	1.8 ± 0.3	(Fig. 8)
for reduced fan rate	1.15 ± 0.03	(Fig. 10)
and the uncertainty due to measurements is	$s_{C(o)} = 0.3\ C(o)$	

We then find the average radon concentration during the heating season to be

$$C_{heat} = 1.7\ C(o) \pm 0.6\ C(o)$$

and the EER when F = 0.40 ± 0.17 for dwellings with F-ventilation (Sw83) to be

$$C_{e,heat} = 0.7\ C(o) \pm 0.4\ C(o)$$

The annual average EER when $k_{sum} = 0.5 \pm 0.2$, is found to be

$$C_{e,y} = 0.6\ C(o) \pm 0.3\ C(o)$$

In house F the k_{sum} was found to be 0.8. It depends on the habits of the family and $k_{sum} = 0.5$ used above may be an underestimation. The value of the F-factor is based on day-time measurements. The value may therefore be different and the spread of the values larger.

The equations have also been used to calculate the annual concentration in a single-family house with S-ventilation. With the exception of the fans and the F-factors the assumptions are the same as for the dwelling in the apartment houses. The correction factors are

for airing	0.8 ± 0.1	(Fig. 9)
for closed bedroom	1.8 ± 0.3	(Fig. 10)
and	F = 0.48 ± 0.14	

For the heating season the average concentration of radon is 1.4 C(o) ± 0.5 C(o), the EER is 0.7 C(o) ± 0.3 C(o) and the annual average EER is 0.6 C(o) ± 0.3 C(o).

When integration measurements are chosen a sampling period of at least one-week should be used. Corrections for calculating the annual average are not so extensive as for grab sampling. It may be appropriate to correct for the heating period measuring by k_{sum}, and when the radon concentration is measured, the F-factor is used in the same way as for the grab sampling.

With the assumption of the same values on k_{sum} and F as in the examples of the instantaneous measurements, we find the annual average of EER for an apartment to be 0.35 C(o) ± 0.16 C(o).

Measurements over an entire year have only been carried out in one house. Long-term measurements have been made for shorter periods, in a number of dwellings, both detached houses and multi-family houses, with various ventilation systems. Besides the type of house and the ground, the habits of the occupants have a larger influence. The results cited above are probably typical for these types of houses and for families with similar habits. For families who are away from home during all the weekdays and at home during all the weekends, long-term measurements in other houses during shorter periods suggest a weekly regularity. In these cases, sampling periods of a week or more can be expected to be required for reasonable results.

The house investigated was very typical of Swedish detached houses with the exception of the tap water. However, where the ground is the dominant radon source, the time variations can be expected to be different. The problems associated with high radon daughter concentrations have been shown to be much smaller in multi-family houses because the ventilation systems work better, even with natural draught systems.

The concentrations of the radon daughters have been found to vary more than the radon concentration. How much more they vary is not yet known for Swedish dwellings. Our plans are to perform continuous measurements in various types of houses of the concentrations of both radon and radon daughters as a basis for statistical analysis.

With other building techniques, heating and ventilation systems and other climates than in Sweden, different temporal variations can be expected and are also found (Yo83, Si81).

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