Indoor Air 1997; 7: 278–286
Printed in Denmark. All rights reserved

INDOOR AIR
ISSN 0905-6947

Radon and Natural Ventilation in Newer Danish Single-Family Houses

Claus E. Andersen[1], Niels C. Bergsøe[2], Benny Majborn[3] and Kaare Ulbak[4]

Abstract To investigate the effect of ventilation on indoor radon (^{222}Rn), simultaneous measurements of radon concentrations and air change rates were made in 117 Danish naturally ventilated slab-on-grade houses built during the period 1984–1989. Radon measurements (based on CR-39 alpha-track detectors) and air change rate measurements (based on the perfluorocarbon tracer technique; PFT) were in the ranges 12–620 Bq m^{-3} and 0.16–0.96 h^{-1}, respectively. Estimates of radon entry rates on the basis of such time-averaged results are presented and the associated uncertainty is discussed. It was found that differences in radon concentrations from one house to another are primarily caused by differences in radon entry rates whereas differences in air change rates are much less important (accounting for only 8O,O% of the house-to-house variation). In spite of the large house-to-house variability of radon entry rates it was demonstrated, however, that natural ventilation does have a significant effect on the indoor radon concentration. Most importantly, it was found that the group of houses with an air change rate above the required level of 0.5 h^{-1} on average had an indoor radon concentration that was only 50% (0.5±0.1) of that of the group of houses with air change rates below 0.5 h^{-1}. The reducing effect of increased natural ventilation on the indoor radon concentration was found to be due mainly to dilution of indoor air. No effect could be seen regarding reduced radon entry rates.

Key words Air change rates; Alpha-track detectors; Natural ventilation; Passive perfluorocarbon tracer (PFT); Radon 222; Radon entry rates.

Received 1 May 1996. Accepted for publication 25 February 1997.

Introduction

The present study of the effect of ventilation on indoor radon levels was motivated by an observation from the Danish nationwide survey of natural radiation in dwellings (Ulbak et al., 1988). In that investigation no significant association could be established between indoor radon levels and types of ventilation system or habits of airing. It could be argued, however, that the reason for the apparent lack of an effect was that the analysis was not based on air change rate measurements (which were not part of the investigation) but only on the more general house information obtained from questionnaires or from the Building and Dwelling Register. In Denmark, increased ventilation is often recommended as a means of reducing indoor radon concentrations, and a more detailed investigation based on actual air change rate measurements is desirable. This paper describes the results of such an investigation.

Experimental studies, for example in Sweden and in the UK (Swedjemark and Mäkitalo, 1990; Cliff et al., 1994), have demonstrated that increased natural ventilation on average can reduce indoor radon levels by a factor of two. In general, increased ventilation is simple to implement, but to achieve large radon reductions in cold climates, high heating costs are to be expected (Henschel, 1988, 1994).

Theory

The coupling between indoor radon concentration and ventilation is complex and a number of theoretical models have been developed as discussed for example by Mowris and Fisk (1988), Nazaroff et al. (1988), Hubbard et al. (1992), Sherman (1992), Arvela (1995), and Kokotti (1995).

We consider the mass-balance equation of radon in a house with only one (well-mixed) zone where ventilation is the sole mechanism of radon removal:

$$V\frac{\mathrm{d}c}{\mathrm{d}t} = J(t) - c(t)Q(t) \tag{1}$$

---

[1] *Risø National Laboratory, Department of Nuclear Safety Research and Nuclear Facilities, DK-4000 Roskilde, Denmark. Fax: +45 46 77 49 59, e-mail: claus.andersen@risoe.dk.,* [2] *Danish Building Research Institute, Hørsholm, Denmark,* [3] *Risø National Laboratory, Denmark,* [4] *National Institute of Radiation Hygiene, Brønshøj, Denmark*

where V is the volume of the house [m^3], $c(t)$ is the indoor radon concentration [$Bq\,m^{-3}$] at time t, $J(t)$ is the radon entry rate from outdoor air, soil, building materials and other sources [$Bq\,h^{-1}$], and $Q(t)$ is the infiltration rate of air to the house from the outdoors and from the soil [$m^3\,h^{-1}$]. The air change rate of the house is $\lambda_v(t)=Q(t)/V$ [h^{-1}].

When $dc/dt \approx 0$ and the radon entry rate is constant, the indoor radon concentration is simply inversely related to the air change rate. The radon entry rate is relatively constant, for example when radon enters from the soil mainly by diffusion or when building materials are the main source of radon. In general, however, both (advective) entry of soil-gas radon and infiltration of outdoor air are coupled since they are both driven by pressure differences created across the building envelope as a result of driving forces such as indoor-outdoor temperature differences and wind.

Radon mitigation involving natural ventilation can be targeted at changes of either infiltration of outdoor air to the house or exfiltration of indoor air from the house. Changes may concern the amount of airflow or the location where the airflow enters or leaves the house. In all cases, an increase of the air change rate will tend to decrease the indoor radon level since radon levels outdoors are almost always much lower than indoors. This is the effect of dilution.

In newer Danish single-family houses, it is standard that natural ventilation is driven by two vertical exhaust vents (also referred to as exhaust stacks) through the ceiling: one in the bathroom and one in the kitchen, and that outdoor-air inlets (1–3 per room) are placed in other rooms. This design is sketched in Figure 1.

Improvement of the efficiency of exhaust vents can lead to an increase of the depressurization of the house. This will increase both the advective entry rate of radon and the air change rate, so that the net reduction effect will be less than that caused by dilution alone. This is particularly important if advective entry is the dominant mode of radon entry. In some cases, the dilution can even be outbalanced by the increased radon entry rate. Conversely, the installation of outdoor-air inlets tends to decrease the depressurization of the house (outdoor air enters the house instead of soil gas) adding to the radon reduction efficiency of the remedial measure. This is the effect of (pressure) neutralization (Henschel 1988; Cavallo et al. 1992). To achieve the best pressure-difference reduction at floor level (where radon entry occurs) outdoor-air inlets should be installed on the lower parts of the walls. However, in cold climates this gives rise to comfort concerns, and in Denmark the general recommendation is therefore that outdoor-air inlets should be placed at about the same height as the top of the window frames, as sketched in Figure 1.

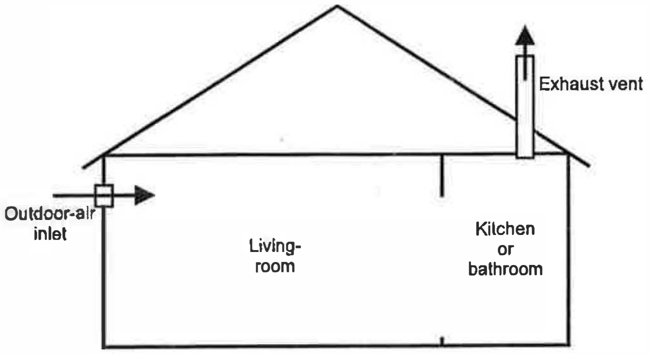

Fig. 1 Sketch of standard Danish single-family house with natural ventilation. The outdoor-air inlets are normally placed at the same height as the top of window frames.

In the foregoing, we have outlined what may happen as a result of remedial measures such as the installation of outdoor-air inlets or exhaust vents. For the analysis included in this study, it is also important to consider the case where the air change rate has changed as a result of changes of indoor-outdoor temperature differences or wind acting on the house. Again, both the advective radon entry rate and the air change rate of the house are affected. The net change of the indoor radon level therefore depends on the mode of radon entry as well as on the distribution of leakage across the building envelope (Sherman, 1992).

As an example, doubling the indoor-outdoor temperature difference under no-wind conditions will approximately double the indoor-outdoor pressure difference at all heights of the building envelope (assuming that other parameters such as house leakage remain constant). Since flow of soil gas increases linearly with the pressure (Darcy flow), this therefore doubles the advective radon entry from the soil. In comparison, the air change rate is likely to change by a factor of only 2^n, where n is the leakage exponent. n is in the range 0.5 to 1, and has a typical value of 0.66 in the US (Sherman, 1992). Under typical conditions when advection is the dominant mode of entry, the doubling of the indoor-outdoor temperature difference is therefore likely to result in a 27% increase of the indoor radon level ($2/2^{0.66}$) and a 58% increase of the air change rate ($2^{0.66}$). In the extreme case of $n=1$, the indoor radon level will remain constant, and the air change rate will double.

Materials and Methods

The present investigation was conducted as an extension of a study by the Danish Building Research Institute (SBI) of ventilation and humidity conditions in single-family houses (Bergsøe, 1994). About 2100 addresses of houses built after 1982 were selected representatively by the Building and Dwelling Register. The register provided information on the size of the houses and other design data. Supplementary information was obtained from householders based on a questionnaire. Approximately 150 of the houses were selected for house inspection and measurement of radon, ventilation, humidity, and other parameters.

The present study concerns results from 117 of these houses. All houses were single-family one-story slab-on-grade houses built during the period 1984–1989. Sixteen of the houses had attics that were fully or partly inhabited and 4 of the houses had attics that potentially could be turned into living areas. The rest of the houses had no attics or had attics that (because of the inclination of the roof) could not be converted into living areas.

All the houses studied were ventilated solely by natural means except for mechanical exhaust fans in an extractor hood above cookers. These fans were, however, only used intermittently. Based on the questionnaire responses it is known that 97 of the houses had outdoor-air inlets and that 18 had not. In 66 of the houses, outdoor-air inlets were normally kept open. In this study, it was not verified whether exhaust vents were in place and whether they were operating properly.

Ninety-four of the houses were situated on Zealand (or its nearby islands) where the surface geology is dominated by clayey till. The remaining 23 houses were situated in the southern part of Jutland where the surface geology is mainly clayey till or sand and gravel.

The radon measurements were carried out in the living rooms using passive, closed detectors equipped with CR−39 foils. The procedures were as described previously (Majborn, 1986a), with the modification that a different type of detector holder (Melander and Enflo, 1992) was used. The uncertainty of the measurements depends on the radon exposure as discussed in Majborn (1986a). In this study, the uncertainty expressed as one standard deviation of a single radon measurement is estimated to be 20–30%.

The ventilation measurements were performed using the passive perfluorocarbon tracer technique, i.e. the so-called PFT-method (Bergsøe, 1992). The measurements comprised the average total infiltration of air to the house and the air exchange between the main bedroom and the rest of the house. The average air change rate is calculated as the ratio between the average total infiltration rate of air and the net volume of the house. As discussed in Bergsøe (1992), the method tends to underestimate the average infiltration of air to the house. However, under normal conditions, the bias is estimated to be less than 15%. The precision of the method expressed as one standard deviation of the result is 10–15%.

Time-averaged radon entry rates J_{avg} [Bq h^{-1}] were calculated for each house as the product of the measured radon concentration in the living room c_{avg} [Bq m^{-3}] and the measured average total infiltration rate of air Q_{avg} [m^3 h^{-1}] to the house. This method has been used also by other investigators (e.g. D'Ottavio et al., 1987; Arvela, 1995). As discussed in the Appendix, the coupling between radon entry and air change rate makes this time-averaging delicate, and the uncertainty expressed as one standard deviation of a single radon entry rate determination was assessed to be as great as 85%.

Measurements included in the study were performed in 89 houses during the period 13 January to 1 March 1992 and in 43 houses from 10 October to 8 November 1992. The duration of measurement periods varied from 7 to 25 days and the arithmetic mean and standard deviation were 14 days and 3.3 days, respectively. Radon detectors and PFT-tubes were placed in the houses by staff from SBI and returned by mail to SBI. For each house, radon and ventilation measurements were therefore performed absolutely simultaneously. Only householders tha had returned detectors in accordance with the in

Table 1 Summary of measurements in the 117 single-family houses

Variable	Arithmetic		Geometric		Range
	Mean	Std.dev.[a]	Mean	Std.dev.[a,b]	
Indoor radon concentration (Bq m^{-3})	146	111	109	2.3	12–620
Air change rate (h^{-1})	0.37	0.16	0.34	1.4	0.16–0.96
Air infiltration rate (m^3 h^{-1})	94	38	88	1.4	35–243
Radon entry rate (kBq h^{-1})	12.6	9.2	9.6	2.2	0.7–45
Radon entry rate per volume (Bq h^{-1}m^{-3})	49	35	37	2.2	2.9–179
Net house volume (m^3)	261	48	234	1.2	166–422
Indoor-outdoor temperature difference (°C)	18.7	2.3	18.5	1.1	13–25

[a] Standard deviation.
[b] Dimensionless.

structions (such as correct capping of PFT samplers) were included in the study.

During transfer from SBI to the houses and after their return to SBI, the radon detectors were sealed in radon-tight pouches, so that the only transit exposure occurred during their return by mail. The transit times varied between 18 and 140 hours, except for 3 detectors with considerably higher transit times that were discarded from the analysis. Minor corrections were made for transit exposures, assuming that the detectors were exposed to an average radon concentration of 20 Bq m^{-3} during transit.

For 8 detectors the net track densities were lower than the standard deviation of the track density for unexposed background detectors, and these results were discarded from the analysis. Furthermore, simultaneous measurements of radon and ventilation were not available for all houses. These results are therefore not included in the group of 117 houses on which the present analysis is based.

Results

The main results are shown in Figure 2 and summarized in Table 1. Radon concentrations and entry rates were found to be well described by lognormal distribution functions (chi-square tests with $P>0.2$) as indicated in the plots. Air change rates were found to be better described by a lognormal distribution function (chi-square test with $P<0.03$) than by a normal distribution function ($P\approx10^{-8}$).

The results of the simultaneous measurements of radon and air change rates are shown in Figure 3. Decreasing ventilation is seen to be associated with higher and more variable radon concentrations. In Denmark, it is a requirement that houses have a minimum air change rate of 0.5 h^{-1} (National Building Agency, 1985), and it is therefore reasonable to analyse the data groupwise, depending on whether the air change rate is below or above this level. In the group of houses with air change rates less than 0.5 h^{-1} (96 houses), the geometric mean and standard deviation of the radon concentration were 122 Bq m^{-3} and 2.2, respectively and 31% of these houses had radon concentrations exceeding 200 Bq m^{-3}. In comparison, for the group of houses with air change rates of 0.5 h^{-1} or higher (21 houses) the geometric mean and standard deviation were 64 Bq m^{-3} and 2.0, respectively and only one house exceeded 200 Bq m^{-3}. The geometric mean radon concentrations of the two groups were significantly different ($P<0.001$), and the ratio between the geometric means of the groups amounted to 0.5±0.1. The indicated uncertainty is one standard error. A similar analysis based on arithmetic means gives the same result. A linear-regression analysis (see Figure 3) between the logarithm of the radon concentrations and the logarithm of the air change rates yielded a regression coefficient −0.64 (95%-confidence interval= [−1.03, −0.24]) that was significantly different from zero ($P=0.0018$). However, the regression could account for only 8% of the variation. Other types of regression analysis based on inverse or linear models yielded comparable results.

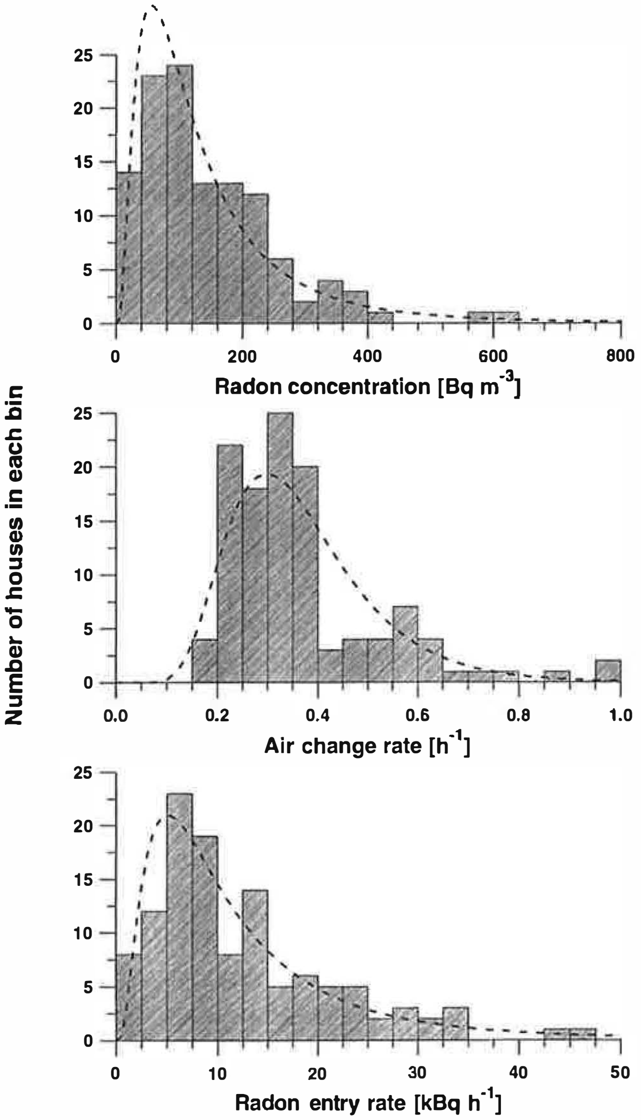

Fig. 2 Plots of radon concentration, air change rate, and radon entry rate for the 117 single-family houses. The dashed curves are lognormal distribution functions corresponding to the geometric means and standard deviations given in Table 1.

Discussion

As will be discussed in more detail below, the house-to-house variation of radon entry rates is much greater than that of air change rates. It is therefore difficult to demonstrate an effect of ventilation on the indoor radon concentration. However, dividing the data into two groups, depending on whether the air change rate is below or above the required level of 0.5 h^{-1} shows that houses with an air change rate of more than 0.5 h^{-1} on average have an indoor radon concentration that is a factor of two lower than that of houses with an air change rate below 0.5 h^{-1}. Hence, it appears that changing the air change rate from 0.31 h^{-1} (corresponding to the mean air change rate of the group with air change rates below 0.5 h^{-1}) to 0.65 h^{-1} (corresponding to the mean of the other group) on average reduces the indoor radon concentration to 50% (0.5±0.1) of the initial value.

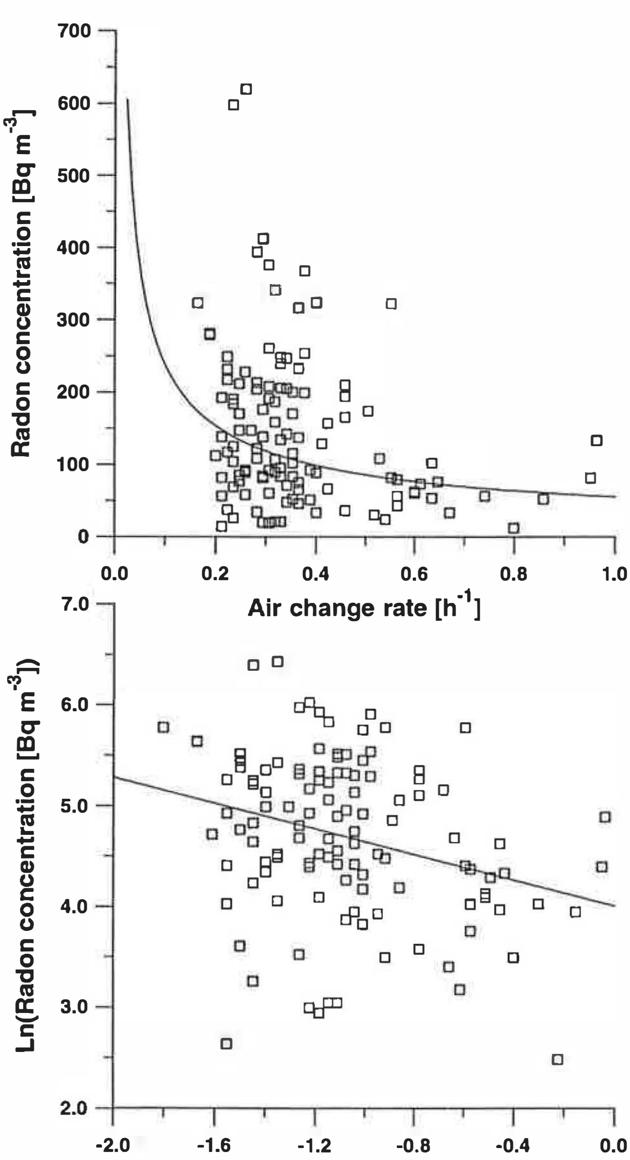

Fig. 3 The top plot is the indoor radon concentration versus the air change rate for the 117 single-family houses. The same data transformed by the natural logarithm (Ln) are shown in the bottom plot. The solid curve (shown in both plots) is a linear-regression line based on the log-transformed data (slope=−0.64; R^2=8%).

Similar results are obtained from analyses based on the logarithm of the radon concentrations or on a separation of the houses into two groups of equal sizes based on whether the air change rate is below or above the median level. In the latter case the effect is, however, less pronounced. The regression analysis of the logarithm of the radon concentration versus the logarithm of the air change rate yielded a slope (−0.64) significantly different from zero. Furthermore, the slope was not found to be significantly different from the theoretical estimate (−1) expected if the radon concentration had simply been inversely related to the ai change rate (see Theory section). This regression analysis therefore supports the above conclusion.

One potential problem connected with these analyses needs consideration. For practical reasons, house measurements were week per week conducted groupwise, partly in accordance with location. This introduces an artificial link between meteorology and geology that could tend to bias the analysis compared to a situation when houses are sampled purely by random. This potential bias is, however, only a real problem if there is a significant difference between the radon potential of the six administrative regions involved (five on Zealand and one in the southern par of Jutland). An analysis of variances shows that this is not the case: there is no significant difference between the indoor radon concentrations of the six regions.

There are two sources for the variability of the ai change rates observed in this investigation. Differen airtightness of the houses and different driving force such as indoor-outdoor temperature differences and wind. In this context, the term airtightness comprises (i) purpose-provided ventilation openings such as windows, outdoor-air inlets, and exhaust vents, and (ii random leaks and cracks in the building envelope Since all measurements were made under winter conditions, we suspect the main part of the variation t result from differences in house airtightness. We hav no information about wind effects to confirm this, bu the mean indoor-outdoor temperature differences based on spot measurements of indoor temperatur during house inspections and weekly outdoor temperatures reported by the Danish Meteorological Institute – are not significantly different for the two group with air change rates below and above 0.5 h^{-1}: Th 95% confidence intervals for the two groups ar 18.5±0.5°C (n=96) and 19.5±1.0°C (n=20), respectively. Therefore, the observed factor-two reduction c indoor radon level referred to above seems to resu mainly from differences in airtightness of the houses involved. This is an important observation for the application of the results since reduction of indoor radon levels by increased natural ventilation is basically a question of changing and controlling the airtightness of the house, and because – as outlined in the introduction – there is a profound difference between the effect of changes of airtightness and changes of driving forces.

The groups of houses with air change rates below or above 0.5 h^{-1} have radon entry rates that are not significantly different (12.6 and 12.3 kBq h^{-1}, respectively with a pooled standard deviation of 9.2 kBq h^{-1}) and in general, there is no correlation between the observed radon entry rates and air change rates: a linear-regression analysis of air change rate and radon entry rates has a R^2-value less than 1%. In other words, this study does not demonstrate that increased natural ventilation reduces radon entry rates, e.g. by neutralizing driving forces responsible for advective radon entry. The main effect of natural ventilation on the indoor radon concentration demonstrated in this study is to dilute the radon concentration in the house.

From the questionnaire and interview forms completed by the occupants of the houses, information has been obtained on the installation and use of outdoor-air inlets and also on the airing habits of the occupants. In agreement with the findings of the nationwide survey (Ulbak et al., 1988), no significant effect could be seen on radon entry rates or radon concentrations. However, this time the results were less surprising since the ventilation measurements revealed that the use of outdoor-air inlets and the airing habits of the occupants were not reflected in significantly different air change rates (Bergsøe, 1994).

Although the above observations stem from statistical analyses of air change rates and radon in a group of houses where no changes of leakage areas etc. were performed, the result implies that if the ventilation is improved in any one house we expect (on average) that this improvement will result in a reduction of the radon concentration as given above. The improvement must, however, be achieved in the same (unknown) way as in the group of houses investigated. Although we do not know the reason for the observed differences in air change rates among the houses, the above analyses suggest that it was not because of differences in driving forces (at least not temperature differences), use of outdoor-air inlets, or habits of airing. This could lead to the hypothesis that the efficiency of exhaust vents are the main reason for the differences. From this study we cannot draw more specific conclusions about the expected radon reduction efficiency of given changes of building designs. The study only confirms investigations such as those by Swedjemark and Mäkitalo (1990) and Cliff et al. (1994) that improved natural ventilation on average reduces indoor radon. The study does not tell how to increase air change rates in specific houses in order to decrease indoor radon levels.

It is plausible that the observed house-to-house variation of radon entry rates is due mainly to differences in geological features such as radon generation rate and gas permeability of the ground. Since the variability of air change rates seems mainly to reflect differences in airtightness of the houses (i.e. house features not related to the geology of the building site), it is reasonable that radon entry rates and air change rates are not correlated although both processes are influenced by some common factors (temperature and wind).

As illustrated by the data in Figure 3, the correlation between indoor radon concentrations and air change rates is weak, and differences in air change rates from one house to another can only account for approximately 8% of the observed variability of the indoor radon concentrations. Furthermore, an extended regression analysis shows that the house volumes have virtually no association with the indoor radon level. Since there seem to be no other reasonable factors to consider, it is concluded that the house-to-house variability of indoor radon levels is caused mainly by differences in radon entry rates. This finding is in agree-

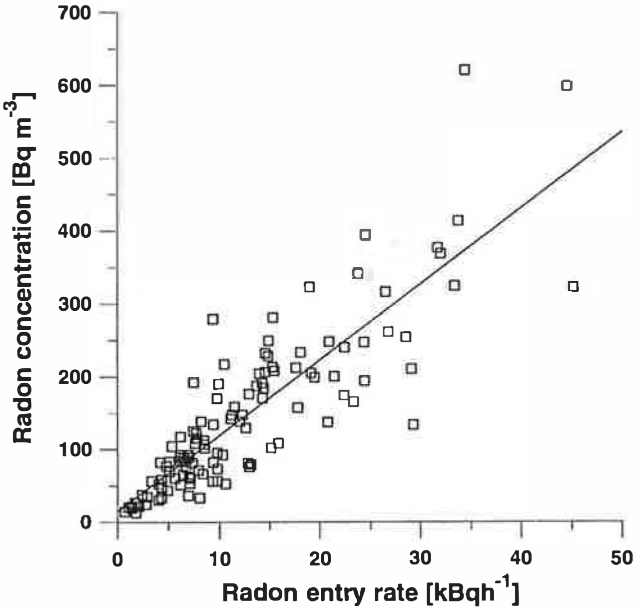

Fig. 4 Indoor radon concentrations versus radon entry rates in the 117 single-family houses. The line is a regression line.

ment with previous studies in the USA and in Finland (Doyle et al., 1984; Nero, 1989; Arvela, 1995).

The relationship between radon concentrations and radon entry rates is illustrated in Figure 4. It should be recalled, however, that our estimates of radon entry rates are not *a priori* independent of the radon measurements, as stated in the Materials and Methods section. A rigorous multiple-regression analysis of the radon concentrations versus air change rates, house volumes, and radon entry rates is therefore not possible in this study.

The geometric mean radon entry rate from soil, building materials, and outdoor air, etc., was calculated to be 9.6 kBq h^{-1}, and it was found that 80% of the houses had entry rates above 6 kBq h^{-1}. In typical Danish single-family houses built of clay bricks and/or aerated concrete, the radon entry rate resulting from the building materials has been estimated to be 1–3 kBq h^{-1} (Jonassen and McLaughlin, 1980; Ulbak et al., 1984). This is much lower than the total radon entry rate for the majority of the houses in this investigation; exhalation from building materials in general is therefore not an important source of indoor radon. This observation is in agreement with the results of the nationwide survey where soil was identified as the dominant source (Ulbak et al., 1988). For completeness, it should be mentioned that the annual average outdoor radon concentration in Denmark is approximately 8 Bq m^{-3} (Majborn, 1986b). Hence, for the houses with the largest infiltration rates of outdoor air (approx. 240 $m^3 h^{-1}$), the outdoor air can account for an entry rate of about 2 kBq h^{-1}.

This investigation focuses on newer slab-on-grade houses in two selected areas of Denmark but since the radon levels and air change rates encountered are typical for Denmark, the findings are probably also valid for Danish single-family houses in general.

Conclusions

The study confirmed that the soil is the dominant source of indoor radon for the majority of Danish single-family houses. It was found that differences in radon concentrations from one house to another are primarily caused by differences in radon entry rates, whereas differences in air change rates are much less important (accounting for only 8% of the house-to-house variation).

In spite of the large variability of radon entry rates, it was demonstrated that natural ventilation does have a significant effect on the indoor radon concentration. Houses with an air change rate of more than the required level of 0.5 h^{-1} on average have an indoor radon concentration that is a factor of two lower than that of the houses with air change rates below 0.5 h^{-1}. The reducing effect of increased natural ventilation on the indoor radon concentration was found to be due mainly to dilution of indoor air; no effect could be seen regarding reduced radon entry rates.

In agreement with the findings of the nationwide survey, no significant effect could be seen of airing habits or use of outdoor-air inlets on radon entry rates or radon concentrations. However, this time the results were less surprising since the ventilation measurements revealed that airing habits or use of outdoor-air inlets were not reflected in significantly different air change rates.

The study implies that search profiles for high-radon houses should primarily focus on entry-related features such as geology and type of house foundation whereas ventilation should be considered only in connection with the planning of mitigation measures for the specific house.

Appendix

This appendix concerns the accuracy of the applied method for estimating the radon entry rate (J) into a house using time-averaged measures of radon (c) and air infiltration (Q). We define the time-averaged radon concentration over the period from 0 to T as:

$$c_{\text{avg}} = \frac{1}{T}\int_0^T c(t)\mathrm{d}t \tag{2}$$

and apply similar definitions for J_{avg} and Q_{avg}.

Rearranging Equation 1 gives the following expression for the instantaneous radon entry rate at time t:

$$J(t) = V\frac{\mathrm{d}c}{\mathrm{d}t} + Q(t)c(t) \tag{3}$$

thus the time-averaged radon entry rate J_{avg} can be found as:

$$J_{\text{avg}} = \frac{V}{T}(c(T)-c(0)) + \frac{1}{T}\int_0^T c(t)Q(t)\mathrm{d}t \tag{4}$$

The term involving $c(T)-c(0)$ (i.e. the net increase over the period T) can be disregarded under most circumstances since indoor radon levels normally change periodically (so that eventually $c(T)\approx c(0)$) and because its importance becomes small for sufficiently long periods T. For example, a two-week measuring period with a 2000 Bq m^{-3} difference between the radon concentration at the beginning and end of the period will result in a contribution to J_{avg} of less than 1.5 kBq h^{-1}.

We therefore have to a good approximation:

$$J_{avg} = \frac{1}{T}\int_0^T c(t)Q(t)\mathrm{d}t \tag{5}$$

In this study, the alpha-track detector measurement gives the time-averaged radon concentration c_{avg} over the period T, and the PFT-measurement gives the total infiltration rate of air Q_{avg} over the same period. As stated in the Materials and Methods section, we use the approximation:

$$J_{avg} \approx c_{avg}Q_{avg} \tag{6}$$

as an estimate of the time-averaged radon entry rate. This is different from the exact result stated in Equation 5, but it is not possible to assess the accuracy of this approximation in full generality.

It is therefore instructive – as a first approximation – to consider the case where $c(t)$ and $Q(t)$ are periodic functions (e.g. with a period time $\frac{2\pi}{\omega}$ of 24 hours) of the forms:

$$c(t) = c_0 + c_1 \cos(\omega t) \tag{7}$$

and

$$Q(t) = Q_0 + Q_1 \cos(\omega t + \phi) \tag{8}$$

where c_0, c_1, Q_0, Q_1, ω, and ϕ are constants and where $c_0 \geq c_1 > 0$ and $Q_0 \geq Q_1 > 0$. Such time series are likely to represent the situation for a naturally ventilated house on non-windy days without too much disturbance from the house occupants. Integrating Equation 5 with these functions over a period that is long compared with the time period of the oscillations (e.g. two weeks) and assuming that $c_{avg}=c_0$ and $Q_{avg}=Q_0$ gives:

$$J_{avg} = c_{avg}Q_{avg} + \tfrac{1}{2}c_1Q_1\cos(\phi) \tag{9}$$

We define the error ε of the measurement as the difference between the reported result $c_{avg}Q_{avg}$ and the true value J_{avg}. We observe that $\varepsilon = -c_1Q_1\cos(\phi)/2$ may be either positive or negative depending on the value of ϕ, and that ε can be in the range −33–100% of the true value J_{avg}, given the above constraints on c_1 and Q_1. The maximum relative error of 100% (i.e. when the method predicts a radon entry rate that is a factor of two greater than the true value) occurs when $\phi=180°$ (i.e. $c(t)$ are phase-shifted by one half-period relative to $Q(t)$), $c_1=c_0$, and $Q_0=Q_1$. This situation appears to resemble certain parts of the data reported by Nazaroff et al. (1985). To be able to combine this source of error with that from other sources, we summarize the uncertainty from the time-averaging procedure as 70%.

The assumption that each house can be treated as a single well-mixed zone is a simplifying – but necessary – assumption in this analysis since the radon concentration was measured only in one room (the living room). Even though the living-room radon concentration is probably a fairly representative measure for the radon concentration of the full house, it is known from previous studies that a considerable difference can exist between individual rooms even for single-storey houses without a basement. For example, in a Danish study (Damkjær et al., 1996) of radon in single-family houses, the living-room radon concentration for houses of the slab-on-grade type (measured over 10 weeks) was more than 2 times greater than the radon concentration of the bedroom for more than 17% of the houses, and the mean and standard deviation of bedroom-to-living room ratios were 0.85 and 0.54, respectively (N=200). The implication of this seems to be that the living-room radon concentration measurement tends to provide an overestimate of the house-averaged radon concentration. Accordingly, this leads to a biased (over)estimate of the radon entry rate. For the majority of houses, the error is expected to be less than about 30%, but in some cases the error may be much greater.

The combined relative uncertainty (expressed as one standard deviation of repeated measurements divided by the mean) based on quadrature summation of the individual error contributions (i.e. we disregard bias and assume that all errors are random) for time-averaging (70%), room-to-room variation of radon concentrations (30%), radon concentration measurements (30%), and air change rate measurements (20%) amounts to 85%. As a first approximation, this is the uncertainty (expressed as one standard deviation) of a single radon entry determination in this study.

Acknowledgements

This study was partially supported by the Danish Ministry of Health's Research Centre for Environmental Health. The SBI-project on ventilation was supported by the National Building and Housing Agency (Danish Ministry of Housing and Building).

References

Arvela, H. (1995) *Residential Radon in Finland: Sources, Variation, Modelling and Dose Comparisons*, Helsinki, (STUK-A124), Finnish Centre for Radiation and Nuclear Safety (Dissertation for the degree of Doctor of Technology).

Bergsøe, N.C. (1992) *Passiv Sporgasmetode til Ventilationsundersøgelser. Beskrivelse og Analyse af PFT-Metoden*, Hørsholm, Denmark, Danish Building Research Institute (SBI-report 227) (in Danish with English summary).

Bergsøe, N.C. (1994) *Ventilationsforhold i Nyere, Naturligt Ventilerede Enfamiliehuse*, Hørsholm, Denmark, Danish Building Research Institute (SBI-report 236) (in Danish with English summary).

Cavallo, A., Gadsby, K., Reddy, T.A. and Socolow, R. (1992)

"The effect of natural ventilation on radon and radon progeny levels in houses", *Radiation Protection Dosimetry,* **45**(1–4), 569–574.

Cliff, K.D., Naismith, S.P., Scivyer, C. and Stephen, R. (1994) "The efficacy and durability of radon remedial measures", *Radiation Protection Dosimetry,* **56**(1–4), 65–69.

Damkjær, A., Andersen, C.E., Majborn, B., Ulbak, K. and Graversen, P. (1996) "A search profile for dwellings with elevated radon levels", *Environment International,* 22(suppl. 1), 783–788.

D'Ottavio, T.W., Dietz, R.N., Kunz, C. and Kothari, B. (1987) "Radon source rate measurements using multiple perfluorocarbon tracers". In: Seifert, B., Esdorn, H., Fischer, M., Ruden, H., and Wegner, J. (eds) *Proceedings of Indoor Air '87,* Berlin, Institute of Water, Soil and Air Hygiene, Vol. 2, pp. 288–292.

Doyle, S.M., Nazaroff, W.W. and Nero, A.V. (1984) "Time-averaged indoor Rn concentrations and infiltration rates sampled in four U. S. cities", *Health Physics,* **47**, 579–586.

Henschel, D.B. (1988) *Radon Reduction Techniques for Detached Houses,* Research Triangle Park, United States Environmental Protection Agency, 2nd ed., (EPA/625/5-87/019).

Henschel, D.B. (1994) "Analysis of radon mitigation techniques used in existing US houses", *Radiation Protection Dosimetry,* **56**(1–4), 21–27.

Hubbard, L.M., Hagberg, N. and Enflo, A. (1992) "Temperature effect on radon dynamics in two Swedish dwellings". *Radiation Protection Dosimetry,* **45**(1–4), 381–386.

Jonassen, N. and McLaughlin, J.P. (1980) "Exhalation of radon−222 from building materials and walls". In: Gesell, T. F. and Lowder, W.M. (eds), *Natural Radiation Environment III.* Vol. 2, pp. 1211–1224.

Kokotti, H. (1995) *Dependence of Radon Level on Ventilation Systems in Residences,* Kuopio, Finland, Kuopio University Publications C. Natural and Environmental Sciences 32, University of Kuopio, (dissertation).

Majborn, B. (1986a) "Measurements of radon in dwellings with CR−39 track detectors", *Nuclear Tracks and Radiation Measurements,* **12**(1–6), 763–766.

Majborn, B. (1986b) (Unpublished results), Risø National Laboratory, DK-4000 Roskilde, Denmark.

Melander, H. and Enflo, A. (1992) "The alpha track method used in the Swedish radon epidemiological study", *Radiation Protection Dosimetry,* **45**, 65–71.

Mowris, R.J. and Fisk, W.J. (1988) "Modeling the effects of exhaust ventilation on radon entry rates and indoor radon concentrations", *Health Physics,* **54**(5), 491–-501.

National Building Agency (1985) *Danish Building Regulations for Small Buildings,* Copenhagen, National Building Agency.

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

Nazaroff, W.W., Moed, B.A. and Sextro, R.G. (1988). "Soil as a source of indoor radon: generation, migration, and entry". In: Nazaroff, W.W. and Nero, A.V. (eds.) *Radon and its Decay Products in Indoor Air,* New York, John Wiley & Sons, pp. 57–112.

Nero, A.V. (1989) "Earth, air, radon, and home", *Physics Today,* April, pp. 32–39.

Sherman, M.H. (1992) *Simplified Modeling for Infiltration and Radon Entry,* Berkeley, CA, Lawrence Berkeley Laboratory (LBL−31305).

Swedjemark, G.A. and Mäkitalo, A. (1990) "Recent Swedish experiences in radon control", *Health Physics,* **58**, 453–460.

Ulbak, K., Jonassen, N. and Bækmark, K. (1984) "Radon exhalation from samples of concrete with different porosities and fly ash additives", *Radiation Protection Dosimetry,* **7**, 45–48.

Ulbak, K., Stenum, B., Sørensen, A., Majborn, B., Bøtter-Jensen, L. and Nielsen, S.P. (1988) "Results from the Danish indoor radiation survey", *Radiation Protection Dosimetry,* **24**, 401–405.