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EXPOSURE TO RADON AND RADON PROGENY IN THE INDOOR ENVIRONMENT

Principal Investigator:

Robert H. Socolow
H102 Engineering Quadrangle
Princeton University
Princeton, NJ 08544

Project Manager: Dr. Matesh N. Varma

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Table of Contents

Chapter	Title	Page
I	Summary of research	1
II	The Use of Radon Entry Rate Measurements to Understand Radon Concentration in Buildings	4
III	Use of Natural Basement Ventilation to Control Radon in Single Family Dwellings	21
IV	The Effect of Natural Ventilation on Radon and Radon Progeny Levels in Houses	34
V	Comparison of Natural and Forced Ventilation for Radon Mitigation in Houses	45
VI	Resulting Publications	57

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Chapter I

Summary

This report discusses the work done by the Center for Energy and Environmental Studies at Princeton University as part of the radon research program sponsored by the Department of Energy, Office of Health and Environmental Research, during the period from July 1, 1990 through June 30, 1993.

The methodology of our research required that building construction and operation be studied and understood both experimentally and theoretically in a small number of buildings and that results of wide applicability be inferred from the particular case studies.

To meet these objectives, research houses were instrumented as follows:

1. Pressure differentials across the building shell and between the basement and upstairs were measured with differential pressure transducers.
2. Basement, living area, attic, and outdoor temperatures are monitored with thermistors.
3. Basement, living area, subslab and basement wall radon concentrations are monitored with passive radon detectors or pumped continuous radon monitors.
4. Basement relative humidity and air handler activity are also recorded.

In addition, a weather station monitors temperature, rainfall, relative humidity, barometric pressure, and wind speed and direction.

Instrumentation to measure the activity-weighted particle size distribution is located in the actual living area of the occupied research house; the large pump associated with this instrument is placed in the basement or outdoors. These measurements are made with the instrumentation built by P. Hopke of Clarkson University.

Although radon and radon progeny screening measurements have been made in many houses, it is the amount of ultrafine aerosol in the air which dominates the dose to sensitive human lung tissue. Thus, it is essential to measure the activity-weighted particle size distribution in occupied houses if the dose from exposure to radon is to be quantified.

Over the past several years we have been very fortunate to find homeowners who are interested in our work and extremely tolerant of these rather intrusive experiments.

The major scientific results of our experiments are:

- Activity-weighted particle size distribution measurements have been completed over six five day intervals in three different normally occupied Princeton research houses. There is a factor of two difference between the two houses in the average amount of ultrafine aerosol for a given radon level. The reason for this difference is not known. (Measurements done with P.Hopke and N.Montassier, Clarkson University.)
- The effect of fan operation in the forced air heating system has been investigated. Continuous fan operation increases the radon level but decreases the equilibrium factor by a factor of two relative to normal house operation. However, the ultrafine aerosol, and thus the dose, remains approximately constant. (Measurements done with P.Hopke and N.Montassier, Clarkson University.)
- Field intercomparisons of activity-weighted particle size distribution measurements between manual graded screen arrays (EML) and an automated semi-continuous system (Clarkson University) have been made twice in Princeton research houses. Although overall agreement between the two systems is reasonable (total working level estimates), there are some discrepancies between the two systems in different parts of the particle size distribution spectrum. Efforts to resolve these differences are continuing.
- A detailed examination of radon entry rates and working level as a function of basement depressurization and ventilation rates has been completed. Ventilation has been found to be much more effective in reducing indoor radon concentration than was previously believed. We have clearly demonstrated that ventilation can reduce radon concentrations both by dilution and by the reduction of building depressurization.
- Measurement of radon entry rate (S) as a function of basement depressurization (ΔP) has shown that the flow of soil gas into our research house is laminar. This is the first time such measurements have been made in a real house under field conditions.
- Measurements of radon entry rate (S) as a function of basement depressurization (ΔP) before and after mitigation measures were performed have demonstrated a new and precise methodology for the evaluation of mitigation schemes.
- Systematic measurements of airflow in gravel and crushed stone have been made in a specially designed laboratory apparatus at

Princeton. These are the first measurements of this kind to be made. Permeabilities for crushed stone (0.5" and 0.75") were found to be 10-20 times as large as our previously reported values for these sizes of river run gravel. This data has been used in a model and compared to field results. The design of subslab depressurization systems will be substantially impacted by these findings.

Chapter II

The Use of Radon Entry Rate Measurements to Understand Radon Concentration in Buildings*

A. Cavallo, K.Gadsby, and T.A.Reddy*
Center for Energy and Environmental Studies
Princeton University, Princeton, NJ, USA

Abstract-The central role played by basement depressurization in drawing radon contaminated soil gas into a structure has been demonstrated by calculating the radon entry rate from radon concentration and air infiltration measurements at different levels of basement depressurization in a single family research house. Radon entry rate is found to be a linear function of basement depressurization in this house, which indicates that the flow of soil gas into the structure is laminar. The radon entry rates calculated before and after using a mitigation procedure is shown to provide a better measure of the mitigation efficacy than the standard before and after mitigation radon measurements in a research house. In addition, an analysis of the possible flow characteristics of soil gas and uncontaminated air into a basement indicates that any attempt to predict long term average radon exposure from short term screening measurements will only be possible under severely restricted conditions.

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Introduction

It was recognized by the late 1920s that radon gas was the carcinogenic agent which had for many years plagued the miners in the Schneeberg and Joachimsthal mining regions of Central Europe (Donaldson 1969). Mitigation systems (increased ventilation) were installed by the late 1930s in European uranium mines, after the Second World War in Canada, and by the early 1960s in uranium mines in the United States (Schneider 1990). In this case it was evident that the source of radon gas was the uranium rich rock either being mined or found in association with other minerals.

It came as a great surprise, however, when in the late 1970s (Sachs et al. 1982; Scott 1988) elevated levels of radon ($>200 \text{ Bq m}^{-3}$) were discovered in homes that were built on rock or soil with normal (40 Bq kg^{-1}) levels of uranium, and that had not had uranium mill tailings used in the construction materials or as fill around the house foundation. It was soon understood that soil gas with only moderate levels of radon (30 kBq m^{-3}) drawn into a house by normal levels of depressurization found in those regions of a house in contact with the soil was the cause of these elevated radon concentrations. This depressurization (normally less than 4 Pa) is caused by: 1) wind; 2) operation of mechanical systems such as exhaust fans and heating and air conditioning (HAC) systems; and 3) the stack effect, which is driven by normal indoor to outdoor temperature differentials.

This depressurization draws soil gas through the soil and into a building; it also draws uncontaminated outside air into the lower part of a building. Indoor air exits from the building generally through cracks and openings in the upper portion of the structure. The final indoor radon concentration is due to a balance between the infiltration of soil gas and the infiltration and exfiltration (ventilation) of uncontaminated outside air.

The infiltration and exfiltration of outside air into houses has been studied extensively both experimentally and theoretically (Lindament 1987). This work indicates that the rate at which air flows through small openings into or out of a building can be described by the following equation:

$$R_a = d \cdot (\Delta P_a)^m, \quad 0.5 \leq m \leq 1. \quad (1)$$

Here R_a is the volumetric flow rate of air, ΔP_a is the pressure differential driving the flow of air, and d is a function of the viscosity of the fluid and the type of the flow path. Flow through long, narrow openings is usually laminar for pressure differentials normally encountered in buildings, in which case the flow exponent m is equal to one. Flow through an opening with a large width to depth ratio is turbulent: in this case the flow exponent m is equal to 0.5. The net flow of outside air into a building is the sum of flows through different types of openings

and in practice this flow can be approximated by a single equation (eqn. 1) in which the exponent lies between 0.5 and 1 (Persily 1982).

In contrast, the flow of soil gas into a building as a function of pressure has not been studied experimentally up to now. Pressure driven flow of a fluid through soils was first investigated by Darcy (1856), who found that at low pressure gradients the water volumetric flow rate in a column of sand was proportional to the pressure gradient driving the flow. This type of fluid flow, generally termed Darcy or laminar flow, is expected to be found in the types of soils and for the soil gas flow rates normally encountered around buildings (Nazaroff et al. 1988).

Although the flow of air through soil is expected to be laminar, the flow of soil gas into a building may also be a combination different types of flows. For example, in New Jersey, recently built homes with basements have a layer of gravel 10-15 cm thick underneath the basement floor slab. Flow of soil gas to and through this gravel volume is expected to be laminar (Gadsby et al. 1991; Reddy et al. 1991); however, soil gas flow into the basement will be described by eqn. 1: the magnitude of the exponent will be between 0.5 and 1, depending on the characteristics of the flow path through the soil and through the concrete into the basement.

The determination of the radon entry rate as a function of basement depressurization allows the flow of soil gas into the structure to be characterized. This is one of the essential parameters needed to understand the long term behavior of radon concentration in a building. It also allows a better evaluation of the efficacy of a soil gas control mitigation technique. Measurement of the radon concentration before and after mitigation without taking into account the depressurization (ΔP) that draws soil gas and outside air into the structure must necessarily be imprecise. In addition, there is substantial interest in using short term screening measurements to predict long term radon exposure (EPA 1990, 1991). Most studies have focused on using statistical methods without considering the fundamental mechanisms that determine radon entry and radon concentration. A closer examination of these mechanisms allows one to determine under what circumstances such a prediction might be possible.

The plan for this paper is as follows: the experimental methods used to determine radon entry rate will be outlined. The computed radon entry rates will be used to characterize soil gas flow into a basement and to evaluate a simple mitigation (sealing an open sump). Finally, the implication of these results, in particular the influence of ventilation-induced changes in house depressurization, on the ability of short term screening measurements to predict long term radon exposure will be discussed.

Experimental Methods

The radon entry rate $S(\Delta P)$ into a Princeton University research house, hereafter referred to as PU31, was computed for the summer cooling season and the winter heating season with both natural and forced ventilation utilized to vary the basement depressurization.

Research house PU31 has the following characteristics:

size: 150 m² living area, 120 m² basement;

type: One story ranch with full attic and full basement; half of an attached slab-on-grade two car garage converted to TV room; hollow concrete block basement walls and hollow concrete block chimney stack in the center of the house; sump (50 cm diameter, 100 cm deep) in basement; no gravel under basement floor slab, floor slab rests on native soil;

attic: Two 1900 m³ h⁻¹ attic fans, thermostatically controlled; heating, cooling system: Central gas forced air heat, furnace located in basement; central air conditioning;

radon level: ~3.0 kBq m⁻³: basement, measured with a continuous passive radon detector, 37 kBq m⁻³: subslab, measured with a continuous radon monitor.

The house was occupied by two adults during the investigation. Since both worked full time, and most of the experimental activity took place in the basement which was used as a storage area and laundry room, the perturbation on the experiments was minimal. An unoccupied research house is to be preferred, but was ruled out by cost considerations.

The house has been instrumented to measure the following parameters:

1. pressure differentials across the building shell above and below grade, and between the basement and the living area;
2. basement, and outdoor temperatures;
3. basement, living area, and subslab radon levels;
4. basement relative humidity; and
5. heating and air conditioning system usage.

In addition, a weather station at Princeton University, a distance of 8 km from PU31, monitored temperature, rainfall, relative humidity, barometric pressure and wind speed and direction. The weather station data as well as house dynamics data were read every 6 s and averaged over 30 min.; these data were plotted weekly to monitor house operating conditions on a continuous basis.

Finally, a perfluorocarbon tracer (PFT) system (Dietz et al. 1986) was used to measure building air exchange rate, interzonal flows, infiltration, and exfiltration. Two different tracer gases were used: perfluoromethylcyclopentane (PMCP) in the basement, and

perfluoromethylcyclohexane (PMCH) in the living area; tracer gas emitters (4-8 per zone, depending on the emission rate of the chosen gas) were placed in temperature regulated holders in the basement and living area. The tracer gases were detected by 6 capillary adsorption tube samplers (CATS) in each zone. The tracer gas measurements were averaged over a minimum of 2 d.

Research house PU31 is illustrated schematically in Fig.1; it is a two zone system, with the basement denoted as zone 1, the living area as zone 2, and the outdoors as zone 0. The air flows (infiltration, exfiltration, and interzonal flows) are calculated from the known tracer gas emission rates and the measured tracer gas concentrations. Average radon entry rates S_1 and S_2 (megabecquerels per hour, MBq h⁻¹), which are functions of house depressurization in their respective zones, are then calculated by setting average radon entry rate equal to the average radon removal rate. The equations are:

$$S_1 = (R_{10} + R_{12})C_1 - R_{21}C_2 \quad (2)$$

$$S_2 = (R_{21} + R_{20})C_2 - R_{12}C_1. \quad (3)$$

Here C_1 and C_2 are radon concentration in zones 1 and 2 respectively, R_{10} and R_{20} the air exfiltration from zones 1 and 2, respectively, and R_{21} and R_{12} the air flows between zones 1 and 2, (interzonal flows). The radon entry rate (S_2) in zone 2 (the living area) is normally zero; although there are exceptions to this (Cavallo et al. 1992).

The above equations are valid for a steady state system with $dC_{1,2}/dt = 0$. However, radon concentration and ventilation rates are not constant: there are often diurnal cycles associated both with air infiltration and radon levels. The steady state system is approximated in these experiments by averaging all of the relevant parameters (radon concentrations, pressure differentials) over the period of interest corresponding to the exposure period of the PFT system CATS, which is a minimum of 2 d. Over this interval, the average value of $dC_{1,2}/dt$ is taken to be zero. Inspection of the data indicates that this is a reasonable assumption; for periods of a few hours this may not be the case. Typical results from these measurements are given in Table 1 which lists infiltration, exfiltration, interzonal flows, radon concentrations, outdoor-basement pressure differentials and the computed radon entry rate for PU31 with basement windows closed and with two basement windows opened. Note the large reduction in basement depressurization and radon entry rate with natural ventilation (windows opened).

The contribution of diffusion of radon gas through and from the concrete slab to the radon entry rate S_1 can be neglected given the relatively modest soil gas radon concentration (37 kBq m⁻³) and the building air change rate of ≈ 0.7 air changes

per hour (ACH) in the winter and ≈ 0.25 ACH in the summer (Kendrick and Langer, 1991, Nielson and Rogers 1991). In addition, the ambient radon concentration has also been assumed to be negligibly small compared to the lowest measured basement radon concentration ($\approx 150 \text{ Bq m}^{-3}$).

To determine S_1 as a function of basement depressurization, the following techniques were utilized to change basement depressurization:

1. Wind and the stack effect, which is driven by indoor to outdoor temperature differentials, normally depressurized the basement relative to the outdoors. The basement radon entry rate was computed in a series of experiments over an entire year in PU31; the basement to outdoor pressure differential was as large as 4 Pa in the winter and less than 0.5 Pa in the summer (positive readings indicate that the basement is depressurized with respect to outdoors).

2. Natural ventilation (opening basement windows) which reduces basement depressurization and changes the location of the house neutral plane from its normal position near the top of the windows in the living area to just above the basement windows (Cavallo et al. 1992).

3. Forced ventilation is the most convenient method of changing basement depressurization. This was accomplished in PU31 by:

- a) using attic fans or
- b) using adjustable speed fans (flow rate $< 500 \text{ m}^3 \text{ h}^{-1}$) installed in a basement window. Window-mounted fans provided the most rapid and precise control of basement depressurization.

Results and Discussion

Characterization of the flow of soil gas into a structure

The basement radon entry rate has been computed using eqn. 2 from air infiltration, exfiltration and interzonal flows measured by the PFT system and from measured radon concentrations. The minimum averaging period for all of the variables was 2 d; wind and the stack effect, natural ventilation and forced ventilation were used to vary the outdoor-basement pressure differential. Results of these calculations are shown in Fig. 2a; error bars associated with these data reflect errors associated with the operation of the PFT system. A linear regression of S_1 on ΔP (for ΔP less than ≈ 3 Pa, to compare with the case of forced ventilation with the sump closed, Fig. 2b.) yields the equation:

$S_1 = 0.429\Delta P + 0.13$. The coefficient of determination (R^2) is 0.96, indicating that the assumption of a linear relationship between S_1 and ΔP is excellent. This implies that the flow of soil gas into the basement is laminar, as would be expected for a basement without a gravel layer underneath the basement floor

slab. That is, flow through the soil and through small cracks must be the dominant entry mechanism of radon into the basement of PU31.

For an outdoor-basement pressure differential of ≈ 5 Pa, the radon entry rate does not increase for reasons which are not understood (Fig. 2a). This data point was obtained by using the continuous operation of the two attic fans to depressurize the basement and, thus, represents an extreme case. For normal house operation, basement depressurization due to wind and the stack effect was less than ≈ 4 Pa.

Evaluation of mitigation efficacy

Measurements of the basement radon entry rate described above were carried out in an unmitigated house. The basement had an open sump, which is a prime entry route for radon contaminated soil gas into buildings. Therefore, the simplest first remediation procedure is to seal off the sump.

Normally, pre-and post-mitigation radon concentration measurements are used to evaluate the effectiveness of such remediation procedures. This is necessarily imprecise since there is no control over the outdoor-basement pressure differential and, thus, no control over the ventilation (infiltration, exfiltration, and interzonal flow) and radon entry rate. Under normal conditions, more extensive measurements are not possible.

In a research house, however, a better comparison is possible if the radon entry rate as a function of outdoor-basement pressure differential is measured before and after mitigation. (This is somewhat analogous (ASTM 1981; Gadsby et al. 1981) to the use of fans to pressurize a building to determine its resistance to air infiltration.) This was done in PU31 by depressurizing the basement using two small (20 W) fans mounted in a basement window. Results are shown in Fig. 2b, which compares pre- and post-mitigation entry rate data. (It was not possible to depressurize the basement to greater than ≈ 3 Pa with the window mounted fans.) A linear regression to the post mitigation data gives $S_1 = 0.103\Delta P + 0.02$, ($\Delta P < 3$ Pa), with a coefficient of determination of 0.97, indicating that soil gas flow into the basement is still laminar after the sump was covered.

It is now possible to predict more rigorously the long term effect of covering the basement sump on radon levels in PU31. The ratio of the slopes of the regression fits to the pre- and post-mitigation radon entry rate (S_1) versus basement depressurization (ΔP) data indicates that covering the sump reduced the radon entry rate by a factor of 4.2. Therefore, the average basement radon concentration should be reduced by this factor, assuming that all house operating parameters remain the same.

The magnitude of the reduction agrees with previous work (Henschel 1988) which reported that sealing radon entry routes reduced radon concentrations by 30-90%. These results were obtained by measuring pre and post mitigation radon concentrations without any control of the outdoor-basement pressure differential.

Use of short term measurements for long term exposure prediction

To predict living area long term average radon concentration in a two zone (living area and basement) system, sufficient data to solve eqns. 2 and 3 are needed. Radon entry rate as a function of the outdoor to basement pressure differential as well as the dependence of air infiltration, exfiltration, and interzonal flow on the appropriate differential pressure in both zones must be known. In addition, if the house is heated and cooled with a forced air system, the interzonal flow is a function of air handler operation and the amount and location (supply side or return side) of duct leakage. Basement depressurization due to the operation of mechanical systems, such as air handlers or attic fans, can further complicate the system. Even if all the above factors can be accounted for, occupant behavior, in terms of the use of natural ventilation, can dominate the system.

An example of the large effect that use of natural ventilation and the associated changes in zone depressurization can have on radon concentrations in a house is shown in Figs. 3a and 3b. Without natural ventilation (windows closed) in the basement zone during this period, radon concentration (Fig. 3a) was $\approx 3 \text{ kBq m}^{-3}$ and basement depressurization (Fig. 3b) was $\approx 1.3 \text{ Pa}$. Opening two basement windows (area 0.2 m^2 each) reduced the basement radon concentration by about a factor of ten, to $\approx 0.3 \text{ kBq m}^{-3}$, and the average basement depressurization to $\approx 0.4 \text{ Pa}$. This decrease in radon concentration is due to two different but complementary effects: increased ventilation and reduced outdoor to basement pressure differential (Fig. 3b) (Cavallo et al. 1990, 1991). Opening the windows increased the flow of uncontaminated outdoor air into the basement and reduced the basement depressurization and, thus, the radon entry rate (Figs 2a,b). In this example the increase in ventilation and the reduction in radon entry rate contribute about equally to the decrease in the basement radon concentration.

Even if wind induced depressurization can be ignored (that is, the house is built in a sheltered location), stack effect depressurization would have to be modeled or measured based on indoor-outdoor temperature differentials. Given all of these requirements, it is most unlikely that long term exposure in the living area could be predicted based on a single short term basement radon measurement in a two zone structure.

For a single zone system, such as single story slab-on-grade house, the prediction of long term average radon concentration is somewhat simpler. From eqn. 1, the radon entry rate S_1 can be written as the product of the volumetric flow rate of soil gas into the basement, R_s , times C_s , the soil gas radon concentration:

$$S_1 = C_s \cdot c \cdot (\Delta P_s)^n.$$

Here c is a constant of proportionality, ΔP_s the soil to indoor pressure differential, and the exponent n in the general case lies between 0.5-1.

Similarly, from eqn. 1 the radon removal rate Q_1 can be written as:

$$Q_1 = C_1 \cdot d \cdot (\Delta P_a)^m, \quad 0.5 \leq m \leq 1,$$

where C_1 is the radon concentration in zone 1, ΔP_a the indoor to outdoor pressure differential driving the flow, and d a constant of proportionality. If we set the radon entry rate equal to the removal rate, we have:

$$C_1 = k \cdot (\Delta P)^{1-m}, \quad (4)$$

where k is a constant of proportionality.

This assumes that:

1. The concrete floor slab is poured over soil (no gravel); thus, the soil gas flow into zone 1 is laminar, and $n = 1$;
2. ΔP_s is equal to ΔP_a ; (ΔP_s could also be proportional to ΔP_a , but this will not be considered here);
3. The soil gas radon concentration is constant.

The behavior of the radon concentration as a function of house depressurization for two extreme cases using eqn. 4 is shown in Fig. 4. In an unweatherized house where air infiltration takes place through larger openings, m is about 0.5, while m might be closer to 1 in modern, well-sealed houses.

To predict the long term average radon concentration from a short term measurement, it is necessary to know the approximate value of ΔP when the radon measurement was taken, the flow exponent m for air infiltration, as well as the long term behavior of ΔP . In addition, given the large effect that changing house operating conditions can have on radon concentrations (Figs. 3a and 3b), the house must be operated with windows closed for most of the year, and the heating and air conditioning (HAC) system should neither pressurize or depressurize the house.

These conditions are quite restrictive. However, note that the radon concentration is only weakly dependent on the house depressurization (Fig. 4). Therefore, if the above restrictions on soil gas radon concentration, house depressurization,

ventilation and HAC system operation apply, it may be possible to determine the average long term radon concentration from a short term measurement to within a factor of 2.

Conclusions

Calculations of radon entry rate as a function of the outdoor to basement pressure differential in research house PU31 show that the flow of soil gas into the basement is laminar, as expected. In addition, the computed radon entry rates have been used to determine the efficacy of a standard remediation method, sealing the basement sump. Finally, by considering the driving forces which determine radon concentration in a building, it can be determined that the use of short term screening measurements to estimate long term radon exposure is problematic and likely to be successful only under drastically limited conditions.

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Table 1
 Typical house operating parameters - PU31, Winter
 Infiltration, exfiltration, interzonal flows
 radon entry rate, outdoor-basement ΔP

Condition	Basement windows closed	Basement windows opened
R_{12} ($\text{m}^3 \text{ h}^{-1}$)	240	385
R_{21} ($\text{m}^3 \text{ h}^{-1}$)	142	83
R_{01} ($\text{m}^3 \text{ h}^{-1}$)	240	648
R_{10} ($\text{m}^3 \text{ h}^{-1}$)	143	346
R_{02} ($\text{m}^3 \text{ h}^{-1}$)	160	66
R_{20} ($\text{m}^3 \text{ h}^{-1}$)	257	368
Basement Radon (kBq m^{-3})	5.0	0.367
Building Air Change (h^{-1})	0.64	1.13
ΔP (Pa)	4.0	0.56
S (MBq h^{-1})	15.5	2.18

C_{ij} = Concentration of tracer i in zone j

Fig. 1. Schematic of research house PU31 as a two zone system, $(i, j = 1, 2)$ illustrating flows and tracer gas concentrations.

Fig. 2a Radon entry rate as a function of outdoor-basement pressure differential (ΔP) for research house PU31. The entry rate is a linear function of ΔP , indicating laminar flow of soil gas into the basement. The error bars reflect uncertainty due to PFT measurements; data for ΔP less than ≈ 3 Pa is fitted to compare with data in Fig. 2b.

Fig. 2b. Comparison of the basement radon entry rate versus outdoor-basement pressure differential (ΔP) with the sump open and with the sump closed, PU31. The change in the slope of the radon entry rate is a better measure of the efficacy of the remediation technique. Note that the radon entry rate is a linear function of ΔP both before and after the sump is closed, indicating laminar flow of soil gas into the basement.

Basement radon (kBq m⁻³)

Julian date

Outdoor-basement
pressure differential (Pa)

Julian date

Fig. 3a. Basement radon concentration as a function of time (Julian date 141 = 21 May). The decrease in radon concentration at JD 142.7 is due both to an increase in natural ventilation as well as a decrease in basement depressurization.

Fig. 3b. Outdoor-basement pressure differential as a function of time (Julian date). The drop in this pressure differential at JD 142.7 is due to the opening of two basement windows. This causes a reduction in the radon entry rate which contributes to the reduction in basement radon concentration.

Fig. 4. Radon concentration as a function of the outdoor-indoor pressure differential (ΔP) for a single zone system, from eqn. 4. Two extreme cases ($m = 0.5$, $m = 1$) are plotted for the following assumptions: a) laminar flow of soil gas into the structure b) constant soil gas radon concentration c) $\Delta P_s = \Delta P_a$. Because of the weak dependence of radon concentration on ΔP , it may be possible to predict yearly average radon concentration from a single short term measurement under restricted circumstances.

USE OF NATURAL BASEMENT VENTILATION TO CONTROL RADON IN SINGLE FAMILY DWELLINGS*

A. Cavallo, K. Gadsby, T.A. Reddy
Center for Energy and Environmental Studies
Princeton University
Princeton, NJ 08544 USA

ABSTRACT

Natural basement ventilation has always been recommended as a means of reducing radon levels in houses. However, its efficacy has never been documented. In these experiments, natural ventilation has for the first time been studied systematically in two research houses during both the summer cooling season and the winter heating season. Ventilation rates, environmental and house operating parameters as well as radon levels have been monitored.

It can be definitively concluded from radon entry rate calculations that natural ventilation can reduce radon levels two ways. The first is by simple dilution. The second is by reducing basement depressurization and thus the amount of radon contaminated soil gas drawn into the structure.

Therefore, basement ventilation can be an effective mitigation strategy under some circumstances. It might be especially useful in houses with low radon concentrations (of the order of 370 Bq m^{-1}) or those with low levels and which cannot be mitigated cost-effectively with conventional technology.

INTRODUCTION

An attractive candidate for a radon mitigation system in regions of mild climate is one which uses natural basement ventilation to reduce indoor radon levels. Such a system would be simple to install and virtually maintenance free. It is very important to determine how effective this kind of system would be in an actual operating household throughout the year, and whether its impact on heating, air conditioning, and basement humidity levels outweighs its obvious advantages.

Although natural ventilation is the simplest of all mitigation schemes, up to now it has not been carefully investigated. Earlier experiments on ventilation (Nazaroff et al., 1981, Nazaroff et al., 1985) were done using an air to air heat recovery ventilator to control the basement ventilation rate. This operates in a balanced mode with inflow and outflow equal and would neither pressurize nor depressurize the ventilated space.

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It is completely different from natural basement ventilation which will reduce basement depressurization and change the location of the house neutral plane from its normal position near the level of the upstairs windows to just above the basement windows.

Radon entry into a building is dominated by pressure-driven flow of soil gas (Scott, 1988). The subsoil pressure field of the building is caused by the following factors (Nazaroff et al., 1988): wind generated depressurization of the structure, air handler operation, and most importantly, by the temperature difference between the outdoor environment and the building interior (the stack effect).

It is clear that the radon entry rate cannot be constant for a given dwelling. Thus, basement ventilation can theoretically reduce indoor radon levels both by dilution and by reducing the radon entry rate by decreasing the basement to soil pressure differential (Cavallo, 1990).

EXPERIMENTS

The effect of natural basement ventilation, that is opening basement windows, on indoor radon levels was examined in two Princeton University research houses (PU31 during the summer cooling season and PU21 during the winter heating season).

The houses have been instrumented to measure the following parameters:

1. pressure differentials across the building shell and between the basement and the upstairs,
2. basement, living area (PU21 only) and outdoor temperatures,
3. basement, living area, subslab and in-the-block radon levels,
4. basement relative humidity, and
5. heating and air conditioning system usage.

A PFT (perfluorocarbon tracer) system (Dietz, 1986) is used to measure building air exchange rate and interzonal flows. Emitters (4 to 8 per zone) are placed in temperature regulated holders in the basement and living area. The tracer gases are detected by 6 capillary adsorption tube samplers (CATS) in each zone.

In addition, a weather station at Princeton University monitors temperature, rainfall, relative humidity, barometric pressure and wind speed and direction.

The weather station data as well as house dynamics data are read every 6 seconds and averaged over 30 minutes, while the air infiltration and interzonal flow measurements are averaged over a minimum of 2 days.

EXPERIMENTS IN RESEARCH HOUSE PU21

Natural ventilation experiments have been carried out in research house PU21 during the winter heating season.

The research house has the following characteristics:

SIZE: 185 m² living area, 50 m² basement,

TYPE: Modified ranch. The living room/dining room has a cathedral ceiling with a large window area facing almost due south. A cinderblock basement underlays about one third of the house, with the remainder being built on a slab. There is a cinderblock chimney stack in the center of the house.

HEATING, AIR CONDITIONING SYSTEM: Central gas forced air heat, furnace in basement; central air conditioning,

RADON LEVEL: $\sim 4.8 \text{ kBq m}^{-3}$ in basement.

The house had been mitigated with a subslab mitigation system which was turned off during the ventilation experiment. The perimeter floor/wall shrinkage crack had also been sealed and Dranjer® basement drain seals installed as part of the mitigation.

The effect of opening a basement window on indoor radon levels and the basement/outdoor pressure differential in PU21 is illustrated using continuous radon and pressure data in Figs. 1a and 1b. Data points are 30 minute averages of the parameters; the experiment was carried out between Julian Date (JD) 47, 1990 (90047) and JD90050.5. Shown in Fig. 1a are basement radon levels as measured with a pumped CRM (continuous radon monitor) which has a response time of less than 30 minutes, and upstairs radon levels as measured with a Pylon passive radon detector, which has a response time of about 3 hours. Plotted in Fig. 1b is the outdoor/basement pressure differential. A normally closed basement window was opened at times JD90048.4 and JD90049.45, and closed at times JD90048.83 and JD90049.8.

The basement radon concentration decreases from about 6.5 kBq m^{-3} to less than 1.0 kBq m^{-3} , and upstairs concentration decreases from about 4.0 kBq m^{-3} to about 1.0 kBq m^{-3} with a basement window open (Fig. 1a). The outside/basement pressure differential responds immediately to the closing or opening of the window with a $\sim 1.5 \text{ Pa}$ change in this parameter. Note that even with the window open the basement still remains depressurized relative to the outdoors. (The rise and fall in indoor radon and basement depressurization which occurs around JD90048 is due to an unusual midwinter temperature spike in which the outdoor temperature rose and fell by 8°C in a 12 hour period, changing the indoor-outdoor temperature differential and the magnitude of the stack effect.) This experiment illustrates the intimate connection between basement depressurization and indoor radon concentrations and strongly suggests that the basement radon entry rate must change; this is in fact the case, as verified by other experiments in which the building air exchange rate, infiltration, exfiltration, interzonal flow, and radon levels were measured, and radon entry rates calculated.

The natural ventilation experiment in PU21 was conducted over a 17 day period in February; two periods of two and three days each were used to determine the baseline building conditions (windows closed), and three four day periods were used to determine the building operating parameters with a single basement window ($\sim 0.22 \text{ m}^2$ window area) open. In Figs. 2 through 4 described below, experiments 1 and 5 are periods when the basement window was closed, and experiments 2, 3, and 4 are periods when the basement window was open.

The effect of basement ventilation on basement and upstairs radon levels is shown in Fig. 2. With the windows closed, basement radon levels were about 4.8 kBq m^{-3} , while upstairs levels were about a factor of 2 lower (2.8 kBq m^{-3}). This is a fairly typical result and is a consequence of the basement being

isolated from the living area. With one basement window open, this ratio was reversed, that is the upstairs levels were about a factor of 2 higher than the basement levels. This is quite unusual and indicates a radon entry route into the living area which bypasses the basement. This result was checked by making two simultaneous continuous measurements of the upstairs radon levels. A similar result was noted in the measurements made in the summer of 1989 on PU31 and will be discussed further; this indicates one way that basement ventilation, while certainly reducing indoor radon levels, might not be as effective in reducing living area radon levels as in reducing basement levels.

A critical factor in this experiment is to quantify the effect basement ventilation has on the building air change rate, since the observed reduction in radon levels could be caused by a large increase in the ventilation rate. In addition, the measurement of the building air change rate is needed to determine the energy penalty associated with increased air infiltration during the winter heating season. Air infiltration and interzonal flows have been measured using the perfluorocarbon tracer (PFT) system; results are illustrated in Fig. 3, in which building air exchange rate and basement radon levels are plotted. The building air change rate increases by a factor of two, from 0.3 h^{-1} to 0.6 h^{-1} , when the basement window is opened. Note that the basement radon levels decrease by a much larger factor ($\sim 6-8$), again indicating that dilution cannot account for the entire decrease in radon levels.

Using the interzonal flows and the exfiltrations obtained from the PFT system and the basement ($C1Rn$) and living area ($C2Rn$) radon concentrations, the basement ($S1Rn$) and living area ($S2Rn$) radon entry rates can be calculated from the following equations:

$$S1Rn = (R10 + R12)C1Rn - R21C2Rn \quad (1)$$

$$S2Rn = (R21 + R20)C2Rn - R12C1Rn \quad (2)$$

Here $R10$ is the basement exfiltration, $R20$ the living area exfiltration, $R12$ the interzonal flow from the basement to the living area and $R21$ the flow in the opposite direction.

The entry rate of radon into the living area can be calculated from Eq. 2 using the interzonal flow data from those periods when the basement window was open and upstairs radon levels were approximately twice as large as the basement levels. It is found that the radon entry rates in both zones are nearly the same in this case, $\sim 0.2 \text{ MBq h}^{-1}$. An entry route which bypasses the basement does complicate the use of natural basement ventilation as a mitigation strategy. It remains to be seen how widely this effect is observed.

Basement radon entry rate, calculated using Eq. 1, is shown in Fig. 4; with the basement window closed the basement radon entry rate is approximately 0.6 MBq h^{-1} . This is far greater than the living area radon entry rate, and thus dominates the system. The average basement radon entry rate with natural basement ventilation is 0.2 MBq h^{-1} ; thus, basement radon entry rate is reduced by a factor of about 3 with natural ventilation.

The measurements in PU21 definitively demonstrate the mechanisms by which natural ventilation acts to lower radon levels. Both dilution and reduction of the basement/outdoor pressure differential and the concomitant reduction in radon entry rate are factors.

EXPERIMENTS IN RESEARCH HOUSE PU31.

Natural ventilation experiments have also been conducted in research house PU31 during the summer cooling season (the house has central air conditioning).

Research house PU31 has the following characteristics:

SIZE: 150 m² living area, 120 m² basement

TYPE: Ranch with full attic and full basement, half of an attached slab-on-grade two car garage converted to TV room, cinderblock wall basement with a sump and cinderblock chimney stack in the center of the house,

ATTIC: Two 1900 m³ h⁻¹ attic fans, thermostatically controlled,
HEATING, COOLING SYSTEM: Central gas forced air heat, furnace located in basement; central air conditioning,

RADON LEVEL: ~3.0 kBq m⁻³ in the basement.

The summer season natural ventilation experiments were conducted in the following manner. A 17 day period was used to establish an operating baseline for the house. During this time the house functioned normally; e.g. thermostatically controlled attic fans operated automatically. Basement and upstairs windows were kept closed, as is normally the case since the house is centrally air conditioned. (Upstairs windows were of excellent quality and could be closed tightly. The basement windows were low quality steel frame casements which were somewhat leaky.)

After the baseline operating conditions of the building were established, two basement windows (one on the west wall and the other on the east wall, each 0.22 m²) were opened and the relevant parameters compared to those obtained in the baseline conditions.

The effect of opening two basement windows on basement radon levels and the soil to basement pressure differential is shown in Figs. 5 and 6. Basement radon levels are shown in Fig. 5; there is a significant drop in basement radon concentration, from an average of about 4.5 kBq m⁻¹ with the basement windows closed to about 370 Bq m⁻¹ with the windows opened on JD89220.6. The magnitude of this drop, based on the assumption that dilution is the mechanism by which ventilation reduces indoor radon levels, was completely unexpected. The large diurnal variation in basement radon levels is due to the operation of the attic fans which depressurize the entire house, increasing the ventilation rate as well as the radon levels. Data from a typical differential pressure transducer are illustrated in Fig. 6 (positive pressure indicates that the soil pressure is above that of the basement). The large peaks (~3 Pa) in the basement to soil pressure differential are due to the operation of the attic fans. There is an abrupt pressure drop when the windows are opened, indicating that the pressure field of the building has been modified. It is clear that for this house only a very small pressure differential (~0.5 Pa) is needed to drive the radon level

to 370 Bq m^{-1} . This result again strongly suggests that a modification of the basement/soil pressure differential is important in reducing the basement radon level; however, the measurement of the building air exchange rate and interzonal flows and a calculation of the radon entry rate are essential for an understanding of these results.

The behavior of the building air exchange rates and basement radon concentration is shown in Figure 7; these two parameters are plotted for seven experiments, each of 3-4 days duration. This period of time was needed to obtain reasonable levels of the PFT gas in the capillary adsorption tubes. Baseline conditions (experiments 1-5) for the building air exchange rate (with the attic fans thermostatically controlled) were about 0.3 h^{-1} with an average basement radon level of about 3.5 kBq m^{-3} .

With the basement windows open (experiment 6), the building air exchange rate increases by about a factor of 2, to 0.6 h^{-1} . Basement radon levels decrease to about 450 Bq m^{-3} , a factor of about 7 below the levels with the windows closed. This decrease is far larger than the increase in the building air exchange rate (about a factor of 2), and indicates that the change in the pressure field of the building is much more important in decreasing radon levels than the increase in the building air exchange rate.

To investigate the impact of the attic fans on building air exchange rates the two basement windows were left open and the attic fans switched off (experiment 7). The building air exchange rate decreases by about a factor of 2, and the basement radon level by about 20%, in this experiment. Such a large decrease in the air exchange rate without any increase in radon level is yet another indication that the modification of the pressure field of the basement and thus the entry rate S_{1Rn} (which is a function of the basement to soil pressure differential) is of prime importance in determining the radon level of this basement.

As for PU21, the basement radon entry rate of PU31 can be computed using the air infiltration and interzonal flow measurements. Results from this calculation using Eq. 1 are shown in Fig. 8. If the baseline house operation (experiments 1-5 of Fig. 8) is compared to the cases of house operation with the attic fans off and the basement windows open (experiments 7-8 of Fig. 8), radon entry rate decreases by about a factor of 7. For the case of house operation with attic fans off and basement windows closed (experiment 6) compared to that of house operation with the fans off and windows open (experiments 7-8), the basement radon entry rate decreases by about a factor of 5. This clearly demonstrates that the radon entry rate does decrease significantly with natural basement ventilation.

Although basement radon levels have been emphasized in the above analysis, radon levels in the living area are of most concern. These have also been measured during the natural ventilation experiments. With all windows closed, the upstairs radon level ($\sim 2.3 \text{ kBq m}^{-1}$) was lower than the basement radon level ($\sim 3.0 \text{ kBq m}^{-1}$), as would be expected. However, with basement windows opened, the upstairs radon level ($\sim 1.0 \text{ kBq m}^{-1}$) was about

2.5 times higher than the basement radon level ($\sim 370 \text{ Bq m}^{-1}$). Instrumental error has been carefully ruled out in this case. It is clear that radon can enter the upstairs zone of this house two ways. The first is the usual one in which soil gas is drawn into the basement and then flows into the upstairs zone. The second entry route must bypass the basement but could not be localized. It may be associated with the central cinderblock chimney stack or the slab on grade garage which has been converted into a TV room. This second route is unaffected by the pressure break provided by the open basement windows.

CONCLUSIONS

Natural ventilation experiments conducted during the summer cooling season in research house PU31 and during the winter heating season in research house PU21 have demonstrated that basement ventilation can reduce indoor radon both by reducing the radon entry rate and by dilution. Calculations based on measurements using the PFT system allow the effects of dilution and entry rate reduction to be delineated and quantified: a decrease in the basement radon entry rate of a factor of 3-5, a decrease in basement radon concentration of a factor of 5-10 and an increase in the building air exchange rate of about a factor of 2 caused by natural basement ventilation have been documented. These results indicate that natural ventilation can very effectively reduce indoor radon levels.

A rough cost estimate for natural basement ventilation in research house PU21 can be made with the following assumptions (Taylor, 1987): 1) 4911 degree days for the Princeton area, 2) $165 \text{ m}^3 \text{ h}^{-1}$ constant increase in the winter ventilation rate, 3) furnace efficiency of 0.7, 4) heating oil costing \$1/gal. With these assumptions the additional heating cost due to natural basement ventilation would be about \$190 yr^{-1} . This compares surprisingly favorably with the running cost of a subslab depressurization system (\$0.12 kWh^{-1} , 90 W fan, \$50-\$100 for exhaust of conditioned air) of \$140-\$190 yr^{-1} . Thus, in certain circumstances, basement ventilation could indeed be a reasonable mitigation strategy.

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Figure 1a. Basement, Living Area Radon Level vs Julian Date;
Sequence of Window Open and Window Closed, PU21.
O - Open; C - Closed; T - Temperature Spike

Figure 1b. Outdoor/Basement Pressure Differential vs Julian Date;
Sequence of Window Open and Window Closed, PU21
O=Open; C=Closed; T=Temperature Spike

Figure 2. Basement, Living Area Radon Concentrations, PU21
Experiments 1,5 Window Closed
Experiments 2,3,4 Window Open

Figure 3. Building Air Exchange Rate, Basement Radon Concentration, PU21
Experiments 1,5 Window Open
Experiments 2,3,4 Window Closed

Figure 4. Basement Radon Concentration,
Basement Radon Entry Rate, PU21
Experiment 1,5 Window Closed
Experiment 2,3,4 Window Open

Figure 5. Basement Radon Concentration vs Julian Date, PU31. Two Basement Windows Were Opened (O) at JD89220.6.

Figure 6. Soil/Basement Pressure Differential (ΔP) vs Julian Date, PU31 Summer. Basement Windows Opened (O) at JD89220.6; Note Effect of Attic Fans.

Figure 7. Basement Radon Concentration, Building Air Exchange Rate, PU31 Experiment 1-5, Baseline (Normal House Operation); Experiment 6, Windows Open, Attic Fan On; Experiment 7, Windows Open, Attic Fans Off.

Figure 8. Basement Radon Concentration, Entry Rate; PU31 Experiments 1-5, Baseline (Normal House Operation) Experiment 6, Windows Closed, Attic Fans Off; Experiments 7-8, Windows Open, Attic Fans Off.

THE EFFECT OF NATURAL VENTILATION ON RADON AND RADON PROGENY LEVELS IN HOUSES*

A. CAVALLO, K. GADSBY, T.A. REDDY, R. SOCOLOW
CENTER FOR ENERGY AND ENVIRONMENTAL STUDIES
PRINCETON UNIVERSITY
PRINCETON, NJ 08544 USA

ABSTRACT

In contradiction to the widely held assumption that ventilation is ineffective as a means of reducing indoor radon concentrations, experiments in a research house have shown that the basement radon level can be reduced by a factor of 5 to 10 using only natural ventilation. Measurements of the outdoor-basement pressure differential and the radon entry rate show that this unexpectedly large reduction in indoor radon levels is caused by two complementary physical processes. The first mechanism is the obvious one: dilution. Radon concentrations are lowered by the addition of uncontaminated outdoor air. The second mechanism is less evident: an open basement window reduces basement depressurization. This decreases the rate at which radon laden soil gas is drawn into the house. It was also found that the radon entry rate is a linear function of basement depressurization up to a differential pressure of about 4 Pa, as would be expected for laminar soil gas flow; opening two basement windows approximately doubles the building air exchange rate and reduces the radon entry rate by up to a factor of 5.

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INTRODUCTION

Although natural ventilation has always been recommended as a means of reducing indoor radon levels, there has never been a systematic attempt to quantify either the magnitude of the reduction possible with natural basement ventilation or the impact this would have on overall house operating conditions. This series of experiments conducted in an occupied research house during both heating and cooling seasons is thus the first program to investigate these effects in any detail.

EXPERIMENTS

Natural ventilation experiments have been conducted in an occupied research house (PU31) with the following characteristics: Type: Ranch with full attic and full unheated basement that is isolated from the living area; half an attached slab-on-grade two-car garage converted to a television room; cinderblock wall basement with sump; cinderblock chimney stack in center of basement;

Size: 140 m² living area; 120 m² basement; and

Cooling/Heating System: Central air conditioning; gas forced air heating.

The house has been instrumented to measure:

1. basement-outdoor and basement-soil pressure differentials,
2. basement and outdoor temperatures and relative humidity,
3. basement and living area radon levels, working levels and subslab and basement wall radon levels,
4. heating and air conditioning usage, and
5. building air exchange rate and interzonal flow (using a perfluorocarbon tracer¹ (PFT) system).

In addition, a weather station at Princeton University monitors temperature, rainfall, relative humidity, barometric pressure, and wind speed and direction.

The weather station data as well as the house dynamics data are read every six seconds and averaged over 30 minutes and recorded, while the air infiltration and interzonal flow measurements are averaged over a minimum period of two days.

One can begin by considering a single zone system² and assuming that the radon entry rate (SR_n) is constant and equal to the removal rate:

$$SR_n = R_v CR_n \quad (1)$$

where R_v is the air exchange rate and CR_n the radon concentration. Results from initial experiments^{3,4} using an air to air heat recovery ventilator verified this simple model. However, this equipment ideally operates in a balanced mode with air inflow equal to outflow, and neither pressurizes nor depressurizes a basement. This is very different from natural ventilation in

which a basement window is opened to reduce basement depressurization⁵.

Radon entry into a building is dominated by pressure driven flow of soil gas; building depressurization is caused by wind, the stack effect, or the operation of an air handler or forced ventilation equipment. Thus, the radon entry rate can be written as:

$$S_{Rn} = k(\Delta P_{Rn})^\alpha \quad (2)$$

where $0.5 < \alpha < 1$. The building air exchange rate is also driven by building depressurization, and can be written as:

$$R_v = c(\Delta P_v)^\beta, \quad (3)$$

where $0.5 < \beta < 1$. Here ΔP_{Rn} and ΔP_v are the differential pressures driving radon and air entry, respectively. If it is assumed that these two are proportional, then the radon concentration can be written as

$$C_{Rn} \propto (\Delta P)^{\alpha-\beta}. \quad (4)$$

The radon concentration at equilibrium is the net result of a balance between entry rate (soil gas infiltration) and removal rate (air exfiltration). Flow of soil gas can be laminar ($\alpha=1$), turbulent ($\alpha=0.5$), or a mixture of the two; except for very loose soils (gravels), flow can be assumed to be laminar⁶. For air infiltration, it has been found experimentally^{7,8} that $\beta \approx 0.65$. Thus, given these assumptions, we have

$$C_{Rn} \propto (\Delta P)^{0.35}. \quad (5)$$

For a factor of 10 variation in house depressurization, which is approximately what is observed in PU31 between summer and winter, radon concentration is expected to vary by at most a factor of 2.2 over the year. However, if soil gas flow into the structure is turbulent, then $\alpha-\beta=-0.15$, and summer radon levels will be about 40% higher than winter levels.

The PFT system using two tracer gases, one in the basement (zone 1) and one in the living area (zone 2), has been utilized to measure air infiltration, exfiltration, and interzonal flows in PU31. These are then combined with basement radon measurements (C_{11}) and living area radon measurements (C_{12}) to obtain the radon entry rate:

$$S_{1Rn} = (R_{10} + R_{12})C_{11} - R_{21}C_{12}. \quad (6)$$

Here R_{10} is the air exfiltration from the basement (zone 1) to the outdoors (zone 0), R_{12} is the interzonal flow from the basement (zone 1) to the living area (zone 2), and R_{21} is the flow

in the opposite direction. These measurements were made over an 18 month period under closed-house, natural ventilation, and forced-air ventilation conditions; the results are shown in Figure 1. The entry rate is a linear function of basement depressurization: a least square fit to the data gives

$$S1Rn = 11.6\Delta P + 0.37, R^2 = 0.96.$$

This implies that soil gas flow is laminar for $\Delta P < 4$ Pa, which is to be expected since the basement slab was poured directly onto the soil. At the greatest basement depressurization ($\Delta P = 5$ Pa) it appears that the entry rate levels off and that the source is effectively finite; this data point was obtained with forced-air ventilation depressurizing the basement. It should be emphasized that the natural operating regime of most houses, and the range over which virtually all of these data was taken, is for an outdoor-basement pressure differential of less than 4 Pa.

Basement radon concentration as a function of outdoor-basement pressure differential for closed-house conditions is shown in Figure 2. Radon levels during the summer cooling season (low ΔP) are significantly lower than during the heating season (high ΔP), as would be expected from Eq. 5. If the radon concentration and differential pressure data are transformed logarithmically and fitted with a straight line, the resulting best fit ($R^2 = 0.53$) is: $\log(C_{11}) = a + 0.25 \log(\Delta P)$. This yields: $C_{11} = 3.22(\Delta P)^{0.25}$, which indicates that the assumptions made above are surprisingly reasonable. Such good agreement is somewhat unexpected since PU31 is a two zone system with an air handler; Eq. 5 applies to a simple one zone system without any air handler. A better model would take into account interzonal flow R_{12} which is a function of the upstairs/basement pressure differential as well as air handler operation.

The effects of natural ventilation (opening a basement window) on the radon entry rate, basement radon concentrations, the outdoor-basement pressure differential, and the building air exchange rate are illustrated in Figures 3a-3d. These results are from a series of experiments conducted in PU31 during the winter heating season. In experiment 1 a single basement window was opened; in experiment 2, two windows were opened; in experiments 3 through 5 the windows were closed. With reference to the operation of PU31 with windows closed, when one or two basement windows are opened:

1. the radon entry rate is reduced by about a factor of five (Figure 3a)
2. basement radon concentrations are reduced by about a factor of ten (Figure 3b)
3. the outdoor-basement pressure differential decreases by about a factor of six (Figure 3c)
4. the building air exchange rate increases by a factor of two (Figure 3d).

This clearly demonstrates that basement ventilation reduces basement radon levels^{9,10} both by increasing the ventilation rate and by reducing the outdoor-basement pressure differential.

The additional heating cost due to the increased building air exchange rate can be estimated as follows¹¹. The additional energy consumed, U , in kilojoules per year, is given by:

$$U = 25 \cdot V \cdot \frac{D}{E} \quad (7)$$

where V is the volume of air to be heated ($\text{m}^3 \text{ h}^{-1}$), D is the number of degree days (4911 for the Princeton, USA area), and E is the furnace efficiency. Assuming an efficiency of 0.7 for the natural gas furnace, the additional energy consumption for an increase in the building air exchange rate of 0.5 h^{-1} (630 m^3 building volume, including the basement), is 55.3 GJ y^{-1} . For a natural gas price of $\$0.195 \text{ m}^{-3}$, the additional cost for heating is about $\$275 \text{ y}^{-1}$. (This is somewhat pessimistic since the basement is unheated.)

This compares surprisingly favorably with the cost of running the subslab depressurization system now installed in PU31 ($\$0.12 \text{ kWh}^{-1}$, 150 W fan, and an estimated $\$50 \text{ y}^{-1}$ for exhaust of conditioned air) of $\$210 \text{ y}^{-1}$.

Because the subslab system reduces basement radon concentrations to less than 40 Bq m^{-3} , among other reasons, it is clearly superior. However, for houses with basements and moderate radon levels ($<800 \text{ Bq m}^{-3}$) in areas with mild winters (<3000 degree days per year) mitigation using natural ventilation may be a viable alternative.

Radon progeny measurements have been made using a working level monitor during the natural and forced-air ventilation measurements in PU31. It appears that, although natural ventilation does reduce indoor radon levels by factors of 5 to 10, no significant change in the living area equilibrium ratio was observed compared to baseline cases without natural ventilation. This is not an unexpected result since building air exchange rates increase by about a factor of 2: 0.7 h^{-1} baseline, 1.2 h^{-1} with natural basement ventilation, winter; and 0.25 h^{-1} baseline, 0.4 h^{-1} with natural ventilation, summer. These low rates of air movement apparently do not enhance progeny plateout in houses.

However, continuous operation of the air handler (100% duty cycle) in PU31 did reduce the equilibrium ratio by about a factor of 2 (see Figure 4), compared to normal house operation with the air handler operating on less than a 25% duty cycle. The effect of different levels of air handler operation on the ultrafine aerosol¹², and thus the dose, is not known.

CONCLUSIONS

Detailed measurements in a research house (PU31) of radon working level, air infiltration, exfiltration, and interzonal flows have demonstrated that:

1. radon entry rate is a linear function of basement depressurization in this house,
2. natural basement ventilation can reduce indoor radon concentrations by a) dilution and b) reduction of basement depressurization and thus the radon entry rate,
3. the equilibrium ratio is not changed significantly with natural ventilation,
4. the equilibrium ratio is decreased by a factor of 2 by the continuous operation of the air handler. The effect of air handler operation on the ultrafine aerosol remains to be determined.

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Figure 1. Radon Entry Rate vs Outdoor-Basement Pressure Differential, Research House PU31. These results were obtained over an 18 month period which spanned both winter and summer house operating regimes. The good linear fit indicates laminar soil gas flow into the basement.

Figure 2. Basement Radon (C₁₁) vs Outdoor-Basement Pressure Differential. These radon concentrations are only for natural operating conditions (no forced-air ventilation) of the house, windows closed.

a. Basement radon entry rate

b. Basement radon concentration

c. Outdoor-basement pressure differential

d. Building air exchange rate

Figure 3. Results from a series of five experiments (minimum duration 3 days) comparing natural basement ventilation to closed house conditions during the winter heating season in research house PU31. Measurements of basement radon entry rate, basement radon concentration, the outdoor-basement pressure differential, and the building air exchange rate for each experiment are shown. Experiment 1: one basement window opened
Experiment 2: two windows opened,
Experiments 3,4,5: windows closed.

Figure 4. Equilibrium ratio versus radon concentration for a series of experiments with the air handler on normally (<25% duty cycle) and with the air handler on continuously (100% duty cycle).

Comparison of Natural and Forced Ventilation for Radon Mitigation in Houses

A. Cavallo, K.Gadsby, and T.A.Reddy+
Center for Energy and Environmental Studies
Princeton University, Princeton, NJ, USA

Abstract

Radon mitigation by natural basement ventilation has been compared to mitigation by forced ventilation (pressurization) and to mitigation by operation of a modified heating and air conditioning (HAC) system in a series of experiments in a research house. With the largest entry route, the basement sump, sealed up, ventilation and pressurization reduced basement radon concentrations from 800 Bq m^{-3} to less than 150 Bq m^{-3} . Natural ventilation reduced radon levels both by dilution and by decreasing basement depressurization and thus the radon entry rate. Pressurization reduced radon levels by increasing ventilation and lowering subslab radon levels, but is significantly more difficult to implement than natural ventilation. Operation of the forced air HAC system with a duct that supplied additional outside air to the return side did not reduce indoor radon concentrations. These results indicate that natural basement ventilation, when coupled with simple measures to seal up major entry routes such as an open sump, can be an efficient radon mitigation technique in regions with mild winters in houses with basement radon concentrations as great as 3 kBq m^{-3} .

Introduction

In the United States, inhaled radon decay products cause about 55% of the total annual average effective dose from all natural and artificial radiation sources (NCRP, 1987). Naturally occurring radon is by far the largest single source of radiation exposure; moreover, exposure at many times the average concentration of 40 Bq m⁻³ is possible (Nero et al., 1986) in a significant number of homes.

If a linear non-threshold response to this average dose is assumed, it is predicted that there will be approximately 16,000 radon attributable lung cancer deaths per year. Most of these deaths will occur among smokers and former smokers; only 500 lung cancer deaths due to the average exposure are calculated to occur among non-smokers (Nazaroff and Teichman, 1990).

It is clear that indoor radon represents a significant threat to public health and that efficient and cost-effective ways to reduce indoor radon levels need to be developed and evaluated. Much has already been done to evaluate radon mitigation methods such as use of heat recovery ventilators (Nazaroff et al. 1981), sealing of entry routes, basement pressurization, and subslab depressurization (Scott, 1988; Dudney et al. 1988). Subslab depressurization, also known as subslab ventilation or active soil depressurization, has been and will continue to be the most widely used and most cost-effective radon mitigation method.

Although natural ventilation has often been recommended as a radon mitigation technique (EPA, 1989), there has not been a systematic effort to quantify either the magnitude of the reduction in radon concentration possible with ventilation, or the impact natural basement ventilation would have on house operating conditions. In the experiments described here, radon mitigation by natural and forced ventilation in conjunction with sealing of an obvious radon entry route, an open basement sump, as well as by operation of the modified HAC system, have been compared and evaluated. These experiments were part of a program to evaluate in detail the effects of natural ventilation (Cavallo et al., 1990, Cavallo et al., 1992) as a radon mitigation technique.

Experimental Methods

Research house PU31, in which these experiments were done, has the following characteristics:

Size: 150 m² living area, 120 m² basement

Type: One story ranch with full attic and full basement; half of an attached slab-on-grade two car garage converted to TV room; cinderblock wall basement and cinderblock chimney stack in the center of the house; sump in basement; no gravel under basement floor slab,

Attic: Two 1900 m³ h⁻¹ attic fans, thermostatically controlled,

Heating and cooling system: Central gas forced air heat, furnace located in basement; central air conditioning,

Radon level: $\approx 3.0 \text{ kBq m}^{-3}$ - basement, sump open
 $\approx 0.8 \text{ kBq m}^{-3}$ - basement, sump sealed
 $\approx 37 \text{ kBq m}^{-3}$ - subslab.

The house has been instrumented to measure the following parameters:

1. pressure differentials across the building shell above and below grade, and between the basement and the living area,
2. basement, and outdoor temperatures,
3. basement, living area, and subslab radon levels,
4. basement relative humidity, and
5. heating and air conditioning system usage.

In addition, a weather station at Princeton University, a distance of 8 km. from PU31, monitors temperature, rainfall, relative humidity, barometric pressure, and wind speed and direction. The weather station data as well as house dynamics data are read every 6 seconds and averaged over 30 minutes.

Two small fans (Feather Fan #103, 22 W) were mounted in the east basement window of PU31 to modify the outdoor-basement pressure differential. The flow rate of the two fans could be varied between 300 and $1000 \text{ m}^3 \text{ h}^{-1}$ using a speed controller.

Finally, a PFT (perfluorocarbon tracer) system (Dietz et al. 1986) is used to measure building air exchange rate, infiltration, exfiltration, and interzonal flows. Two different tracer gases were used (PMCP - perfluoromethylcyclopentane - in the basement, and PMCH - perfluoromethylcyclohexane - in the living area); tracer gas emitters (4 to 8 per zone, depending on the emission rate of the chosen gas) are placed in temperature regulated holders in the basement and living area. The tracer gases are adsorbed by activated charcoal in the capillary adsorption tube samplers (CATS), 6 of which are deployed in each zone. The tracer gas measurements are averaged over a minimum of 2 days.

In order to compare the efficacy of different mitigation techniques, it is necessary to know the radon entry rate as a function of basement depressurization for PU31. Using infiltration, exfiltration, and interzonal flow measurements from the PFT system and radon concentration measurements in the living area and basement (Cavallo et al. 1992), radon entry rate (S_1 , MBq h^{-1}) as a function of the outdoor-basement pressure differential (ΔP , Pa) has been calculated using the following equation:

$$S_1(\Delta P) = (R_{10} + R_{12})C_1 - R_{21}C_2. \quad (1)$$

Here R_{10} is the basement exfiltration, R_{12} the basement to living area interzonal flow, R_{21} the flow in the opposite sense, and C_1 and C_2 are the basement and living area radon concentrations, respectively. The radon entry rate with the sump open was:

$$S_1 = 0.429\Delta P + 0.13, \quad (2)$$

and with the sump sealed:

$$S_1 = 0.103\Delta P + 0.02. \quad (3)$$

The ratio of the slopes of Eq. 2 and 3 indicates that sealing the basement sump reduced the radon entry rate by about a factor of 4.2.

Results and Discussion

a. Comparison of Radon Reduction By Pressurization and Natural Ventilation (With Sump Sealed)

Forced ventilation (basement pressurization) and natural ventilation have been compared in a series of experiments in PU31 with the basement sump sealed. The comparison was done in five experiments, each of which lasted four to seven days:

Experiment 1: basement windows closed to obtain a baseline,

Experiment 2: two basement windows opened (one on the east wall, one on the west wall, each with an area of 0.2 m²).

Experiment 3 and 4: windows closed and the fans installed in the east window to pressurize the basement.

Experiment 5: fans removed from the window and the window closed to check the baseline.

Soil-basement pressure differentials are monitored by pressure transducers mounted at several heights on each of the four basement walls and at several locations in the basement floor slab; the outdoor-basement pressure differential is monitored at the band joist¹ on the north basement wall. Average pressure differentials during these experiments from a set of these transducers is shown in Fig. 1. The reversal in the normal outdoor-basement pressure differential when the fans are used to pressurize the basement (Experiment 3 and 4) as well as the decrease in outdoor-basement pressure differential when the windows are opened (Experiment 2 compared to Experiment 1, windows closed) are evident on all of the pressure transducers. (Here positive ΔP indicates that the basement is depressurized with respect to outdoors.) The basement depressurization with the windows closed is quite low (0.8 Pa measured at the band joist), which is normal for the season (early summer) in which these measurements were taken. During the heating season, however, a basement depressurization of 3-4 Pa is often observed in PU31. Under these conditions basement pressurization would not be practical without extensive modifications to seal the basement off from the living area.

Basement radon concentrations and building air exchange rates are shown in Fig. 2. The increase in the building air exchange rate, about a factor of 2.5, is nearly the same for both natural ventilation and pressurization, an indication that infiltration, exfiltration, and interzonal flows are similar for these

¹Band joist - also called a header joist, header plate, or rim joist. A board (typically 5x20 cm) that rests on its short dimension on top of the basement wall around the perimeter of the house.

experiments. Basement radon concentrations are reduced by a factor of about 6.0 by natural ventilation.

These results indicate that natural ventilation decreased indoor radon concentration by:

- 1) reducing the outdoor-basement pressure differential (Experiment 2, Fig. 1), thus reducing the radon entry rate (see Eq. 2 and Eq. 3), and
- 2) increasing the flow of uncontaminated outside air into the building.

Basement pressurization reduced basement radon concentrations by:

- 1) reversing the soil-basement pressure differential and lowering the subslab radon concentration to ambient levels and
- 2) increasing the supply of outside air to the house.

Living area and basement radon concentrations for the five experiments are shown in Fig. 3. Both natural ventilation and pressurization reduce basement and upstairs radon concentrations to less than 150 Bq m^{-3} ; basement and upstairs concentrations are approximately equal due to the large interzonal flow from the basement to the upstairs. Ambient radon concentrations were not measured during these experiments but may be a significant fraction of the levels measured during the pressurization experiments. Ambient concentrations in New Jersey are about 7.4 to 14.8 Bq m^{-3} (Gesel, 1983), compared to 20 and 29 Bq m^{-3} measured during pressurization experiments.

The main advantage of natural ventilation compared to pressurization is its simplicity and low cost (no fan is necessary), even though the reduction in radon concentrations was higher with basement pressurization. For example, in PU31 basement depressurization (ΔP) varies from $\Delta P \leq 0.25 \text{ Pa}$ in the summer to $\Delta P \geq 3 \text{ Pa}$ in the winter. Even in milder climates a large variation in ΔP could be expected. Thus, a pressurization system adequate for the cooler months would have much too large a flow rate in the summer months, unless some sort of feedback control was installed. Natural ventilation is, on the other hand, self-regulating: the amount of outside air supplied to the house is a direct function of the outdoor-basement depressurization which is decreased by the open basement windows.

b. Radon Reduction by Modification of the HAC System (With Sump Open)

The forced air heating and air conditioning system in PU31 has a "makeup duct", which is a conduit that connects the return (low pressure) side of the air handler to the outdoors and increases the supply of fresh air to the living area. The impact of the use of the makeup duct on radon concentrations and house operating parameters has been examined in a series of four experiments; the makeup duct was alternately connected and disconnected to the outdoors over four consecutive three or four day periods. During periods denoted as Experiment 1 and 3, the duct was connected to the outdoors; during periods 2 and 4, the duct was disconnected.

Air infiltration to the upstairs (living area) and HAC usage are shown in Fig. 4. Average HAC usage during this period was about 25%; there is little if any change in the air infiltration rate with the duct open or closed. Upstairs and basement average radon concentrations are shown in Fig. 5 for the four Experiments; again, there is virtually no change in the radon concentrations over this period. It is clear that modification of the HAC system in this fashion has a negligible effect on radon concentrations at these levels of HAC operation, which are close to the yearly average for typical HAC systems. Thus, using the HAC system to increase the supply of fresh air to the living area does not seem to be a reasonable mitigation technique.

Radon concentrations during the makeup duct experiments, about 3.5 kBq m^{-3} (see Fig. 5), observed in PU31 with the basement sump open, should be compared to levels of about 800 Bq m^{-3} found when the sump was closed (Fig. 3, Experiments 1 and 5). It should be noted that basement depressurization was about 2.8 Pa during the makeup duct experiments, compared to 0.6-0.8 Pa before and after the pressurization and natural ventilation comparison. (The different basement depressurizations are due to the different magnitudes of the stack effect in each case. The first set of experiments were conducted during the early spring, and the second set in early summer.) Due to the large difference in basement depressurization during the two periods, the difference in radon concentrations is only indicative of the efficacy of sealing the basement sump. A precise evaluation of the efficacy of a mitigation (e.g. sealing the basement sump) can only be made by comparing the radon entry rate as a function of basement depressurization in each case, as was done with Eq. 2 and 3, or by comparing radon concentrations at the same outdoor-basement pressure differential.

Conclusions

Results from these experiments indicate that natural ventilation, coupled with sealing of the main entry route (the basement sump), reduced radon concentrations from about 800 Bq m^{-3} to below 150 Bq m^{-3} in this research house. A rough estimate for the additional heating cost due to the increase in the building air exchange rate with natural basement ventilation (Taylor et al., 1987) can be made as follows: the additional energy consumed (U , kJ) is $U = 25 \cdot V \cdot D / E$, where V ($\text{m}^3 \text{ h}^{-1}$) is the additional volume of air to be heated, D is the number of degree days (4911 in the Princeton, NJ area), and E is the furnace efficiency. Assuming a furnace efficiency of 0.7, the additional energy consumption for an increase in the building air exchange rate of 0.6 h^{-1} (building volume, 630 m^3 , including the unheated basement), is 66.4 GJ y^{-1} . For a natural gas price of 0.195 m^{-3} , the additional cost is about $\$330 \text{ y}^{-1}$. (This is somewhat pessimistic since the basement is unheated.) This can be compared to the cost of running the subslab depressurization system now installed in PU31 ($\$0.12 \text{ kWh}^{-1}$,

150 W fan, \$50.y⁻¹ estimated cost of exhausted conditioned air) of \$210 y⁻¹. Because the subslab system decreases radon concentrations to less than 40 Bq m⁻³, among other reasons, it is clearly superior. However, in regions with mild winters, natural basement ventilation combined with sealing of major entry routes such as an open sump could be a reasonable mitigation technique even in houses with basement radon concentrations as great as 3 kBq m⁻³.

Basement ventilation (pressurization) was also effective in reducing radon concentrations, but compared to natural ventilation appeared much more difficult to implement. Modification of the HAC system to increase the supply of outside air to the living area did not change the building radon concentration and does not seem to be a viable mitigation technique.

Acknowledgments

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Fig. 1. Outdoor-basement (measured at the band joist) or outdoor-soil pressure differential (ΔP) for typical transducers. Positive ΔP indicates that the basement is depressurized relative to the soil or outdoors.

Experiments 1,5: Windows Closed; Experiment 2: Windows Open
Experiments 3,4: Basement Pressurized

Fig. 2. Building air exchange rate (air changes per hour) and Basement radon concentration.
Experiments 1,5: Windows Closed; Experiment 2: Windows Open
Experiments 3,4: Basement Pressurized

Fig. 3. Basement and upstairs (living area) radon concentration
 Experiments 1,5: Windows Closed; Experiment 2: Windows Open
 Experiments 3,4: Basement Pressurized

Fig. 4. Percentage of heating and air conditioning (HAC) on time (%HAC Usage) and upstairs air infiltration, makeup duct experiments.
 Experiments 1,3: Duct connected to outdoors
 Experiments 2,4: Duct closed.

Fig. 5. Basement and upstairs radon concentrations.
Experiments 1,3: Duct connected to outdoors
Experiments 2,4: Duct closed.

Chapter VI

Resulting Publications

Cavallo, A., Berkner, C., Gadsby, K., Use of Ventilation to Control Radon in Single Family Dwellings, presented at the Fifth International Conference on Indoor Air Quality and Climate, Toronto, Canada, August 1990.

Cavallo, A., Reddy, T.A., and Socolow, R.H., The Effect of Natural Ventilation on Radon and Radon Progeny Levels in Houses", presented at the 5th International Symposium on the Natural Radiation Environment, Salzburg, Austria, September 1991.

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Cavallo, A., Gadsby, K. and Reddy, T.A., The Use of Radon Entry Rate Measurements to Understand Radon Concentrations in Buildings", to be published in Health Physics, January, 1994.

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