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Project Summary

The Effects of Natural and Forced Basement Ventilation on Radon Levels in Single Family Dwellings

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For the first time, the effect of ventilation on radon concentrations and radon entry rate in a single-family dwelling has been extensively studied and documented. Measurements of radon concentrations, building dynamics, and environmental parameters made in Princeton University research houses over several seasons and under different building operating conditions have demonstrated the functional dependence of radon entry rate on basement depressurization.

This work clarifies the role of natural ventilation in reducing indoor radon concentrations. Although natural ventilation has always been recommended as a way to reduce indoor radon levels, its erratic behavior has been noted and its efficacy has never been documented. This work shows conclusively that natural ventilation can decrease radon levels two ways: (1) by simple dilution, and (2) although less obvious, by providing a pressure break (defined as any opening in the building shell which reduces the outdoor/indoor differential pressure). This reduces building depressurization and thus the amount of radon contaminated soil gas that is drawn into the building.

The most important results of these experiments show the linear dependence of radon entry rate on basement depressurization and the precise, quantitative comparison between radon entry rates possible when, for example, radon mitigation is attempted by sealing off the basement sump. This is the first time such a scientific approach has been taken to quantify the results of this mitigation strategy.

The experiments also examine the role of basement forced pressurization and depressurization in determining radon concentration in the basement and living area of a house.

This Project Summary was developed by EPA's Air and Energy Engineering Research Laboratory, Research Triangle Park, NC, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

This systematic investigation of natural and forced ventilation in Princeton University research houses, instrumented to measure house dynamic and environmental parameters, has filled an important gap in understanding the role of natural ventilation in reducing radon levels in single-family dwellings. It is noteworthy that, although natural ventilation is often mentioned as a simple way to reduce indoor radon levels, experiments have never been conducted to quantify the magnitude of reduction achieved. The lack of understanding of this element of radon entry into houses was the motivation for this work, which is the first program to investigate these effects in detail.

A consequence of this lack of experimental work has been considerable confusion in the size of the reduction of radon concentration possible as well as the relative importance of each of the mechanisms (dilution and the reduction in basement depressurization) by which natural ventilation effects these reductions. Although the flow of radon-contaminated soil gas due to basement depressurization has long been known as the most important cause of high radon levels in houses, the critical role of introducing a pressure break in the building shell to reduce radon levels has never before been quantified.

A 1988 EPA mitigation manual emphasizes the importance of the pressure break and dilution mechanisms in achieving high reductions through natural ventilation, but has only anecdotal data on the reductions achievable with natural ventilation and *no* data to separate out the relative effects of the two mechanisms. Another detailed discussion of natural ventilation in 1988, while more complete, lacks a theoretical background and experimental verification, and tends to be somewhat anecdotal. This serves to emphasize the need for this series of experiments to clarify these issues.

One set of ventilation experiments explored the following simple model: if the radon entry rate S_{Rn} is assumed to be constant and set equal to the removal rate, we have: $S_{Rn} = R_v C_{Rn}$, where R_v is the air exchange rate and C_{Rn} is the radon concentration.

Results from these experiments, in which it was found that basement radon concentrations were inversely proportional to the ventilation rate when S_{Rn} is constant, as predicted by the above equation, confirmed this model. Thus, to reduce radon levels by a factor of 10 when S_{Rn} is constant (i.e., when only the dilution mechanism comes into play), would require an increase in the air exchange rate by that same factor. In most cases, such a large exchange rate is neither practical nor desirable. The experiments were done using an air/air heat exchanger to control the basement ventilation rate. An air/air heat exchanger operates in a balanced mode with inflow and outflow equal and would neither pressurize nor depressurize the basement. This is actually very different from natural ventilation in which a basement window is opened, providing a pressure break.

It is widely recognized that the mechanisms which bring radon into a structure are completely different from those causing high levels of many other indoor air pollutants. Most often the source of undesirable indoor chemicals is found within the structure itself, such as poorly sealed paint cans and cleanser containers, or rug pads and foam stuffing in furniture. In contrast, radon entry into a building is dominated by the pressure-driven flow of contaminated soil gas rather than by emissions from building materials. The subsoil pressure field of the building is caused by three factors:

(1) wind-generated depressurization of the structure,

(2) basement depressurization caused by the operation of the air handler and ventilation equipment, and most importantly,

(3) by the stack effect, that is basement depressurization induced by the temperature difference between the outdoor environment and the building interior.

To understand the relative importance of the competing effects of ventilation and radon entry begin with the simplest case: a single-zone system such as a slab-on-grade-house. In a steady state condition the radon entry rate (S_{Rn}) must be equal to the removal rate by ventilation. The mass balance equation is:

$$S_{Rn} = R_v C_{Rn} \tag{1}$$

where R_v is the ventilation flow rate and C_{Rn} is the radon concentration.

From the above discussion, the radon entry rate must be a function of the depressurization of the structure:

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

where $0.5<\alpha<1$, ΔP_{Rn} is the pressure differential driving radon into the structure, and k is a constant. For air flow through soil, the flow is laminar and α is equal to 1. For air flow through gravel or crushed stone, the flow is often (depending on gravel size) turbulent and α is about 0.5.

Similarly, the ventilation flow rate is driven by the indoor/outdoor pressure differential, and can be written as:

$$R_v = c(\Delta P_v)^{\beta} \tag{3}$$

where ΔP_v is the pressure differential driving the flow of outdoor air indoors and $0.5<\beta<1$. Theoretical and experimental work indicates that β is approximately equal to 0.65 under field conditions.

Combining Eqs. 2 and 3 with Eq. 1, we have:

$$C_{Rn} = \frac{k(\Delta P_{RN})^{\alpha}}{c(\Delta P_v)^{\beta}} \tag{4}$$

We are now in a position to consider two extreme but realistic cases. The first case is a house with soil underneath a basement slab and α sump which is the major entry point for radon into the house. Here, the flow of soil gas to the sump is laminar and the exponent α is equal to 1. Radon entry rate as a function of differential pressure (ΔP) for the laminar flow regime is shown in Figure 1a. It can be further assumed that ΔP_{Rn} is equal or at least proportional to ΔP_v ($\Delta P = \Delta P_v = \Delta P_{Rn}$) and $\beta = 0.65$; ventilation flow rate as a function of the differential pressure is shown in Figure 1b. From measurements in research house PU31, for example, the minimum and maximum outdoor/indoor differential pressures are about 0.25 Pa (summer) and 4.0 Pa (winter). Thus, the maximum ratio between winter and summer basement radon concentrations for closed house conditions should be about 2.6, which is approximately what is observed; radon concentration as a function of differential pressure is shown in Figure 1c. For a factor of 16 change in basement depressurization, this is a relatively small change in radon concentration. This is quite reasonable since the same differential pressure is assumed to drive both air and radon infiltration, and one effect (air infiltration) cancels the other (radon infiltration) to a large extent. If this differential pressure is created mostly by the stack effect, the correlation between radon concentration and temperature differential should be detectable, but with some difficulty.

The second case to be considered is that of a house with gravel under the slab and again with a sump. Here the flow of soil gas in the gravel may be turbulent and and the exponent α is equal to 0.5. This is shown in Figure 2a ($\Delta P = \Delta P_v = \Delta P_{Rn}$), and the ventilation flow rate as a function of differential pressure is shown in Figure 2b. If the same winter to summer range of differential pressure were to occur in this house, the maximum ratio between winter and summer radon concentrations for closed house conditions would be 0.66; the behavior of radon concentration as a function of differential pressure for the case of turbulent soil gas flow is shown in Figure 2c. In this case, radon concentrations would be higher in the summer than in the winter, which is contrary to what is normally assumed. In addition, there would be little correlation between temperature differentials and radon concentrations. These results are summarized in Table 1.

Conditions in houses are further complicated by the operation of mechanical ventilation systems (air handlers, exhaust fans, and attic fans), by heavy rain which drives radon concentrations to very high levels (most likely due to a rising water table which acts as a piston to drive soil gas into the house), wind-induced depres-

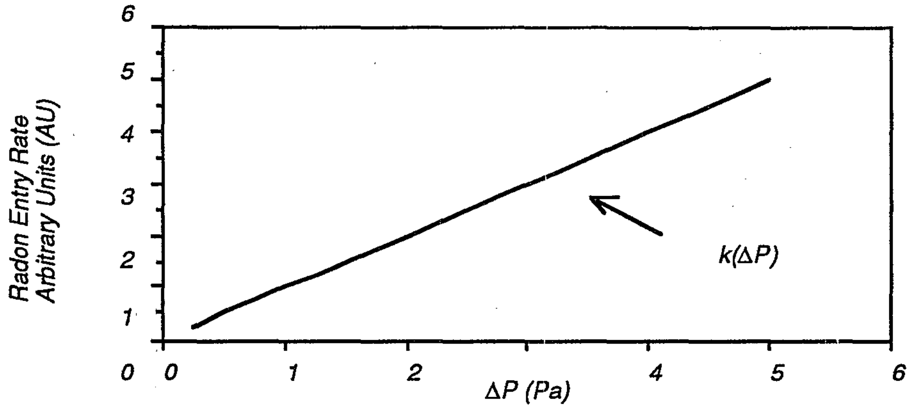

Figure 1a. *Radon entry rate vs. differential pressure for soil underneath basement slab. Soil gas laminar flow $S = k(\Delta P)$.*

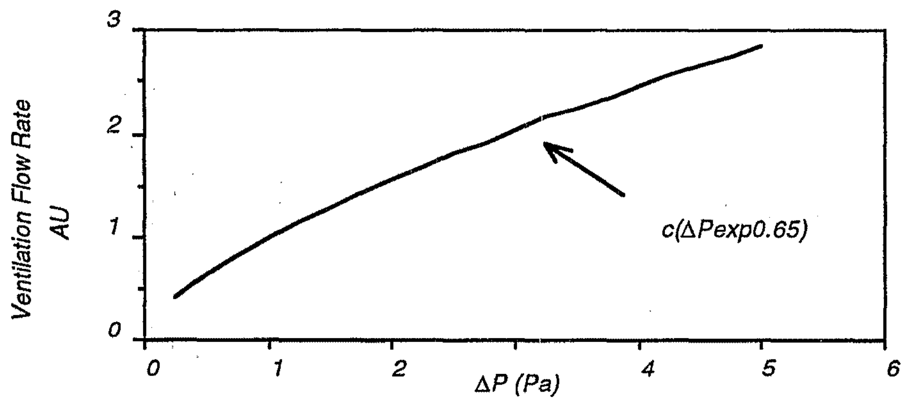

Figure 1b. *Ventilation flow rate vs. differential pressure for soil underneath basement slab. Flow turbulent/laminar $R_v = c(\Delta P\exp 0.65)$.*

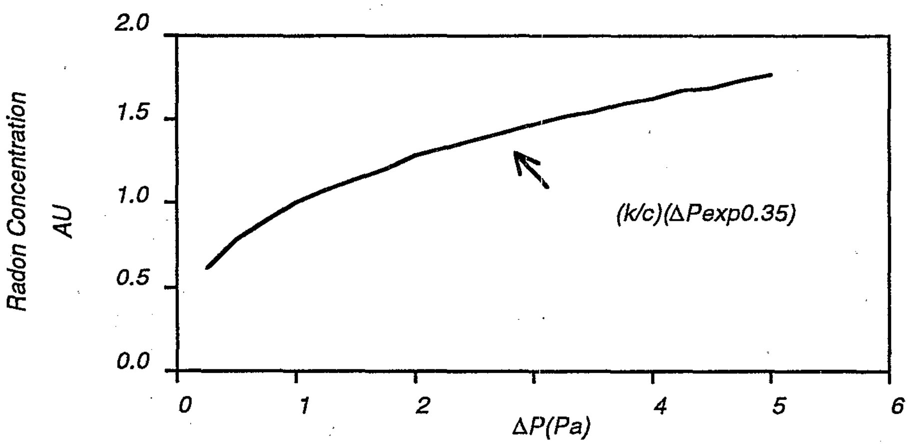

Figure 1c. *Radon concentration vs. differential pressure for soil underneath basement slab. Soil gas flow laminar C_{Rn} (k/c) (DPexp0.35).*

surization, and possible saturation of the entry rate of radon. However, the following important general conclusions may be drawn from these fundamental considerations:

1. Radon concentrations resulting from stack effect depressurization should not vary by much more than a factor of 3 under closed house conditions on a yearly basis.
2. The correlation between radon concentrations and the indoor/outdoor temperature differential may be small, even if it is the most important factor driving radon into houses.
3. A generalized correction factor to predict, for example, closed house summer radon levels from winter radon measurements is not possible unless details of house construction are known, even for houses with identical subslab conditions.

The assumption made above, that ΔP_{Rn} is equal or proportional to ΔP_v can be examined more closely. It is clear that the locations of radon entry into a structure (cracks and penetrations through the floor slab or through a cinderblock wall) may generally be completely different from those through which outdoor air enters. The pressure drop across each entryway may be different and the associated exponent may be different, depending on whether the flow is laminar, turbulent, or a combination of the two. In general, it is very difficult to make enough measurements on, underneath, and around an arbitrary structure to predict the radon concentration in that structure. For a building which has been very carefully assembled on a homogeneous soil bed, however, it may be possible to compare theory and experiment in some detail.

Experiments

Natural Ventilation Experiments

The effect of natural basement ventilation, that is opening basement windows, on indoor radon levels has been examined in two Princeton University research houses: in PU31 during the winter heating season and the summer cooling season and in PU21 during the winter heating season. The effect on indoor radon concentrations of forced ventilation and the presence or absence of a makeup duct in the air handling system have been examined in research house PU31. Only the most important results from experiments in PU31 are discussed here.

The houses have been instrumented as follows:

1. Pressure differentials across the building shell and between the

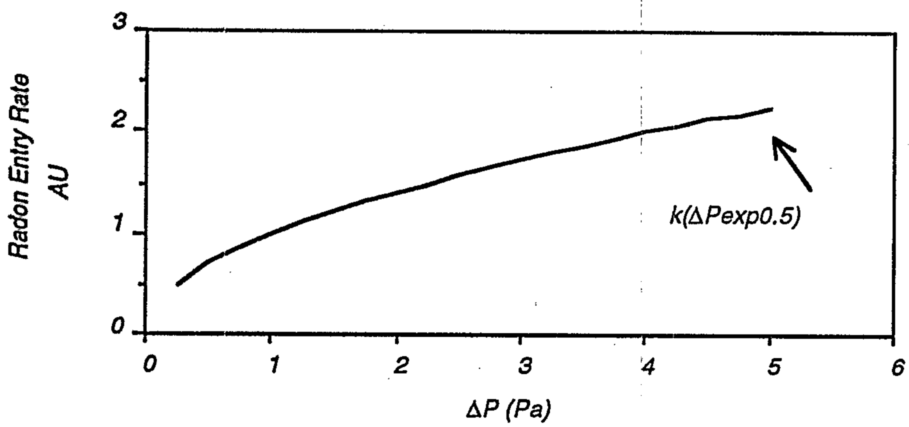

Figure 2a. Radon entry rate vs. differential pressure for gravel underneath basement slab. Soil gas flow turbulent $S=k(\Delta P exp0.5)$.

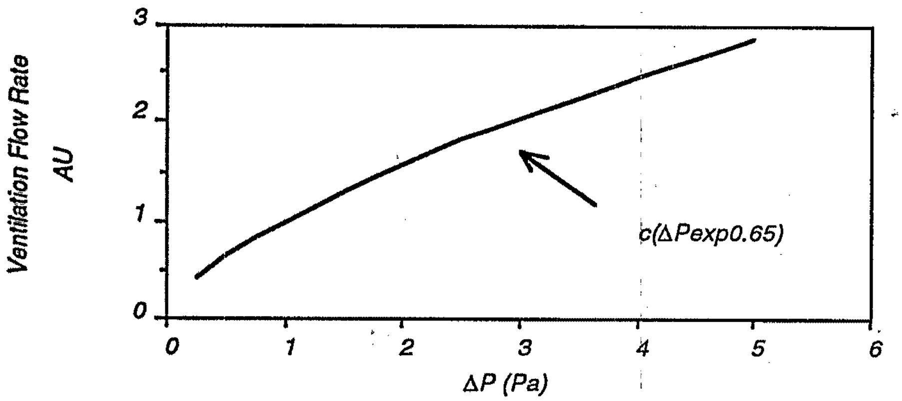

Figure 2b. Ventilation flow rate vs. differential pressure for gravel underneath basement slab. Flow turbulent /laminar $R_v=c(\Delta P exp0.65)$.

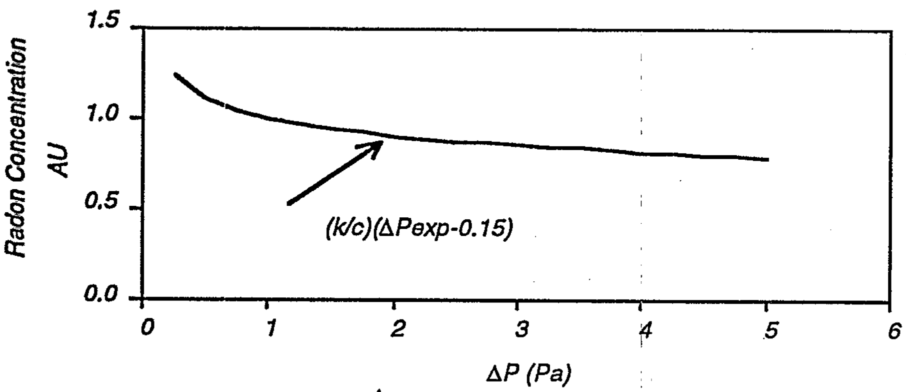

Figure 2c. Radon concentration vs. differential pressure for gravel underneath basement slab. Soil gas flow turbulent $C_{Rn}=(k/c)\ (\Delta P exp\text{-}0.15)$.

basement and the upstairs are measured with differential pressure transducers.

2. Basement, living area, and outdoor temperatures are monitored using thermistors.
3. Basement, living area, and subslab, and in-the-block radon levels are monitored with a CRM (Lawrence Berkeley Continuous Radon Monitor) or a PRD (Pylon passive radon detector).
4. Basement relative humidity is monitored with a relative humidity probe.
5. Heating and air conditioning system air handler use is monitored using a sail switch.
6. A PFT (perfluorocarbon tracer) system is used to measure building air exchange rate and interzonal flows. Up to four gases may be used in this system, but for these experiments only two were needed. Emitters (four to eight per zone) are placed in temperature regulated holders in the basement and living area.

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.

The effect of opening two basement windows on basement radon levels and the outdoor/basement pressure differential is shown in Figures 3 and 4. Basement radon levels are shown in Figure 3; there is clearly a significant drop in this parameter, from an average of about 90 pCi/L to about 10 pCi/L when the windows were opened on JD89220.6. The magnitude of this drop was completely unexpected. The large diurnal variation in basement radon levels is due to the operation of the attic fans which depressurizes the entire house, increasing the ventilation rate as well as the radon levels. Measurements of a typical differential pressure transducer are illustrated in Figure 4 (positive pressure indicates that the outdoor pressure is above that of the basement). The large peaks (~3 Pa) in outdoor/basement 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

Table 1. *Ratio of Winter to Summer Radon Levels in Houses (Assuming ΔP_{max} =4 Pa, ΔP_{min}=0.25 Pa)*

Soil Gas Exponent	Ventilation Exponent	Radon Level as Function of ΔP	C_{Rn}, Winter/ C_{Rn}, Summer
Laminar $\alpha=1$	$\beta = 0.65$	$C_{Rn} \propto (\Delta P)^{0.35}$	2.6
Turbulent $\alpha=0.5$	$\beta = 0.65$	$C_{Rn} \propto (\Delta P)^{-0.15}$	0.66

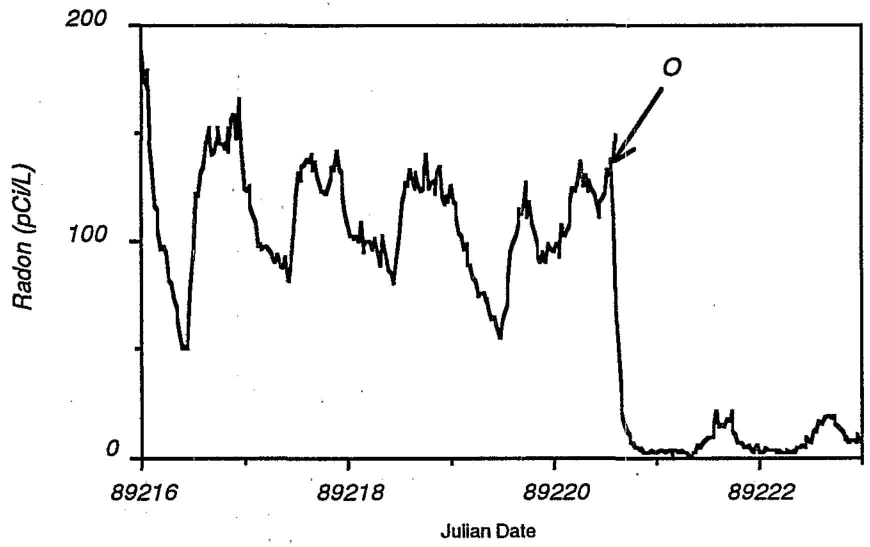

Figure 3. *Basement radon vs. Julian date, PU31. Two basement windows were opened (O) at JD89220.6.*

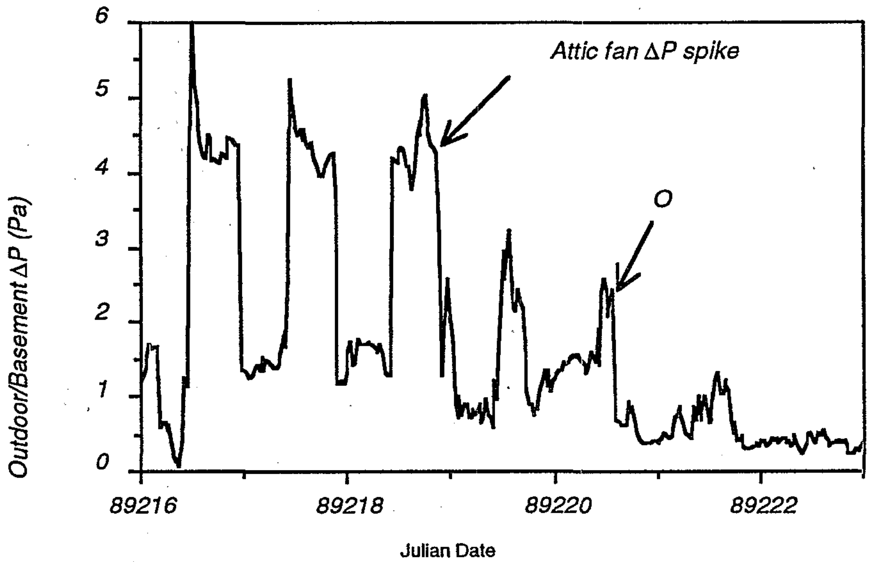

Figure 4. *Outdoor/basement pressure differential vs. Julian date, PU31. Basement windows opened (O) at JD89220.6; Note effect of attic fans.*

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 10 pCi/L. 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 a definitive evaluation of this problem.

Radon entry rate can be calculated using:

$$S_{1Rn} = (R_{10} + R_{12})C_{11} - R_{21}C_{12} \qquad (5)$$

where C_{11} and C_{12} are basement and living area radon concentrations, R_{10} is the exfiltration from zone 1 (basement), and R_{12} and R_{21} the interzonal flows from the basement to the living area and the living area to the basement, respectively. The interzonal flows and exfiltration are measured with the PFT system.

The central role of basement depressurization in driving radon entry in houses is shown in Figure 5, where basement radon entry rate (S_{1Rn}) calculated using Eq. 5, is plotted as a function of outdoor-to-basement pressure differential measured at the north band joist. These data are the result of measurements made over 18 months with basement windows closed, natural ventilation (basement windows open) and forced basement ventilation. The duration of each experimental period was between 2 and 7 days; each data point used values averaged over the appropriate period.

The radon entry rate is clearly a linear function of basement depressurization for ΔP < 4 Pa, implying that the flow of soil gas into the basement is laminar. This is to be expected since the basement slab for PU31 was poured directly onto the soil (that is, there is no gravel layer beneath the slab); as mentioned previously air flow through most soils is expected to be laminar. At the highest basement depressurization (ΔP = 5 Pa) it appears that the radon entry rate does not increase relative to 4 Pa; it may be limited by the flow of radon through the soil. This data point was obtained in an experiment in which the attic fans were on continuously to depressurize the house. It must 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-to-basement pressure differential of less than 4 Pa.

Basement radon concentration as a function of the outdoor/basement pressure differential for closed-house conditions is

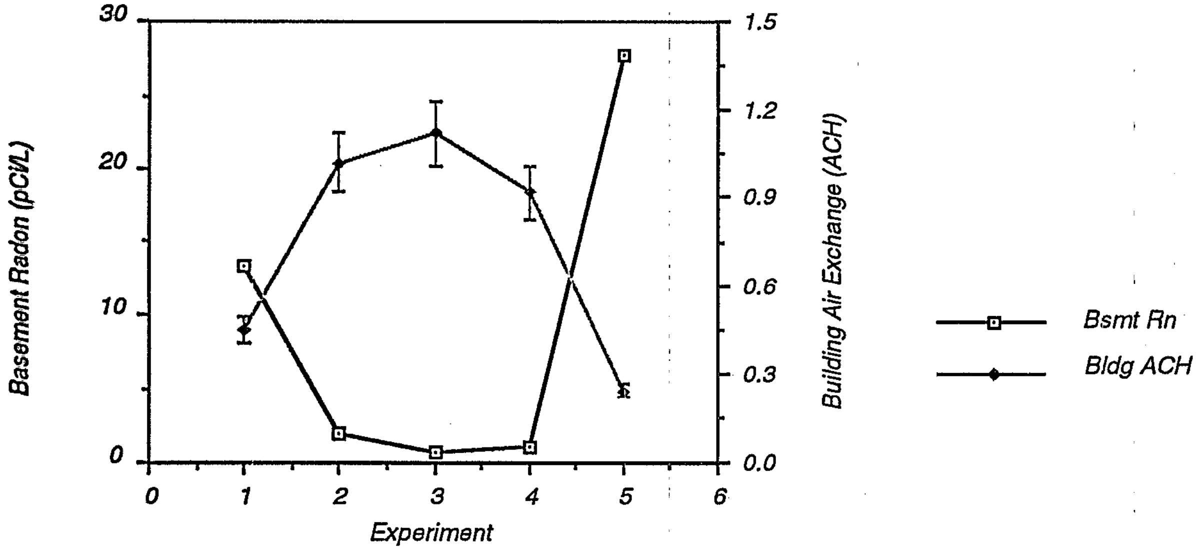

Figure 7. Basement radon, Building ACH.
Experiments 1,5, windows closed; Experiment 2, windows open; Experiments 3,4, basement pressurized.

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Timothy M. Dyess is the EPA Project Officer (see below).

The complete report, entitled "The Effects of Natural and Forced Basement Ventilation on Radon Levels in Single Family Dwellings," (Order No. PB92-192 194/AS; Cost: $19.00, subject to change) will be available only from:

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