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Project Summary

Natural Basement Ventilation as a Radon Mitigation Technique

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Natural basement ventilation has always been recommended as a means of reducing radon levels in houses. However, its efficacy has never been documented. It has generally been assumed to be a very inefficient mitigation strategy since it was believed that dilution was the mechanism by which radon levels were reduced.

Natural ventilation has been studied in two research houses during both the summer cooling season and the winter heating season. Ventilation rates, environmental and house operating parameters, and radon levels have been monitored; it can be definitively concluded from radon entry rate calculations that natural ventilation can reduce radon levels two ways: (1) by simple dilution, and (2) although less obvious, by providing a pressure break which reduces basement depressurization and thus the amount of radon-contaminated soil gas drawn into the house.

Thus, basement ventilation can be a much more effective ventilation strategy than was previously believed. It might be especially useful in houses with low radon concentrations (of the order of 10 pCi/L) or those with low levels that cannot be mitigated cost-effectively with conventional technology.

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

Radon emanation from naturally occurring soils, as distinguished from building materials and mine tailings used as construction fill, has been suspected of being a significant source of indoor air pollution in single family houses since the early 1980s. This concern grew out of studies undertaken after the first energy crisis in 1973 to understand energy consumption patterns in houses and to reduce energy consumption, among other ways, by sealing houses and reducing building air exchange rates. It was immediately realized that reducing ventilation rates had the undesirable side effect of causing an increase in trace gases such as volatile organic compounds, oxides of carbon and nitrogen, and moisture, decreasing both comfort and safety.

It was initially believed that the effect of ventilation on indoor radon concentration was the same as for all other indoor air pollutants; i.e., that ventilation reduced indoor radon levels by dilution. This is based on a very simple model: if radon entry rate S_{Rn} is assumed to be constant and equal to the removal rate, $S_{Rn} = \lambda_v C_{Rn}$, where λ_v is the air exchange rate and C_{Rn} is the radon concentration.

Results from initial experiments (in which it was found that basement radon concentrations were inversely proportional to the ventilation rate), as predicted by the above equation, seemed to confirm this hypothesis. Thus, to reduce radon levels by a factor of 10 would require an increase in the air exchange rate by that same factor, which in most cases is neither practical nor desirable. The experiments used an air-to-air heat exchanger to control the basement ventilation rate. An air-to-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; nevertheless, it resulted in ventilation's being thoroughly discredited as a means to control indoor radon.

However, the mechanisms which bring radon into a house are completely different from those causing high levels of many other indoor air pollutants. Most often, the source of undesirable indoor chemicals is within the house itself; e.g., poorly sealed paint cans and cleanser containers, or rug pads and foam stuffing in furniture. Radon entry into a house is dominated by pressure-driven flow of soil gas rather than by emissions from building materials. The subsoil pressure field of the house is caused by: wind-generated depressurization of the house, basement depressurization caused by air handler operation, and (most importantly) by basement depressurization induced by the temperature difference between the outdoors and the house interior (stack effect).

The above discussion indicates that radon entry rate S_{Rn} cannot be a constant but must be a function of the basement-to-subsoil pressure differential. Thus, basement ventilation can theoretically reduce indoor radon levels both by dilution and by providing a pressure break which reduces the basement-to-subsoil pressure differential which in turn reduces the radon entry rate.

Experiments

The effect of natural basement ventilation (i.e., opening basement windows) on indoor radon levels has been examined in two Princeton University research houses: PU31 during the winter heating season and the summer cooling season, and in PU21 during the winter heating season. This Summary reviews only the results from research house PU21.

Instrumentation

The houses are instrumented to measure:

1. Pressure differentials across the building shell and between the basement and the upstairs (PU21 only), using differential pressure transducers.
2. Basement, living area (PU21 only), and outdoor temperatures, using thermistors.
3. Basement, living area, and subslab and in-the-block radon levels (PU21 only), using a CRM (Lawrence Berkeley Continuous Radon Monitor) or a PRD (Pylon passive radon detector).
4. Basement relative humidity, using a CS 207 relative humidity probe.
5. Heating and air-conditioning system usage, using a sail switch.
6. Building air exchange rate and interzonal flows, using a PFT (perfluorocarbon tracer) system. As many as four gases may be used in this system, but for these experiments only two were needed. Emitters (four to eight per zone) were placed in temperature regulated holders in the basement and living area.

In addition, a weather station at Princeton University 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 seconds and averaged over 30 minutes, while the air infiltration and interzonal flow measurements were 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 results of these experiments are summarized here.

The research house has the following characteristics:

SIZE:
1970 ft²* living area, 525 ft² 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 underlies about 30% of the house, with the remainder built on a slab. There is a cinderblock chimney stack in the center of the house.

FIREPLACE:
Large fireplace in the living room.

HEATING SYSTEM:
Central, gas, forced-air heat furnace in basement.

COOLING SYSTEM:
Central air conditioning.

HOT WATER: Gas hot water heater in basement.

RADON LEVEL:
~120 pCi/L 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. Figure 1 is a basement floor plan of research house PU21; locations of the basement window, radon instrumentation, and capillary adsorption tubes (CATS) are indicated. Figure 2 is the upstairs (living area) floor plan for PU21; locations of the CATS and radon instrumentation are indicated.

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 Figures 3 and 4. 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 Figure 3 are basement radon levels as measured with a pumped CRM, which has a response time of less than 30 minutes, and upstairs radon levels as measured with a Pylon (PRD), which has a response time of about 3 hours. Plotted in Figure 4 is the pressure differential across the south wall of the basement (positive values indicate that the basement is depressurized relative to the outdoors). A normally closed basement window was opened at JD90048.4 and 90049.45, and closed at JD90048.83 and 90049.8.

The basement/outdoors pressure differential responds immediately to the closing or opening of the window with a ~1.5-Pa change in this parameter. (Note that, even with the window open, the basement still remains depressurized relative to the outdoors.) This is a strong indication that the radon entry rate into the basement must change; this is in fact the case, as verified by measurements in other experiments of building air change rates and interzonal flows, radon levels, and radon entry rates.

Radon levels respond over a longer period of time to a window opening or closing. This is to be expected since the total basement air exchange rate (defined as the flow of outdoor air plus the flow from the living area into the basement) is approximately 1 air change per hour (ACH), and the building air exchange rate is about 0.3-0.6 ACH. Thus, the time necessary to

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* 1 ft² = 0.0929 m²

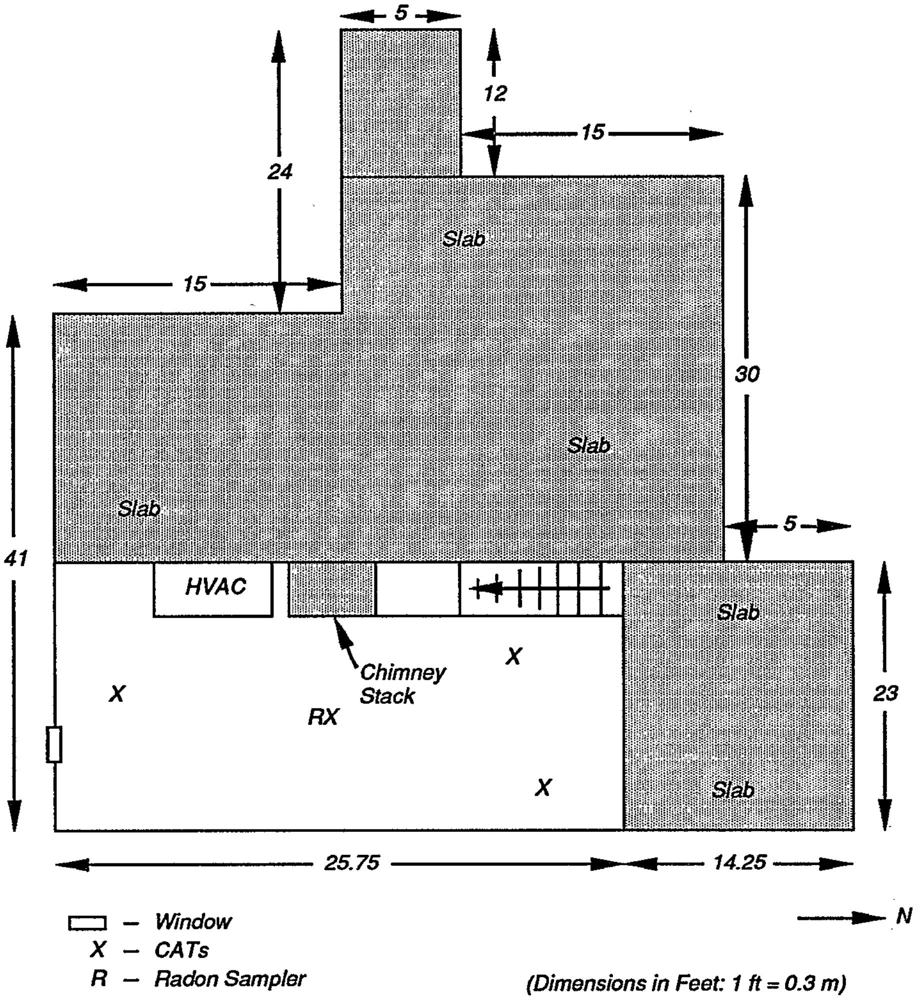

Figure 1. *Basement floor plan of PU21 showing CATs, radon sampler, and window.*

achieve a new steady state must be of the order of 2 to 3 hours. In addition, the response time of the upstairs radon detector is itself of the order of 3 hours, which is why there is such a difference in the time response of the upstairs and basement radon levels.

It is also of some importance to note that natural variations in the building behavior are of the same order of magnitude as those caused by opening a basement window. An example of this occurs around time JD 90048. The decrease in indoor radon and basement depressurization in this time period was caused by 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. It is essential that an experiment be of sufficient duration to be able to average over such excursions.

The natural ventilation experiment in PU21 was conducted over a 17-day period in February; two periods of 2 and 3 days each were used to determine the baseline building conditions (windows closed), and three 4-day periods were used to determine the building operating parameters with a single basement window (~2.2 ft^2 window area) open. In Figures 5 through 7, described below: in experiments 1 and 5, the basement window was closed; and in experiments 2,3, and 4, the basement window was open.

The effect of basement ventilation on basement and upstairs radon levels is shown in Figure 5. With the windows closed, basement radon levels were about 120 pCi/L, while upstairs levels were about a factor of 2 or less lower (80 pCi/L). This is a fairly typical result, and a consequence of the basement's being isolated from the living area. With one basement window open, 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; 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.

Another consequence of a reduction in basement radon entry rate is an increase in subslab and basement radon levels. This is observed, as shown in Figure 6, in which basement and subslab radon levels are plotted for the different experiment periods. The strong decrease in basement radon levels with the window open and the simultaneous increase in subslab radon levels are clear. The reason for the magnitude of the increase in subslab radon levels is not obvious, since it would depend on the amplitude and spatial distribution of subslab soil permeability, moisture, and radium content. Qualitatively, the effect is certainly present.

A critical factor in this experiment is to quantify the effect that basement ventilation has on the building air exchange rate, since the observed reduction in radon levels could be caused by a large increase in the ventilation rate. This has been done using the perfluorocarbon tracer (PFT) system: results are illustrated in Figure 7, in which building air exchange rate and basement radon levels are plotted. The building air exchange rate increases by a factor of 2, from 0.3 to 0.6 ACH, when the basement window is opened. Note that the basement radon levels decrease by a much larger factor (~6-8), again indicating that dilution cannot account for the entire decrease in radon levels. Doubling the air exchange rate corresponds to a ventilation rate of 115 cfm,* roughly comparable to that achieved by a subslab depressurization system, which for this house reduces radon to much lower levels than basement ventilation. However, the main application of natural ventilation is expected to be in lower radon level houses where installation of a subslab system might not be justified.

Using the interzonal flows and tracer gas concentrations measured by the PFT system, the basement and living area ra-

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* 1 cfm = 0.0004719 m^3s.

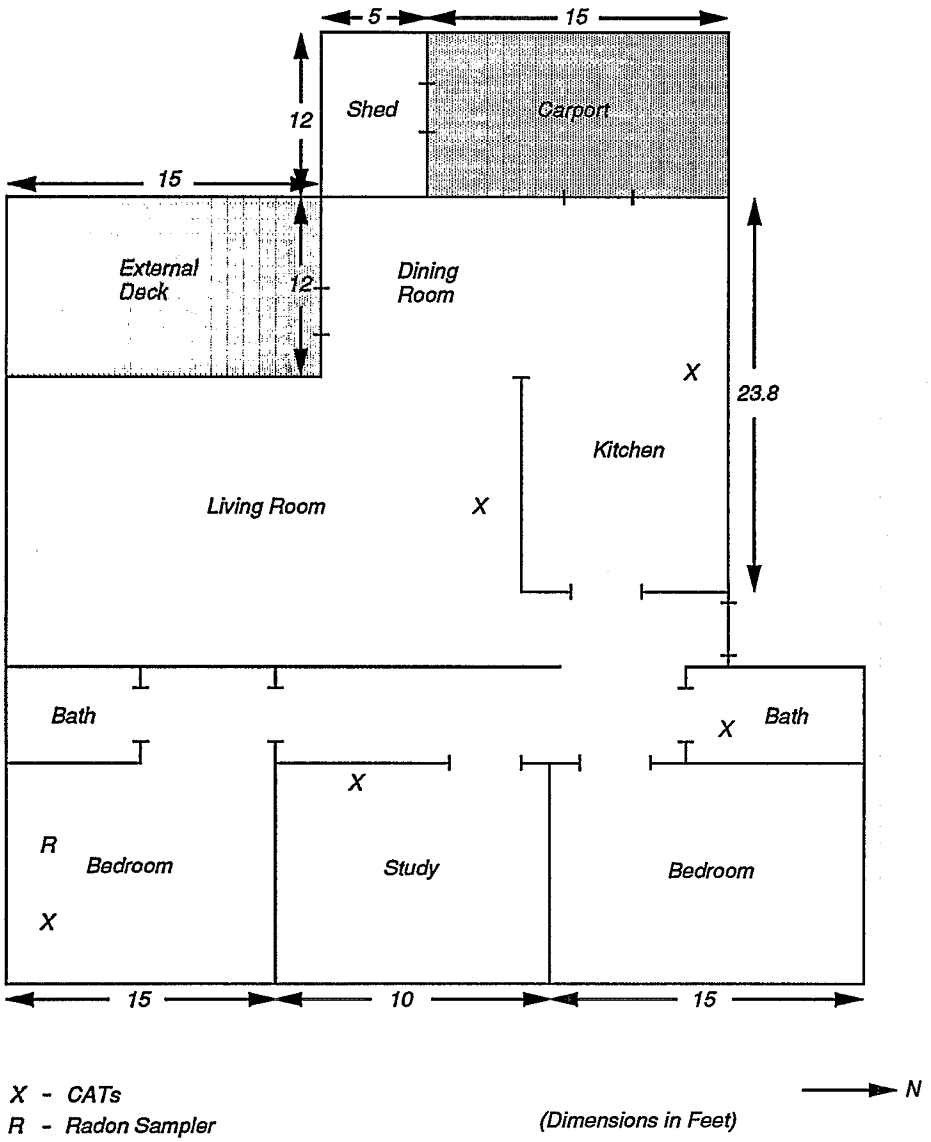

Figure 2. Upstairs floor plan of PU21 showing CATs and radon sampler.

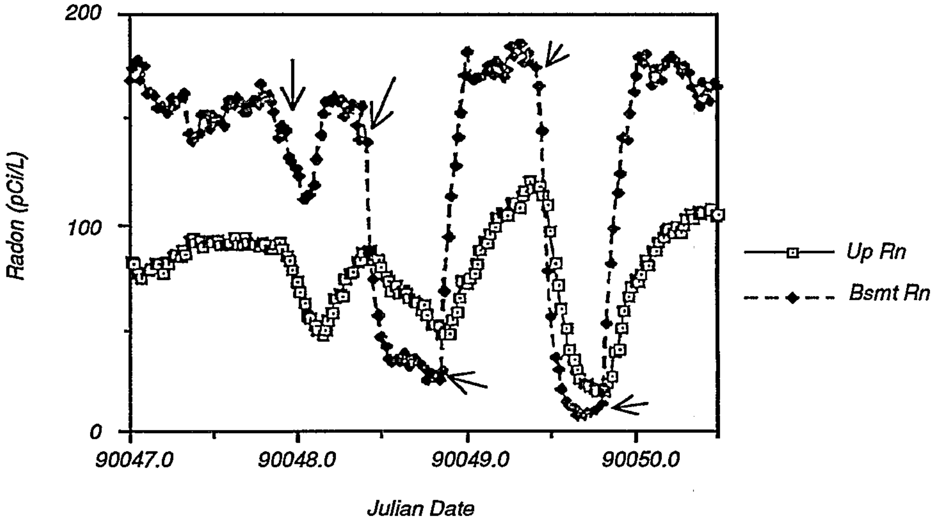

Figure 3. Basement, upstairs radon level vs. Julian date; sequence of window open and window closed, PU21—O = open; C = closed; T = temperature spike.

don entry rates can be calculated. The two-zone system of flows and tracer concentrations is illustrated in Figure 8. Radon entry rates S_{iRn} (i=1,2) can be calculated two ways. The first method is to use the flow rates deduced from tracer gas measurements but assume that C_{11} and C_{12} are the radon concentrations in zones 1 (basement) and 2 (living area), respectively:

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

$$S_{2Rn} = (R_{21} + R_{20})C_{12} - R_{12}C_{11} \qquad (2)$$

The second method is to assume that the tracer gas and radon behave in the same fashion once they enter the house and that the interzonal flow from the living area to the basement (R_{21}) is very small compared to the basement infiltration plus interzonal flow from the basement to the living area (R_{10} + R_{12}). In this case the ratio of the tracer gas emission rate in zone 1, S_{11}, to the concentration of tracer gas in zone 1, C_{11}, is the same as the ratio of the radon entry rate in zone 1 to the radon concentration in zone 1:

$$S_{11}/C_{11} = S_{1Rn}/C_{1Rn} \qquad (3)$$

Results of the entry rate calculation using Eq. 3 are shown in Figure 9. There is a factor of 3 decrease in the entry rate with natural basement ventilation compared to that without ventilation, and this difference is substantially outside the error bars of the individual data points.

The two methods for calculating the entry rate are compared in Figure 10. Using the computed interzonal flow rates (Eq. 1) results in substantially more uncertainty than when Eq. 3 is used; this is a consequence of the errors inherent in the interzonal flow calculations using tracer gas measurements. There is, nonetheless, general agreement between the two methods. The computation using the interzonal flows always yields a lower entry rate than the second method: this is consistent with the presence of an entry route into the living area which bypasses the basement.

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. The radon entry rates in both zones are about equal in this case, about 5 µCi/h. With the basement window closed, the basement radon entry rate (about 20 µCi/h) predominates. This adds an extra complication to the use of natural ventilation as a mitigation strategy. It remains to be seen how widely this effect is observed.

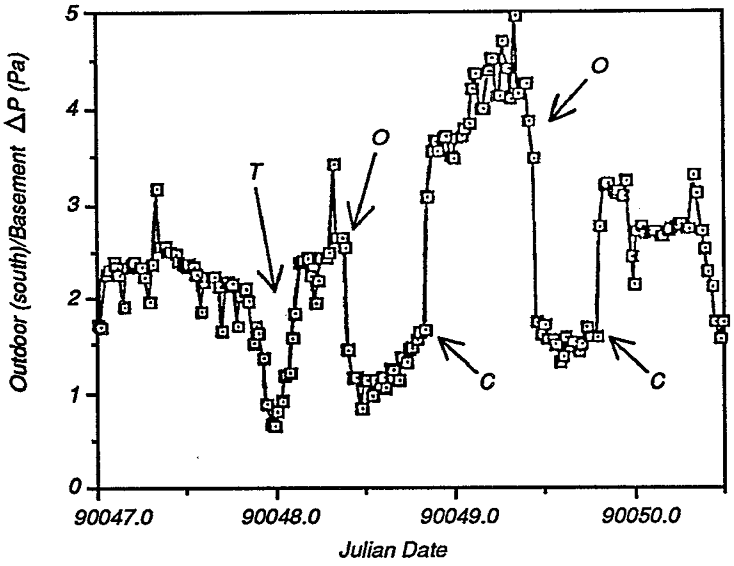

Figure 4. *Outdoor/basement pressure differential vs. Julian date; sequence of window open and window closed, PU21—O = open; C = closed; T = temperature spike.*

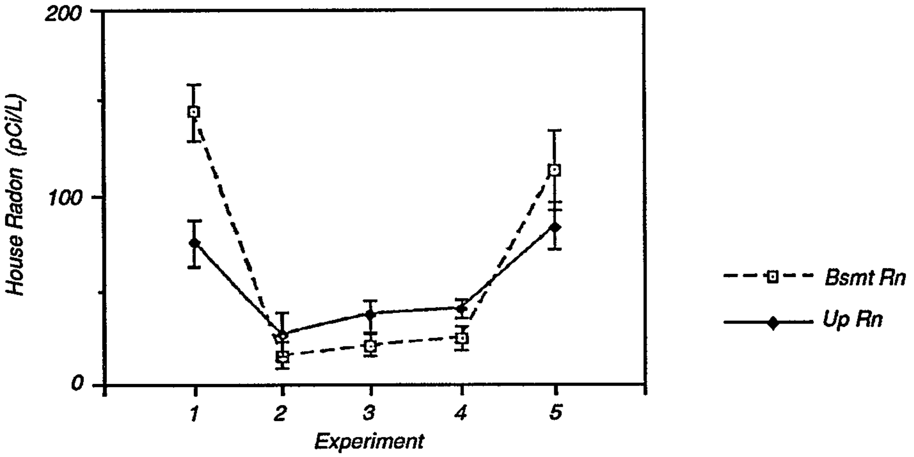

Figure 5. *Basement, upstairs radon, PU21: experiments 1, 5, window closed; and experiments 2, 3, 4, window open.*

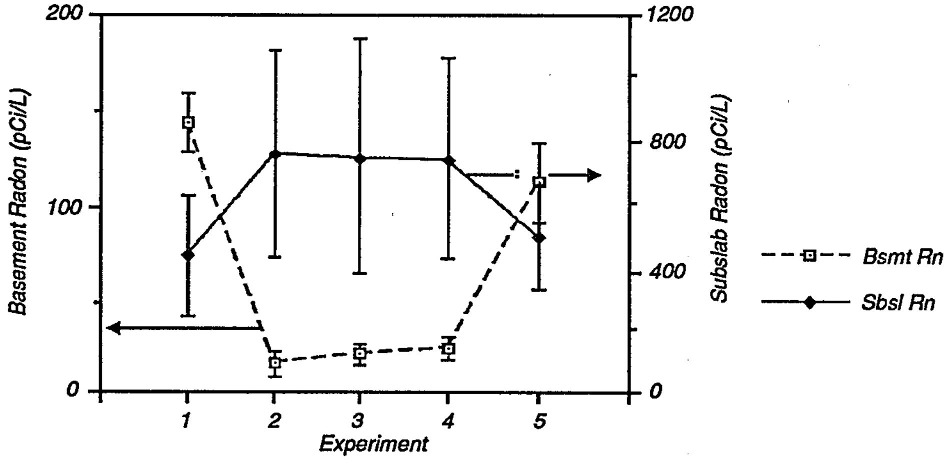

Figure 6. Basement, subslab radon, PU21: experiments 1, 5, window closed; and experiments 2, 3, 4, window open.

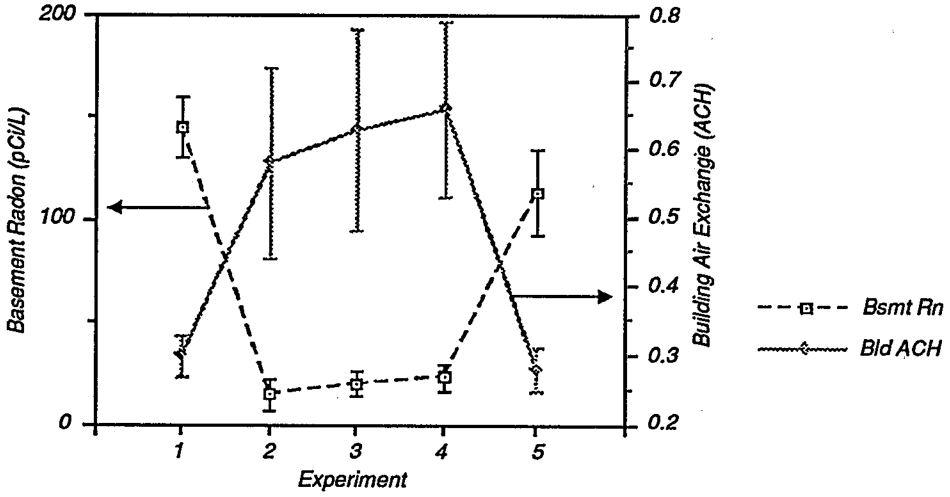

Figure 7. Building ACH, basement radon, PU21: experiments 1, 5, window closed; experiments 2, 3, 4, window open.

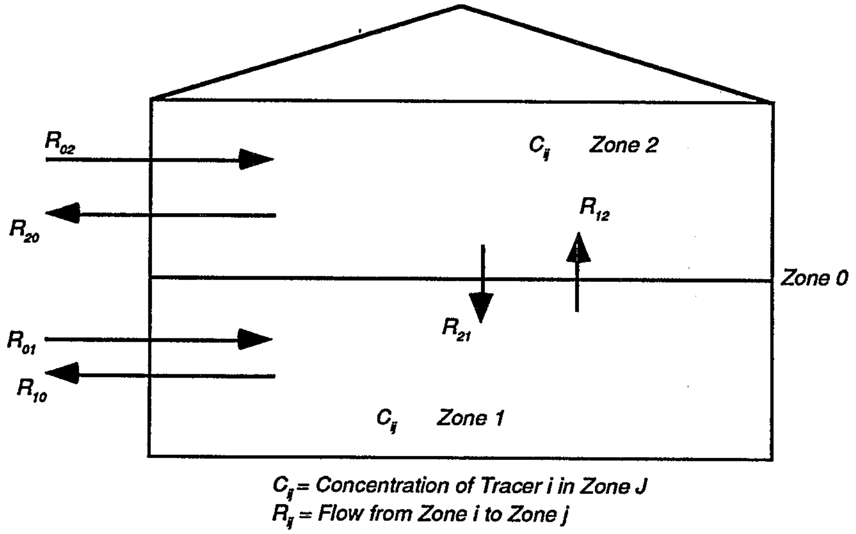

Figure 8. Flows and tracer concentrations for two zones.

Therefore, measurements in PU21 clearly 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, with the second effect being the more important.

Conclusions

Natural ventilation experiments conducted during the summer cooling season and the winter heating 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 2-5 and an increase in the building air exchange rate of about a factor of 2 have been documented. These results contradict earlier assumptions of the efficacy of (and mechanisms by which) natural ventilation can reduce indoor radon levels, and indicate that natural ventilation can reduce indoor radon levels by much larger factors than was previously believed.

A rough cost estimate for natural basement ventilation in research house PU21 can be made with the following assumptions: 1) 4911 degree days for the Princeton area, 2) 115 cfm constant increase in the winter ventilation rate, 3) furnace efficiency of 0.7, and 4) a heating oil cost of $1/gal.* With these assumptions, the additional heating cost would be $225/yr. This compares surprisingly favorably with the running cost of a subslab depressurization system ($0.12/kWh, 90 W fan, $50-$100 for exhaust of conditioned air) of $140-$190/yr. Thus, in certain circumstances, basement ventilation could indeed be a reasonable mitigation strategy.

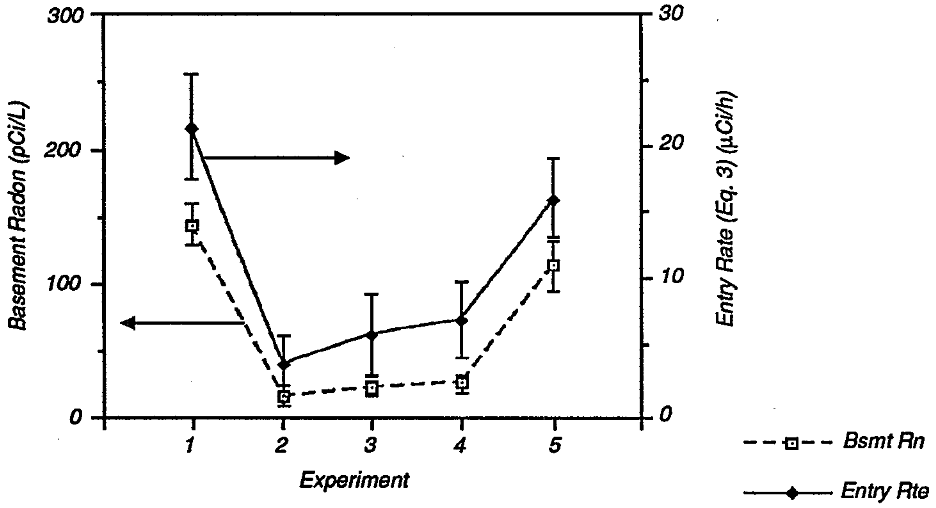

Figure 9. *Basement radon entry rate, basement radon, PU21: experiments 1, 5, windows closed; experiments 2, 3, 4, windows open.*

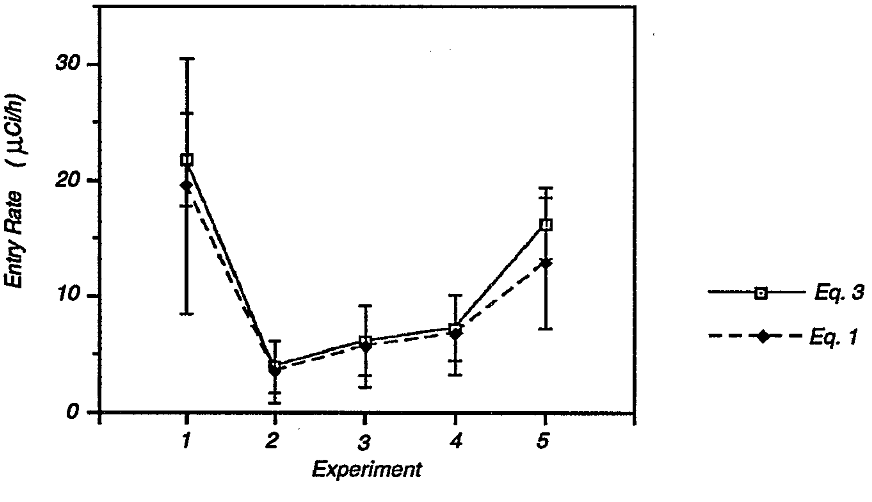

Figure 10. *Entry rate calculations compared, PU21: experiments 1, 5, window closed; experiments 2, 3, 4, window open.*

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* 1 gal. = 3.785 L.

*U.S. Government Printing Office: 1992 — 648-080/60021

Recommendations

Experiment results suggest that:

1. Further experiments on natural ventilation should be undertaken in:
    - a. Low radon level houses (basement radon concentrations of 10 pCi/L or less) to verify that low radon levels can be adequately reduced by this method.
    - b. Houses of different construction styles (to document the magnitude of reduction in radon concentration attainable).
2. Other natural ventilation strategies, such as living area ventilation instead of or in conjunction with basement ventilation, should be examined.
3. Forced ventilation using air-to-air heat exchangers should be carefully compared to natural ventilation.

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Ronald B. Mosley is the EPA Project Officer (see below).

The complete report, entitled "Natural Basement Ventilation as a Radon Mitigation Technique," (Order No. PB92-166958/AS; Cost: $17.00, subject to change) will be available only from:

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