Natural Basement Ventilation as a Radon Mitigation Technique

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Abstract

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 concluded that natural ventilation can reduce radon levels two ways. The first, evidently, is by simple dilution. The second, less obvious, way is by providing a pressure break which reduces basement depressurization and thus the amount of radon contaminated soil gas drawn into the structure.

Thus, basement ventilation can be a much more effective mitigation 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 paper has been reviewed in accordance with the U.S, Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication.

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

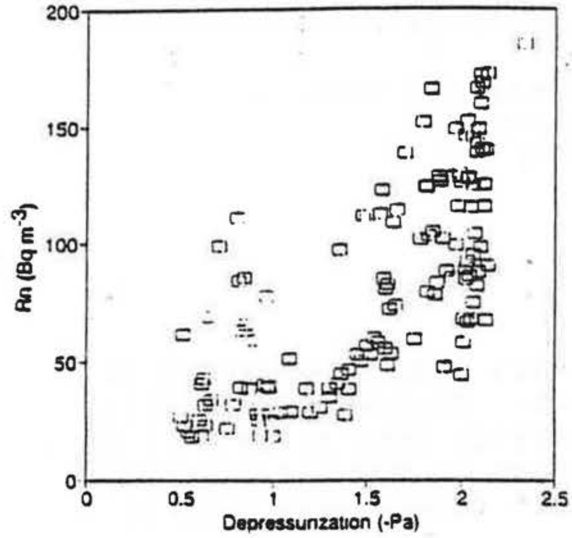

Fig. 5. Room Depressurization vs. Rn Activity

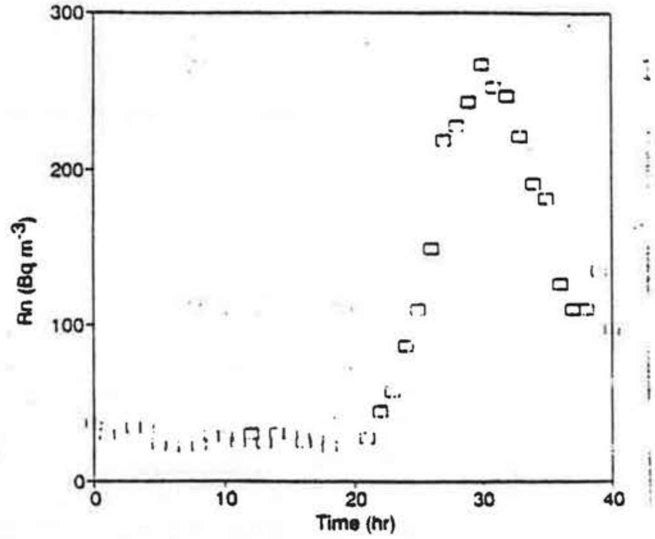

Fig. 6. Depressurization Ending at 18:00 Hrs

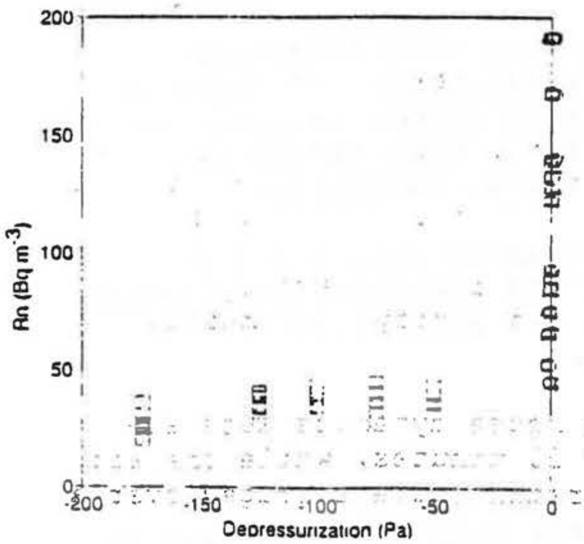

Fig. 7. Indoor Rn as a Function of Subslab Depressurization

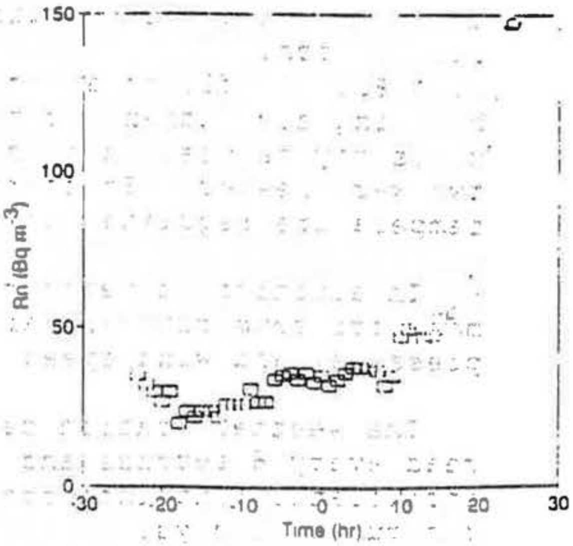

Fig. 8. Indoor Rn as a Function of Time (-50 Pa depressurization ending at 0 hrs)

early 1980s [1,2,3,4]. This concern grew out of studies undertaken after the first energy crisis in 1973 to understand energy consumption patterns in homes and to reduce energy consumption, among other ways, by sealing up structures and reducing building air exchange rates [5]. 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, that is that ventilation reduced indoor radon levels by dilution. This is based on a very simple model [6,7]: if the radon entry rate S_{Rn} is assumed to be constant and set equal to the removal rate, we have: $S_{Rn} = \lambda_v C_{Rn}$, where λ_v is the air exhange rate and C_{Rn} is the radon concentration.

Results from initial experiments [8,9] 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 were done using 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 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. Radon entry into a building is dominated by pressure-driven flow of soil gas rather than by emissions from building materials. The subsoil pressure field of the building is caused by the following factors: wind generated depressurization of the structure, basement depressurization caused by air handler operation, and most importantly, by basement depressurization induced by the temperature difference between the outdoor environment and the building interior (the stack effect).

It is clear from the above discussion that the 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 reduces the radon entry rate [10].

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 (PU31 and PU21) during the winter heating season and the summer cooling season.

The houses have been instrumented as follows:

1. Pressure differentials across the building shell and between the basement and the upstairs (PU21 only) are measured with differential pressure transducers.
2. Basement, living area (PU21 only), and outdoor temperatures are monitored using thermistors.
3. Basement, living area, subslab, and in-the-block radon levels (PU21 only) 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 CS 207 relative humidity probe.
5. Heating and air-conditioning system usage 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.

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 ft^{2*} living area, 525 ft^2 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.
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 located 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 Dranger© 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, 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 Fig. 1b 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 times JD90048.4 and JD90049.45, and closed at times JD90048.83 and 90049.8.

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*Readers more familiar with metric units may use the factors at the end of this paper to convert to that system.

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's 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 achieve a new steady state must be of the order of 2 or 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 there are natural variations in the building's behavior which 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 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 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 is 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 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.

Another consequence of a reduction in basement radon entry rate is an increase in subslab and basement radon levels. This is indeed observed, as shown in Fig. 3, 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 clearly present. The expected magnitude of the increase in subslab radon levels is not obvious, since it would depend on the details of 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 change 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, and results are illustrated in Fig. 4, 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. The doubling of the air exchange rate corresponds to a ventilation rate of 115 cfm, very 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 level homes 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 radon entry rates can be calculated. The two zone system of flows and tracer concentrations is illustrated in Fig. 5. 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.

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

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

The second method [11] is to assume that the tracer gas and radon behave in the same fashion once they enter the house, so that 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:

$$S_{11}/C_{11} = S_{1Rn}/C_{1Rn} \tag{3}$$

Results of the entry rate calculation using Eq. 3 are shown in Fig. 6. 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 different methods for calculating the entry rate are compared in Fig. 7. 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 [12]. There is, nonetheless, general agreement between the two methods. The computation using the interzonal flows always yields a lower entry rate than the other 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. It is found that 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, approximately 20 μCi/h, predominates. This does add an extra complication to the use of natural ventilation as a mitigation strategy. It remains to be seen how widely this effect is observed.

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.

EXPERIMENTS IN RESEARCH HOUSE PU31.

Natural ventilation experiments have been conducted in research house PU31 over a complete seasonal cycle; that is, during the summer cooling season and the winter heating season. The results of these experiments are summarized for both.

Research house PU31 has the following characteristics:

SIZE: 1600 ft^2 living area, 1300 ft^2 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 1100 cfm attic fans, thermostatically controlled; insulated with 8 in. blown-in insulation.
FIREPLACES: Two: one in living room, one in kitchen.
HEATING SYSTEM: Central gas forced air heat, furnace located in basement.
COOLING SYSTEM: Central air conditioning.
RADON LEVEL: ~80 pCi/L in the basement.

Research house PU31 has been instrumented in a similar fashion to PU21, except that subslab and cinderblock wall radon are not measured, and the pressure field of the basement is measured at three heights on each basement wall and at three subslab locations.

Cooling Season Measurements

The summer season natural ventilation experiment was 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 could not be shut very tightly.)

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 2.2 ft^2) 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. 8 and 9. Basement radon levels are shown in Fig. 8; 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 are 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 depressurize the entire house, increasing the ventilation rate as well as the radon levels. Measurements of a typical differential pressure transducer are illustrated in Fig. 9 (positive pressure indicates that soil pressure is above that of the basement). The large peaks (~3 Pa) in soil/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 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 calculation of the radon entry rate are essential for a definitive evaluation of this problem.

The behavior of the basement air exchange rates and basement radon level is shown in Fig. 10; 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 for the building (with the attic fans thermostatically controlled) were about 0.3 ACH for the entire building with an average basement radon level of about 80 pCi/L.

With the basement windows opened, the building air exchange rate increases by about a factor of 2, to 0.6 ACH. Basement radon levels decrease to about 12 pCi/L, 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. The building air exchange rate dropped by about a factor of 2, while the basement radon level dropped by about 20%. 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 soil to basement pressure differential) is of prime importance in determining the radon level of this basement.

As for house PU21, the basement radon entry rate of house PU31 can be computed using the air infiltration and interzonal flow measurements. Results from this calculation using Eq. 3 are shown in Fig. 11. If the baseline house operation (Experiments 1-5 of Fig. 11) is compared to house operation with the attic fans off and the basement windows open (Experiments 7-8 of Fig. 11), radon entry rate decreased by about a factor of 7. For house operation with attic fans off and basement windows closed (Experiment 6) compared to that with the fans off and windows open (Experiments 7-8), the basement radon entry rate decreased by about a factor of 3. This demonstrates clearly that the radon entry rate decreases 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 (~62 pCi/L) was lower than the basement radon level (~80 pCi/L), as would be expected. However, with basement windows opened, the upstairs radon level (~25 pCi/L) was about 2.5 times higher than the basement radon level (~10 pCi/L) (see Fig. 12). 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.

Heating Season Measurements.

A series of measurements on natural basement ventilation were conducted in PU31 during the winter heating season; a temporary mitigation system was installed in the house in January 1990. This system was turned off and the vent pipe capped during the ventilation experiment.

Measurements to determine the house baseline operating conditions were begun in December 1990. Radon levels in the living area of 70 pCi/L were routinely found, and it was deemed advisable to install a temporary mitigation system immediately. This was done on January 5, 1990, and reduced upstairs radon levels to about 4 pCi/L. The mitigation system was turned off on JD90030 and an attempt made to measure another baseline point. Radon levels were about a factor of 2 less than those found in other baseline measurements (Compare Fig. 13, Experiment 1 with Experiment 5, 6, or 7.) It appears either that it takes several days for the house to return to its unmitigated operating point from the time when the mitigation system is turned off, or that this was an exceptional case, perhaps because of some other change in the house operating point. Since the building air exchange rate was 40% lower for this experiment than for other experiments with the windows closed in this series (see Fig. 13, Experiment 1 compared to Experiments 5,6,7), this change in the operating point certainly could explain much of the discrepancy. Experiment 1 is included for completeness, but the baseline experiments (windows closed) to which others will be compared (windows open) will be Experiments 5, 6, and 7.

Basement radon and building air exchange rate for PU31 are shown in Fig. 13 for the winter ventilation experiments. The baseline air exchange rate is about a factor of 2 larger than that found in the summer measurements (0.3 ACH, summer; 0.65 ACH, winter). This is due to the larger indoor/outdoor temperature differentials which occur in the winter. The air exchange rate doubles, from 0.65 to 1.2 ACH, when either one or two windows (2.2 ft^2 per window) are opened. Basement radon levels, also higher than the summer values, decreased by more than a factor of 10, from ~130 to ~12 pCi/L with the east and west windows open or with the west window open. The west window is just above the sump pump and ~10 ft away from installed instrumentation. It is not clear why the west window should be more effective in reducing basement (and upstairs) radon levels than the east window, but it may be that providing a pressure break immediately above the sump pump, which may be a strong source, is more efficient than locating the pressure break at a distance of 44 ft.

Basement and upstairs radon levels are shown in Fig. 14. Both are strongly reduced by natural basement ventilation, but the reduction in upstairs radon is about a factor of 2 less than that by which basement radon is reduced. This is to be expected when the radon source is located in the basement, and can be understood from the interzonal flow and infiltration and exfiltration measurements.

In contrast to the measurements made during the cooling season, there is no indication that upstairs radon levels are higher than basement radon levels with the basement windows open, and no indication of an entry path which bypasses the basement. It is not clear why this change has occurred.

The radon entry rate and basement radon levels are shown in Fig. 15 for the winter natural ventilation experiments. The first data point shows an anomalously low entry rate and radon level as discussed above. With either the east and west windows open or only the west window open, the radon entry rate is reduced by about a factor of 5, compared to with the windows closed. Note that, with only the east window open, the entry rate is approximately the same as when the windows are closed, although the radon levels are about a factor of 2 lower. This may be the result of an ineffective pressure break with only dilution reducing basement radon levels.

Thus, heating season natural ventilation experiments in PU31 indicate that radon in houses is reduced both by dilution and by the introduction of a pressure break when basement windows are opened. The factor by which radon levels are reduced is even larger in the winter than in the summer: basement radon levels are reduced from much higher winter levels to about the same value as in the summer measurements.

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 gas 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 about 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) heating oil costing $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.

Based on the results of these experiments, the following recommendations can be made:

1. Further experiments on natural ventilation should be undertaken in:
   a. Low radon 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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system.

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Conversion Factors

Readers more familiar with metric units may use the following factors to convert to that system.

Non-metric	Times	Yields Metric
cfm	0.00047	m^3/s
ft	0.30	m
ft^2	0.093	m^2
gal.	0.0038	m^3
in.	2.54	cm
pCi/L	37	Bq/m^3

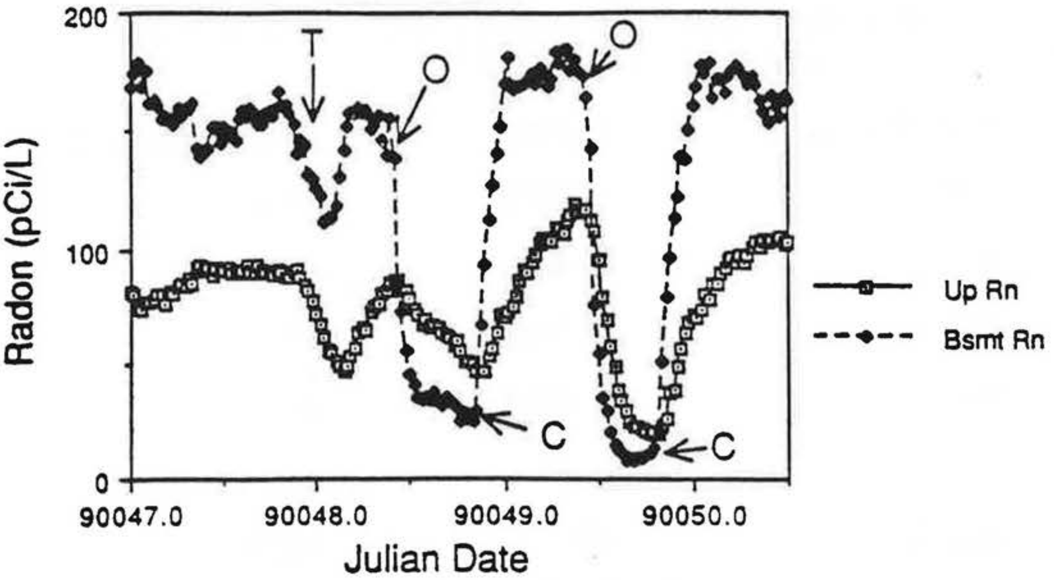


Figure 1a. Basement, Upstairs Radon Level vs Julian Date
Sequence of Window Open and Window Closed, PU21
O=Open; C=Closed; T= Temperature Spike

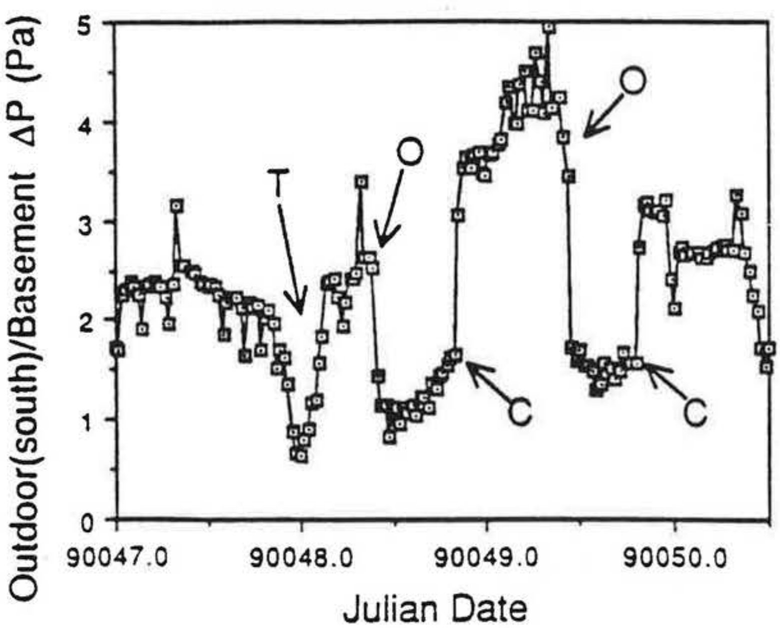


Figure 1b. Outdoor/Basement Pressure Differential vs Julian Date;
Sequence of Window Open and Window Closed, PU21
O=Open; C=Closed; T=Temperature Spike

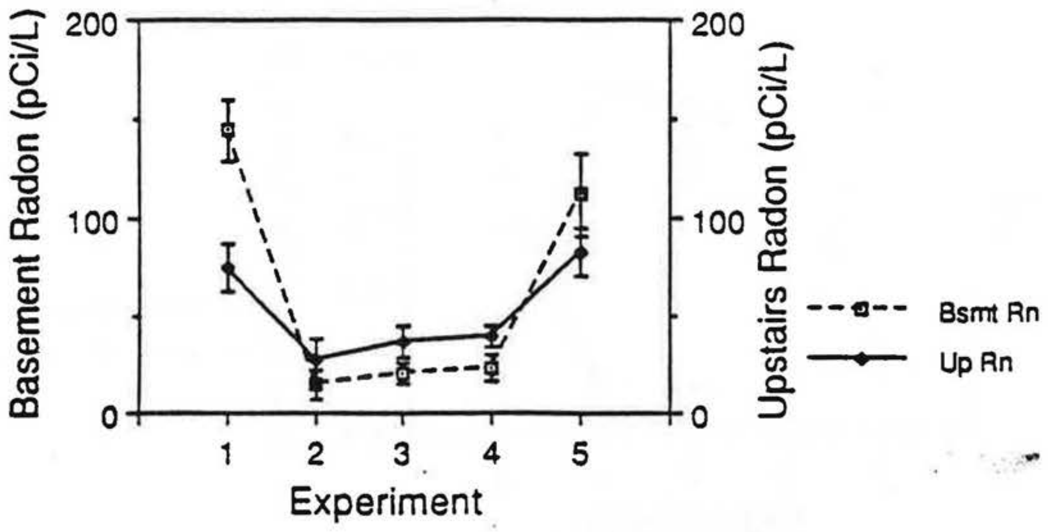


Figure 2. Basement, Upstairs Radon,PU21
Experiments 1,5 Window Closed;
Experiments 2,3,4 Window Open

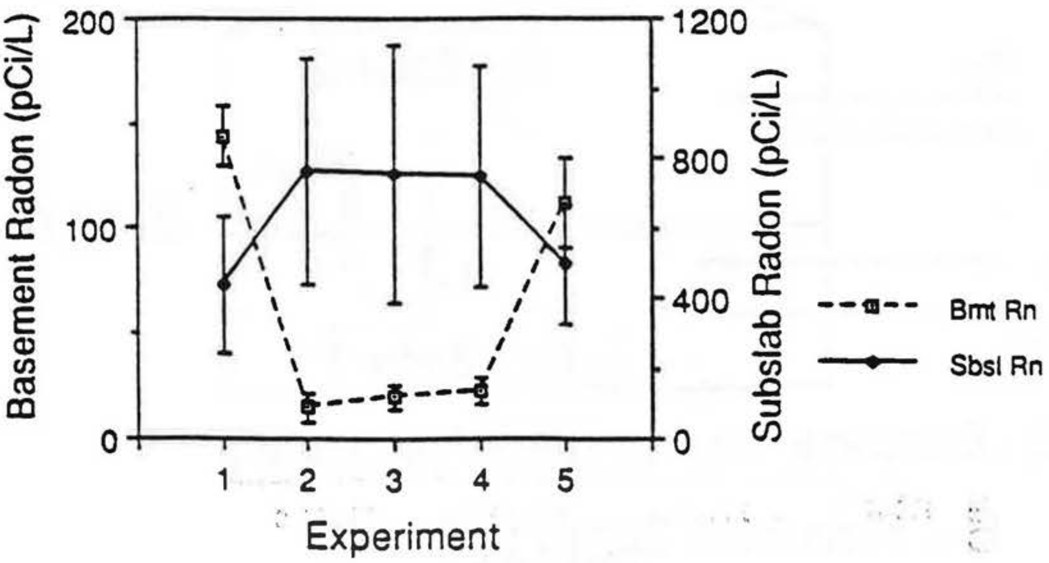


Figure 3. Basement, Subslab Radon PU21
Experiments 1,5 Window Closed;
Experiments 2,3,4 Window Open

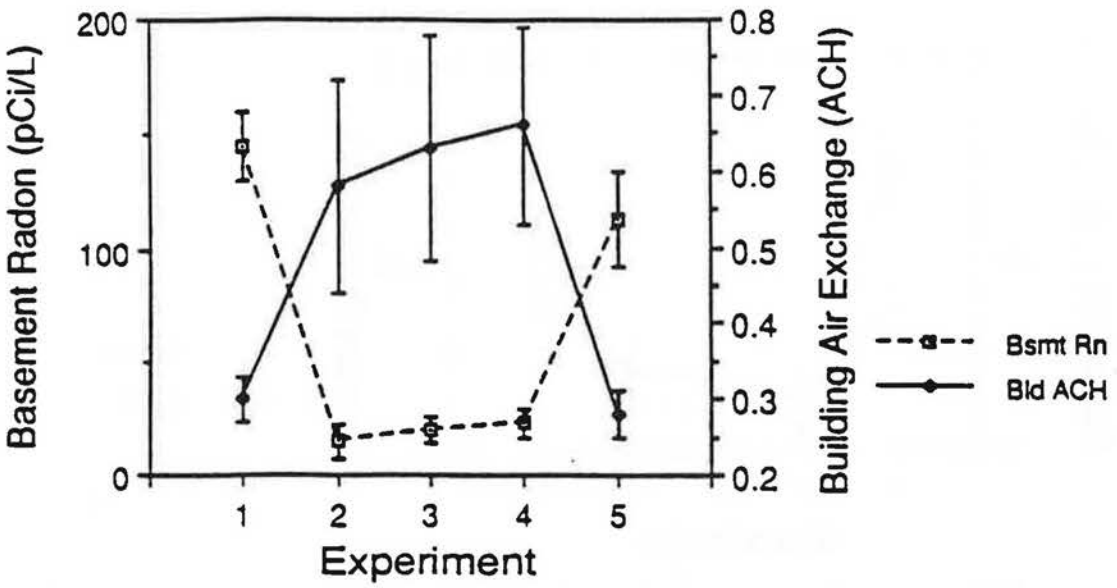
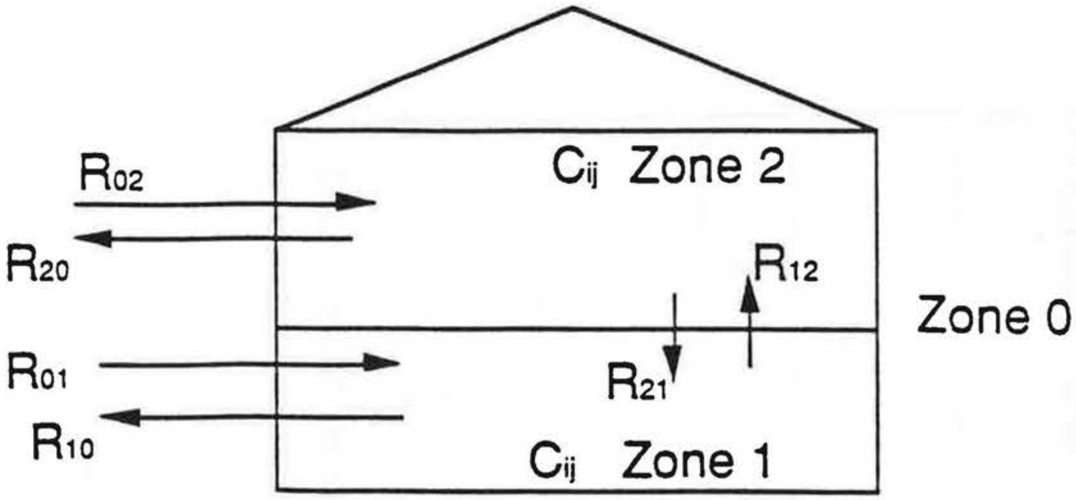


Figure 4. Building ACH, Basement Radon,PU21
Experiments 1,5 Window Open;
Experiments 2,3,4 Window Closed



C_{ij} = Concentration of Tracer i in Zone J

R_{ij} = Flow from Zone i to Zone j

Figure 5. Flows and Tracer Concentrations for Two Zones

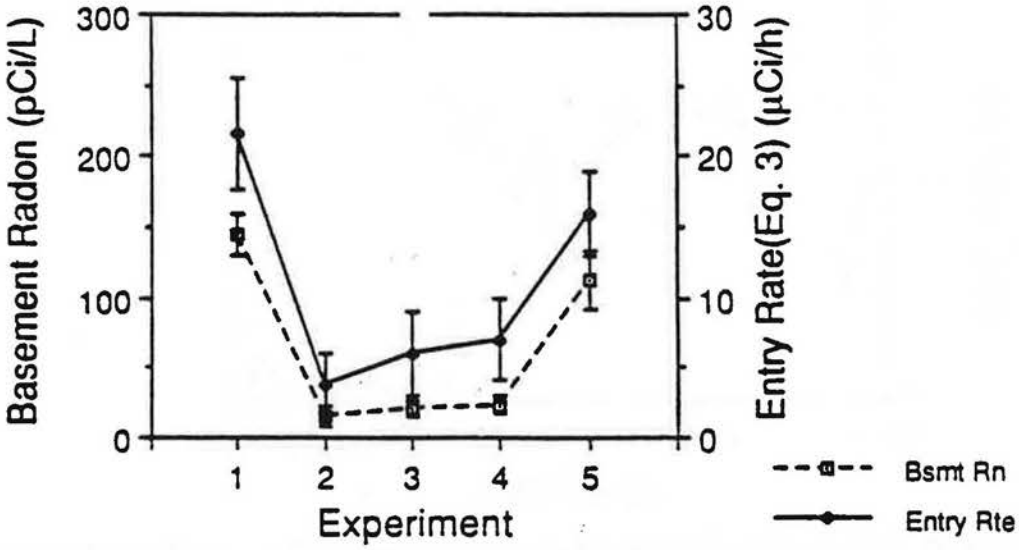


Figure 6. Basement Radon Entry Rate, Basement Radon,PU21
Experiments 1,5 Windows Closed;
Experiments 2,3,4 Windows Open

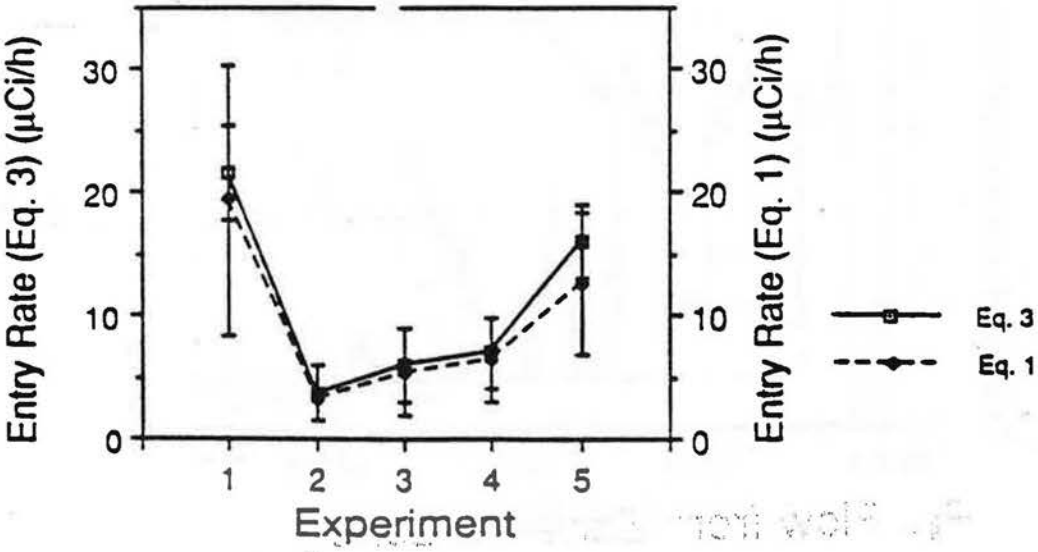


Figure 7. Entry Rate Calculations Compared, PU21
Experiments 1,5 Window Closed;
Experiments 2,3,4 Window Open

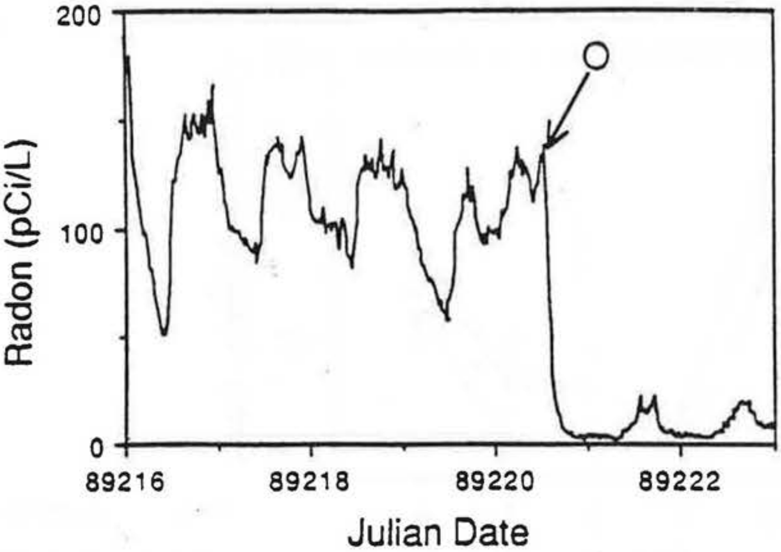


Figure 8. Basement Radon vs Julian Date, PU31. In This Experiment, Two Basement Windows Were Opened (O) at JD 89220.6.

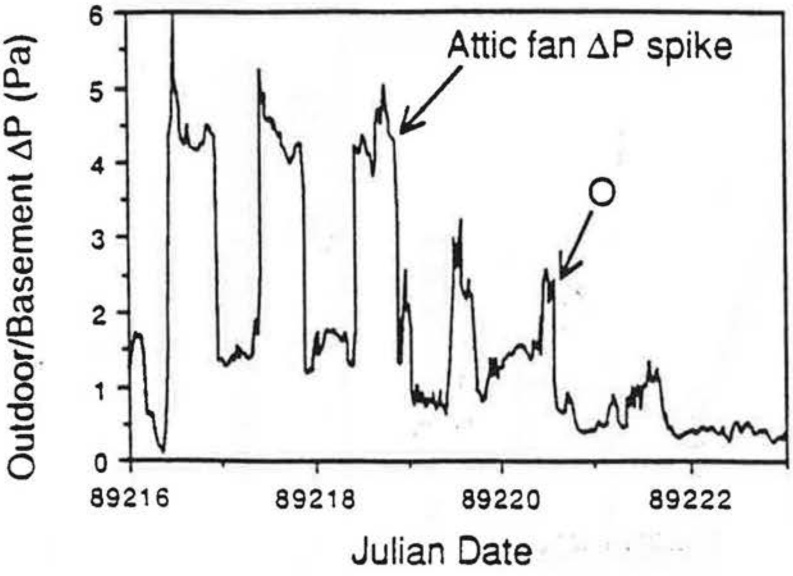


Figure 9. Outdoor/Basement Pressure Differential (ΔP) vs Julian Date. Basement Windows Opened (O) at JD 89220.6; Note Effect of Attic Fans.

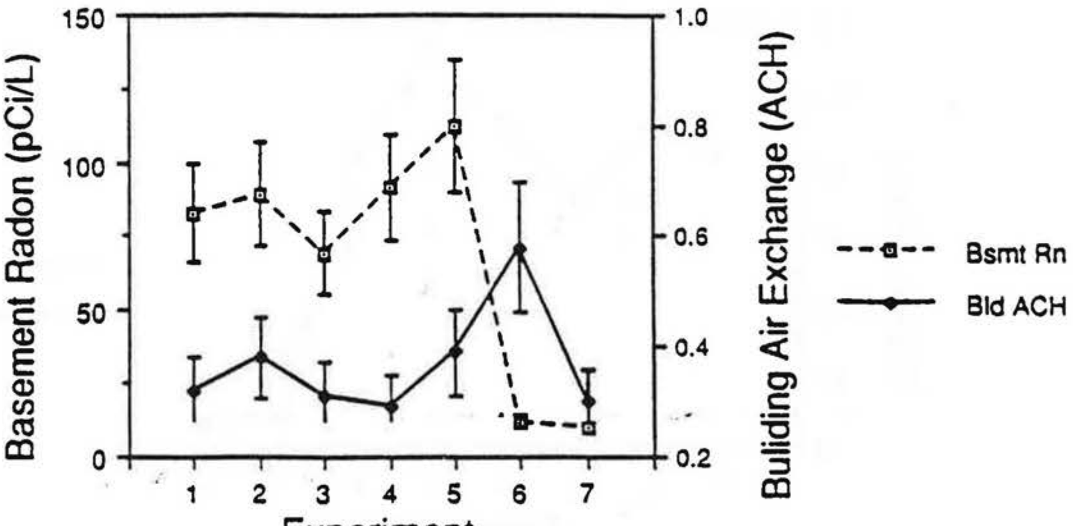


Figure 10. Basement Radon, Building Air Exchange , PU31 Summer
Experiments 1-5, Baseline (normal house operation)
Experiment 6, Windows Open, Fan On;
Experiment 7, Windows Open, Fan Off

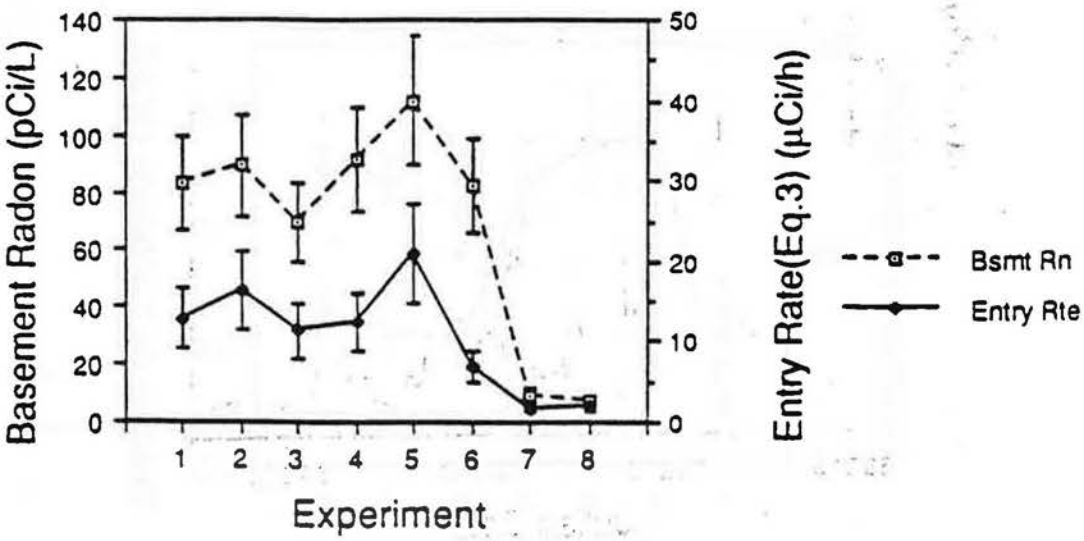


Figure 11. Basement Radon Level, Entry Rate; PU31 Summer
Experiments 1-5, Baseline (normal house operation);
Experiment 6, Windows Closed, Fan Off;
Experiments 7-8, Windows Open, Fan Off

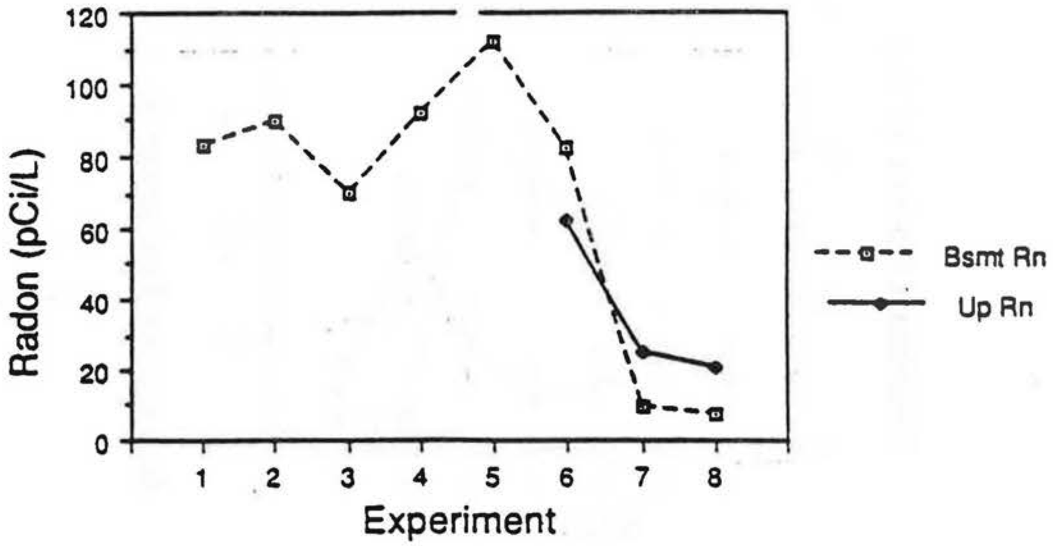


Figure 12. Basement, Upstairs Radon Level,PU31 Summer
Experiments 1-6, Baseline (normal house operation);
Experiments 7-8, Windows Open

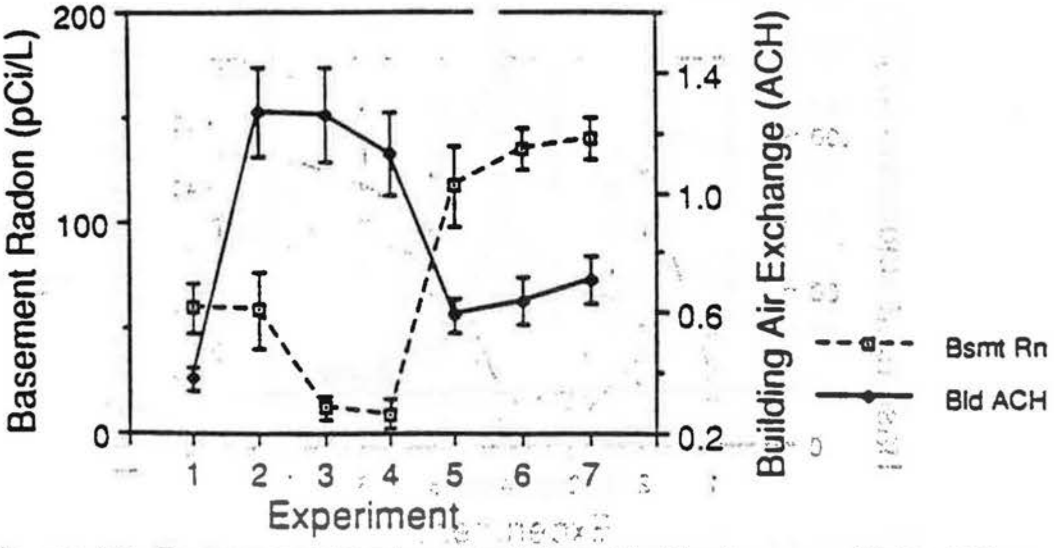


Figure 13. Basement Radon, Building Air Exchange, PU31 Winter
Experiments 1,5,6,7: Windows Closed;
Experiment 3: East and West Open;
Experiment 2: East Open;
Experiment 4: West Open

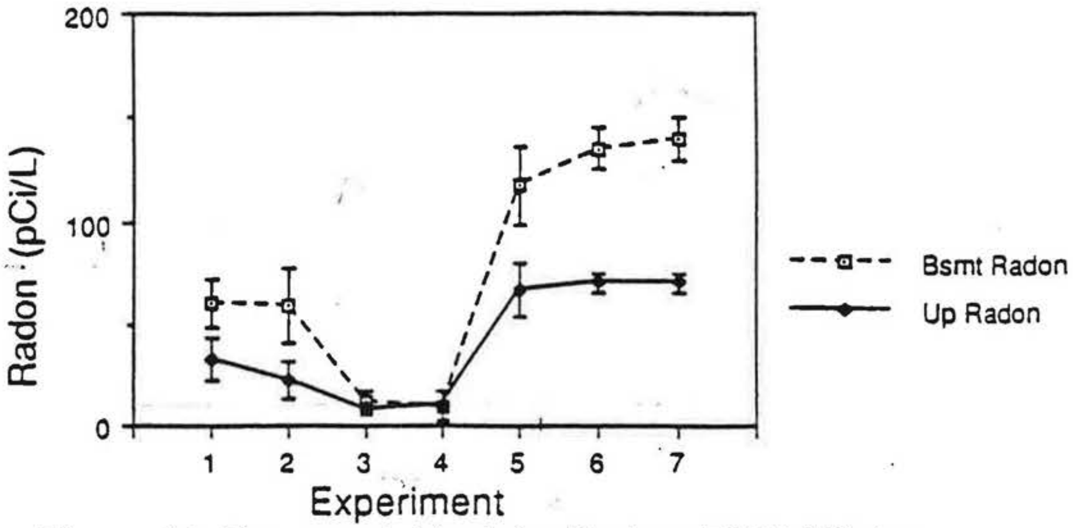


Figure 14. Basement, Upstairs Radon; PU31 Winter
Experiments 1,5,6,7: Windows Closed;
Experiment 3: East and West Open;
Experiment 2 :East Open;
Experiment 4: West Open

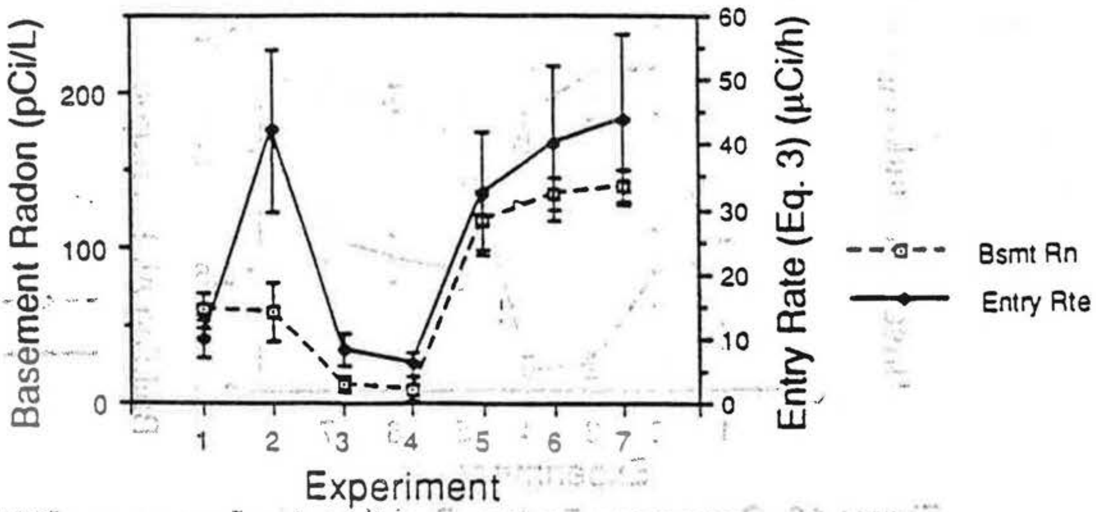


Figure 15. Basement Radon, Entry Rate PU31 Winter
Experiments 1,5,6,7: Windows Closed;
Experiment 3, East and West Open;
Experiment 2, East Open;
Experiment 4, West Open