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MEASUREMENTS IN EIGHT "RADON-RESISTANT" NEW HOUSES

Conrad Weiffenbach, Wisconsin Division of Public Health, Madison, Wisconsin
Clint Marshall, Dane County Health Department, Madison, Wisconsin

ABSTRACT

We have logged continuous radon, differential air pressures and other characteristics for eight houses built with radon-resistant features by Habitat for Humanity of Dane County. Pressures logged in the bases of the passive stacks were predominantly below basement air pressure, varying with time, while pressures in the sealed sump pits were above basement air pressure. Wind speed, wind direction and outdoor temperature affected the depressurization in the stack bases. With the stacks closed, the pressures in their bases increased to about 2 Pascals above basement air, and indoor radon increased by factors of 1.3 to 8 among the houses. In some houses, when appliance fans withdrawing air from the house envelope were operated, they pulled the basement air pressure below the pressure in the base of the stack, and bursts of indoor radon resulted. Basement radon averaged 1, 1.3, 2.6, 2.8, 3.8, 4.0, 4.0, and 12 pCi/L in winter in the eight houses. The latter house, which had poor sealing of basement floor-wall joints, was mitigated to 0.5 pCi/L with a 14-watt fan.

INTRODUCTION

Studies (Saum 1990; Dewey 1994; Lafollette 2001) of radon in homes constructed trying to meet recommended radon-resistant standards (EPA, 1994) indicate that, while capping the passive stacks almost always results in an increase of indoor radon, the radon levels with the stacks open are often not below 4 pCi/L. In this study we measured not only by how much the passive stacks reduced indoor radon, but under what conditions and by how much they depressurized in the bases of the passive stacks and in sealed sump pits.

Funded with a small grant from the National Environmental Health Association, the Dane County Health Department trained the construction managers of Dane County Habitat for Humanity (Habitat, 2003) to include radon-resistant construction in six houses they built in the year 2001. For 2002, Dane County Health continued working with Habitat, supported through the EPA State Indoor Radon Grant, and more houses were built with radon-resistant features.

METHODS

Construction and Inspection

The houses we have studied are all one story above an exposed basement, and have about 1,200 to 1,500 square feet of finished space. They have bathrooms, showers, and other finished rooms in their basements as well as main floors. Each basement was built with walls of poured concrete, a drain tile around the inside of the sub-floor region connected to a sealed sump pit, and six inches of clear stone (rounded river gravel 3/4-inch in diameter and larger) in which the PVC tee to a four-inch passive stack was set before the floor slab was poured.

Before six-mil plastic membranes were laid on the gravel and the floor slabs were poured, the houses were inspected by staff of the Dane County Health Department. The two open ends of the tees have slotted PVC fittings across them that keep gravel out, that also cut the opening area by about 50% and may restrict air flow into the stack, by how much compared to if the gravel fell into the tee not being clear. The ends of the tees do not have extensions of perforated pipe in the gravel that are recommended in the EPA Model Standards (EPA, 1994; EPA, 2001), and for that reason the impedance to air flow up the stacks may be higher than would be the case with extensions. In the various houses, the tees lie from four to fifteen feet away through gravel from the sump pits or the nearest of the perimeter drain tiles.

In each house, the passive stack is routed up through the house interior to pass through the roof near the peak. Some stacks have short forty-five degree sections, as indicated in Table 1. Each has room for a fan in the attic with an electrical junction box nearby. All floor-wall joints are sealed, and a submersible pump, plumbed with a flap valve in the pipe that expels water outdoors through the sill of the house, is installed in the sump pit, which is covered and sealed.

Two of the houses, identified as 'FAL' and 'CH' in the tables and graphs, are virtually identical in design and construction, built by the same crews and leaders, about 150 yards apart, one facing east and the other west, with their roof ridges running north-south. We made measurements in these identical houses simultaneously. Seven of the houses are in Madison, and the other, labeled 'BUR' in the tables and figures, is about 30 miles west of Madison.

Measurements

The radon results reported below are for measurements in unfinished basement rooms with continuous radon monitors. Results of a variety of other radon measurements with activated carbon detectors in different rooms and floors showed the types of variation expected, and are omitted here for simplicity.

The continuous radon monitors are custom diffusion scintillation cells, with photomultiplier tubes attached to Canberra model S-10 nuclear pulse-height analyzers, operated in a multichannel scaling mode, typically with dwell time one hour per channel.

The scintillation cells were machined from aluminum at the University of Wisconsin physics shop, then coated with silver-activated zinc-sulfide and assembled in Division of Public Health facilities. Their sensitivity is 1.2 counts per minute per pCi/L. They are calibrated annually at the Bowser-Morner Corp. radon chamber. Grab sample measurements of radon in sump pits and the bases of stacks were made with plastic scintillation cells, manufactured and calibrated in our facilities.

We measured differences in air pressure between the basements and the interiors of bases of the passive stacks, and between the basements and the interiors of sealed sump pits, using differential pressure transducers (Setra model 264), with DC voltage output to data loggers (Campbell models 21X and 23X). Tubing ran from a 1/8-inch hole through the base of a stack about four to six inches above the floor, to the transducer four feet above the floor, the other port of which was open to basement air. The range of the transducers was -62 to +62 Pascals (- to + ¼ inch water column). They were calibrated against an Infiltec digital micromanometer, and their zeros were checked during each house visit, typically once per week. Two transducers blew out from overpressure, one induced by us, the other by some unknown event while monitoring a house. Figure 1 shows the typically significant variation in differential pressure to the stack base during a series of measurements separated by five seconds for ten minutes. To represent a characteristic differential pressure for each hour, we programmed the Campbell data loggers to average one pressure measurement per minute over the hour.

We made measurements in the houses with the passive stacks capped and open, under closed-house conditions, in winter and spring, beginning within a few months of when the houses were first occupied. Some owners could only be persuaded to participate in the closed-stack phase of measurement for a few days, and one not at all. We were able to get two full weeks of closed stack data for three houses.

For the hourly history of wind speed, wind direction, barometric pressure and outdoor temperature, we used information from a log (www.anythingweather.com) on the internet for weather at the Dane County Airport, which is located one mile from the first three houses studied.

We used miniature Onset HOBO data loggers for recording some pressure transducer voltages, times of operation of appliance fans, indoor and outdoor temperatures, and the temperature profile across the inside of one stack.

RESULTS

Indoor radon with stacks capped and open

Graphs of some continuous radon data for times with stacks open and capped are shown in Figures 2 through 9. Figure 3 also indicates hourly data for speed and direction of the wind, rate of change in barometric pressure, and outside temperature. Most of that information has been suppressed in the other graphs. We have more open-stack data for the houses than are shown in the figures, up to a year for the two identical houses.

The increases in radon appeared within less than a day of the stacks being capped. For the exception, Figure 3, there is a possibility that windows were not kept closed as requested despite what the occupants reported. They only agreed to have the stack capped when they were going to be out of town, and they left town the day after we capped the stack.

Table 1 gives a summary of results for basement indoor radon measured with the continuous radon monitors, with the passive stacks capped and open. The radon in the unfinished basement rooms increased when the stacks were capped by a factor ranging from 1.3 to 8. The ratios in the fourth column of Table 1 indicate representative open-stack levels at times near when the stacks were capped, which for a couple of houses are different from the averages over longer time intervals (second column).

One house (BUR), having indoor radon 12 pCi/L with the stack open and 30 pCi/L with it closed, had a poor sealing job. Some kind of silicone or transparent sealant was smeared and peeling on the floor-wall joints and sump cover, completely unlike the sealant and workmanship in the other seven houses, which looked very good. In the BUR house, the sealant was applied at the bottom of base-plate 2x4s of the roughed-in finish walls in some places, indicating it may not have been applied at the slab-wall joint before they were installed. Installing a low-power fan (RP140, nominally 14 W) in the stack in the attic of that house reduced the basement radon to below one pCi/L.

Changing barometric pressure was strongly associated with fluctuations of indoor radon levels in some houses at the times we studied them. Figures 5, 7 and 8 (for the houses GWA, FAR and TRA) include a line indicating the rate of change in outdoor barometric pressure. (The zero for change in barometric pressure has been raised to 2 on the vertical axis, and the line goes above 2 proportional to the rate of *fall* in barometric pressure in an hour, and below 2 proportional to the rate of increase, with arbitrary normalization for best visualization.) Indoor radon can be seen to rise when barometric pressure falls, and fall when barometric pressure rises, in the data for GWA and FAR. The effect is less pronounced in the data for TRA and CH, and in the data for FAL (Figure 3), it can be seen that changing barometric pressure had virtually no influence on indoor radon, at the same times that it did seem to influence the radon in CH somewhat. In the other houses, the influence was less pronounced or minimal, and the line for change in barometric pressure is omitted their graphs for simplicity. No influence on indoor radon or depressurization from wind speed, wind direction and outdoor temperature could be noticed by examining the time series graphs directly.

Pressures in the bases of the passive stacks and in the sealed sump pits

The stack bases were depressurized relative to basement air in these houses almost all of the time (Figures 2 through 7.) This differential pressure (represented with the symbol dP, although we sometimes refer to it as simply pressure) helps to prevent flow of gasses high in radon from below the floor slab into the basement through any cracks and openings. The house MOR (Figure 9) was the exception, with stack pressure wavering above basement air pressure.

With the fourth house (FAR), we began logging pressures in sump pits. We found the sump pits were *pressurized* relative to basement air virtually all of the time (Figures 4 through 6, plus 8 and 9). Thus, while the passive stacks are depressurized in their bases, the depressurization does not reach the sump pits, nor (presumably) does it reach the perforated tiles around the interiors of the foundations, which are connected to the sump pits.

Grab samples of radon in the bases of the passive stacks and in sealed sump pits, taken after the stacks had been closed or open for a few days, are summarized in Table 2. They ranged from less than one hundred to seven hundred pCi/L, without a consistent pattern for the sump pit versus stack base, or for the stack being closed versus open. Dane County is in the zone with the highest radon potential, of three zones on the EPA's 1993 Map of Radon Zones (EPA, 1993a)

Dependence of stack depressurization on wind speed, wind direction, and outdoor temperature

Figure 10 shows the variation of hourly averaged depressurization at the stack base as a function of wind direction and wind speed, for the house CH. Note that with increasing wind speed, but only from westerly and easterly directions, the depressurization increases. The roof ridge of this house is oriented north–south, suggesting the variation in depressurization is a Bernoulli effect, most pronounced with winds perpendicular to the ridge of the roof. The indoor radon concentration, however, did not follow any pattern that we could associate with winds.

Figure 11 shows the data for only easterly and westerly winds, organized by wind speed, and by outdoor temperature within given wind-speed categories. Again we see an overall depressurization increase as wind speed increases, the trend being about one Pascal per mph increase in wind speed. Within given wind speeds, the depressurization tends to be greater for lower outdoor temperatures, by about one Pascal per degree Celsius.

Fluctuations in indoor radon at times of appliance fan operation

In the CH house, the pressure in the stack base was higher than basement air at brief times associated with radon spikes, as shown in Figure 2. Closer correlation in time between pressure and radon spikes is shown in Figure 12 with ten-minute data intervals.

By operating appliances fans (the powered-draft fan of the water heater, bathroom fans, clothes dryer fan, kitchen ceiling fan) that withdraw air from the house, we found they would cause this change in differential pressures, as shown in Figure 13. The results of a similar study of fan effects in FAL, the identical twin of CH, were virtually the same. Various fans changed the pressure by 8 to 12 Pascals, making air in the base of the stack (and presumably other sub-slab regions) positive, which would tend to drive radon into the house.

However, almost no events when the stack base went positive and radon increased are indicated in Figure 3 for the house FAL, 100 m away, with data recorded at the same time as Figure 2 for CH. The one exception, weakly evident in Figure 3, was at times of laundering clothes and use of the clothes dryer, Friday nights and Saturday mornings. The occupants of FAL volunteered that they didn't use bathroom or kitchen exhaust fans, preferring to retain the humidity from showers in their house during winter when the data shown was recorded. In contrast, the occupants in CH said (and we observed) that they used those fans quite frequently. In fact, much of the fan operation in Figure 13 was natural use by the occupants as we recorded that data at around 5 PM.

We used some Hobo data loggers to record the operating times and durations for the clothes dryer, the exhaust fan in the basement bathroom (with shower), and the water heater fan for eight days in July in the CH house. The data, presented in Figure 14, indicates a time pattern generally consistent with the pressure and radon spikes of Figure 2.

From the results for pressure versus fan operation (Figure 12), and fan throughputs estimated for typical such appliance fans, we estimated with blower door calculations that the ventilation rate of the CH and FAL houses was about 0.1 air change per hour.

The differences between CH and FAL, with regard to radon spikes driven by fans depressurizing the house envelope, may not be entirely attributable to occupant behavior. The water heater depressurized both houses similarly, and it surely was used in both houses with some frequency, but it had little or no effect in FAL. Moreover the clothes dryer had minimal effect on the radon in FAL, as indicated in the stack depressurization information in Figure 3 on Friday evening and Saturday when the occupants did their laundry.

Figure 13 also shows that operating the furnace forced air blower did not alter the stack-to-basement pressure. Although the furnace doesn't withdraw air from the envelope of the house, it has been suggested (Saum, 1990) that leakage in return air ducting in basements could cause a dynamic depressurization there when blowers are on. That was not found to be the case here.

Miscellaneous results

We experimented with a four-inch wind turbine on the stack of CH, one of the two identical houses, and left it in place for a period of several weeks. In comparison with data for the identical house measured at the same time, we found no changes in depressurization at the base of the stack and no changes in indoor radon associated with the wind turbine.

We hypothesized that there could be a simultaneous cold down-flow and warm up-flow of air in a passive stack, so we measured the temperature profile across the base of the stack in the GWA house on Feb. 25, when the temperature outside was about –14 C (10 F). We used a Hobo miniature temperature logger from Onset Corp., taking the thermistor on its fine wires outside of the logger. The technique was based on experimentation outside of the stack and preliminary runs inside the stack. We supported the thermistor on a very light plastic strip which we inserted through the 1/8-inch hole where the tube for pressure sensing had been inserted. We moved it, in half-inch steps, from the center of the stack out to the edge, waiting one minute at each position to include time for it to come to thermal equilibrium with air in the pipe. The temperature of air in the stack was about 60 F from the center out to the tube wall, providing no evidence for a cold current.

DISCUSSION

One can ask if the impedance to airflow under the slab might be a factor limiting the regions depressurized by the passive stacks in these houses. The passive stacks had only a PVC pipe tee in the gravel, with screens across open tee ends to keep gravel out, and were not connected to perforated pipe. One of the recommendations for radon-resistant construction (EPA 1994) is that a length of perforated pipe should be inserted horizontally into the tee embedded in the gravel before the slab is poured, to enhance the permeability beneath the slab. The passive stack in the MOR house had the least depressurization of the eight houses, and was the closest (four feet) to the sump and drain tile, and may have had the lowest connecting impedance. For whatever reasons, the stack base pressure wavered above zero relative to basement air for extended periods in this house, though it was lower than the sump pressure (Figure 9). The indoor radon for MOR averaged near 4 pCi/L and was not increased much by capping the stack. We may yet install a fan in that stack.

If a passive stack does not hold indoor radon below 4 pCi/L, the system with a low-power fan added (a 14 Watt fan in the BUR house) should cost the homeowner significantly less for operation than retrofit mitigation systems of houses not built as radon resistant. The operating costs of retrofit sub-slab depressurization have been estimated (EPA, 1993b) at $40 to $300 per year, for fans of 50 to 90 watts, which cause increased house ventilation rates of 5 to 80 cubic feet per minute. For radon-resistant construction, with the sealing of openings to soil that will be hidden behind finish walls and under showers and bathtubs, with good permeability to air flow under the slab, and with a 15 watt fan, operating costs should be at or below the lower end of this range. Radon resistant construction with a low-power fan in the stack can save homeowners $1,000 or more every ten years in operating costs, compared to retrofit mitigation of houses not built to radon-resistant standards.

CONCLUSIONS

While the passive stacks do depressurize some of the sub-slab region in these houses, the stacks do not depressurize the sump pits. With soil gas in the sump pits (and presumably in the drain tiles around the interiors of the foundations) at pressures higher than basement air, good sealing of joints and gaps to the soil during construction would seem to be the main feature holding the indoor radon low. However, the observation that capping the stacks led to increased radon for all houses suggests that the passive stacks must cause significant depressurization, or decrease in pressurization, at some important points of radon entry.

The tees at the bases of the passive stacks in these houses do not connect to extension perforated pipes in the sub-slab gravel, and we cannot conclude that the performance we measured represents systems built with such extensions on the tees.

The depressurization in the bases of passive stacks is affected by wind speed, wind direction, and indoor-outdoor temperature difference. Fans exhausting air from the house envelopes can overcome the few Pascals of depressurization from a passive stack, and resulted in significantly increased indoor radon in at least one, but not all, of the houses studied.

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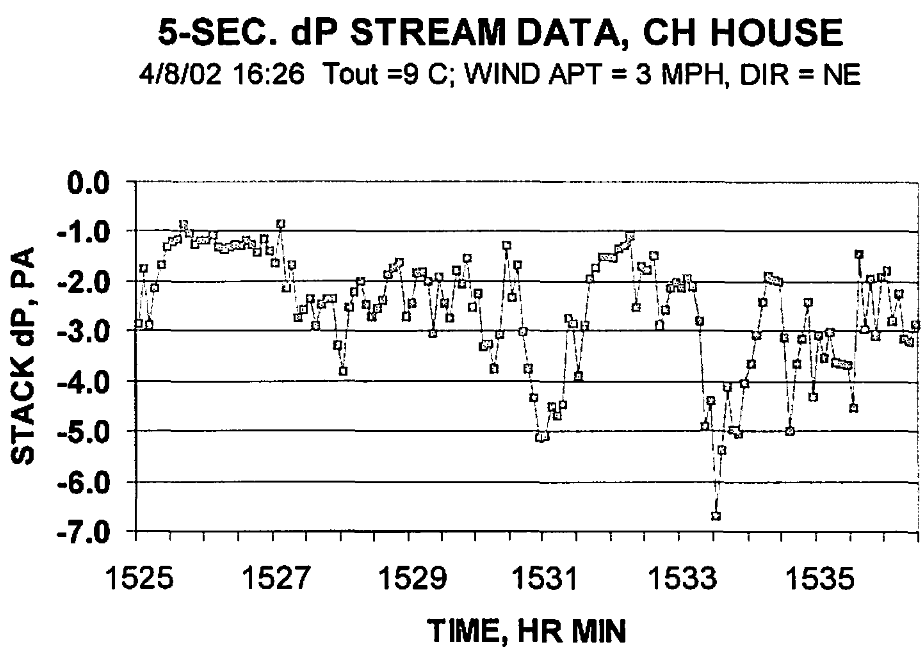

Figure 1. Depressurization in the base of a passive stack, measured in five-second intervals.

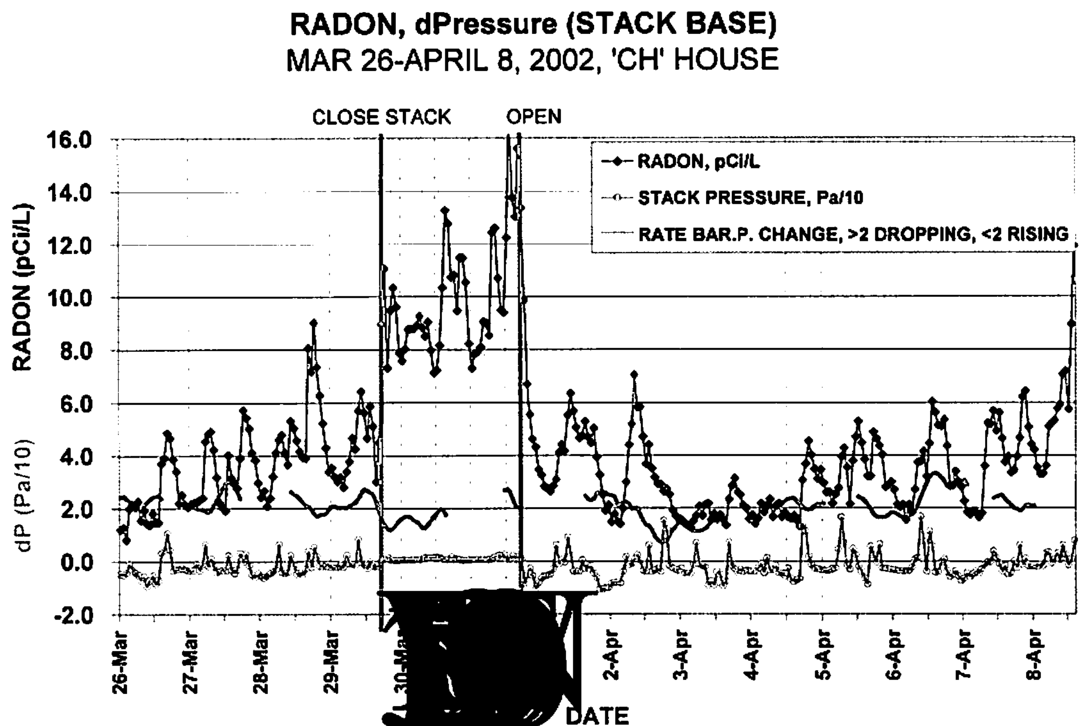

Figure 2. Some data for the house 'CH', taken at the same time as the data in the following figure for the nearly identical 'FAL' house

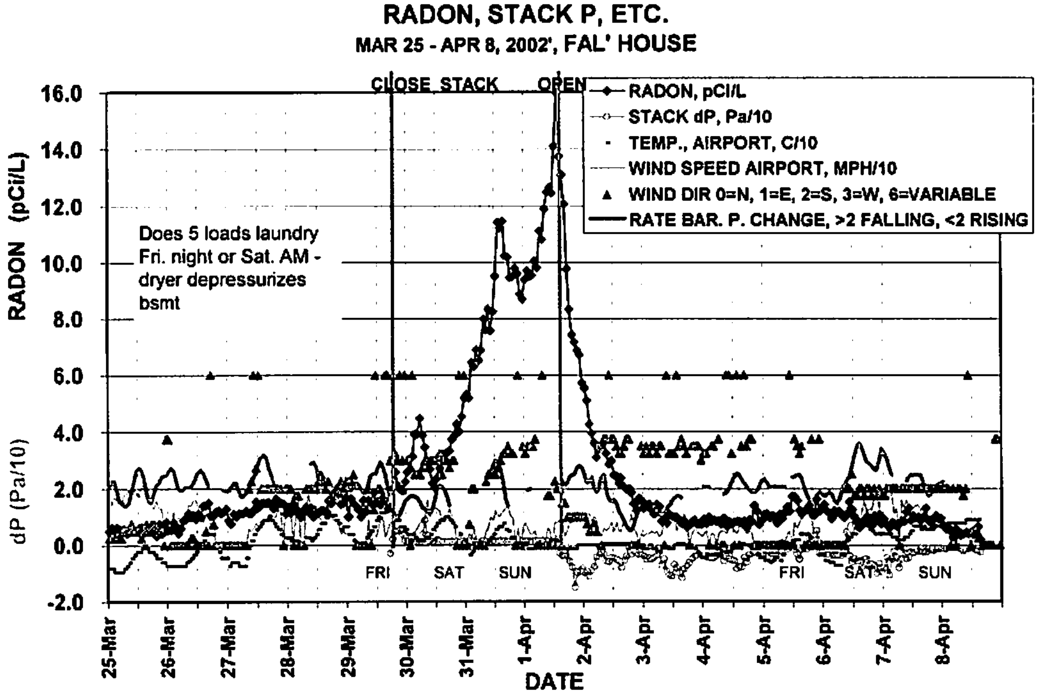

Figure 3. Some data for the house 'FAL', with information suppressed in other figures.

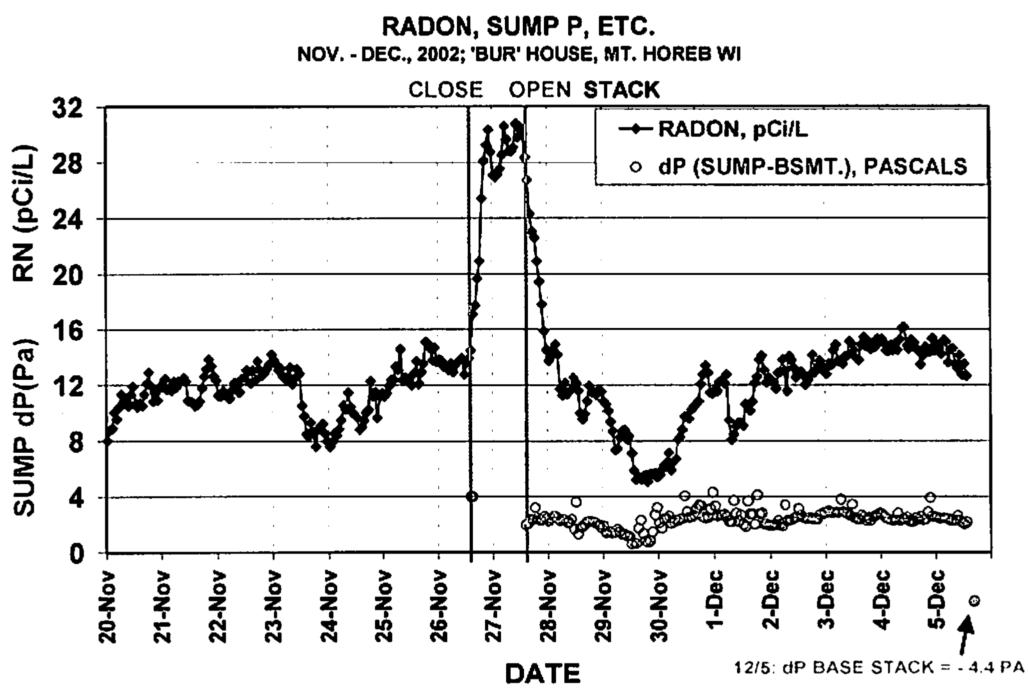

Figure 4. Some data for the house 'BUR', which had poor sealing.

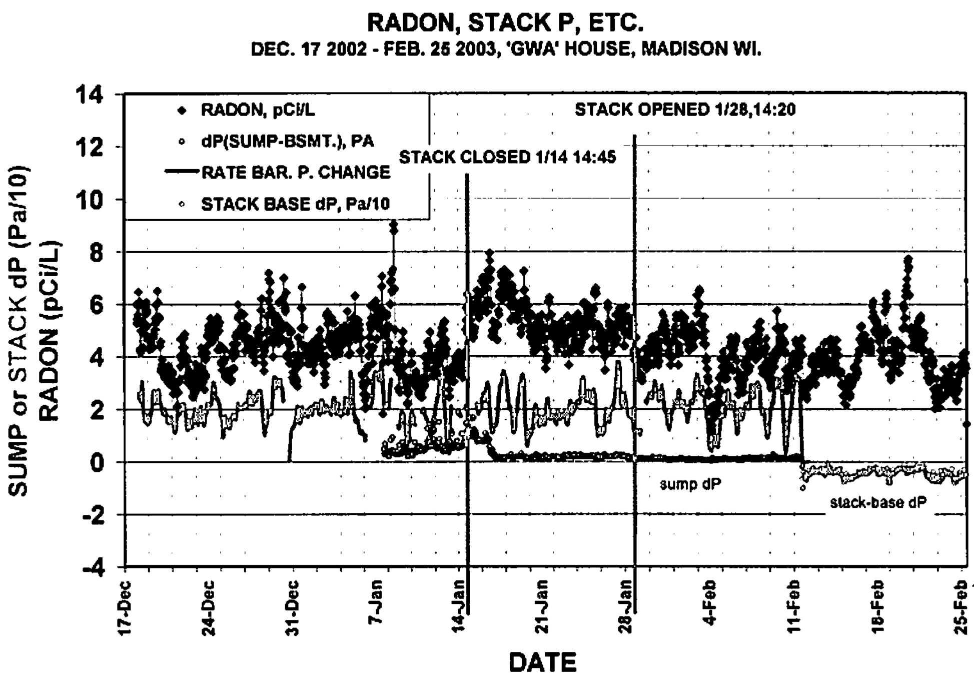

Figure 5. Some data for the house 'GWA'.

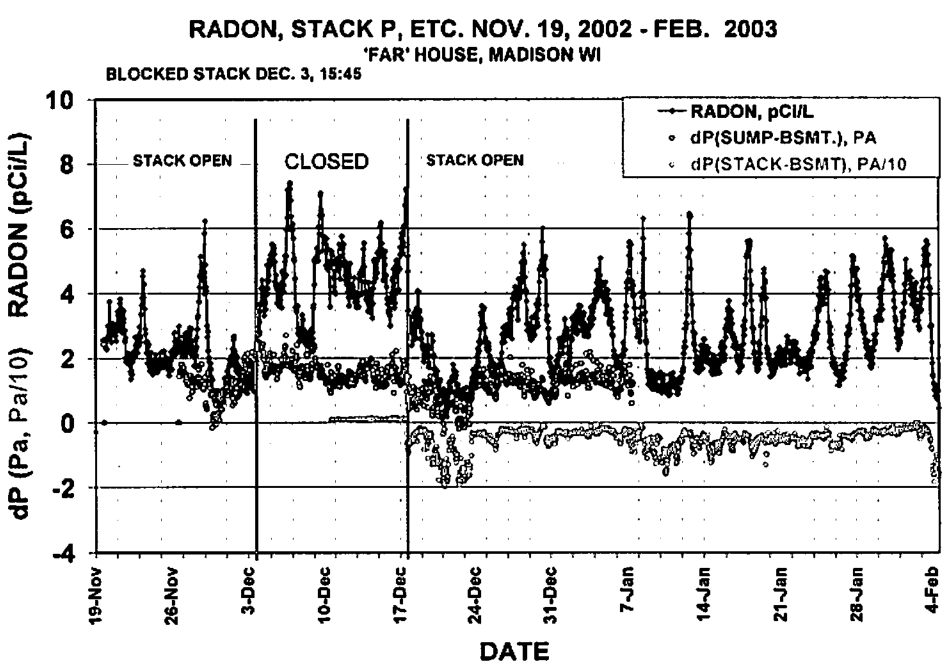

Figure 6. Some data for the house 'FAR'.

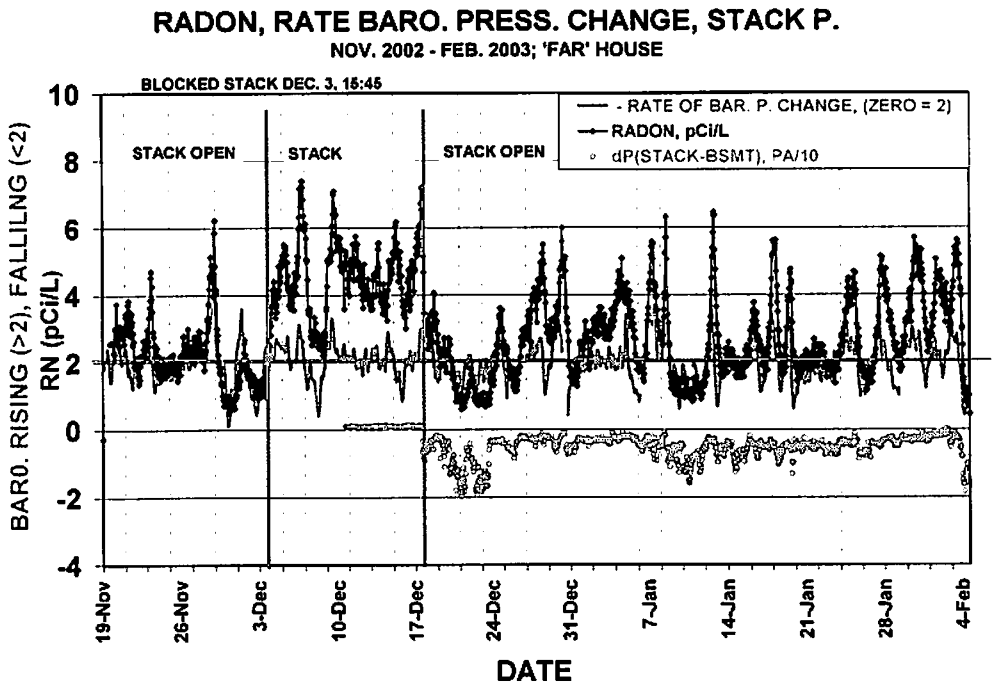

Figure 7. Figure 6 data and rate of change of barometric pressure; >2 falling, <2 rising.

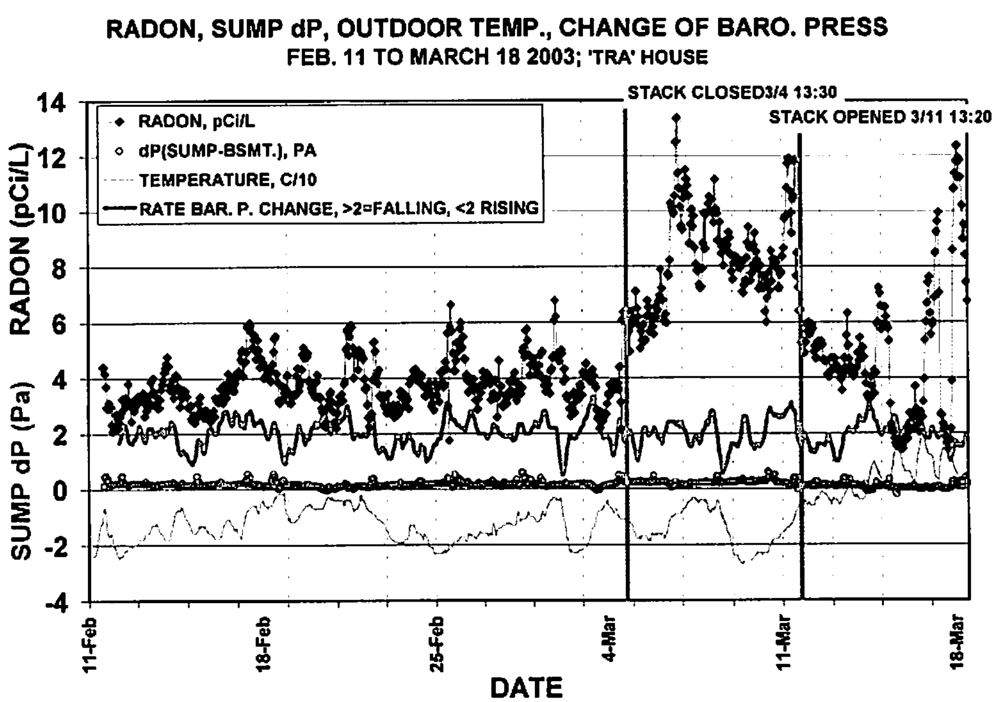

Figure 8. Some data for the house 'TRA'.

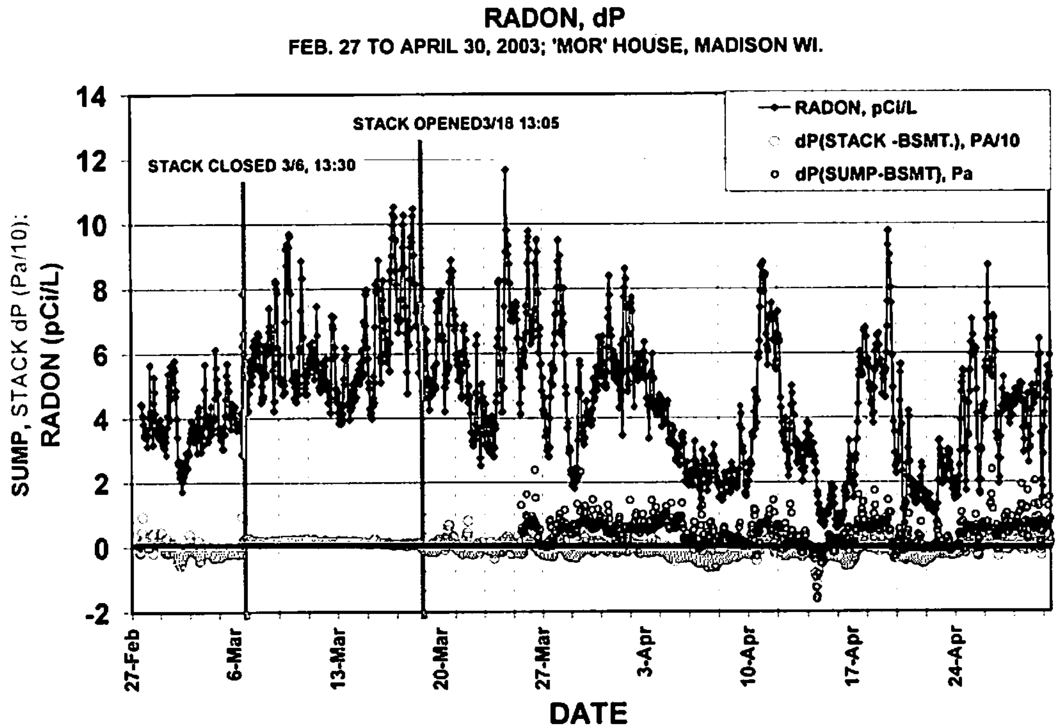

Figure 9. Some data for the house 'MOR'.

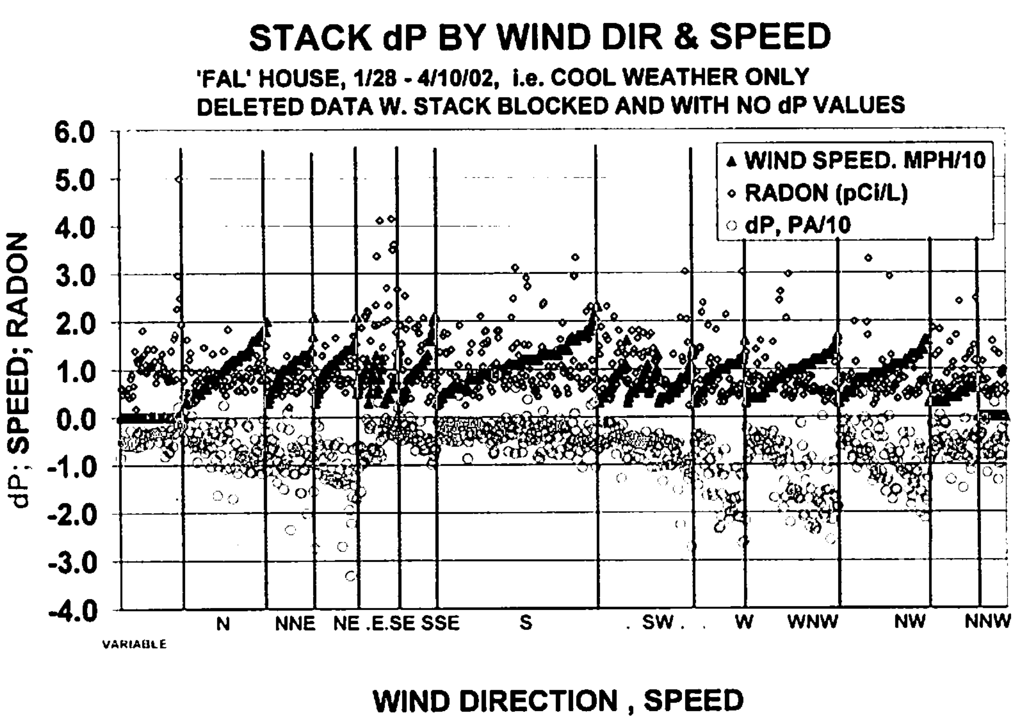

Figure 10. The effect of wind direction and wind speed on stack depressurization.

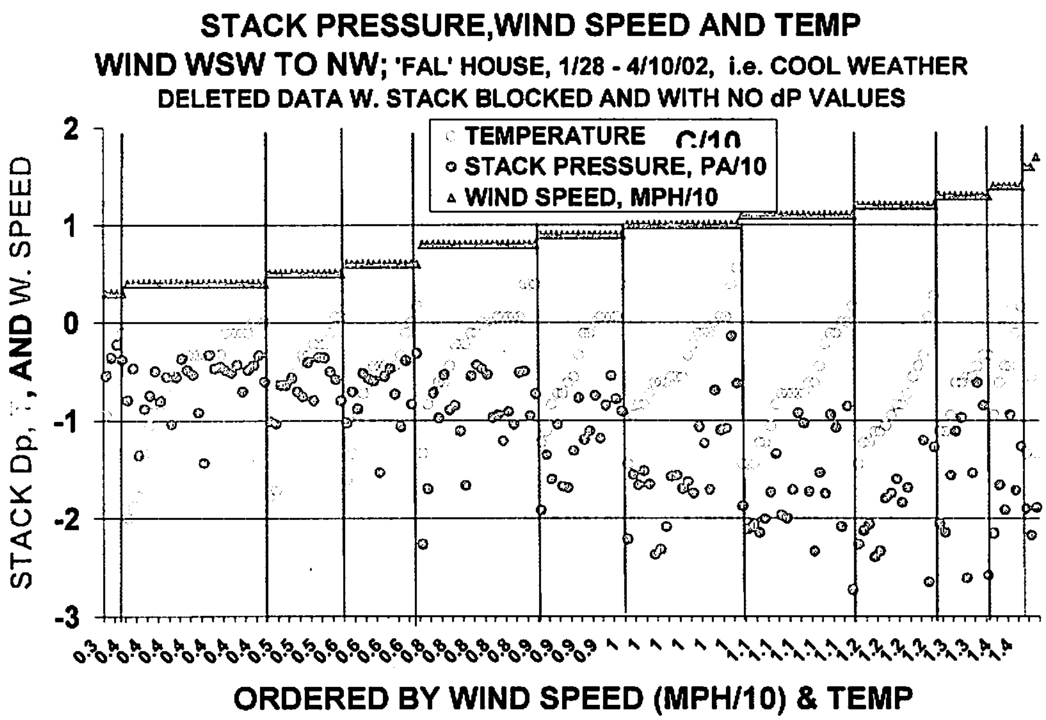

Figure 11. The effect of wind speed and outdoor temperature on stack depressurization .

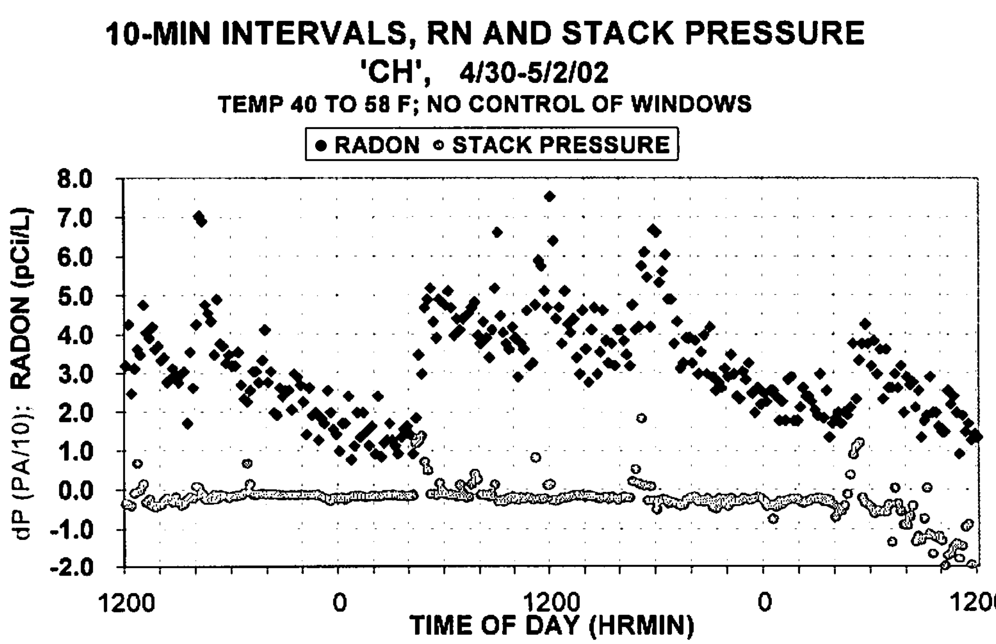

Figure 12. Radon entry at times of basement depressurization.

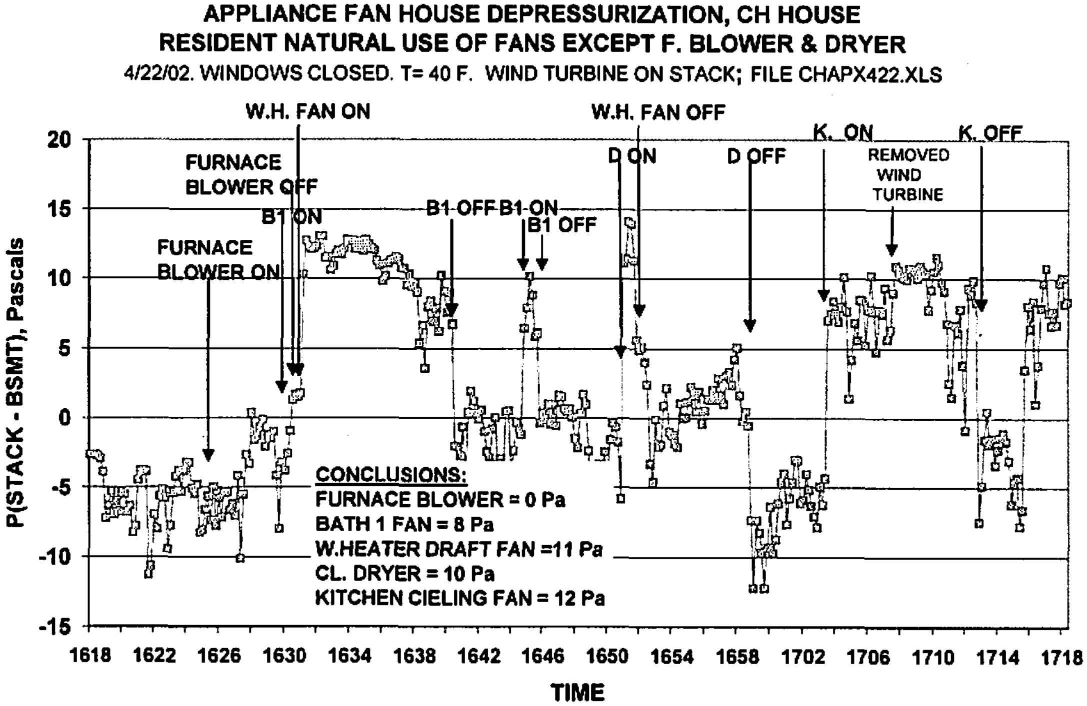

Figure 13. Pressure difference, stack base to basement, in fan depressurization tests.

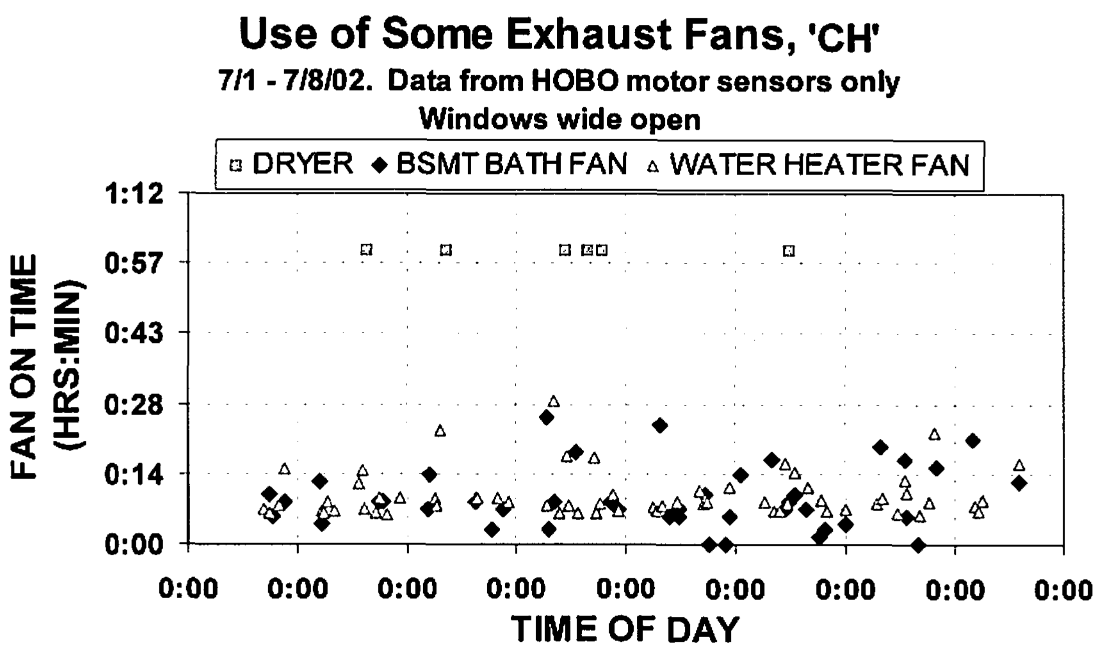

Figure 14. Times logged for occupant uses of three fans, 'CH' house.

Table 1. Summary, basement radon and comparisons of radon with stacks capped and open.

House code	Basement radon, pCi/L	Bsmt. radon, stack closed / stack open	Stack bends, #, deg.	Comments
HAR	1.3	-- / 1.3	2, 45°	Permission to close stack denied
FAL	1.0	13./ 1.5	2, 45°	FAL & CH are identical houses
CH	2.6	10./ 3.5	2, 45°	FAL & CH are identical houses
BUR	12.	29./ 12.	0	Reduced to 0.5 pCi/L w. 14 W fan
FAR	2.8	5.0/ 2.8	0	---
GWA	4.0	5.5/ 4.0	2, 45°	---
TRA	3.8	8.5/ 3.8	2, 45°	---
MOR	4.0	6.5/ 5.0	2, 45°	---

Table 2. Results of grab samples.

House code	Date	pCi/L, stack open		Date	pCi/L, stack closed	
		sump	stack base		sump	stack base
HAR	18-Feb-03	---	215	---	---	---
FAL	04-Mar-02	---	150	01-Apr-02	---	715, 780
CH	04-Mar-02	---	95	31-Mar-02	---	650, 670
BUR	05-Dec-02	257, 276	346, 382	---	---	---
FAR	03-Dec-02	38, 51	160, 168	10-Dec-02	262, 274	508, 524
GWA	14-Jan-03	230, 255	---	16-Jan-03	266, 292	---
TRA	04-Mar-03	48, 52	---	06-Mar-03	304, 324	---
MOR	06-Mar-03	260	125, 135	12-Mar-03	312, 295	65, 72