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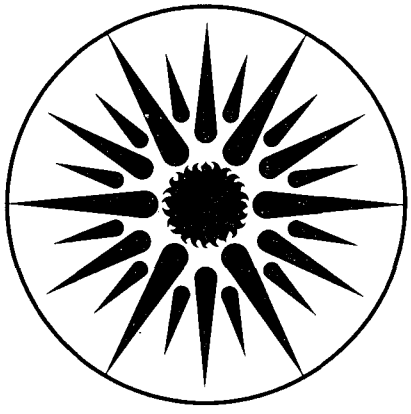

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CHARACTERIZING THE OCCURRENCE, SOURCES, AND VARIABILITY OF RADON IN PACIFIC NORTHWEST HOMES

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Abstract

A compilation of data from earlier studies of 172 homes in the Pacific Northwest indicated that approximately 65% of 46 homes in the Spokane River Valley/Rathdrum Prairie region of eastern Washington/northern Idaho had heating season indoor radon (^{222}Rn) concentrations above the U.S. EPA guideline of 148 Bq m^{-3} (4 pCi l^{-1}). A subset of 35 homes was selected for additional study. The primary source of indoor radon in the Spokane River Valley/Rathdrum Prairie was pressure-driven flow of soil gas containing moderate radon concentrations (geometric mean concentration of 16,000 Bq m^{-3}) from the highly permeable soils (geometric mean permeability of 5×10^{-11} m^2) surrounding the house substructures. Estimated soil gas entry rates ranged up to 39 m^3 h^{-1} and comprised up to 21% of total building air infiltration. Radon from other sources, including domestic water supplies and building materials was negligible. In high radon homes, winter indoor levels averaged 13 times higher than summer concentrations, while in low radon homes winter levels averaged only 2.5 times higher. Short-term variations in indoor radon were observed to be dependent upon indoor-outdoor temperature differences, wind speed, and operation of forced-air furnace fans. Forced-air furnace operation, along with leaky return ducts and plenums, and openings between the substructure and upper floors enhanced mixing of radon-laden substructure air throughout the rest of the building.

Introduction

During surveys of indoor pollutant concentrations and ventilation rates in Pacific Northwest buildings conducted between 1983 and 1986,[1,2,3] we discovered that indoor radon (^{222}Rn)* concentrations were frequently elevated in houses located in eastern Washington and northern Idaho.

In response to this discovery, a research project was initiated with the following two objectives: (1) investigate the causes of the high indoor radon levels, and (2) evaluate various techniques that would reduce those levels. This paper summarizes the survey data and presents results on the first project objective, while two companion papers [4,5] discuss the performance and long-term reliability of the radon control systems. Project results are provided in more detail by Turk *et al.*[6] and Prill *et al.*[7]

Study Design

House Participation

A total of 38 commercial buildings and 172 single-family residences participated in the original surveys. Sixty-nine of the residences were from eastern Washington and northern Idaho (clustered around Spokane and Coeur d'Alene), while 103 were from the milder, near-coastal region of Salem and Portland, Oregon, and Vancouver, Washington. Distributed between these two regions were 61 new homes -- some built to model energy conservation standards and others built with current construction practices; and 111 existing homes. Based on observed radon levels (see experimental section for measurement locations and times), diversity of construction type, and homeowner/occupant interest, a subset of 35 homes was selected for additional study. Fifteen of these homes were determined to be suitable for experimental installations of radon control systems and continuous monitoring instrumentation and had homeowners willing to participate. These 15 were classified as "high concentration" homes with winter indoor levels averaging greater than 260 Bq m^{-3} and a group geometric mean (GM) of 860 Bq m^{-3}.

* In this paper, radon refers only to the isotope ^{222}Rn. Thoron (^{220}Rn) was not measured.

Fourteen of the 15 "high" homes were located in eastern Washington and northern Idaho, while the remaining home was located in Vancouver, Washington and was the only entirely slab-on-grade structure. Two of the 14 houses were designated as "control" buildings: one in Post Falls, Idaho approximately 15 kilometers west of Coeur d'Alene; and the other in Veradale, Washington, approximately 15 kilometers east of Spokane. These two did not undergo any radon control until the conclusion of the project, so that seasonally-varying indoor radon concentrations and the effects of changing environmental conditions could be monitored.

The fifteen "high" houses ranged from two to 86 years of age and from 79 to 330 square meters (m^2) of occupied floor area in size. The substructure types represented were: three houses with finished, full-depth basements (approximately 1.5 to 2.0 meters below grade); two houses with half-depth basements (approximately 1.0 to 1.5 meters below grade); two houses with both half-depth and full-depth basements; five houses with a basement and adjoining crawlspace; and three houses with substructures that were either partially or exclusively slab-on-grade. None of the 15 had only a crawlspace. Perimeter basement walls were of poured concrete, except house ESP120* which had fieldstone and mortar walls and house NSP204 which had treated wood walls.

Ten homes had central forced-air electric furnaces located in a basement or crawlspace. One newer home with a forced-air furnace, NSP204, had been constructed with a central air-to-air heat exchanger in the crawlspace. Houses ESP101, ESP113, ESP120, and EVA604 had baseboard electric heating systems. As far as could be determined, none of the houses had drain tile beneath or surrounding the foundation, nor any evidence of water entry into the basement.

*The first letter of the three character house code determines whether the house was an existing "E" or new "N" structure, while the next two letters define the house location: CD = Coeur d'Alene, SP = Spokane, and VA = Vancouver.

The remaining 20 homes were classified as "low concentration" homes with winter indoor levels averaging less than 240 Bq m^{-3} and a group GM of 67 Bq m^{-3} and were less intensively monitored. Sixteen of these "low" homes were located in eastern Washington and northern Idaho. The other four were from the near-coastal region.

Experimental Procedures

Initial survey measurements of radon concentrations in the 172 houses were usually made with Terradex Type SF Track Etch® alpha track detectors. The alpha track detectors were either mailed to the occupants with detailed installation instructions or were put in place by technicians. From one to five indoor locations that were occupied (including some basements) were monitored and the data averaged for each house. The alpha track detector was placed on the lowest commonly occupied floor (generally one floor above the basement) in houses with a single measurement location. The indoor detectors were exposed for 21 to 70 days between October, 1984 and June, 1985. One detector was placed outside at each of the 61 newly-constructed houses and exposed for 55 to 70 days between March and June 1985. All detectors were either removed by technicians or the occupants. Recent determinations of the measurement uncertainty for the alpha track detectors have a very large range: from a bias of 0.91 with a coefficient of variation (CV) of 16%[8] to a bias of 1.32 with a CV of 59%.[9] Because of time constraints, sixteen homes in the Spokane/Coeur d'Alene area were surveyed in December, 1984 and January, 1985 by making 30-minute grab sample measurements with a continuous radon monitor. In 13 of these 16 homes, follow-up measurements using continuous monitors were made for an additional two weeks.

In the subset of 35 houses, different measurements were made that depended on the availability of equipment and instrumentation, geographic distribution, and access to the houses. These measurements were conducted during the summer of 1985 (between June and September). Water samples were collected at 33 houses, 19 that had municipal water supplies and 14 that had private wells. Soil samples were collected at

27 of the 35 houses. Radon emanation rates from building materials were measured at 11 houses: nine that had measurements made on both walls and floors, and two that had only floor measurements. Indoor air concentrations were monitored during the summer at 25 houses from the subset.

Water samples were collected from an outside faucet that was not conditioned or filtered upstream. To avoid aeration of the sample, two one-liter polyethylene bottles were slowly filled with a short tube directed to the bottom of the container. Within three days of collection, the bottled samples were analyzed for radon concentration by gamma spectrometry by placing the bottles directly on a 20 by 10 cm sodium iodide crystal. Measurements of radon-in-water had also been made at 16 of these houses during the previous winter and spring, using Terradex Type SW Track-Etch® alpha track cups placed on the bottoms of frequently-used toilet tanks.

As many as eight soil samples were collected from up to four locations at each of the 27 houses. A sliding hammer coring tool that collects "undisturbed" core samples 4.8 centimeter (cm) in diameter and 15 cm long in an aluminum sleeve was used for some samples. However, because much of the soil in eastern Washington and northern Idaho was rock-filled, many of the soil samples from that area had to be collected using a bucket auger. Sample depths ranged from 0.15 m to 1.8 m, but were typically from 0.5 to 0.8 m. These samples were then analyzed for emanating radium after being air-dried and placed in a sealed container with open charcoal adsorption canisters. The canister activity was then measured using gamma spectrometry. "Emanating radium" is the radium concentration in the soil multiplied by the emanating fraction -- that portion of radon that reaches pore spaces and is available for transport.

Building material radon flux rates were measured with shallow pans, 21.6 cm in diameter, that contained two or three activated charcoal adsorption canisters that had both faces open. The pan was attached with sealant to an uncracked wall or floor surface for 24 to 48 hours. On open soil floors, the pan was placed on the soil surface with the edges of the pan below the soil surface. The charcoal canisters were then

analyzed within three days for adsorbed radon using gamma spectrometry. Typically, measurements were made at two wall locations and one floor location in the 11 houses where these measurements were made.

Indoor air radon concentrations were measured between June and September, 1985 for periods between 65 and 115 days in 25 of the houses. Two Terradex Type SF Track-Etch® alpha track detectors were placed side-by-side for replication in an occupied first floor space. The detectors were deployed by technicians, but returned through the mail by the occupants.

A comprehensive instrumentation package was installed in each of the 15 "high" concentration homes starting in October, 1985. Data for indoor and outdoor temperatures, wind speed and direction, forced-air furnace fan operation, and inside-outside pressure differentials (at some houses) were sampled every 15 seconds and recorded as 30-minute averages on a data logger. Pulses from a continuous radon monitor (CRM) were accumulated and also recorded by the data logger at 30-minute intervals. This CRM continuously flows air through a chamber of sufficient path length to allow thoron (^{220}Rn) to decay before the air is filtered and then passed through a scintillation cell attached to a photomultiplier tube. At least one CRM was installed at each house to sample air from the first floor above grade that was frequently occupied. Additional CRM's for sampling air from crawlspaces and basements were available for only a few houses. The uncertainties in average concentrations measured with these CRM's are estimated at 10%. Independent, hourly meteorological observations for barometric pressure, precipitation, dry bulb temperature and wind speed and direction were obtained from the National Weather Service station at the Spokane airport.

Average ventilation rates were measured over approximately seven-day periods with a passive system from Brookhaven National Laboratory that employed constant emission of perfluorocarbon tracers (PFT) from permeation tubes and diffusion-controlled sampling.[10] PFT samplers and up to four different types of PFT sources

were placed at two to five locations in the houses and in unoccupied zones including basements and crawlspaces to measure zone flows and total ventilation. The PFT technique is estimated to underpredict actual ventilation rates by 20% to 30% with a measurement uncertainty of approximately 25%. During the periods of radon and ventilation monitoring, the occupants completed logs of daily activities in and near to their homes that might affect pollutant concentrations or ventilation rates.

At each of the 15 "high" houses, two pipe probes, 13 millimeter (mm) in outside diameter, were driven into the soil, following undersized pilot holes, to depths ranging from 1.0 to 1.5 m. These soil probes generally were located from one to seven meters in distance from the houses. Filtered soil gas grab samples were periodically collected from the soil probes into evacuated 100-cubic centimeter (cc) scintillation flasks. After the radon and its progeny reached radioactive equilibrium in three hours, the samples were analyzed for radon concentration on a portable photomuliplier tube counting station.

An *in situ* soil air permeability measurement was performed once on the soil probes at each of the 14 "high" houses in eastern Washington and northern Idaho. The measurement procedure was based on a device suggested by DSMA: a cylinder of compressed air is connected to a pipe via a pressure gauge and flow meter, and air is forced into the soil.[11] Permeability, k, is calculated, assuming Darcy's Law, from:

$$k = 2.5 \times 10^{-11} \, Q/rP \qquad (1)$$

where:
- k = air permeability (m^2),
- 2.5×10^{-11} = lumped constant (m^3-min-Pa-l^{-1}),
- Q = flow rate (l/min),
- r = inside radius of pipe probe (m), and
- P = pipe probe pressure (Pa).

Detection limits for the various components of this device restrict the range of measureable permeabilities from approximately 10^{-13} to 10^{-8} m^2. The uncertainty in these measurements is estimated to be 50%.

Results and Discussion

Initial Survey

Summarizing the radon data collected in the initial surveys, we find that the 103 homes in the near-coastal region of Portland and Salem, Oregon, and Vancouver, Washington, had a GM indoor concentration of 44 Bq m^{-3} (arithmetic mean of 63 Bq m^{-3}) with a GSD of 2.2 (Figure 1a). This contrasts with the data from the 69 new and existing homes in Spokane County, Washington, and Kootenai County, Idaho, that have a GM of 160 Bq m^{-3} (AM of 360 Bq m^{-3}) and a GSD of 3.4. See Figure 1b. A review of the data from Spokane and Kootenai counties reveals that 46 of the 69 residential buildings surveyed are located within the approximate boundaries of the Spokane River Valley (Washington) and the contiguous Rathdrum Prairie (Idaho) and have indoor radon concentrations that are substantially higher than the mean (Figure 1c). The large tail of Figure 1b is largely due to the presence of these homes in our measurement sample. The GM concentration for these 46 residences was 240 Bq m^{-3} (with a median of 220 Bq m^{-3} and an AM of 490 Bq m^{-3}), with a GSD of 3.1. Thirty, or 65%, of these residences had indoor radon concentrations above the U.S. Environmental Protection Agency (EPA) annual average guideline of 148 Bq m^{-3} (4 pCi l^{-1}).[12] Twenty-six, or 57%, had concentrations above the BPA mitigation action level of 185 Bq m^{-3} (5 pCi l^{-1}),[13] and twenty, or 44%, had concentrations above 296 Bq m^{-3} (8 pCi l^{-1}), the recommendation of the National Council on Radiation Protection and Measurements.[14] The comparison of these survey results to guidelines for annual average concentrations should be viewed with caution, since the survey results are based primarily on measurements during the heating season, when indoor radon concentrations are generally higher.

These survey results also contrast with those from other studies, such as the analysis of corrected annual average measurements in 817 U.S. residences by Nero *et al.*,[15] in which the data were approximated by a lognormal distribution with a GM of 33 Bq m^{-3} and a GSD of 2.8. Nero's data, if assumed to apply to the U.S. single-

family housing stock, suggest that approximately 7% of all U.S. single-family houses have radon concentrations above 148 Bq m^{-3}; six percent would be above 185 Bq m^{-3}; and approximately 2% would be above 296 Bq m^{-3}. In a three-month study by Thor[16] of 267 BPA employee houses in the Pacific Northwest, the resulting data, also approximated by a lognormal distribution, had a GM radon concentration of 30 Bq m^{-3} and a GSD of 2.5.

Soil as a Source of Radon

The Spokane River Valley and Rathdrum Prairie are generally made up of soils that are defined by the Soil Conservation Service (SCS) of the U.S. Department of Agriculture (USDA)[17,18] as excessively drained sandy and gravelly soils formed from the outwash of glacially-dammed Lake Missoula following the retreats of the Cordilleran ice-sheet, 18,000 to 30,000 years ago. Deposits are reported to be over 25 m in depth. Figure 2 shows Spokane and Kootenai Counties, the predominant soil associations of the Spokane River Valley and Rathdrum Prairie, and the approximate locations of 14 "high" houses. These soils typically have high water permeabilities (0.06 to greater than 0.25 mh^{-1}) and therefore will have high air permeabilities for soil gas movement.[19]

Most recent work indicates that the pressure-driven flow of soil gas containing radon is the dominant mechanism for radon entry into the majority of homes with elevated radon concentrations.[19,20,21] Therefore, our preliminary conclusion was that the highly permeable soils surrounding the house substructures in the Spokane River Valley/Rathdrum Prairie greatly enhanced soil gas mobility and were the main factor causing the elevated indoor radon levels in these homes.

Visual inspection indicated that the soils were loosely packed and likely to be highly permeable. Permeability measurements made at 24 soil probes at the 14 "high" houses in eastern Washington/northern Idaho ranged from 10^{-13} to 10^{-10} m^2 with a GM of 5×10^{-11} m^2 and a GSD of 4.9. These data are typical of soils categorized as gravelly and sandy.[22]

The emanating radium concentrations of the soil samples collected at each house were averaged and are summarized in Table I. The data are close to values for other typical soils (~9.3 Bq kg^{-1}) reported by Nazaroff *et al.*[19] but are somewhat lower than those measured by Moed *et al.*,[23] for other soils in the Spokane area (7.4 to 56 Bq kg^{-1}). The average emanating radium concentrations at house sites ranged from 4.4 Bq kg^{-1} (ESP111) to 8.8 Bq kg^{-1} (EVA604 in Vancouver) for the "high" houses, and from 5.0 Bq kg^{-1} (ESP112) to 17 Bq kg^{-1} (ECD152) for the "low" houses. We might expect the emanating radium concentrations to be only modestly higher if the samples were analyzed at the more moist field conditions.[19]

Using the emanating radium concentrations, the maximum concentration of radon in soil gas, C_∞, can be calculated, assuming large depths typical of basement floors, using the equation:

$$C_\infty = \rho e/\epsilon, \qquad (2)$$

where ρ, bulk soil density was taken to be 1.4×10^3 kg m^{-3}; e, emanating radium concentration from measured samples (Bq kg^{-1}); and, ϵ, soil porosity was assumed to be 0.4 m^3 (air) per m^3 (soil). These data are also summarized in Table I where it is apparent there is little difference between the two groups of homes. For the "high" houses, C_∞ ranged from 16,000 Bq m^{-3} to 31,000 Bq m^{-3}, and for the "low" houses from 18,000 Bq m^{-3} to 60,000 Bq m^{-3}.

Grab samples of soil gas from the soil probes were collected prior to the installation of any radon control equipment and were analyzed for radon concentrations. Average concentrations at 12 of the 15 "high" houses are shown in the last column of Table I. These measured concentrations are within 50% of the calculated maxima, C_∞, and also have a relatively small range: from a low mean of 10,000 Bq m^{-3} (ESP108C) to 25,000 Bq m^{-3} (ECD153). Measured concentrations may be lower than C_∞ because: 1) radon in the soil gas at the soil probe depth (1.0 to 1.5 m) may be depleted due to diffusion to the soil surface; 2) for probes near the house,

outside air is drawn into the soil by the depressurization or "pumping" action of the house that establishes a pressure gradient in the soil; or 3) the moisture content used in determining emanating radium concentrations, or the porosity and soil density used in calculating C_{∞}, do not correspond to actual field conditions.

Non-Soil Sources of Radon

To determine the approximate contribution of sources other than the soil to indoor radon levels, radon concentrations in the outdoor air and domestic water and radon emanation from building materials were measured.

Outdoor Air. Both the eastern Washington/northern Idaho and western Washington/Oregon regions had outdoor radon concentrations with a GM of 15 Bq m^{-3}; data from the eastern region had a GSD of 2.2; while data from the western region had a GSD of 2.0. Because of the low activity being measured, the measurement uncertainty is quite high: approximately 20% to 150% standard deviation. A small number of grab samples of outdoor air were collected with scintillation cells in December 1985 near houses ESP120 and NSP204. The radon concentrations in these samples were less than 19 Bq m^{-3}. These outdoor air concentrations were far below those encountered in houses with elevated radon levels and therefore outdoor air is not a major source.

Domestic Water. Four of the 15 "high" homes and ten of the 20 "low" homes used water from private wells. The 14 well-water samples had radon concentrations with a GM of 22,000 Bq m^{-3}-water, while the 19 municipal water samples had a GM of 19,000 Bq m^{-3}-water. In Table I, radon-in-water concentrations are compared for the "high" homes (GM of 21,000 Bq m^{-3}-water) and the "low" homes (19,000 Bq m^{-3}-water). Other than four extreme concentrations in well water (with a maximum of 300,000 Bq m^{-3}-water and a minimum of 1900 Bq m^{-3}-water), water concentrations show little variation, possibly because both municipal and private wells draw water from the same, or related, aquifers.

For 16 paired measurements of radon-in-water using gamma spectrometry and alpha track cups, the concentrations measured with the alpha track cups were generally lower (7000 Bq m^{-3}-water vs. 18,000 Bq m^{-3}-water). Possible explanations for the discrepancy include: long residence times and aeration of the water in the toilet tanks; inaccuracies in the measurements with the alpha track cups; or a seasonal difference in actual radon-in-water concentrations -- the alpha track cups were exposed in winter and spring and the grab samples were collected in summer.

Building Materials. The maximum emanation rates for the floors and walls of each house were averaged and are presented in Table I. Most rates fall within the range for earth-based construction materials cited by Nero and Nazaroff: 0.0009 Bq $m^{-2}s^{-1}$ to 0.0067 Bq $m^{-2}s^{-1}$.[24] Only one house, ECD027, had an excessively high flux (0.19 Bq $m^{-2}s^{-1}$) at one wall location, one meter below grade. This rate was only partially corroborated by the measurement at the other wall location (0.024 Bq $m^{-2}s^{-1}$). Construction materials were the same at both wall locations. The high rate may have resulted from a sampling error caused by a poor seal between the sampling pan and the very irregular surface of the hand-made basement wall. This poor seal could have allowed basement air with a high radon concentration to leak into the pan or could have coupled the inside of the pan to negative basement pressures thereby drawing soil air with high radon concentrations through the porous wall and into the pan to contaminate the exposed charcoal. However, it is possible that there is significant radium in the materials of this wall that includes local field stone. A flux of 0.12 Bq $m^{-2}s^{-1}$ was measured on the open soil floor and compares with the flux measured in an unpaved crawlspace (0.27 Bq $m^{-2}s^{-1}$) by Rondo *et al.*[25]

Discussion of Source Contributions

Using the available data collected on the various sources of radon, we estimated the contribution to the winter season indoor radon levels for the 15 "high" homes. These estimates are presented in Table II.

With unusually high concentrations of radon-in-water, sufficient radon may come out of solution during indoor water use (showers, dish washing, etc.) to cause significant increases in the indoor air concentration. Researchers have estimated that 370,000 Bq m^{-3}-water of radon yields an average of 37 Bq m^{-3} of radon in indoor air.[26,27] The relationship for a particular house depends on the house ventilation rate, building volume, water usage, and the device-dependent release rate of radon from the water. The air-to-water ratio of 1 to 10,000 was used to estimate the contribution of water sources to indoor air radon levels in 13 of the 15 "high" homes. The estimates shown in column eight of Table II are always less than 11 Bq m^{-3}-air (in house ECD027 where radon-in-water concentrations were 110,000 Bq m^{-3}-water) and are never a significant fraction of the measured indoor air levels. This is not surprising, since we saw in Table I that radon-in-water concentrations were similar for both "low" and "high" homes. Only in one "low" level house, ECD146, could the water from a private well with a radon concentration of 300,000 Bq m^{-3}-water have accounted entirely for the indoor air radon concentrations of 37 Bq m^{-3} during the heating season.

To date, relatively few homes have been identified with indoor air radon problems resulting from building materials contaminated with radium. The notable exceptions have occurred in areas where high-radium mine wastes or slags were used as aggregates.[28,29] To estimate the contribution from building materials in six of the "high" homes in this study, we used the following steady-state concentration model for a single, well-mixed zone with radon concentrations in outdoor assumed to be zero:

$$C = \frac{S/V}{\lambda}, \qquad (3)$$

where: C = predicted, steady-state, indoor air concentration (Bq m^{-3}),

λ = ventilation rate, air changes per hour (h^{-1}),

V = building volume (m^3), and

$$S = JA \qquad (4)$$

where: S = radon source or entry rate (Bq h^{-1}),

J = material emanation rate (Bq $m^{-2}h^{-1}$), and

A = surface area of material (m^2).

The results are shown in column seven of Table II. Once again, the contributions to the indoor air levels are very small as was suggested by the comparable emanation rate data for "low" and "high" homes in Table I.

Based on this assessment, we conclude that the predominant source of radon for these "high" houses is the soil surrounding the building substructure. The amount of radon that is available for transport in the soil (emanating fraction) depends on soil moisture and the size distribution of soil grains. Once in the soil pore space, radon can move by diffusion, which is influenced by soil porosity, moisture content, and the concentration gradient; and by bulk flow of soil gas, which depends on soil air permeability and the applied pressure field. These factors are, in turn, affected by other environmental parameters including precipitation, air and soil temperatures, and wind speed; by house operating parameters such as indoor air temperature and mechanical systems operation; and by house structural characteristics such as air leakage area of the shell above and below grade. Of the two migration processes, convective flow of radon-bearing soil gas through cracks, penetrations, and open areas in the substructure surfaces has been found to be the most important entry mechanism for the majority of houses with elevated radon levels.[19,20,21]

The convective flow of soil gas containing radon is driven by a slight depressurization within the substructure relative to the surrounding soil. The persistent negative pressures in the substructure are caused, in part, by temperature differences between the warm indoor and the colder outdoor air that create a "stack effect" that "pumps" air and soil gas into the lower levels of the house and exhausts it near to the top. With other factors remaining constant, larger indoor-outdoor temperature differences (ΔT) cause substructure pressures to be more negative relative to the soil:

Aggravating this depressurization are leaky forced-air furnace ducts and return air plenums in the substructure; exhaust fans in kitchens, bathrooms, and clothes dryers; vented combustion devices (furnaces, fireplaces, and woodstoves); and wind interacting with the complex distribution of structural air leakage area.

Since the soil gas radon concentrations are not excessive and are comparable in the "low" and "high" homes, high indoor radon concentrations must require good coupling of the house to the soil, resulting from sufficient substructure leakage area and high soil air permeabilities. Sizable quantities of soil gas must be entering these buildings to account for the indoor radon concentrations observed during the winter season in the "high" homes. Soil gas entry rates for each of the 15 "high" homes were estimated from a steady-state mass balance:

$$Q = \frac{C_w \lambda V}{C_\infty} \qquad (5)$$

where: Q = soil gas entry rate ($m^3 h^{-1}$), and
C_w = steady-state, winter season, average indoor radon concentration (Bq m^{-3}).

Contributions from water and building material emanation were neglected because they were negligible. Results are tabulated in column seven of Table II. The very high soil gas entry rates for some of the houses can be related to construction features of the substructures: ECD027 has a basement with a soil floor; NCD077, ESP119, and NSP204 have basements plus adjoining crawlspaces with loosely fitting plastic over soil floors; ESP111 has many webbing cracks in the slab floor; and ESP120 has foundation wall constructed of fieldstone and mortar. The soil gas entry rates for the other houses (except EVA604) are still higher than the 1 $m^3 h^{-1}$ calculated by other researchers for houses in less permeable soils.[11,30] Fisk and Mowris have calculated a range of winter average soil gas entry rates for a representative Spokane house with a 2-mm wall/floor gap to be 0.18 $m^3 h^{-1}$ to 1.8 $m^3 h^{-1}$ for soil permeabilities of 10^{-11} m^2 and 10^{-10} m^2, respectively.[31] For ESP108C, Mowris assumed a 5-mm wall/floor gap and predicted soil gas entry rates of from approximately 4$m^3 h^{-1}$, at a ΔT of 18 °C, to 6 $m^3 h^{-1}$, at a

ΔT of 34 °C.[32]

In column ten of Table II, we see that the soil gas entry may be a significant portion of the infiltrating ventilation air. For example, in house ESP120, with a building volume of 487 m^3, the soil gas entry rate is approximately 21% of the infiltrating air. Additional evidence for the good coupling of the substructure to the soil at ESP120 is that approximately 80% of the air exhausted from a subsurface ventilation radon control system originated in the basement.[4]

Spatial and Temporal Variations in Indoor Radon

In those 15 homes where continuous monitoring and periodic measurements were conducted, it is possible to briefly examine the response and relationship of indoor radon concentrations to other factors. Some of these factors vary over time, while others depend on location within the building.

Indoor radon concentrations measured during the winter, or heating season, are compared with summer concentrations in column four of Table II. The average winter/summer ratio for 11 of these 15 "high" homes was 13 (standard deviation of 9.0), ranging from a ratio of 3.6 to 33. For 18 homes with low indoor concentrations (with winter averages less than 210 Bq m^{-3}), the average winter/summer ratio was 2.5 with a standard deviation of 1.4. This result demonstrates that seasonal variations in radon entry rates (due to soil conditions, house depressurization, and soil-substructure coupling) and/or possibly removal mechanisms are different between the two groups of homes.

Figure 3 shows approximately 20 weeks of continuous radon data, averaged over one day, for the main floor and basement for control home ESP108C. The system to control indoor radon levels was not installed until the second week of March. The forced-air furnace mixed air within the building so that average substructure and main floor radon levels are approximately equal, although basement levels were always somewhat higher. A gradual increase in radon levels is observed from the start of

monitoring in October through January and may be caused by the increase in indoor-outdoor temperature differences. Throughout the monitoring, large variations in indoor concentrations are generally unexplained, but may be due, in part, to occupant activities (e.g., window opening), lack of occupancy, or meteorological phenomena.

To help explain some of the variations in indoor radon levels, a radon source strength was calculated for each five- to nine-day period and compared with the average measured ΔT for the same period for the two control homes. Figure 4 shows a modest correlation between radon entry rate and ΔT that is due to the increased driving force caused by the increasing temperature difference. Radon source strengths were calculated for 12 other "high" homes during baseline conditions. Values ranged from 0.12×10^5 Bq h^{-1} (EVA604) to $13. \times 10^5$ Bq h^{-1} (ECD027).

In addition to the effects of indoor-outdoor temperature differences, the wind interaction with the structure also affects indoor radon concentrations. Figure 5 illustrates the clearest example of the dependence of indoor (main floor) radon levels on wind speed and indoor-outdoor temperature difference over a three week period at house ESP111. Typically, one expects that increased wind speed will lead to additional depressurization of the structure, driving both radon entry and ventilation rates. In this particular case, dramatic decreases in indoor radon levels were closely associated with increases in wind speed (Pearson correlation coefficient of approximately -0.8). Since the house has only a moderate specific air leakage area, 4 cm^2 m^{-2} (where specific leakage area is defined as the measured air leakage area, cm^2, normalized by the floor area, m^2), the factor of ten reduction in indoor radon does not appear to be due to increased ventilation. Instead, the increased wind speed may directly affect the radon entry rate by ventilating the soil surrounding the house.[11,20] The wind creates a positive pressure region on the windward sides of the building and a negative pressure on the leeward sides, forcing a flow of outside air through the soil surrounding the substructure. This wind-driven venting of soil gas is possible only in soils of high permeability. During calm periods at this house, the figure indicates that indoor radon

levels respond to changes in ΔT as expected. Data for precipitation in the form of rainfall was compared with baseline radon concentrations in several homes and no relationship was observed.

In homes with forced-air furnaces that have leaky return air ductwork or plenums located in the substructure, furnace fan activity transports large quantities of substructure air containing radon to other zones of the building. It may also result in additional depressurization of the substructure. Revzan found in a modeling study of New Jersey houses with forced-air furnace systems that the length of time that the furnace fan operated was one of the most important factors that influenced the variation in radon levels on the upper floors.[33] This mixing is evident in Figure 6, which shows the normalized half-hourly radon concentrations and indoor-outdoor ΔT averaged over 86 winter days (i.e., each time-of-day value is normalized by the average for each day, then averaged over the 86 days to generate each point on the plot) for house ESP108C. The average basement concentration for this period was 590 Bq m^{-3} and for the first floor was 520 Bq m^{-3}. The diurnal swing in basement radon concentrations does not appear to be attributable to the diurnal changes in depressurization due to changes in ΔT. The large cyclic change is primarily due to the operation of the furnace (and fan), which is controlled by a set-back thermostat that requests higher house temperatures at approximately 7:30 A.M. and lower temperatures at approximately 22:00 P.M. Standard error bars are shown for radon concentration data points. The average main floor-to-substructure ratio of winter radon concentrations for this house (ESP108C) was 0.91. In four other homes, the ratios of main floor to substructure radon concentrations in the winter before mitigation were: 0.44 (ESP119), 0.53 (ECD027), 0.82 (ESP120), and 0.90 (ECD026C). Explanations for the differences in the ratios may depend upon a number of factors: 1) the area of structural openings between the zones; 2) the outdoor air ventilation rates for the individual zones; 3) the leakage area of any forced-air furnace return air ducts and plenums in the substructure and the length of time that the furnace fan operated; and 4) the amount of time that

- doors between zones were open.

Summary

An area in eastern Washington/northern Idaho, known as the Spokane River Valley and Rathdrum Prairie, has an unusually high number of homes with indoor radon concentrations exceeding most commonly accepted guidelines. Forty-six of these homes had a geometric mean indoor radon concentration of 240 Bq m^{-3} with a geometric standard deviation of 3.1. Although radon concentrations in local samples of soil gas are only moderate, the high air permeability of the soils increases soil gas mobility and entry into house substructures; this is the main factor causing the large number of houses with elevated indoor radon concentrations. Based on our data, we have estimated that soil gas entry ranges up to 21% of the total building air infiltration, but typically the percentage is smaller. Contributions from the domestic water supplies, building materials, and outdoor air to the indoor radon levels are either small or negligible.

Indoor radon levels show considerable temporal variability, over both the long-term and short-term. The average ratio of winter indoor concentrations to summer concentrations was approximately five times higher in homes with high winter concentrations than in homes with low winter concentrations. Short-term variations in radon levels depend, in a complex way, on environmental factors, including indoor-outdoor temperature differences and wind effects.

In homes with forced-air furnace systems, return duct and plenum leakage combined with furnace fan operation enhances mixing of the substructure air with the rest of the house and may even aggravate substructure depressurization. For five "high" concentration homes, the average main floor-to-substructure ratio of winter radon concentrations ranged from 0.44 to 0.91.

The temporal and spatial variations in radon concentrations can have considerable implications for monitoring efforts intended to determine the distribution of indoor radon concentrations or to identify homes with elevated concentrations. Monitoring over too short a period (using grab samples or charcoal canisters) may not provide data

that is representative of the annual average concentration in a structure -- the basis of most guidelines for exposure. The location where monitoring is conducted is also important because concentrations measured on the upper floors can be considerably lower than those in the substructure. Failure to account for temporal and spatial variations in indoor radon during monitoring programs could lead to both unnecessary remedial action and excessive radon exposure.

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Table I. Summary of radon source measurements.

	HOUSE CATEGORY	
	High Indoor Radon Concentrations	Low Indoor Radon Concentrations
Soil Emanating Radium Concentration[a] (Bq kg^{-1} - soil)		
[Geo. Mean (GSD) - # Houses]	6.3[d] (1.2) - 12	7.4[f] (1.4) - 15
Soil Gas Radon Concentration (Bq m^{-3})		
C_{∞}, Calculated [b]		
[Geo. Mean (GSD) - # Houses]	22,000[d] (1.2) - 12	26,000[f] (1.4) - 15
Measured [c]		
[Geo. Mean (GSD) - # Houses - # Locations]	16,000[e] (1.3) - 12 - 23	ND
Soil Air Permeability ($m^2 \times 10^{-11}$)		
[Geo. Mean (GSD) - # Houses - # Locations]	5 (4.9) - 14 - 24	ND
Building Material Emanation [g] (Bq m^{-2} s^{-1})		
[Geo. Mean (GSD) - # Houses]		
Walls	0.015 (5.7) - 4	0.002 (2.4) - 5
Floors	0.005 (5.2) - 6	0.003 (3.4) - 5
Water Supply Rn Concentration (Bq m^{-3} - water)		
[Geo. Mean (GSD) - # Houses]		
Gamma Spec.[h]	21,000[j] (2.1) - 13	13,000[l] (2.4) - 20
Alpha Track Detector[i]	4,800[k] (5.0) - 6	8,700[m] (5.8) -10

(a) Using average of all samples (at air-dry conditions) from each house .

(b) Calculated from Equation 2

(c) From grab samples obtained during pre-mitigation periods from one to three soil probes at each house at depths from 1.0 to 1.5 meters

(d) Twelve of the 15 homes with average indoor winter concentrations greater than 260 Bq m^{-3} and a group geometric mean of 880 Bq m^{-3}

(e) A different set of 12 of the 15 homes with average indoor winter concentrations greater than 390 Bq m^{-3} and a group geometric mean of 1000 Bq m^{-3}

(f) Fifteen of the 20 homes with average indoor winter concentrations less than 210 Bq m^{-3} and a group geometric mean of 67 Bq m^{-3}

(g) Using maximum value of all measurements from each house to display worst case

(h) Gamma spectrometry counting facility

(i) Track Etch ® type SW detector in toilet tank

(j) Thirteen of the 15 homes with average indoor winter concentrations greater than 260 Bq m^{-3} and a group geometric mean of 860 Bq m^{-3}

(k) A different set of the 15 homes with average indoor winter concentrations greater than 260 Bq m^{-3} and a group geometric mean of 830 Bq m^{-3}

(l) Twenty homes with average indoor winter concentrations less than 240 Bq m^{-3} and a group geometric mean of 67 Bq m^{-3}

(m) Ten of the twenty homes with average indoor winter concentrations less than 33 Bq m^{-3} and a group geometric mean of 52 Bq m^{-3}

ND = No data available

Table II. Estimated contribution to indoor radon from various radon sources.

	MEASURED INDOOR AIR RADON Bq m^{-3}					ESTIMATED CONTRIBUTION			
								Soil Gas Entry	
HOUSE ID	Winter Seasons 1984-86[a]	Summer 1985 [b]	WINTER/SUMMER RATIO	PRE-MITIGATION WINTER VENTILATION RATE[c] [ACH (h^{-1})]	RADON ENTRY RATE [d] (Bq h^{-1} x 10^5)	Building Materials (Bq m^{-3})[e]	Water Supply (Bq m^{-3})[f]	m^3h^{-1}[g]	% of Ventilation
ECD026C	640	41	16	0.45(15)	1.4	ND	4	7	3
ECD027	1700	140	12	1.1(1)	13	96	11	39	5
ECD153	900	37	24	0.25(1)	0.97	11	<4	5	4
NCD077	860	ND	ND	0.46(1)	1.8	ND	ND	11	4
ESP101	1000	130	7.9	0.16(1)	0.77	41	4	4	5
ESP108C	570	160	3.6	0.35(15)	1.6	ND	4	9	3
ESP109	260	67	3.8	0.31(1)	0.42	ND	4	2	2
ESP111	1100	33	33	0.31(1)	0.93	ND	<4	12	7
ESP113	730	140	5.4	ND	ND	ND	4	3[i]	3[i]
ESP116	750	ND	ND	0.45(1)	0.70	7[h]	4	8	5
ESP119	1800	ND	ND	0.47(1)	3.1	ND	<4	17	8
ESP120	5200	440	12	0.20(1)	5.8	37	4	20	21
ESP121	410	44	9.4	0.29(1)	0.52	ND	4	2	2
NSP204	970	ND	ND	0.74(1)	4.6	ND	ND	23	6
EVA604	380	33	12	0.18(2)	0.12	15	4	0.4	1

(a) Average based on intermittent, continuous monitoring throughout the months November 1984 - March 1986, prior to mitigation

(b) Alpha track monitors

(c) PFT-measured average for all pre-mitigation 7-day monitoring periods between November 1985 - March 1986. () is number of periods.

(d) Using average winter season concentrations (column 2) and ventilation rate (column 5)

(e) Calculated from Equation 3

(f) Based on measured radon-in-water concentrations from samples and assuming the air-to-water concentration ratio is 10^{-4} (see text).

(g) Quantity of the soil gas entry needed to yield measured winter season concentrations, calculated using Equation 5.

(h) Using only the measured emanation rate from floors for entire wall and floor area

(i) Using ventilation measurements of 0.2 ACH (h^{-1}) made during mitigation periods

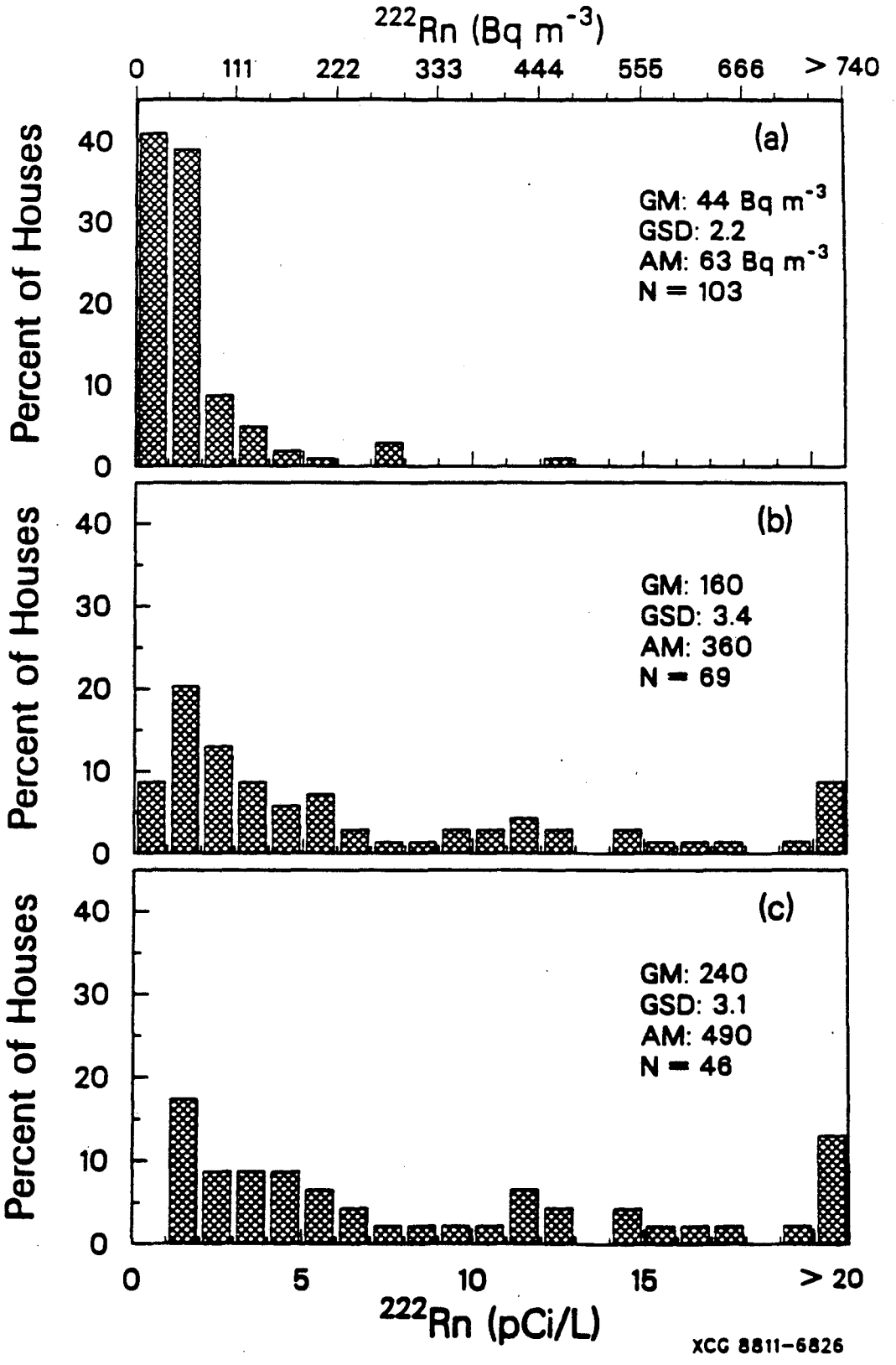

Figure 1.a,b,c Heating season indoor radon concentrations for 103 homes in the near-coastal region of western Washington and Oregon (a) and 69 homes in the Spokane, WA, and Coeur d'Alene, ID, area (b). The higher GM and the larger GSD in (b) are influenced by 46 of the homes which are approximately located in the Spokane River Valley/Rathdrum Prairie (c).

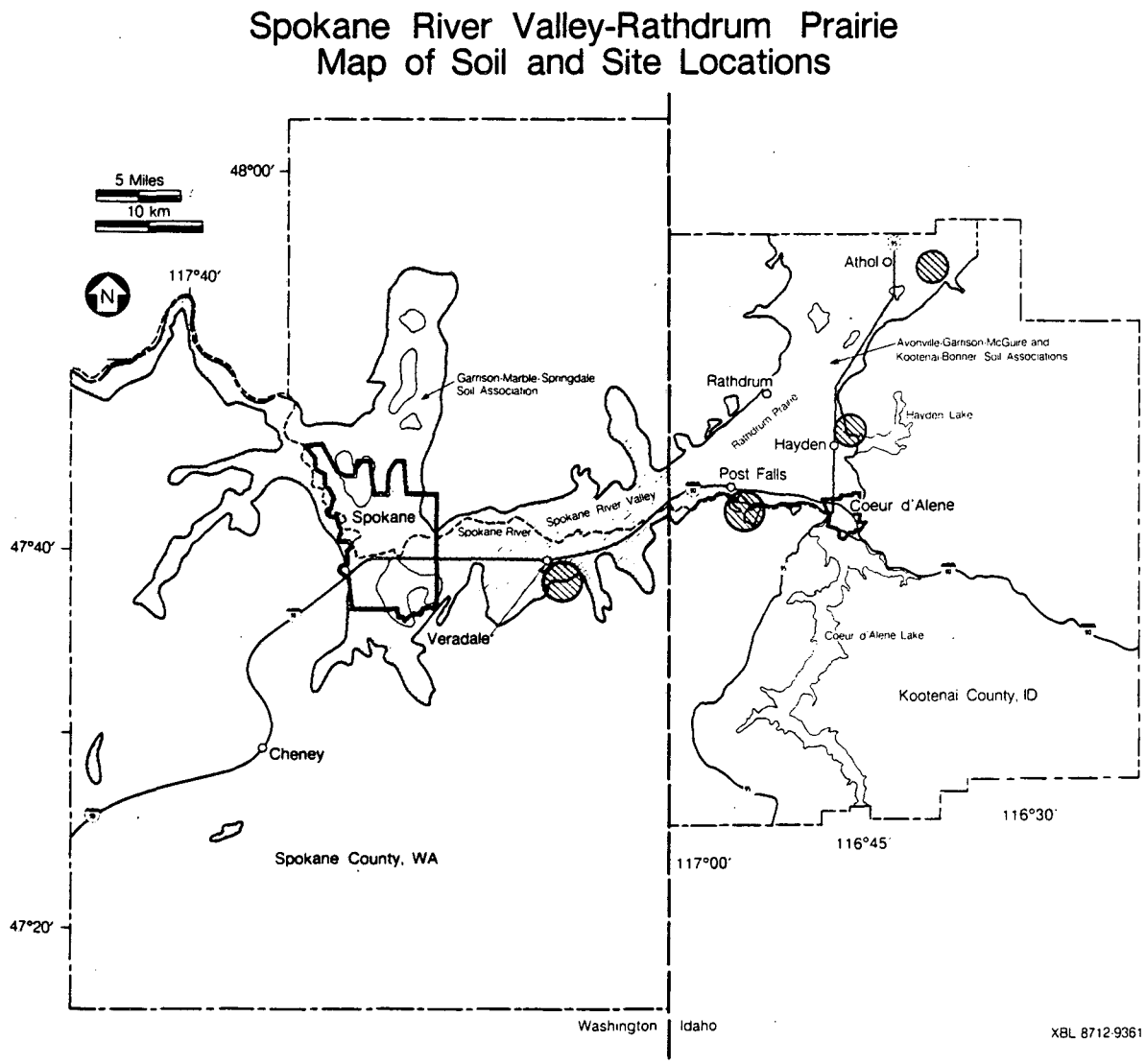

Figure 2. **A map of Spokane County, WA and Kootenai County, ID delineating the Spokane River Valley - Rathdrum Prairie soil associations in hatching. These soils are typically defined as excessively drained sandy and gravelly soils formed in glacial outwash. The general locations of the 14 "high" houses from this area are shown by cross-hatched circles.**

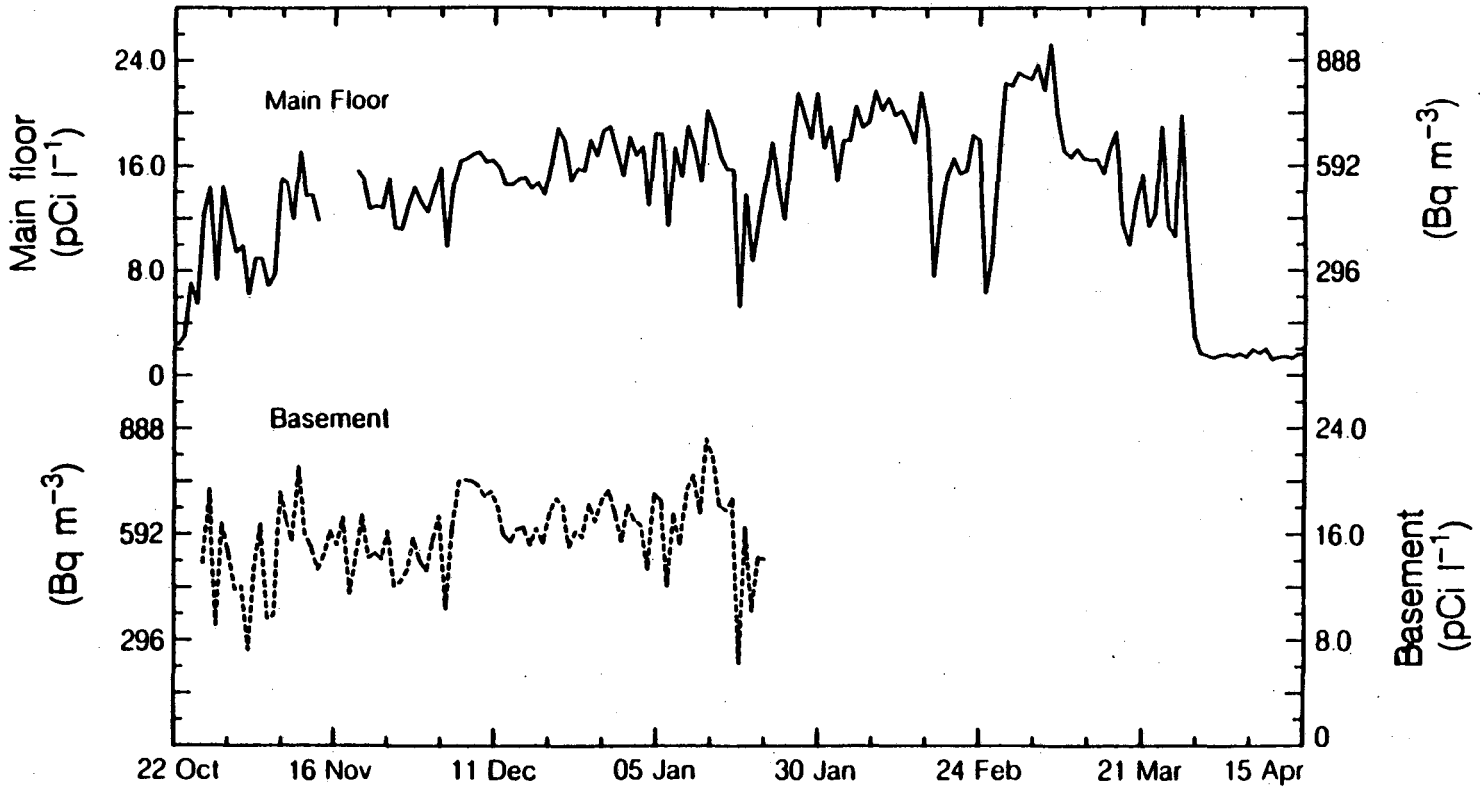

Figure 3. **Daily averages of the continuous radon data for the main floor and substructure of control home ESP108C during the heating season. Mitigation did not begin until the second week of March.**

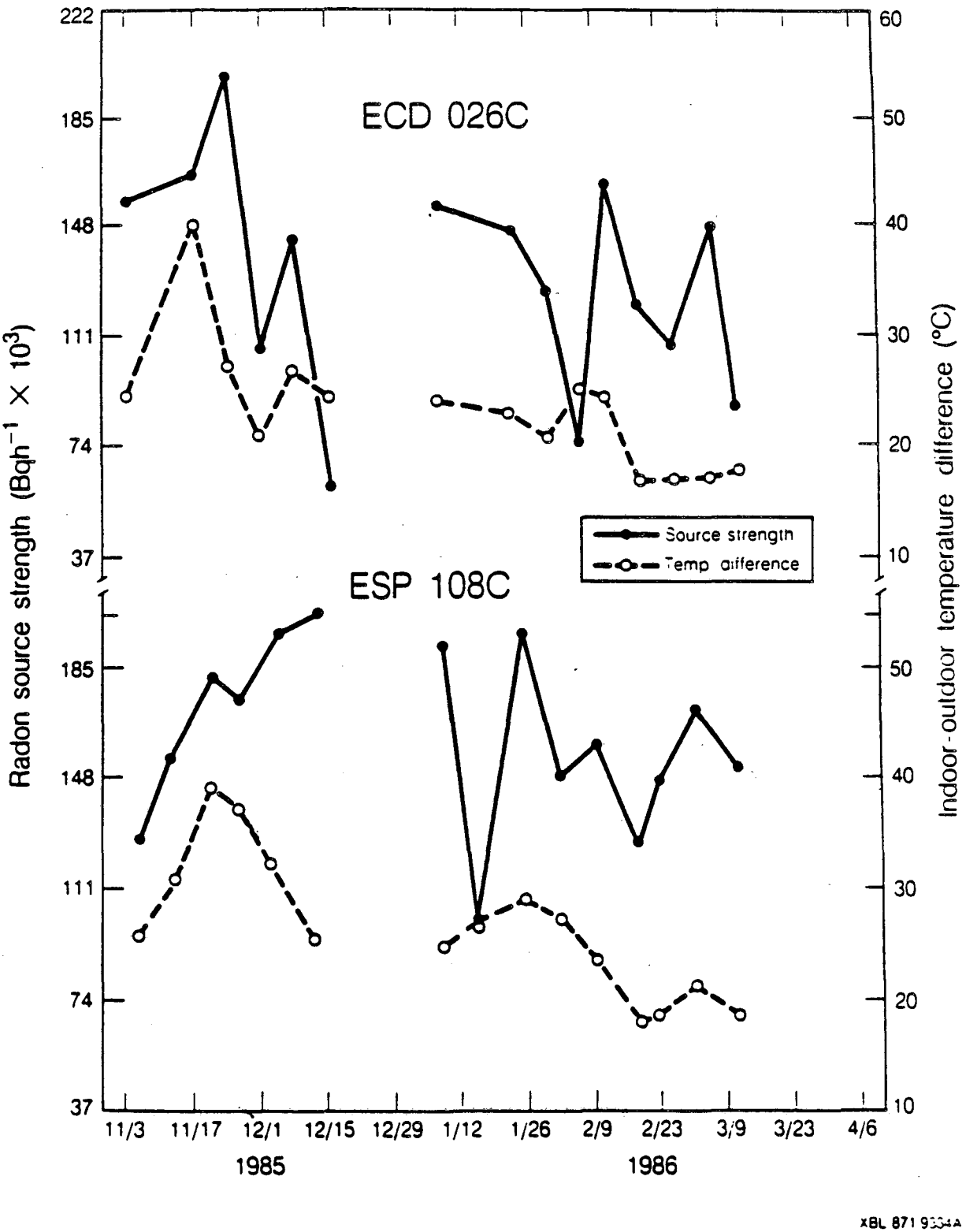

Figure 4. Variations in radon source strength (entry rates) and the indoor-outdoor temperature difference (ΔT) for two control homes. The entry rates show a weak dependence on ΔT.

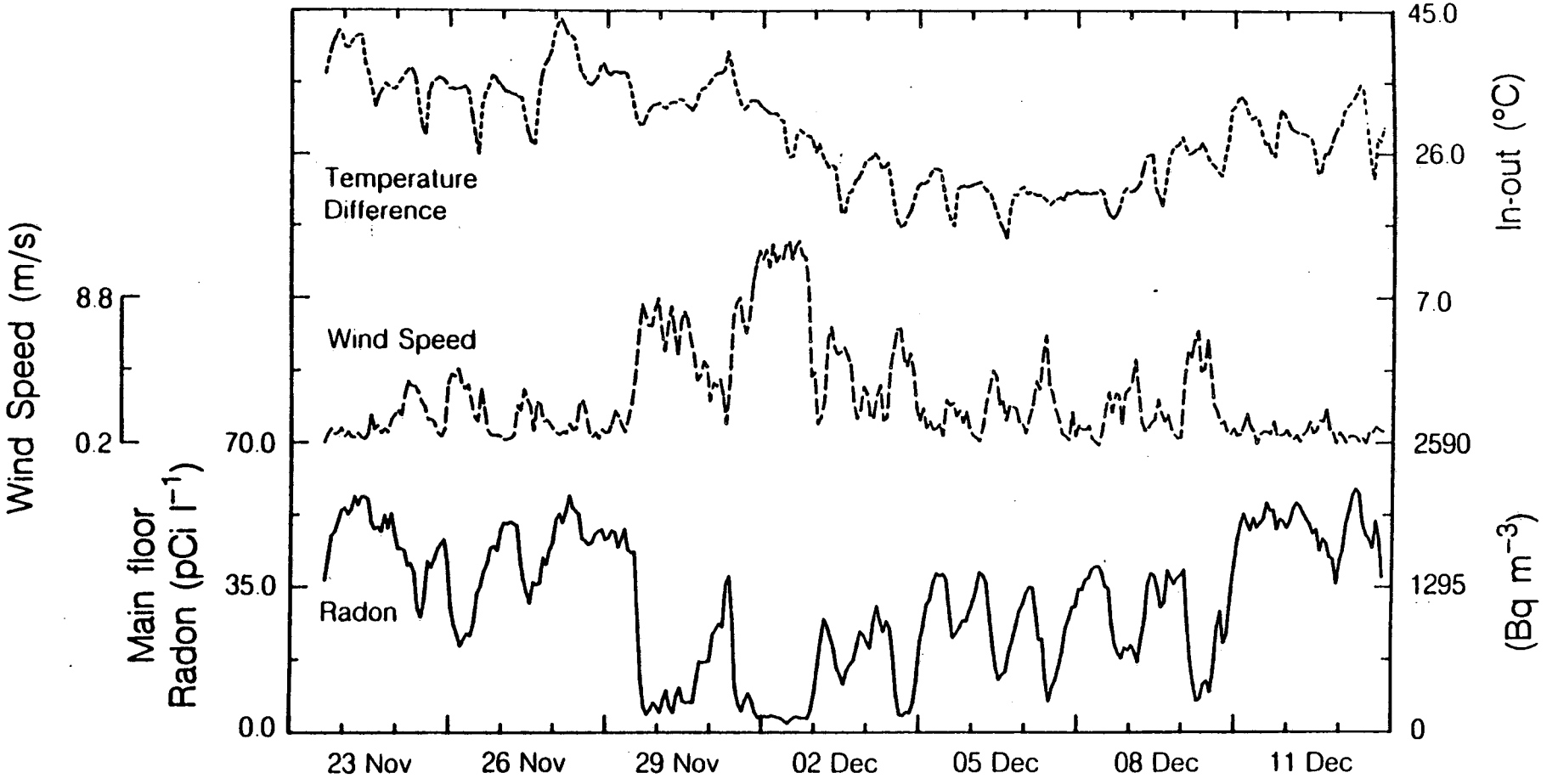

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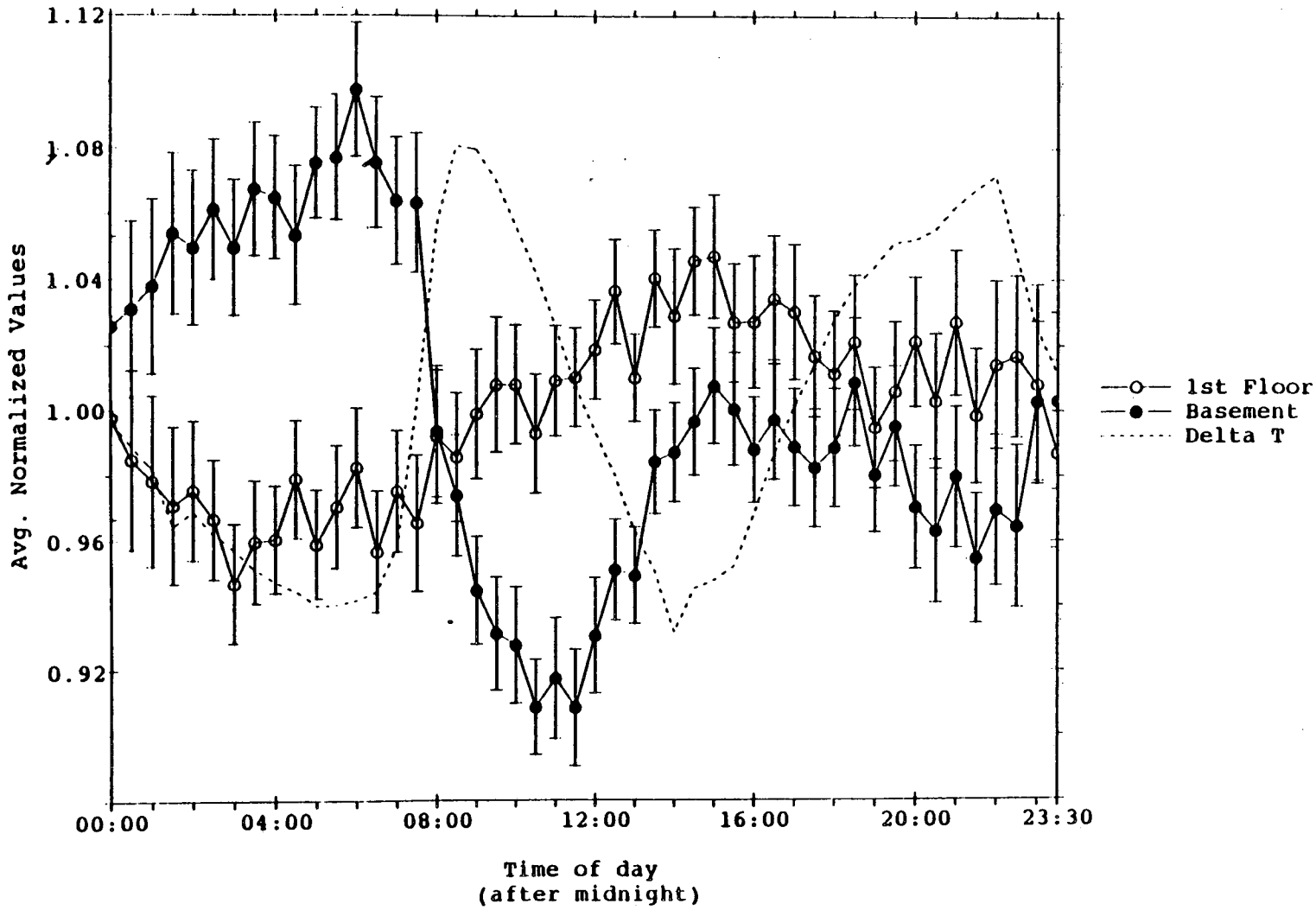
Figure 5. **Continuous radon, windspeed, and indoor-outdoor temperature difference data for a three-week period at ESP111. These data suggest that the soil surrounding the structure is being ventilated with outside air during windy periods.**



Figures 6. Time-of-day ΔT, and basement and first floor radon concentrations are normalized by the daily average for each of 86 winter days, then averaged over the entire period. Error bars are standard error of the mean. The set-back thermostat requested higher house temperatures from approximately 07:30 A.M. to 22:00 P.M. Furnace fan operation between these times tended to mix basement and main floor air.

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