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Characterizing the Occurrence, Sources, and Variability of Radon in Pacific Northwest Homes

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A compilation of data from earlier studies of 172 homes in the Pacific Northwest indicated that approximately 65 percent of the 46 homes tested 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 from 0.4 to 39 m^{3}h^{-1} and 1 percent to 21 percent 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.

During surveys of indoor pollutant concentrations and ventilation rates in Pacific Northwest buildings conducted between 1983 and 1986,[1–3] 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]

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

Implications

This paper identifies a region in the Pacific Northwest where indoor radon levels are unusually elevated. Made aware of this information, health and building officials can more carefully define the extent of the problem, and provide guidance to owners and occupants of affected structures. Data are also presented that show elevated indoor radon levels are most closely linked to the underlying soils and geologic features. Because building materials and construction had a very small impact on indoor radon concentrations, designers, builders, and building officials were not responsible for the elevated radon levels measured in these existing houses.

Study Design

House Participation

A total of 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 and 111 existing homes. Based on radon levels, 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. These 15 were classified as high-concentration homes (hereinafter referred to as high homes) with winter indoor levels averaging greater than 260 Bq m^{-3} and a group geometric mean (GM) of 860 Bq m^{-3}.

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. 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 in age. 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. 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

† 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.

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 remaining 20 homes, in the set of 35, were classified as low-concentration homes (hereinafter referred to as low 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 exposed for 21 to 70 days between October 1984 and June 1985. From one to five indoor locations that were occupied (including some basements) were monitored and the data averaged for each house. In houses with a single measurement location, the alpha track detector was placed on the lowest commonly occupied floor (generally one floor above the basement). 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. 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 percent[8] to a bias of 1.32 with a CV of 59 percent.[9] Because of time constraints, 16 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 (15 high houses plus 20 low 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; of these, 19 had municipal water supplies and 14 had private wells. The one-liter water samples, collected to avoid aeration, were analyzed using gamma spectrometry by placing the bottle directly on a 20 by 10 cm NaI detector, previously calibrated for the counting geometry. Alpha-track detectors were also placed in the water within toilet tanks. Soil samples were collected at 27 of the 35 houses either using a coring tube or with a bucket anger. Sample depths ranged from 0.5 m to 0.8 m. The soil samples were analyzed for emanating radium, which 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. The methods of collecting and analyzing samples are discussed in greater detail in the project report.[6] Radon emanation rates from building materials were measured at 11 houses: nine had measurements made on both walls and floors, and two had only floor measurements. A shallow, 21.6 cm diameter pan containing charcoal canisters was sealed to walls or floors and left in place for 24 to 48 h. The charcoal canisters were subsequently analyzed for radon by gamma spectrometry.[6]

Indoor air radon concentrations were also measured during the summer between June and September, 1985 for periods between 65 and 115 days in 25 of the 35 houses. Two Terradex Type SF Track-Etch® alpha track detectors were placed side-by-side for replication in an occupied first floor space.

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 recorded by the data logger at 30-minute intervals. At least one CRM was installed at each house to sample air from the first frequently-occupied floor above grade. Additional CRMs for sampling air from crawlspaces and basements were available for only a few houses. The uncertainties in average concentrations measured with these CRMs are estimated at 10 percent. 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 and interzonal flow 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] The PFT technique is estimated to underpredict actual ventilation rates by 20 percent to 30 percent with a measurement uncertainty of approximately 25 percent. During the periods of radon and ventilation monitoring, the occupants completed logs of daily activities in and near their homes that might affect pollutant concentrations or ventilation rates.

At each of the 15 high houses, two pipe probes, 13 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 cm^3 scintillation flasks. After the radon and its progeny reached radioactive equilibrium in three hours, the samples were analyzed for radon concentration on a portable photomultiplier 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 conversion constant (m^3-min-Pa-L^{-1}); Q = flow rate (L/min); r = inside radius of pipe probe (m); and P = probe pressure (Pa) with respect to atmospheric pressure. 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 percent.

Results and Discussion

Initial Survey

Summarizing the radon data collected in the initial surveys, 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 (AM) of 63 Bq m^{-3}) with a geometric standard deviation (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, where radon concentrations have a GM of 160 Bq m^{-3} (AM of 360 Bq m^{-3}) and a GSD of 3.4 (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

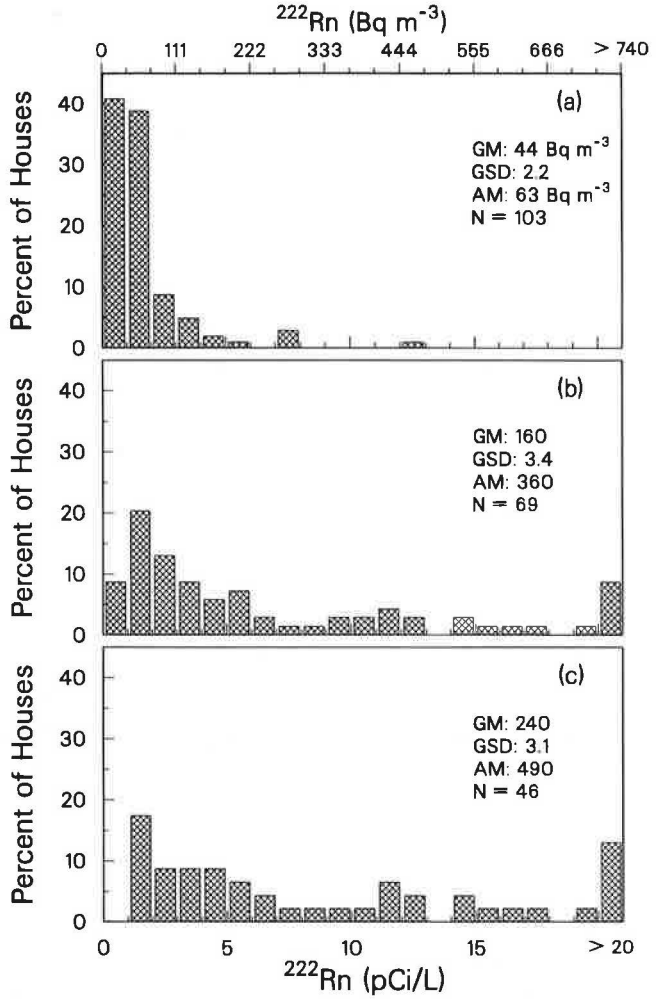

Figure 1. Heating season indoor radon concentrations for 103 homes in the near-coastal region of western Washington and Oregon (a) and 69 homes in the Spokane, WA, and Coeur d'Alene, ID, area (b). The higher GM and the larger GSD in (b) are influenced by 46 of the homes which are approximately located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

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 percent, 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 percent, had concentrations above the BPA mitigation action level of 185 Bq m^{-3} (5 pCi L^{-1}),[13] and twenty, or 44 percent, 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 percent 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 percent 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. These soils typically have high water permeabilities (0.06 to greater than 0.25 m h^{-1}) and therefore will have high air permeabilities for soil gas movement.[19]

Most recent research 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.[19-21] 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.

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 which have above-average permeabilities.[22]

The emanating radium concentrations of the soil samples collected at each house were averaged and are summarized in Table I. The concentrations are close to values for other typical soils (~9.3 Bq kg^{-1}) discussed 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 would 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, using the equation:

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

where ρ, bulk soil density, was assumed 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). C_∞ is the expected soil gas concentration if there were no loss of radon by diffusion or convective flow. 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

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 (10^{-11} m^2)		
[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 (R), 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.

probes were collected prior to the installation of any radon control equipment and were analyzed for radon concentrations. House-average concentrations at 12 of the 15 high houses are within 50 percent of the calculated maxima, C_∞, and also have a relatively small range: from 10,000 Bq m^{-3} to 25,000 Bq m^{-3}. 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 percent to 150 percent standard deviation. 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 of water samples collected from a faucet versus radon measured using alpha track cups placed in toilet tanks, 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 density (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 handmade basement wall. However, it is possible that there is significant radium in the materials of this wall which includes local field stone. A flux density of 0.12 Bq $m^{-2}s^{-1}$ was measured on the open soil floor and compares with the flux density measured in an unpaved crawlspace (0.27 Bq $m^{-2}s^{-1}$) by Rundo et al.[25]

Discussion of Source Contributions

Using the data collected on the various sources of radon, we estimated (Table II) the contribution to the winter season indoor radon levels for the 15 high homes.

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 increase in the indoor air concentration. While the relationship between the radon concentration in water and that contributed to indoor air 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, an average of 10,000 Bq m^{-3} in water yields 1 Bq^{-3} in air.[26,27] This 10,000-to-1 ratio 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. 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 steady-state concentration model for a single, well-mixed zone, assuming there is no contribution from radon in outdoor air:

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

where: C = predicted, steady-state, indoor air concentration (Bq m^{-3}); J = material emanation rate (Bq $m^{-2}h^{-1}$); A = surface area of material (m^2); λ = ventilation rate, air changes per hour (h^{-1}); and V = building volume (m^3). 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 and structural parameters. 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.[19–21]

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 and soil that create a stack effect that draws air and soil gas into the lower levels of the house and exhausts it near the top. With other factors constant, larger indoor-outdoor temperature differences (ΔT) cause greater negative pressures in the substructure relative to the soil. Aggravating this depressurization are leaky forced-air furnace ducts and return air plenums in the substructure exhaust fans, vented combustion devices, 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, substantial volume quantities of soil gas must be entering the high homes to account for the indoor radon concentrations observed during the winter season. These high indoor radon concentrations must therefore require good coupling of the house to the soil, resulting from sufficient substructure leakage area and high soil air permeabilities. Soil gas entry rates for each of the 15 high homes were estimated from a steady-state mass balance:

$$Q = \frac{C_w \lambda V}{C_\infty} \qquad (4)$$

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

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

House ID	Measured indoor air radon Bq m^{-3} Winter seasons 1984–86[a]	Summer 1985[b]	Winter/ summer ratio	Pre-mitigation winter ventilation rate[c] [ACH (h^{-1})]	Radon entry rate[d] (10^5 Bq h^{-1})	Estimated contribution Building materials (Bq m^{-3})[e]	Water supply (Bq m^{-3})[f]	Soil gas entry m^3h^{-1}[g]	Soil gas entry % 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 rates (column 5), and building volumes from Reference 6.
[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.

and building material emanation were neglected because they are negligible. Results are tabulated in column nine of Table II. The very high soil gas entry rates for some of the houses are possibly 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 high houses (except EVA604) are still greater than the 1 m^3h^{-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^3h^{-1} to 1.8 m^3h^{-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 approximately 4 to 6 m^3h^{-1}, at a ΔT of 18 and 34° C, respectively.[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 percent of the infiltrating air. Additional evidence for the good coupling of the substructure to the soil at ESP120 is that approximately 80 percent 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), with a range 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 suggests 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.

The radon concentrations measured every 30 minutes for approximately 20 weeks in the control houses varied greatly over time[6] (e.g., by more than a factor of 5 in a 24-hour period). The large temporal 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 (i.e., the product of indoor radon concentration, the building volume, and the ventilation rate) was calculated for each five- to nine-day period for the two control homes and compared with the average measured ΔT for the same period. Figure 2 shows a modest correlation between radon entry rate and ΔT that is due to the increased driving force caused by the increasing temperature difference (Pearson correlation coefficient of 0.39 and 0.37 for ECD026 and ESP108, respectively). Radon source strengths were calculated for 12 other high homes during baseline conditions (without operation of radon mitigation systems) and ranged from 0.12×10^5 Bq h^{-1} (EVA604) to $13. \times 10^5$ Bq h^{-1} (ECD027), as seen in column six of Table II.

In addition to the effects of indoor-outdoor temperature differences, the wind interaction with the structure also affects indoor radon concentrations. Figure 3, based on three weeks of data from ESP111, illustrates the clearest example of the dependence of indoor (main floor) radon levels on wind speed and indoor-outdoor temperature difference. Typically, one expects that increased wind speed will lead to additional depressurization of the structure, driving both radon entry and ventilation rates. However, in ESP 111, 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 mod-

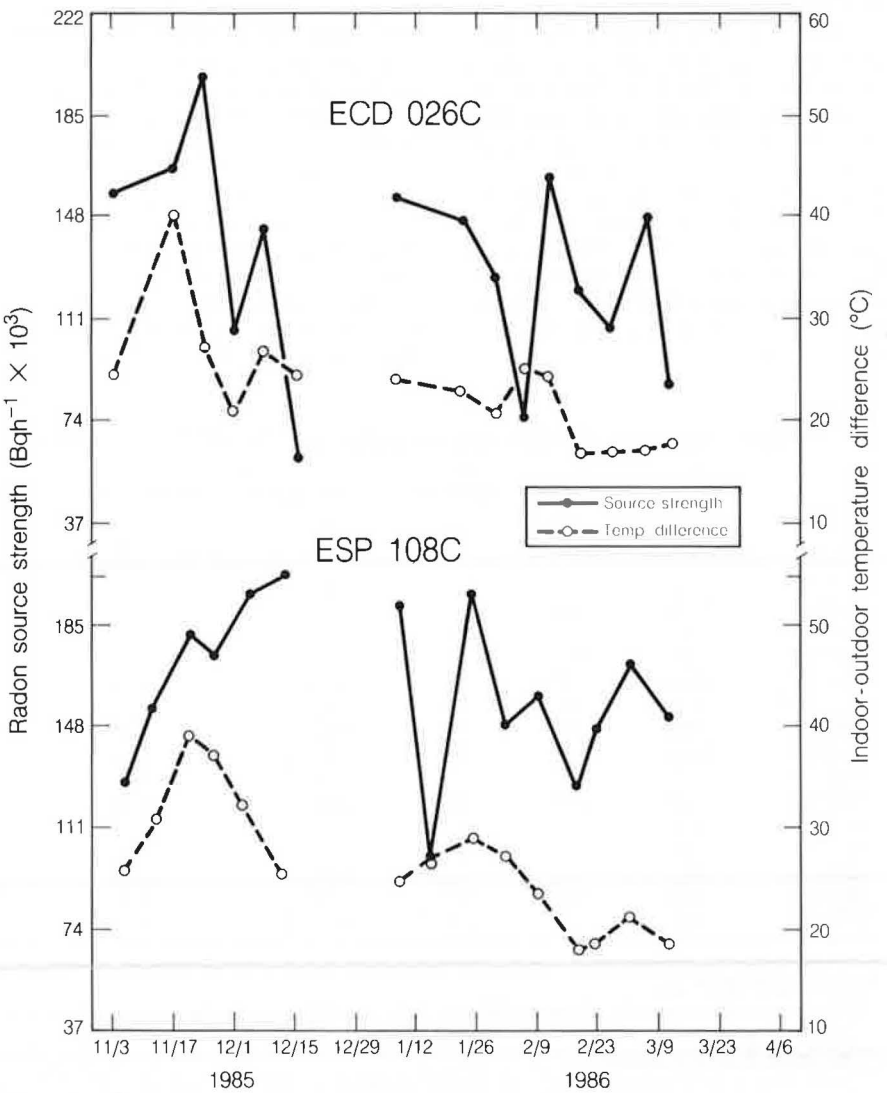

Figure 2. Variations in radon source strength (entry rates) and the indoor-outdoor temperature difference (ΔT) for two control homes. The entry rates show a modest dependence on ΔT (Pearson correlation coefficients of 0.39 and 0.37 for ECD026 and ESP108, respectively).

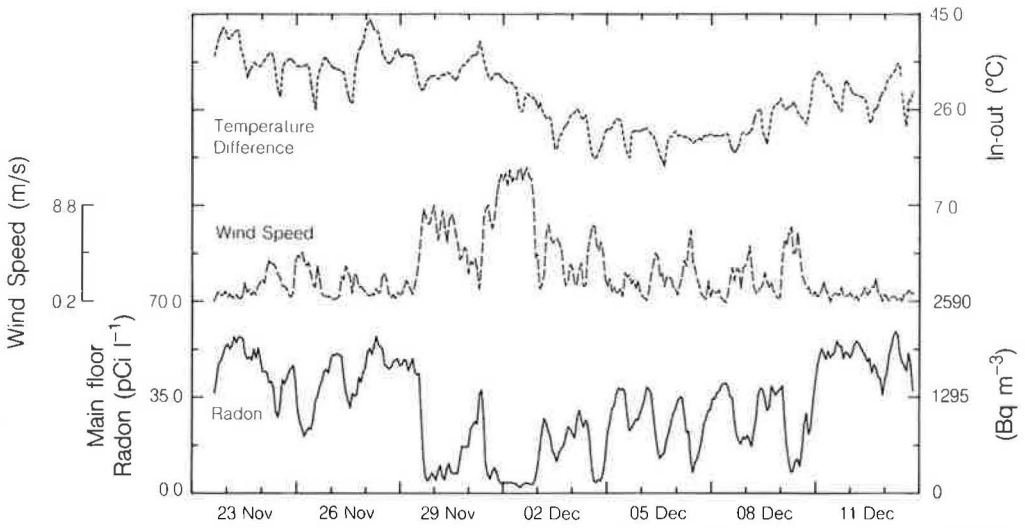

Figure 3. Continuous radon, windspeed, and indoor-outdoor temperature difference data for a three-week period at ESP111. These data suggest that the soil surrounding the structure is being ventilated with outside air during windy periods.

erate 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 data indicate that indoor radon levels respond to changes in ΔT as expected. Rainfall data were 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 4, 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. The average main floor-to-substructure ratio of winter radon concentrations for this house (ESP108C) was

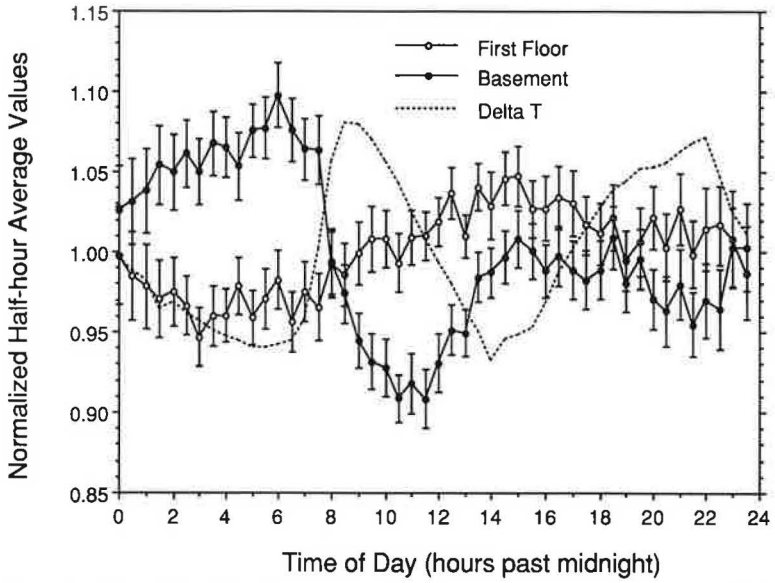

Figure 4. Time-of-day ΔT, and basement and first floor radon concentrations are normalized by the daily average for each of 86 winter days, then averaged over the entire period. Error bars are standard error of the mean. The set-back thermostat requested higher house temperatures from approximately 07:30 to 22:00. Furnace fan operation between these times tended to mix basement and main floor air.

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). The differences in the ratios may be due to 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 the soil gas entry rates ranges up to 21 percent of the total building air infiltration, but the average percentage for this group of houses is 5 percent. 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 are 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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