RADON CONTROL - TOWARDS A SYSTEMS APPROACH

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ABSTRACT

The normal operation of a continuous mechanical ventilation system, incorporated into a relatively airtight house, and designed to control pressure-differences, has been demonstrated to provide sufficient control of radon entry in a two story residential building.

This was accomplished via a "two-cell barrier-enhanced pressure-difference control system."

Ventilation rates, energy usage, moisture levels, pressure-differences, and radon concentrations were monitored. Changes in radon concentrations in several building locations, as a function of distinct pressure-difference configurations, have been measured.

Indications are that this design offers the new residential construction industry an opportunity to realize affordable control of radon entry, while simultaneously optimizing potentials for moisture control, energy efficiency, and control of other indoor air pollutants.

INTRODUCTION

This project explores the use of an airtight building envelope (and separately isolated airtight crawlspace) integrated with a continuously operating mechanical ventilation system, to enhance pressure-difference control strategies for minimizing soil-air entry into the indoor air.

This approach seeks to obtain robust control of radon entry, while concurrently optimizing potentials for several building design goals including: moisture control, energy efficiency, control of other indoor air pollutants.

CONTEXTING ASSUMPTIONS

There are several primary design goals for the environment control system "house:" safety, comfort, durability, healthy indoor air, and energy efficiency. These goals are not only increasingly achievable, but can be mutually advantaged in a manner that can reduce net system cost.

A systems approach that seeks to optimize a building's performance with regard to several desirable performance qualities might well include several very successful radon solutions.

The radon source of concern is soil-air. The primary goal with regard to control of indoor radon is the prevention of soil-air entry into the indoor air. Radon is a given component of soil-air though its concentration both varies from one site to another and is not readily predictable. In one case, measurements of soil radon within a distance of 9 meters varied by a factor of 250 (1). Hence, the degree of soil-air entry control required is neither constant nor predictable.

Two conditions are necessary for soil-air entry:

- There must be openings in the building envelope that couple the soil-air to the indoor air.
- There must be a driving force, a pressure-difference that results in a flow from the soil-air zone into the indoor air zone.

While significant reduction of all coupling pathways from the soil zone is reasonably achievable, elimination of them is not. It has been observed that even very small openings are sufficient to allow unacceptable radon levels (2). Control of pressure-differences may be the practical key to adequately limiting the entry of soil-air pollutants, including radon. Envelope tightness may be most important for its role in enabling and enhancing pressure-difference control.

The tight building envelope, coupled with a properly designed mechanical ventilation system, can play a central role in a systems approach that incorporates pressure-difference control to limit soil gas entry. The tighter the air barriers of the system, the more effective the pressure-difference control for a given amount of fan power. This dovetails nicely with the desirable advantages of a tight building envelope for several other building performance purposes, including:

- Comfort - fewer drafts; minimal temperature stratification; reduced noise, dust, pollen, insects.
- Energy efficiency - large net reduction in heating/cooling loads.

- Moisture control - structural durability and reduced maintenance costs.
- Enhanced dilution/removal of pollutants generated indoors - via improved ventilation effectiveness, control and capability.

Several of the design elements serve to advantage multiple design goals. This should be recognized when attempting to allocate costs. For example, soil-air may also contain other pollutants of concern, such as garbage gasses (methane), herbicides, fungicides, pesticides, spores of soil fungi, etc. (3). The cost of preventing soil-air entry should be life-cycled against the delivery of several health benefits. Also, in this particular project, the cost of mechanical ventilation and the tight envelope must be apportioned to comfort, energy performance, radon control, moisture control, and control of other pollutants.

SPECIFIC HYPOTHESIS

The normal operation of a commercially available continuous mechanical ventilation system incorporated into a tight house, and designed to control pressure-differences, can provide sufficient day-to-day control of those pressure-differences (induced by weather, internal household activities, and mechanical systems) to prevent entry of radon and other soil-air pollutants. This can be reasonably accomplished by developing a "two-cell, barrier-enhanced pressure-difference control system." (4).

BUILDING DESCRIPTION

In 1988, a tightly sealed and energy efficient two-story residential building was constructed with the intent to exceed any energy performance standards currently in place in the U.S. The building was among those instrumented and continuously monitored for one year as part of the Residential Construction Demonstration Program (RCDP), a multipurpose research and development effort of the Bonneville Power Administration and the Washington State Energy Office. As an RCDP Cycle II Future House, the expected energy performance of the building was designed to exceed that required by the Northwest Power Planning Council's Model Conservation Standards by 30%.

The building was constructed in Spokane, WA. Spokane has a winter outdoor design temperature of 4°F (-15°C), 6882 normal heating degree days, and 411 normal cooling degree days. Spokane weather has the characteristics of a mild arid climate in the summer and a cold coastal climate in winter. Winter solar potentials are limited by both the climate and the site. The building was calculated to have an annual need of 2.5 kWh/ft^2 (97 MJ/m^2) for space heating.

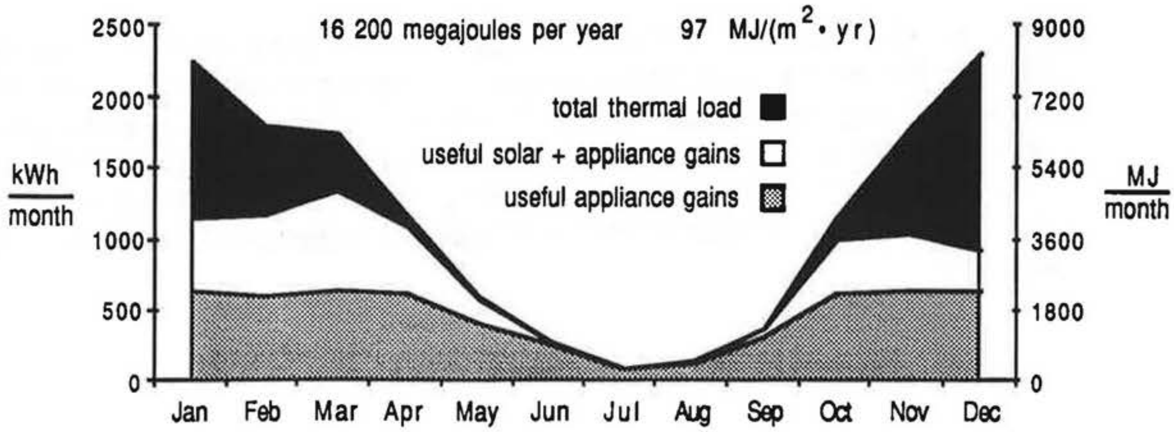

Figure 1. Predicted space heating profile.

The building is of double-wall construction and the wall thermal resistance is approximately R45 (.126 W/[m^2•K]). This insulation level extends from the ceiling to the concrete footing, except as interrupted by doors and glazing (Figure 2). The glazing area is 328 ft^2 (30.5 m^2) and is 18% of the conditioned floor area 1780 ft^2 (166 m^2). Fifty-five percent of the glazing faces south. The glazing thermal resistance is approximately R4 (1.5 W/[m^2•K]). The ceiling is insulated to R60 (0.095 W/[m^2•K]). The continuous thermal envelope is completed by R25 (0.227 W[(m^2•K]) fiberglass batt insulation laid directly upon the ground (over a gravel capillary break).

A continuous air barrier was established with the interior drywall by gasketing the drywall to the wood framing and sealing any penetrations through the drywall. Upon completion of construction, the building had a tested air leakage rate of 1.2 air changes per hour (ACH) at an induced indoor/outdoor pressure-difference of 50 pascals. One year later it was tested at 1.4 ACH at 50 pascals. The measured Pacific Northwest average is 9.3 ACH at 50 pascals (5). The vapor retarder was established on the interior surface of the drywall with a rated paint. The glue in the laminated subflooring provided the floor vapor retarder.

The building is divided into two distinct cells, that are atmospherically decoupled from both each other and the outdoor air (Figure 2). The tightness and isolation of these two "cells" enables pressure-difference control with the mechanical ventilation system (and prevents contamination of air in cell 1 by air in cell 2. Cell 1 contains all occupied space, so that the breathable indoor air is contained in cell 1. The volume of cell 1 is 16,500 ft^3 (467 m^3). Cell 2 is a plenum by which stale air from cell 1 is removed. Though atmospherically decoupled, it is thermally coupled to cell 1, so it provides warm floors. Cell 2 adds another 3000 ft^3 (85 m^3) to the conditioned volume.

The first floor subfloor was the selected air barrier between cell 1 and cell 2. All joints in the tongue and groove exterior grade plywood were sealed with urethane sealant during installation. Special care was taken to identify and seal any holes created in this barrier by the construction process (eg; temporary nailing for wall bracing, sawhorses, measuring and cutting tables). A tracer gas was injected into cell 2 prior to carpet installation and two small air leaks were located using a detection instrument.

HVAC SYSTEM

A small (5000 to 7000 btuh) commercially available integrated residential heat recovery ventilation system (HPV) provides continuous ventilation, partial space heating, space cooling, water heating, as well as the desired pressure-differences (6). The unit consists of a water heating tank and a space conditioning module (SCM). The SCM contains 2 constant speed fans, 2 coils, and utilizes a reversible refrigeration cycle to provide heating or cooling via the same ductwork. During the winter heating cycle, heat is extracted from stale exhaust air and delivered to either the domentic hot water tank or the mixed air supply. In summer, heat is extracted from the mixed air supply and either exhausted outside or used to heat domestic water.

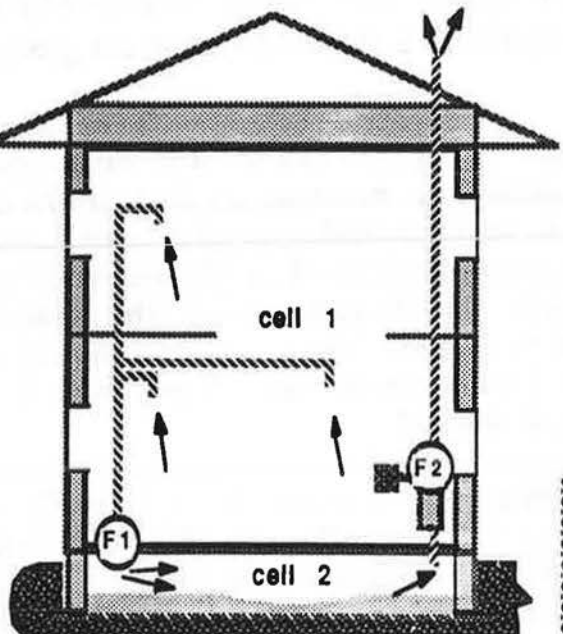

Figure 2. Exhaust Air Side.

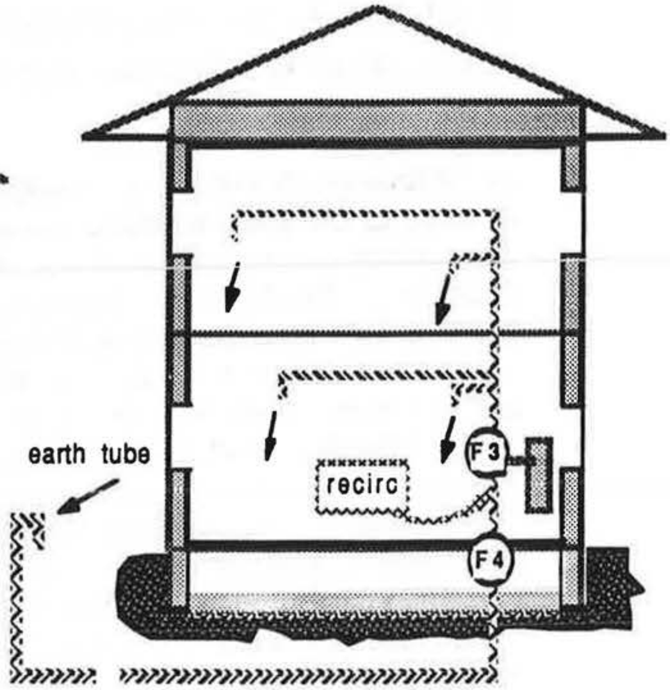

Figure 3. Supply Air Side.

On the supply air side, two 60 ft (18 m) long by 4 in (10 cm) diameter PVC earth tubes provide filtered outdoor air which is mixed with recirculating air before it passes over the supply-side coil and is distributed to individual living areas by fan F3 (Figure 3). The earth tubes are buried approximately 4 ft (1.2 m) below grade and serve to temper both winter and summer air.

On the exhaust air side, stale indoor air is removed from kitchen and bathrooms by fan F1 and ducted to cell 2. From this point it remains isolated from cell 1. The stale air travels across cell 2, then exits via a sealed duct which leads to the SCM. Continuous operation of fan F2 (SCM exhaust fan) is necessary to maintain a lower pressure inside the SCM than in the mechanical room, so that no leakage back into the indoor air occurs. After passing through the SCM the air is exhausted above the roof line.

TWO-CELL, BARRIER ENHANCED PRESSURE-DIFFERENCE CONTROL

Cells 1 and 2 are isolated from each other, from the outdoor air, and from the indoor air; by accessible and maintainable air barriers. Sealed ducts allow controlled air passage. Continuous mechanical ventilation removes stale air from cell 1 and delivers it outside via cell 2. Depending on which fans are selected to operate, cell 2 can be either pressurized or depressurized relative to cell 1 and/or the soil-air. This project incorporated four fans in the ventilation system in order to enable comparison between these two approaches, as well as other possible ventilation and pressure-difference configurations:

• Continuously pressurize and flush cell 2: This is the baseline operating condition. Fan F1 removes stale indoor air from cell 1, depressurizing cell 1 relative to outside and pressurizing cell 2. Fans F2 and F3 are part of the commercial unit and operate at a constant speed. Fan F1 must produce a greater flow than fan F2 in order to maintain cell 2 at a greater pressure than cell 1. A solid state speed control allows adjustment of fan F1. Dampers allow adjustment of the flows through the SCM, but adjustment is limited to the range of flows required by the SCM.

• Continuously depressurize and flush cell 2: Fan F1 does not operate, so fan F2 depressurizes both cell 1 and cell 2. Cell 2 is at a lower pressure than cell 1.

• Continuously pressurize cell 2: Fan F1 operates but no flushing of cell 2 occurs. Cell 2 is decoupled from the exhaust loop, and stale air is removed directly from cell 1.

• Mimic typical housing leakage and ventilate: Increase the envelope equivalent leakage area of cell 1 to typical levels by introducing deliberate openings in floor and ceiling (The northwest average is 125 in^2 (806 cm^2). The measured cell 1 leakage area is 16-20 in^2 (100-130 cm^2). The ventilation system operates (decoupled from cell 2). Leakage distribution can also be adjusted. Typical outside vents can be installed in the crawlspace.

• Mimic typical housing leakage and do not ventilate: Increase the envelope equivalent leakage area of cell 1 to typical levels by introducing deliberate openings in floor and ceiling. Typical outside vents can be installed in the crawlspace.

ENERGY PERFORMANCE

Limited data is available at this time and results should be considered preliminary. The building was completed and occupied during January of 1989. Shortly thereafter extensive energy performance monitoring was begun by the Washington State Energy Office, via a subcontract with W.S. Fleming Inc. Selected air and water temperatures, air and water flows, relative humidities, and electrical energy usage have been monitored and recorded (six second averages) on a multi-channel datalogger. Data collection for the first year has been completed. Once the data are analysed a more complete energy performance profile will become available.

Zoned electric resistance heaters were separately submetered. The integrated heat recovery ventilation system, which provides continuous ventilation, partial space heating, space cooling and water heating was also submetered. Electrical main and submeter data were recorded by the author. For the one year period between March 4, 1989 and March 3, 1990, electric resistance heating used 1.4 kWh/ft^2 (54 MJ/m^2). The HPV unit used 3.5 kWh/ft^2 (135 MJ/m^2) for continuous ventilation, space heating and cooling, water heating, and pressure-difference control. The HPV system is estimated to provide 44% of the space heating load. This brings the total cost of space heating to $216/year. The measured average Kwh consumption for heating conventional electrically heated homes in the Pacific Northwest is 12,420 Kwh, which amounts to $596 (5).

MOISTURE PERFORMANCE

Humidity sensors (7) were calibrated and placed inside structural wood framing in six locations prior to completion of construction. Two sensors were placed in the attic, two in the walls, and two in the floor of cell 1. An attempt was made to select locations with the greatest moisture potential; generally downwind from the prevailing wind direction, shaded areas on the north side, and (for walls) high in the building:

- Attic top chord - north side near center of building.
- Attic bottom chord - north side near center of building.
- East wall exterior framing stud - north side on upper level.

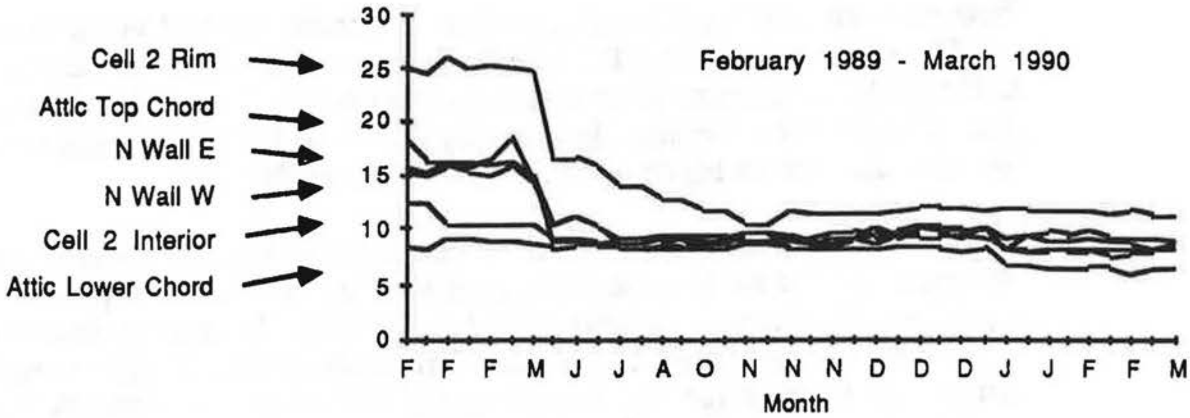

Figure 4. Percent wood moisture content in six locations.

- West wall exterior framing stud - north side on upper level and near electrical outlet.
- Warm joist in cell 2 - center of building.
- Cold joist cell 2 - next to north rim joist and on cold side of air-vapor barrier and insulation.

Thirty-seven intermittent readings were recorded (approximately weekly during the heating season) and corrected for temperature. Monitored moisture levels in all locations dropped by the end of the summer following completion of construction, and remained approximately constant through the following winter (Figure 4). Moisture levels remained constant during the second winter as well.

VENTILATION PERFORMANCE DYNAMICS

The clock timer on the HPV unit is set to provide continuous exhaust ventilation, so the unit's exhaust fan (F2) drawing stale air from cell 2 is always activated. If there is a demand for water heating the compressor also operates. If there is a demand for space heat or cooling the supply fan (F3) also activates. Both fans operate at a constant speed and flows must be adjusted by dampers.

The baseline mode of operation has been to adjust fan F1 to maintain a slightly lower pressure at the ceiling of cell 1 than that outside (thus also pressurizing cell 2). This typically resulted in a 2-13 Pa lower pressure at the ceiling of cell 1 relative to outdoors during space heating. The neutral pressure plane was maintained above the ceiling of cell 1, there was no exfiltration, and therefore all air exchange was induced by the HPV unit. The resultant pressure in cell 2 was generally 3 to 7 pascals greater than the pressure in cell 1, during space heating mode of operation. The supply air fan (F3) operates during space heating and cooling, and tends to pressuize the building, by increasing the flow of outside air through the earth tubes.

However, when it is off (during periods of ventilation and water heating), fans F1 and F2 remain on, so the cell 1/cell 2 pressure-difference increases (10 to 20 Pa). Additionally, a manual timer switch in the bathrooms enables short pulses of greatly increased ventilation by boosting fan F1 to full power, and the cell 1/cell 2 pressure-differences become even larger (45 to 60 Pa).

Intermittent measurements by the author indicate that the mechanically induced air exchange rate for the first year has been roughly .6 ACH, or equivalent outdoor air supply for 11 persons at 15 cfm (7 L/s) per person. Since the pressure in cell 1 was lower than the pressure outside (therefore no exfiltration), all the air leaving cell 1 had to pass through fan F1. A Kurz Model 435 Linear Air Velocity Transducer was used to measure the mass flow of air in the duct downstream of fan F1.

The purpose of fan F4 is to pull outdoor air through the earth tubes and provide adequate outdoor air supply. It was found to be unecessary and was not operated. The negative pressure of cell 1 induced sufficient flow in the earth tubes. When the unit's supply fan (F3) did not operate (ventilation and water heating modes) the earth tube flow averaged 27 cfm (13 L/s). When the supply fan operated the average earth tube flow was 57 cfm (27 L/s). Approximately one third of the outside air supply was via the earth tube. Envelope infiltration, due to the induced negative pressure of cell 1, provided the remaining outside air.

The pressure-difference control under these conditions appears to have been very robust. Though pressure-differences were not continuously monitored, they were frequently observed during cold and windy periods. No reversals of the desired pressure-difference directions were observed.

CONTROL OF RADON

RADON PHASE ONE

Five continuous radon monitors (CRMs) were placed in the same location for five days to establish a comparison baseline. The monitors were then placed in five different locations in the building for a thirteen day period between November 11, 1989 and November 23, 1989. Fan F1 was off during the first part of of this period, so that fan F2 depressurized both cell 1 and cell 2 relative to outside.

After the first 112 hours, Fan F1 was activated and adjusted to maintain a slightly lower pressure at the ceiling of cell 1 relative to outside during the space heating mode. This resulted in a 10 to 60 Pa greater pressure in cell 2 (depending on the HPV system's operating mode at time of read).

Cumulative CRM data were recorded intermittently and averaged over each elapsed time period. Thirty-two readings were recorded. Average radon levels in cell 2 decreased dramatically when fan F2 was activated; average radon levels in cell 1 also showed a tendency to decrease (Figure 5).

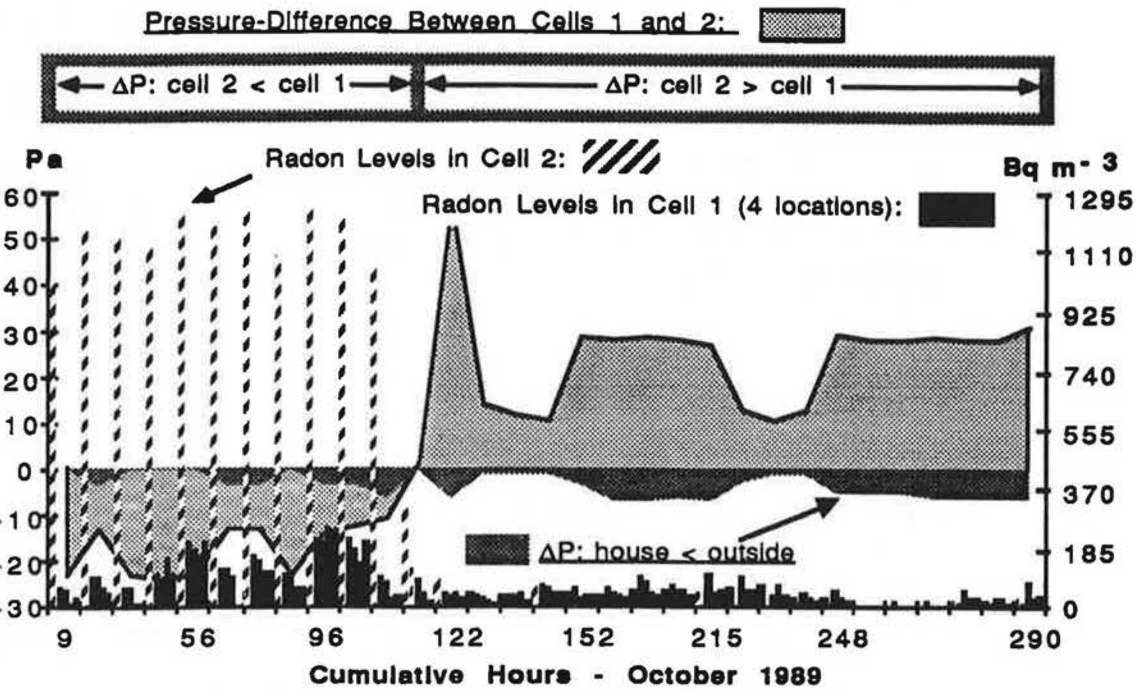

Figure 5. Radon levels in five locations.

RADON PHASE TWO

Two CRMs were placed in separate locations within cell 1 (CRMs 1a and 1b) and two CRMs were placed in separate locations within cell 2 (CRMs 2a and 2b). Hourly radon averages were recorded for the three month period between 17 February and 21 May 1990. During this period, the baseline system configuration (continuously pressurize and flush cell 2 while depressurizing cell 1) was held constant for the first 23 days. Then 9 deliberate alterations in system configuration were made. After each alteration the system was returned to the baseline configuration, before the next alteration was initiated. Upon completion of the 9 alterations the system was returned to the baseline configuration for 22 days.

The alterations had powerful effects upon Cell 2 radon levels, and clear effects upon radon levels in Cell 1. Effects of wind, rainfall, and temperature did not appear to have noticeable influence on radon levels, except that Cell 2 radon levels may have showed some indication of response to temperature. Nonetheless the effect was subtle relative to the effects of system operation.

The baseline system configuration and the alterations to it are discussed below, and referenced in the following graphs.

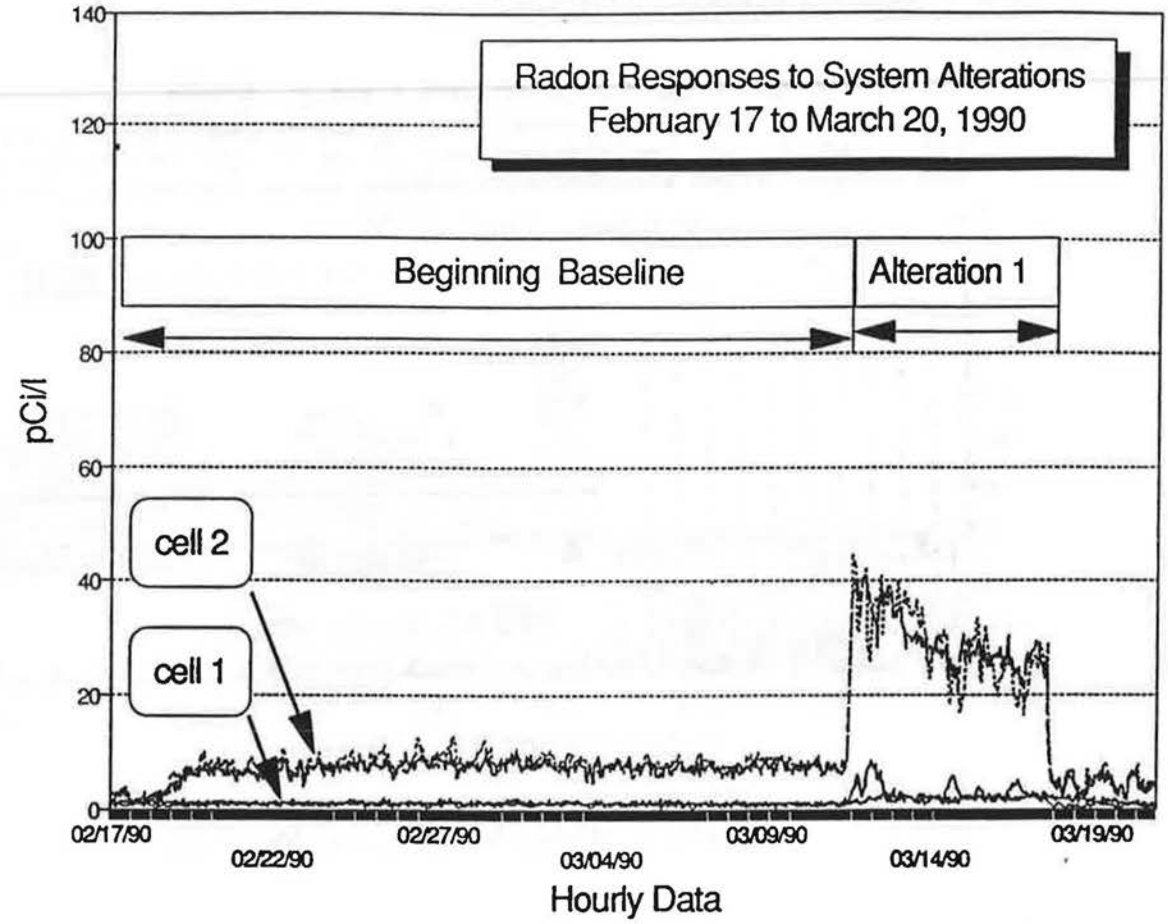

Figure 6. Baseline and Alteration 1.

Baseline. The baseline operating condition was established for 23 days, from 2/17 to 3/11. During this period the average radon concentration in cell 1 was on the order of 1 pCi/l. The average radon concentration in cell 2 was 7 pCi/l. Intermittently recorded cell 2 pressures ranged from 1 to 7 pascals greater than those of cell 1. The average was 3 pascals. Cell 1 was 7 to 15 pascals lower in pressure than outside. The average was 9 pascals.

Alteration 1. Fan F1 was turned off on 3/11 at 10:20 am. The pressure in cell 2 had been greater than the pressure in cell 1, but now shifted to about 30 pascals lower than cell 1, since F2 now pulled air through the cell 2 plenum. In two hours radon levels in cell 2 had increased by a factor of three. Radon levels in cell 2 averaged 29 pCi/l. Radon levels in cell 1 increased also to an average of about 2.5 pCi/l. On 3/17, six days later, fan F1 was turned back on. Pressure in cell 2 returned to 3-4 pascals greater than cell 1. Radon levels in cell 2 dropped by a factor of three in three hours and returned to baseline levels.

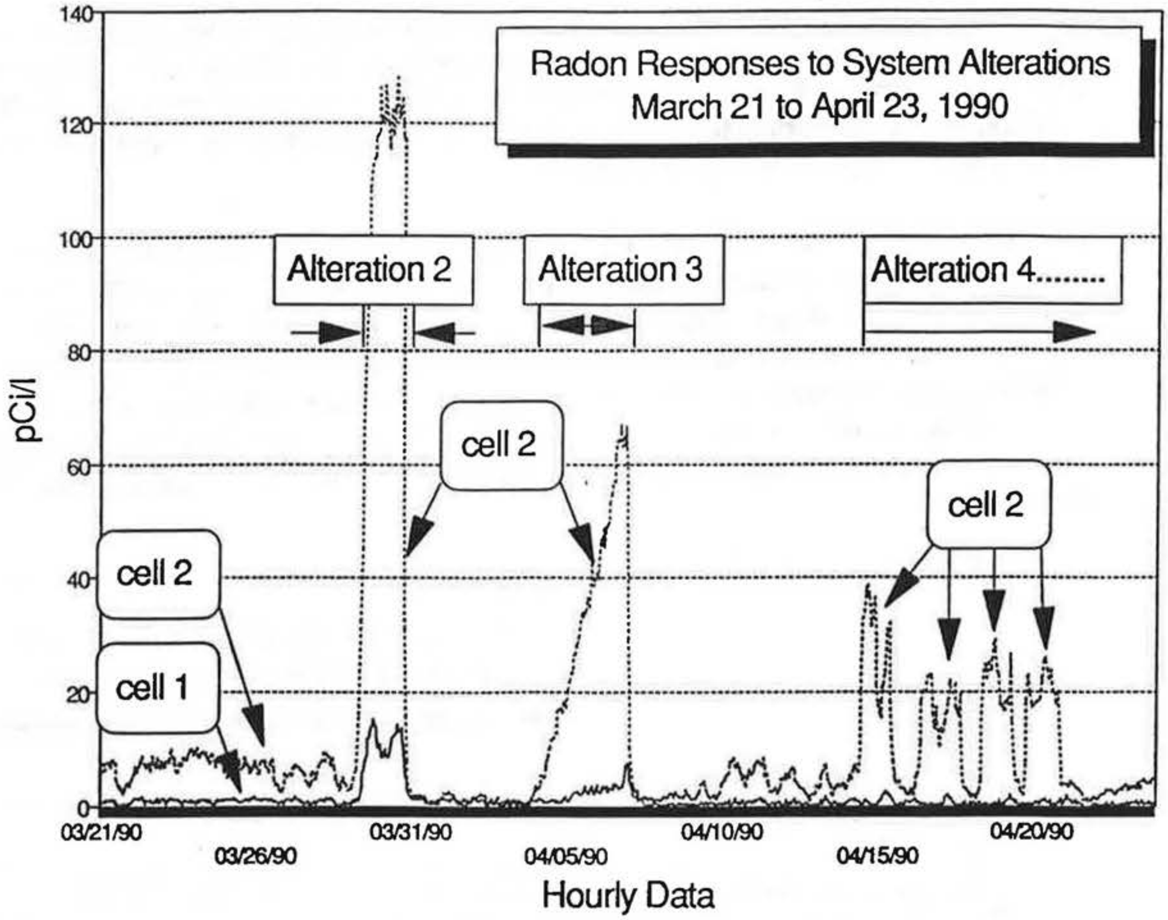

Figure 7. Alterations 2,3, and 4.

__Alteration 2.__ On 3/29 fan F1 was turned off again for approximately 34 hours. F2 continued to operate, but the duct connection from F2 to cell 2 was disconnected and exhaust air taken from cell 1 instead. The ductwork joining the two cells remained open. Cell 2 was atmospherically coupled to cell 1, but was decoupled from the ventilation loop. During this condition the cell 1 pressure was 10 pascals lower than the outdoor pressure and cell 2 was about 7 pascal lower than than the outdoor pressure. Hence, both cells sucked on the ground, but only cell 1 recieved ventilation. Cell 1 radon levels increased by a factor of 12 to an average peak of 12 pCi/l. Cell 2 radon levels increased by roughly a factor of 20 to an average peak of 120 pCi/l. When the system configuration was returned to the baseline, radon levels quickly returned to baseline levels.

__Alteration 3.__ On 4/4 fan F1 was turned off for 62 hours. Also F2 and F3 were turned off. There was no ventilation. The ductwork joining the two cells was sealed to atmospherically decouple the cells from each other. Radon levels in cell 2 rose gradually (whereas in the previous alterations they had risen abruptly) to a peak of

66 pCi/l. Then F1, F2, and F3 were reactivated and radon levels in both cells returned abruptly to baseline levels. The pattern of a more gradual rise in radon levels also seemed to occur in the cell 1 radon levels which rose to over 5 pCi/l. The gradual rise is assumed to be attributed to soil recharging and the slower response related to the lesser stack pressures.

The three fans were activated 62 hours after the initial alteration. However, cell 2 remained atmospherically decoupled from the ventilation cycle (F2 drew exhaust air from cell 1), as well as isolated from cell 1 by the sealed ductwork. The condition was that cell 2 was pressurized by fan F1 but there was no flushing of the air in cell 2. The resultant pressure in cell 2 was 45 pascals greater than that in cell 1. Radon levels returned to baseline in about 6 hours, hence were already at baseline levels when the ductwork was reconnected and the system configuration returned to baseline.

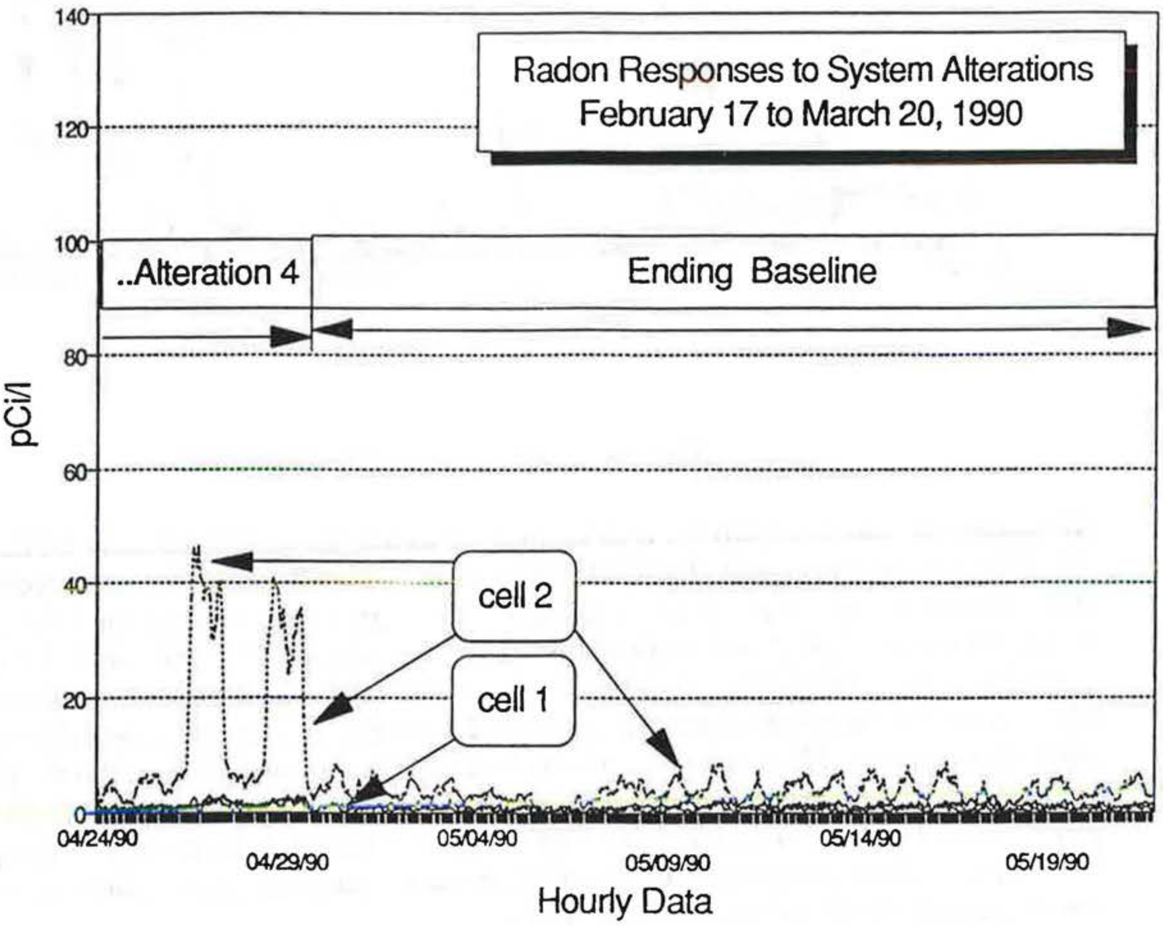

Figure 8. Alteration 4 and Baseline.

__Alteration 4.__. Fan F1 was turned off. The system was altered as described in alteration #2 for roughly 24 to 30 hours, then returned to the baseline configuration. This process was repeated six times. In each case cell 2 radon levels responded as they had in alteration #2.

Baseline. The baseline operating condition was restablished for 22 days, from 4/29 to 5/21. During this period the average radon concentration in cell 1 was less than one pCi/l. The average radon concentration in cell 2 was about 2.5 pCi/l.

There is some uncertainty associated with the radon measurements. The CRMs were research instruments that were not calibrated immediately prior to these measurements. However, they were compared to each other by operating them in the same location for six days at the beginning of this project. All 4 CRMs tracked radon levels consistently (Figure 9).

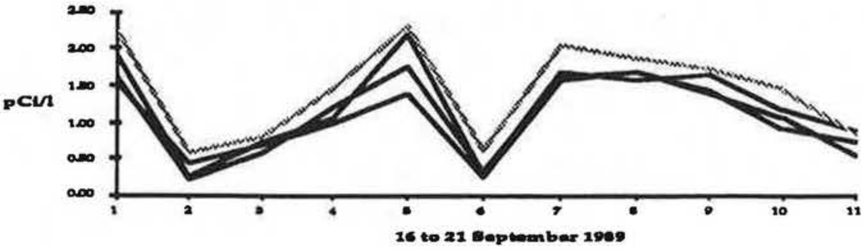

Figure 9. Radon instrument comparisons.

Several months after the project they were again compared to each other, and it was discovered that only CRM 1a had a correctly operating air pump. This CRM was then compared for about 30 hours to a Pylon AB5 with a PRD, which had been recently calibrated with a Pylon Calibration Standard. The two monitors tracked radon fluctuations consistently. When the data from this project was later reviewed*, it was discovered that CRMs 1b and 2b had diverged widely (radon levels declined) from their respective matched pairs and never recovered. These were suspected to be the points of pump failure. Data from these units was removed from the data set for the time periods after their responses suggested pump failures.

CRMs 1a and 2a did respond in a consistent manner throughout the entire measurement period. Fortunately one was located in cell 1 and the other in cell 2. It was also fortunate that CRM 1a -- which was recording the lowest and least variable radon levels -- was also the CRM that continued to have a correctly operating pump and was compared to the calibrated Pylon instrument after the study. Both the consistent response of these two remaining CRMs to the repetitive nature of alteration #4, and the similarity of their ending baseline responses to their starting baseline responses, suggest that these two CRMs responded with acceptable accuracy to radon fluctuations throughout the study.

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* This study was not funded and was conducted as time allowed.

It is not known when the the pump on CRM 2a began to fail. The data set suggests that CRM 2a was operating correctly during the study period and likely failed after the study period.

COST

It is very difficult to assign costs to the radon prevention and mitigation features of this building, since virtually all the features that control radon also enhance energy performance, durability, comfort, and the control of other pollutants. The simple energy-only payback for these features is 10 to 20 years. The building's useful life has also been extended due to such features as the vented rain screen designed to extend siding life, and the elimination of air transported moisture into the exterior walls. Since these features primarily address energy, and there is a clear energy payback for them, it can be argued that there is no incremental cost for the control of radon entry. The building cost $80,824, approximately $45 to $48 per square foot.

INDICATIONS

1. Control of soil-air entry with pressure-differences using a continuous mechanical ventilation system incorporated into a tight house is readily achievable.
2. The initial radon experiment indicates that the radon source at this building location may be sufficient to allow the demonstration of radon control, as well as the comparison and evaluation of the impact of different pressure-difference configurations on radon entry.
3. Airflows through the HPVAC-80 can be reduced by installation and adjustment of dampers so that the flows necessary to maintain required pressure-differences can be reduced (within the limits of the range of flows required by the HPV). The target goal of maintaining soil gas entry control with a mechanical system operating at .35 ACH may be achievable at this level of envelope tightness.
4. Careful attention to air-vapor barrier installation can enable sufficient control of moisture levels in the Spokane climate, even under conditions of constant and relatively large pressurization.

FUTURE DIRECTIONS

- Evaluate this concept at sites where the known soil radon source is high.
- Evaluate the degree of pressure-difference necessary to control radon and determine the associated air exchange rates, climatic conditions, and energy costs.
- Compare different pressure-difference scenarios and their impact on radon levels.

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