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Pressure Differentials for Radon Entry Coupled to Periodic Atmospheric Pressure Variations

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Abstract

A dedicated research house is used to investigate the interactions of the house, soil, and atmosphere on indoor radon concentrations. Semi-diurnal variations of atmospheric pressure, resulting from atmospheric tides, are observed to produce differential pressures capable of driving radon-containing soil gas into slab-on-grade structures built over low permeability soils. These naturally induced pressure differentials could continue to provide major contributions to radon entry when other sources of house pressurization or depressurization, and consequently outdoor air infiltration rates, are small. The observed driving force pressure differentials are well predicted from atmospheric pressure changes by a simple model based on an exponentially damped response of the sub-slab pressures to changes in atmospheric pressure. The observed radon entry rates are in good agreement with the predictions of radon entry models developed by other investigators when time-averaging of the driving forces is applied.

KEY WORDS:
Indoor radon, Atmospheric pressure, Pressure-driven flow, Depressurization, Radon entry, HVAC

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Introduction

It is widely accepted that the entry of radioactive ^{222}Rn (radon)-laden soil gas into residential structures occurs principally through pressure-driven flow processes, with much smaller contributions from diffusion processes. House depressurization contributes to increased radon entry rates by increasing the pressure-driven flow of radon-containing soil gases into the structure. Typical sources of house depressurization that have previously been investigated include wind and temperature effects (Nazaroff et al., 1987), the stack effect (Nero, 1988; Nazaroff et al., 1988), and the mechanical depressurization of a structure by household appliances and the heating, ventilation and air-conditioning (HVAC) system. Other investigators have proposed that transient atmospheric pressure changes associated with changing meteorological conditions contribute to radon transport (Tsang and Narasimhan, 1991; Narasimhan et al., 1990; Owczarski et al., 1990; Clements and Wilkening, 1974). In this paper we present experimental evidence and a simple model to describe how periodic barometric pressure changes associated with atmospheric tides can provide a driving force for the pressure-driven flow of soil gas into structures built over low permeability fills and soils.

The data presented were collected on a dedicated research house operated by the University of Florida (UF) as part of the Florida Radon Research Program. The research program is directed towards the development of radon-resistant building codes for Florida houses. The research house effort by the University of Florida is designed to provide a detailed characterization of the effects of HVAC-induced radon entry and modeling of the radon entry and transport. The research house is extensively instrumented to monitor a number of key parameters simultaneously.

Our experiments demonstrate that the neutral pressure conditions that exist when no mechanical pressurization or depressurization of the house occurs (i.e. for a well balanced HVAC system) can be particularly critical for producing elevated indoor radon concentrations. This paper demonstrates a mechanism creating a driving force that can contribute to elevated indoor radon concentrations even for structures maintained under neutral pressure conditions.

Methodology

The University of Florida Radon Research House is a 163 m^2 (1750 square foot) single story residential structure that utilizes slab-on-grade type of construction with a 10.1 m × 16.2 m footprint. Fill materials are sandy with a measured air permeability averaging 2×10^{-11} m^2. The foundation consists of a poured concrete slab set on a 0.5 m deep block stemwall. Interior plumbing penetrations and a perimeter crack having a width less than 1×10^{-3}m provide soil gas entry routes into the structure. The house remains unoccupied for all experimental periods and data is collected by an IBM PS/2 computer interfaced to a Keithley Metrabyte data acquisition and control system. The house has been instrumented with a variety of instrumentation for measurement of the critical parameters in these studies.

Characterization of the house shell and HVAC duct system leakage area were performed using both a blower door/calibrated fan and flow hood to quantify flow rates through individual ducts. These tests measure a ventilation rate of 7.6 air changes per hour at 50 Pa house depressurization (ACH_{50}), which is very close to the average for houses surveyed across Florida by the Florida Solar Energy Center (FSEC) (Cummings et al., 1991). The duct system is well balanced and the 3-ton HVAC unit is typical for a Florida house of this size.

The house was artificially pressurized, or depressurized, during the experimental periods using the blower door/calibrated fan apparatus. A constant differential pressure was maintained until equilibrium radon concentrations were reached and maintained for at least another 24 hours.

Pressure transducers monitor differential pressures across the house shell. Setra model C264 pressure transducers having full-scale ranges to ± 25 Pa provide a current output that is monitored continuously by the Keithley Metrabyte system. Measurements are recorded once every 600 seconds by the interfaced IBM PS/2. The minimum sensitivity of the pressure transducers is less than 0.25 Pa. All pressure transducers are zero checked at the beginning of each experimental period and calibrated monthly.

Pressure transducers monitor the indoor/outdoor differential pressure across each exterior wall of the house. The exterior pressure port is covered by a perforated, hollow sphere to dampen rapid pressure variations caused by wind gusts.

An array of sixteen pressure transducers are distributed across the slab in a uniform grid pattern. These transducers monitor the differential pressure above and below the concrete slab at each grid point. Indoor pressure is very uniform throughout the house interior during the experiments described here. Variations in sub-slab/indoor pressure differentials measured across the slab at different locations are therefore representative of the spatial variation of sub-slab pressures.

Temperature is monitored in each room, the supply and return ducts, HVAC thermostat location, attic and outdoors with thermocouples. A meteorological station located on site monitors wind direction, wind speed, and rainfall. Barometric pressure measurements were measured hourly by the Gainesville, Florida Flight Service Station (FSS) operated by the Federal Aviation Administration. The FSS is located 12.5 km from the research house. The close proximity of these sites, coupled with the slow spatial variation of barometric pressure (typical gradients are on the order of 1 Pa km^{-1}) (Blair and Fite, 1965), permits us to be reasonably assured that these pressure measurements are equivalent to the atmospheric pressure at the research house.

Indoor radon concentrations were measured continuously throughout each experimental period. Pylon AB-5 radon monitors utilizing the passive radon detector (PRD) were used to continuously measure indoor radon. Counts accumulated over 600 second intervals are stored to the radon monitor memory at the end of each interval and downloaded to an IBM PC at the conclusion of the experimental period. Sub-slab radon concentrations were measured using Pylon AB-5 radon monitors and flow-through scintillation cells. Soil gas grab samples were collected from a sampling port near the center of the slab and held for 4 hours prior to counting. Each monitor is calibrated through intercomparisons performed through the DOE Environmental Measurements Laboratory radon measurement intercomparison program.

The same experimental protocol is followed for each experimental period. Experiments typically

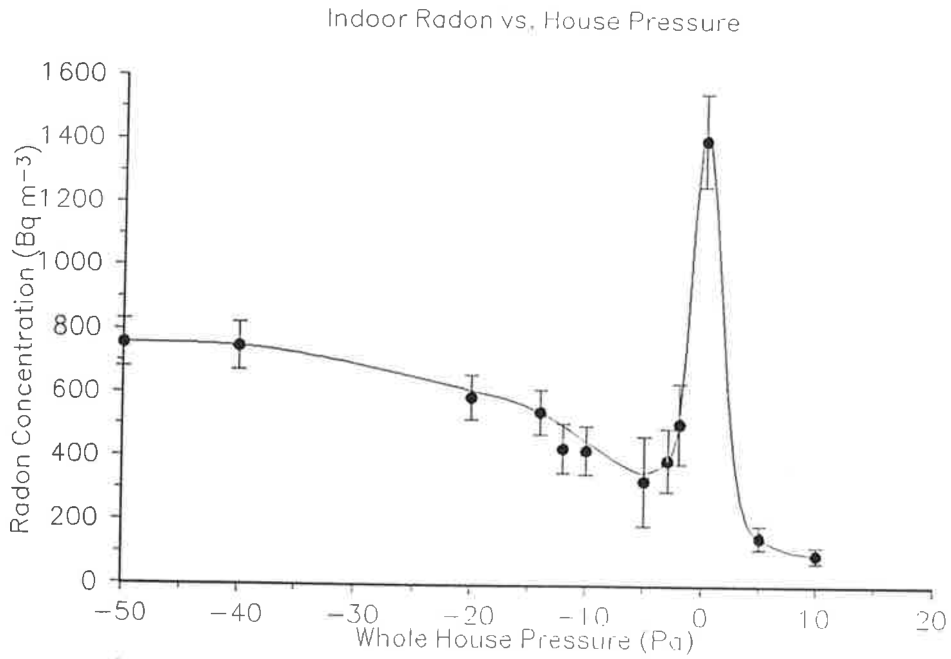

Fig. 1 Equilibrium indoor radon concentration for the UF Radon Research House as a function of whole house pressure. Negative pressure denotes the house depressurized relative to the outdoors, positive pressure denotes pressurization relative to the outdoors.

consist of performing zero checks on all instrumentation and transducers, setting the desired differential pressure using the blower door, and monitoring the instrumentation over a period of time. The experimental period is typically 96 hours. This provides information on the transient response of the house system as well as the steady-state values of each parameter after the house system has stabilized.

Results and Discussion

Figure 1 illustrates how the indoor radon concentrations vary in the UF Radon Research House with the magnitude of whole house pressurization/depressurization. Each of these measurements represents at least one 24-hour average of the equilibrium indoor radon concentration for each pressurization or depressurization level. The highest concentrations of indoor radon occur when the house is maintained under neutral pressure conditions. This is surprising because the pressure-driven flow contributions under neutral, or low, pressure are generally expected to be very close to zero.

Neutral pressure conditions are defined to exist when the research house experiences indoor/outdoor pressure differentials of less than 1 Pa.

The investigation to explain the elevated indoor radon concentrations under these conditions focuses on pressure-driven flow mechanisms, since no established diffusion-driven mechanisms appear capable of producing the observed radon entry rates and indoor concentrations (Clements and Wilkening, 1974). In order to explain the elevated radon concentrations under neutral pressure conditions, we examined the time-dependent behavior of small amplitude pressure differential variations across the house shell and slab. It is important to note that the pressure differential across the house shell (i.e. indoor/outdoor across the walls) and across the slab (indoor/sub-slab) are not well coupled. Most models for radon entry assume the outdoor and sub-slab air volume pressures to be identical, which we demonstrate to be inaccurate for houses built over low-permeability fill materials.

Pressure differentials monitored across the walls of the house demonstrate that outdoor and indoor pressures are well coupled. The measured ACH_{50} of 7.6 and ELA_4 of 0.06 m^2 permit infiltration air to quickly equalize indoor and outdoor pressures. Figure 2 illustrates that the average indoor/outdoor pressure differentials are not well coupled to the indoor/sub-slab pressure differentials. A small diurnal cycle is exhibited by the indoor/outdoor pressure differentials having a peak amplitude of approximately 0.5 Pa. The effect of wind on the house shell is detected by pressure differentials measured across different walls of the house shell. If the pressure differential across each wall is averaged, however, it becomes evident that the wind does not typically result in substantial indoor/outdoor pressure differentials. The small variation of the indoor/outdoor pressure differential illustrates that the indoor pres-

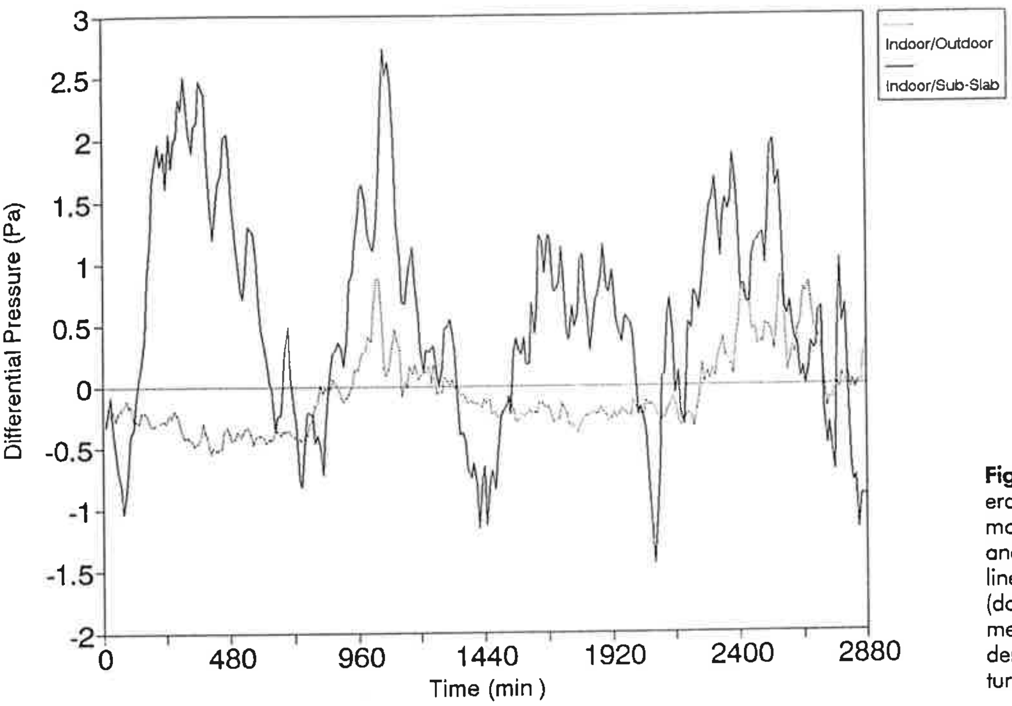

Fig. 2 Time variation of the average differential pressures monitored between the indoor and sub-slab volumes (solid line) and indoor and outdoors (dotted line) with no active mechanical pressurization, or depressurization, of the structure.

sure responds nearly instantaneously to variations of the outdoor pressure.

Output from pressure transducers distributed across the floor slab of the house indicate that the indoor/sub-slab pressure differentials are substantially larger than the indoor/outdoor pressure differentials. Figure 3 illustrates the indoor/sub-slab pressure differential observed at two points on the slab. Figure 3a shows the response at a point located 1 m from the edge of the slab and 3b shows the response at a point located near the center of the slab (4 m from the nearest edge). Comparison of the indoor/sub-slab and indoor/outdoor pressure differentials shows that the sub-slab air volume is not well coupled to the indoor, and consequently, the outdoor air volumes. The magnitude of the pressure differentials observed in Figure 3 are nearly an order of magnitude greater than the indoor/outdoor pressure differentials of Figure 2, with the peaks from the centrally located point reaching nearly 4 Pa.

It is important to note that the indoor/sub-slab pressure differentials vary with a semi-diurnal periodicity (12-hour cycle), rather than a diurnal period (24-hour cycle). The source of this semi-diurnal period provides an explanation for elevated indoor radon concentrations under neutral indoor/outdoor pressure conditions. Barometric pressure data collected over the same time period (Figure 4) illustrate a similar semi-diurnal periodicity. Comparison of the pressure variations of Figures 3 and 4 illustrate that both vary with identical periods although the indoor/sub-slab pressure differential lags in phase behind the barometric pressure oscillations.

The semi-diurnal variation of barometric pressure is a well documented result of atmospheric tides resulting from solar heating and coriolis forces on the earth (Beer, 1976; Fejer, 1967). While they are frequently small in amplitude compared to barometric pressures associated with changing meteorological conditions, they are readily observable. These oscillations have been largely ignored by radon researchers searching for radon entry mechanisms. We believe, however, that this effect is responsible for the elevated indoor radon concentrations in many houses, particularly those built over low permeability soils and fills where soil gas velocities are low.

Atmospheric tide-induced oscillation of barometric pressure provides a natural pumping of soil gas and radon into houses by inducing oscillating indoor/sub-slab pressure differentials. The cyclic pressure differentials across the slab provide a natural driving force for the pressure-driven flow of soil gas radon into the house. Although the radon entry rates associated with this mechanism may be small, it is present at all times. This mechanism is particularly significant because it provides a means of pumping radon into a house without depressurizing the interior of the house relative to the outdoors. Other mechanisms that result in house depressuri-

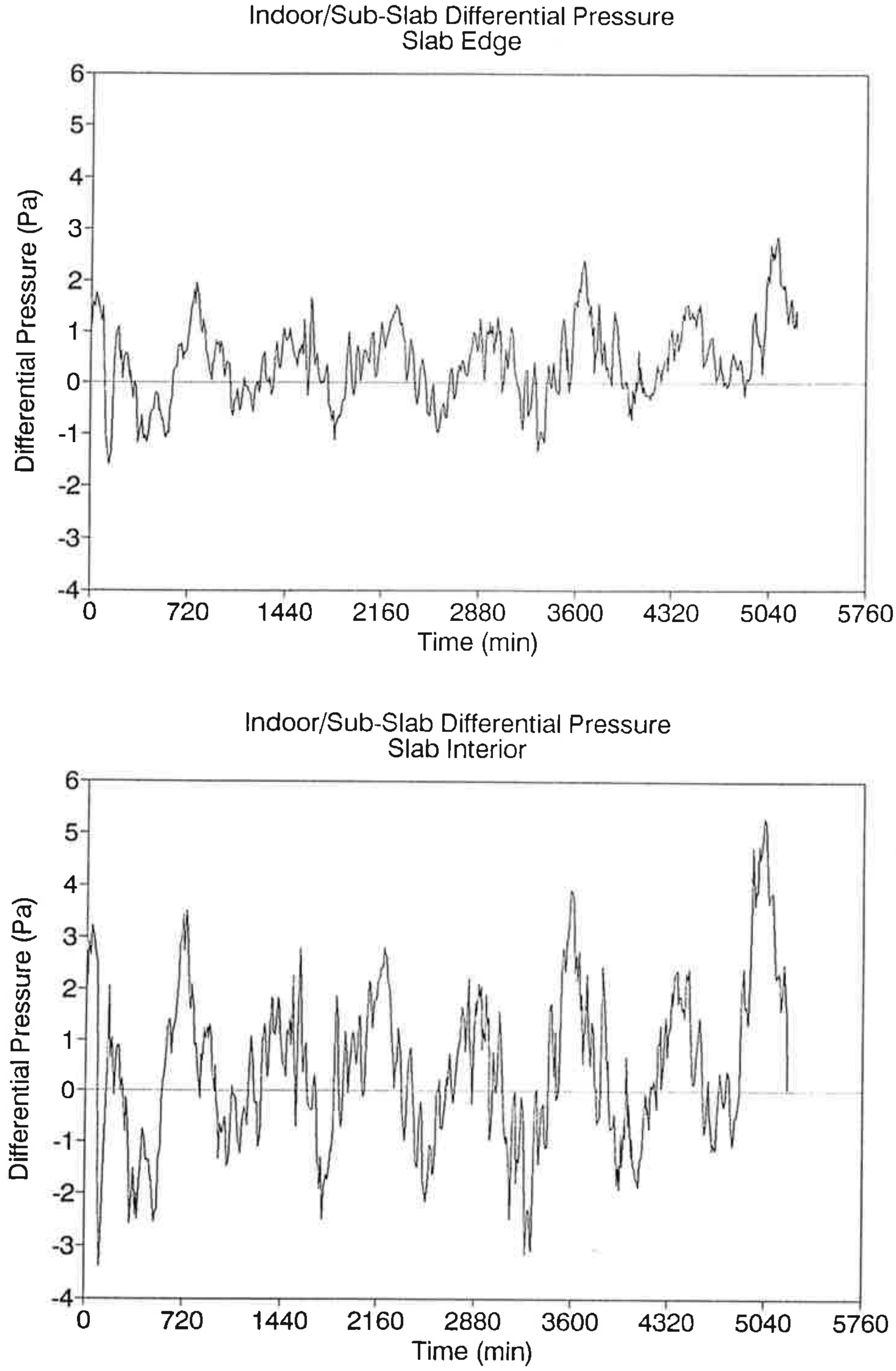

Fig. 3 Time variation of the differential pressures monitored between the indoor and sub-slab volumes; (a) 1 m from the slab edge and (b) near the center of the slab.

zation relative to outdoors also provide greatly increased air exchange rates, with enough infiltration air to significantly dilute, and frequently lower, indoor radon concentrations. Increased air infiltration does not occur when this pressure-driven flow mechanism is present. Thus under "neutral pressure" conditions barometric pressure variations provide radon entry, but little infiltration air since the outdoor/indoor pressures equalize so quickly, resulting in the build-up of elevated indoor radon concentrations.

A quantitative prediction of the indoor/sub-slab pressure differentials may be determined by recognizing that airflow into and out of the sub-slab air volume is heavily damped by low permeability soils and fill. When rapid changes in barometric pressure

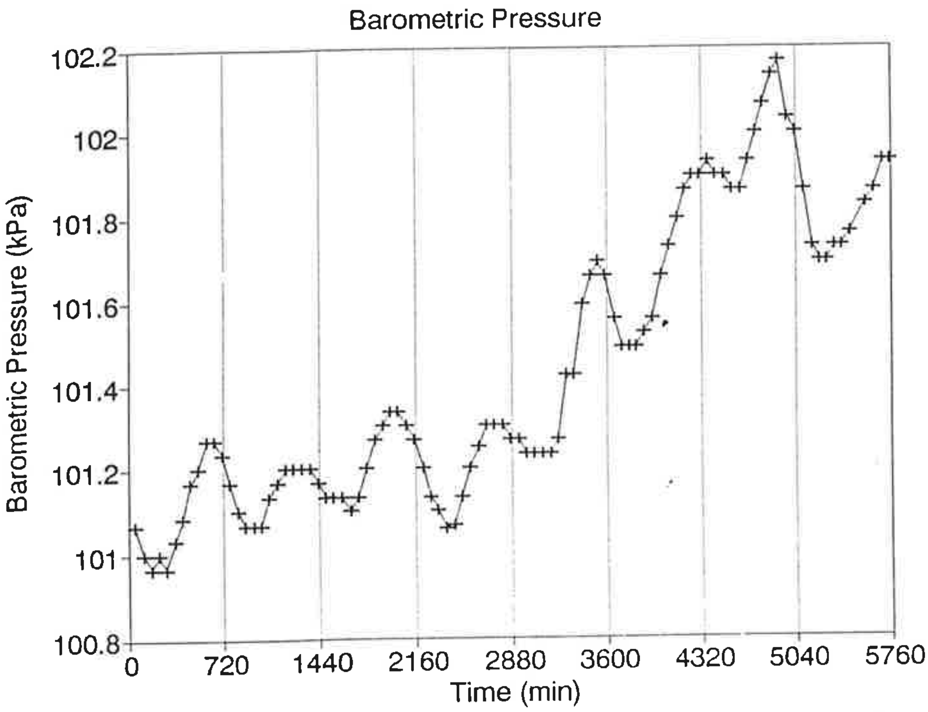

Fig. 4 Time variation of the barometric pressure (+) and modeled pressure in the sub-slab volume near the center of the slab (solid line).

occur, the indoor pressure equalizes with the outdoor pressure very rapidly, but the sub-slab pressures respond much slower because of the slow airflow into, or out of, the sub-slab volume.

The flow velocity of gas through permeable soils is governed by Darcy's Law:

$$v = -\frac{k}{\mu} \nabla P \quad (1)$$

where k is the air permeability of the soil (m^2), μ is the soil gas dynamic viscosity (1.8×10^{-5} Pa s) and ∇P describes the driving force pressure differential (Pa m^{-1}). An elementary calculation for barometric pressure changes of a few hundred Pa applied over several meters (the characteristic length from the edge to center of the slab) shows that the expected soil gas flow velocities are $< 10^{-2}$ m s^{-1}. For the distances and volumes typically encountered, these velocities represent sub-slab pressure response times on the order of tens of minutes. The equilibration of sub-slab volume pressures with outdoor pressures is therefore heavily damped and we expect the absolute sub-slab volume pressures to respond slowly, when compared to indoor pressures, to variations of barometric pressure.

We quantitatively model the sub-slab pressure response to outdoor barometric pressure change as a damped exponential. Thus, a step function change in barometric pressure results in the pressure of the sub-slab responding with an exponential approach to the new pressure, governed by a response time, T_R. The sub-slab pressure after each time interval, Δt, is calculated by:

$$P_{ss}(t+\Delta t) = P_b(t+\Delta t) - [P_b(t+\Delta t) - P_{ss}(t)] \exp(-\Delta t/T_R) \quad (2)$$

where $P_{ss}(t)$ is the sub-slab pressure at time, t, $P_b(t)$ is the barometric pressure and T_R is the characteristic time for the sub-slab volume to adjust to the pressure change. We model the sub-slab pressure over time by assuming that each hourly measurement of barometric pressure acts as a step function change in the pressure at the time of measurement. The response of the sub-slab pressure is then calculated, resulting in the solid line passing near the measured barometric pressure readings of Figure 4.

The difference between the absolute barometric pressure (discrete points in Figure 4) and calculated absolute sub-slab volume pressure (solid line in Figure 4) provides a prediction of the indoor/sub-slab pressure differential (Figure 3).

The results of this calculation produce the heavy lines of Figure 5, where only the response time of the sub-slab volume, T_R, is varied to obtain the illustrated fit. The predicted curves for both Figure 4 and Figure 5 result from T_R = 19 minutes. T_R is

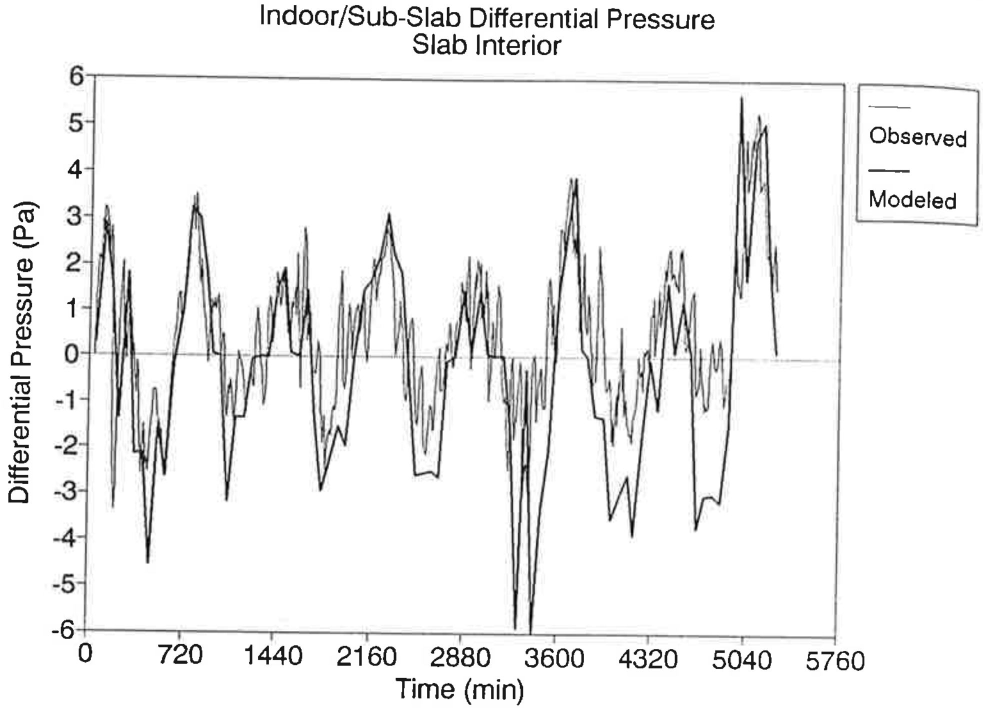

Fig. 5 Time variation of the modeled differential pressure between the indoor and sub-slab volumes near the center of the slab with T_R = 19 minutes (heavy solid line) superimposed over the measured differential pressure (thin solid line).

sensitive enough that the fit for T_R = 19 minutes is distinguishable from fits obtained by varying $T_R \pm$ 1 minute. The predicted indoor/sub-slab pressure differential matches not only the periodicity and magnitude of the observed pressure differential, but also provides the appropriate phase delay from barometric pressure oscillations that drive the indoor/sub-slab pressure differential.

On the absolute pressure scale of Figure 4 the difference between sub-slab and outdoor pressures is barely discernible. On the scale of Figure 5, however, the agreement between the predicted and observed indoor/sub-slab pressure differential demonstrates the significance of the damped response of the sub-slab air volume to barometric pressure changes for creating natural pressure differentials that drive radon into residential structures. Soil gas radon is naturally drawn into the structure as the indoor/sub-slab pressure differential oscillates between a positive and negative pressure differential. During the positive portion of the cycle, sub-slab pressures are greater than the indoor pressure, and provide pressure-driven flow of soil gas into the building interior. It may be expected that the cyclic nature of radon entry into the house might be observed from time-dependent measurements of indoor radon concentrations. We have attempted to observe this by monitoring the build-up of radon in the research house following complete ventilation of the house. The indoor radon concentration initially increases linearly, the slope of which permits us to calculate a radon entry rate of 6.8 Bq s^{-1}. Time-dependent variations of the indoor radon concentration are not well enough resolved to be correlated with the time-dependent, semi-diurnal, pumping mechanism because of the damping effects of the large house volume and slow (approximately 2 hour) response time of the continuous radon monitor.

The average radon entry rate may be quantitatively predicted by modeling the flow of sub-slab radon that would be driven into the house by the mean of the positive portion of the indoor/sub-slab pressure differential cycle. From the data of Figure 3a we calculate the time-averaged radon driving-pressure differential to be 0.9 Pa. Nielson and Rogers (1991) have developed a model for radon transport and entry (RAETRAD) for a simple cylindrical slab-on-grade structure. For sub-slab radon concentrations of 1.295×10^5 Bq m^{-3}, as observed at the UF research house, RAETRAD predicts a radon entry rate of 7.5 Bq s^{-1}, at 0.9 Pa house depressurization, comparable to our observation of 6.8 Bq s^{-1}.

The house parameters utilized by RAETRAD are similar to, but do not precisely describe the UF research house. The RAETRAD prediction is based upon a 140 m^2 cylindrical slab-on-grade structure built over sandy soil, with pressure-driven radon entry through a 1×10^{-2} m wide perimeter crack. The structure of our slab is 14% larger, of rectangular shape, has a smaller perimeter crack, and includes plumbing penetrations. Current research efforts are addressing the adaptation of RAETRAD to the specific conditions at the UF radon research house in order to provide a more accurate comparison between observed quantities and theoretical predictions, as well as the extension of the model to account for time-dependent variations of the pressure-driven flow. Although the physical structure has not been exactly modeled and we have approximated the time-varying driving force with the time-averaged differential pressure contribution to the driving force, the good correlation between observed and predicted values demonstrates the feasibility of the proposed mechanism. Numerical modeling studies (Tsang and Narasimhan, 1991; Narasimhan el al., 1990) provide qualitatively similar predictions and predict that this mechanism can dominate radon entry under certain conditions. Detailed comparisons with our experiments are, however, limited by the different foundation types (basement vs. slab-on-grade) and pressure pumping periods between the modeled and experimental conditions. Our observations and elementary theoretical predictions are consistent with the application of natural variations of barometric pressure as a driving force contributing to elevated indoor radon concentrations.

Conclusions

The semi-diurnal variation of barometric pressure provides a potentially dominant driving force for radon entry into houses built over low permeability soils and fills. The driving force is the pressure differential that results from the slow response of the sub-slab air volume to outdoor pressure changes, compared to the indoor response. These naturally induced, periodic pressure differentials could provide an additional source of radon entry when other sources of house pressurization or depressurization, and consequently air infiltration rates, are small. These effects dramatically influence the philosophy of design of HVAC systems related to minimizing indoor radon concentrations. Under conditions where the HVAC system is well balanced, little house pressurization/depressurization occurs, and natural atmospheric pressure variations may contribute to significantly elevated indoor radon concentrations. Continuing research is evaluating the impact of this radon entry mechanism on the optimum parameters for HVAC system operation and design in radon-prone geographical regions in order to minimize indoor radon concentrations.

Acknowledgement

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References

Beer, T. (1976) *The Aerospace Environment*, New York, Springer-Verlag, pp. 52-55.

Blair, T.A. and Fite, R.C. (1965) *Weather Elements*, Englewood Cliffs, N.J., Prentice Hall, pp. 122-123.

Cummmings, J.B., Tooley, J.J. and Moyer, N. (1991) *Investigation of Air Distribution System Leakage and its Impact on Central Florida Houses*, Cocoa Beach, FL., Florida Solar Energy Center (Report FSEC-CR-397-91).

Clements, W.E. and Wilkening, M.H. (1974) "Atmospheric pressure effects on ^{222}Rn transport across the earth-air interface", *Journal of Geophysical Research*, **79** (33), 5025-5029.

Fejer, J.A. (1967) "Atmospheric tiders". In: Fairbridge, R.W. (ed.) *The Encyclopedia of Atmospheric Sciences and Astrogeology*, New York, Reinhold Publishing, pp. 97-105.

Narasimhan, T.N., Tsang, Y.W. and Holman, Y. (1990) "On the potential importance of transient air flow in advective radon entry into buildings", *Geophysical Research Letters*, **17(6)**, 821-824.

Nazaroff, W.W., Lewis, S.R., Doyle, S.M., Moed, B.A. and Nero, A.V. (1987) "Experiments on pollutant transport from soil into residential basements by pressure-driven airflow", *Environmental Science Technology*, **21**, 459-466.

Nazaroff, W.W., Moed, B.A. and Sextro, R.G. (1988) "Soil as a source of indoor radon: generation, mitigation and entry". In: Nazaroff, W.W. and Nero, A.V. (eds) *Radon and its Decay Products in Indoor Air*, New York, John Wiley & Sons, pp. 57-112.

Nero, A.V. (1988) "Radon and its decay products in indoor air: an overview". In: Nazaroff, W.W. and Nero, A.V. (eds) *Radon and its Decay Products in Indoor Air*, New York, John Wiley & Sons, pp. 1-52.

Nielson, K.K. and Rogers, V.C. (1991) "Modeling indoor radon entry from soil radon emanation and transport". In: Hintenlang, D.E. (ed.), *Proceedings of the Radon Modeling Workshop of the Florida Radon Research Program*, Research Triangle Park, N.C., US EPA – AEERL, (in press).

Owczarski, P.C., Holford, D.J., Freeman, H.D. and Gee, G.W. (1990) "Effects of changing water content and atmospheric pressure on radon flux from surfaces of five soil types," *Geophysical Research Letters*, 17(6), 817-820.

Tsang, Y.W. and Narasimhan, T.N. (1991) *Effects of Periodic Atmospheric Pressure Variation on Radon Entry into Buildings*, Berkeley, CA, Lawrence Berkeley Laboratory Report LBL-31164, (submitted to Journal of Geophysical Research).