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THE IMPACTS OF BALANCED AND EXHAUST MECHANICAL VENTILATION ON INDOOR RADON

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Abstract

Models for estimating radon entry rates, indoor radon concentrations, and ventilation rates in houses with a basement or a vented crawl-space and ventilated by natural infiltration, mechanical exhaust ventilation, or balanced mechanical ventilation are described. Simulations are performed for a range of soil and housing characteristics using hourly weather data for the heating season in Spokane, WA. For a house with a basement, we show that any ventilation technique should be acceptable when the soil permeability is less than approximately $10^{-12} m^2$. However, exhaust ventilation leads to substantially higher indoor radon concentrations than infiltration or balanced ventilation with the same average air exchange rate when the soil permeability is $10^{-10} m^2$ or greater. For houses with a crawl-space, indoor radon concentrations are lowest with balanced ventilation, intermediate with exhaust ventilation, and highest with infiltration.

Introduction

In U.S. houses with elevated indoor radon (Rn) concentrations, pressure driven flow is generally the primary mechanism by which Rn enters.[1] For example, the flow of soil gas through penetrations in a basement floor and the flow of air from a crawl space to a living space can carry Rn into houses. Pressure differences, caused by wind and because heated indoor air is less dense than outdoor air, can drive these flows. These pressure differences also drive infiltration -- the uncontrolled leakage of air through cracks and holes in building envelopes. Mechanical exhaust ventilation can also drive both Rn entry and ventilation since it causes a slight decrease in indoor air pressure. In contrast, balanced mechanical ventilation, which occurs when one fan supplies outdoor air to the house and another fan exhausts an equal amount of indoor air to outdoors, will increase the ventilation rate but have no effect on Rn entry. Since ventilation is also the primary process by which Rn is removed from indoors, the net effect of various methods of ventilation on indoor Rn must be considered.

Models

Models were developed for estimating radon entry rates, ventilation rates, and indoor Rn concentrations in houses with either a basement or a naturally ventilated crawl space. Some validation of the models has been performed[2] but further validation is desirable. In this paper, only an abbreviated description of the models and key assumptions are provided -- detailed information is available elsewhere.[1,2]

Pressure Differences

The first step is to estimate the magnitude of the pressure differences which drive Rn entry. We use procedures that were originally derived for models of air infiltration in buildings.[3] We also borrow the concept of "effective leakage area" (ELA) from infiltration models where the ELA is a measurable indicator of the resistance to air flow through a building envelope. The indoor-outdoor pressure difference at the level of the basement floor (ΔP_f) is used to estimate the rate of soil gas entry into basements,[2] where

$$\Delta P_f = \Delta P_s + \Delta P_w + \Delta P_{ev}, \quad (1)$$

and each pressure difference is an outdoor pressure minus an indoor pressure.

The term ΔP_s is the stack - (i.e., temperature -) induced indoor-outdoor pressure difference at floor level

$$\Delta P_s = \rho g \Delta T \, (z_f - z_n)/T_i \quad (2)$$

where: ρ is the density of air, g is the acceleration due to gravity, ΔT is the indoor temperature minus outdoor temperature, T_i is the indoor temperature, z_f is the height of the floor (normally set equal to zero), and z_n is the height of the neutral pressure level. The neutral pressure level is the level at which indoor and outdoor pressures are equal when only the stack effect is acting and z_n can be estimated mathematically if the ELA of the total building, plus the ELAs of the floor and ceiling are known.[1,3] However, for houses with a basement, it is difficult to justify any particular assumptions regarding the distribution of ELA and, when a basement is present, we simply assume that the neutral pressure level is half way up the above-grade wall.

The term ΔP_w is proportional to the square of the wind speed (w)

$$\Delta P_w = C_i \rho w^2/2 \quad (3)$$

where: C_i is calculated based upon building geometry, distribution of ELA, and the degree of shielding from the wind. In general, wind will lead to a slight depressurization.

The final differential pressure term, ΔP_{ev}, is the pressure difference that results from mechanical exhaust ventilation,

$$\Delta P_{ev} = (\rho/2)\,(Q_{ev}/ELA)^2 \tag{4}$$

where: Q_{ev} is the exhaust flow rate and ELA is the total ELA of the house.

The pressure difference between a crawl space and outdoors can be estimated in the same general manner. If the crawl space is unheated and contains significant vents to outside, only the wind will substantially affect the crawl-space pressure.

Pressure-Driven Flows

For houses with a basement, we consider only one common penetration to the soil -- a wall-floor gap around the perimeter of the basement floor at the junction of the floor and the walls. Using an analogy to heat transfer and simplifying the problem by treating it as two-dimensional, the soil gas flow rate (Q_{sg}) is computed using the equation

$$Q_{sg} = \frac{L \Delta P_f}{\mu} \left[\frac{L_s}{12t^3} + \frac{1}{\pi k} \cosh^{-1} (2z/t) \right]^{-1} \tag{5}$$

where: L is the length of the gap, L_s is the thickness of the siab, μ is the viscosity of soil gas, t is the gap width, k is the soil permeability, and z is the depth of the gap below grade level. Equation 5 accounts for both the resistance to flow through the wall-floor gap and the resistance of the soil. The rate at which soil gas carries Rn into the house per unit house volume (S_{sg}) is based on assumed values of soil gas Rn concentration (C_{sg}), i.e.,

$$S_{sg} = Q_{sg}C_{sg}/V \tag{6}$$

where V is the volume of the house.

For a house with a crawl space, the concept of effective leakage area is used for calculation of flow rate through the floor, yielding the equation

$$Q_{cs} = ELA_f\,[(2/\rho)(\Delta P_f - \Delta P_{cs})]^{0.5} \tag{7}$$

where: ELA_f is the ELA of the floor, ΔP_f is the indoor-outdoor pressure difference just above the floor, and ΔP_{cs} is the pressure difference between the crawl-space and outdoors. The rate of Rn entry from the crawl-space per unit house volume (S_{cs}) is based on an assumed crawl-space Rn concentration (C_{cs}), i.e.,

$$S_{cs} = Q_{cs}C_{cs}/V. \tag{8}$$

The building ventilation rate (Q_v) is computed using standard methods of combining the ventilation due solely to the stack effect (Q_s), wind (Q_w), exhaust ventilation (Q_{ev}), and balanced ventilation (Q_{bv}), i.e.,

$$Q_v = (Q_s^2 + Q_w^2 + Q_{ev}^2)^{0.5} + Q_{bv}. \tag{9}$$

The reader is referred elsewhere[1,3] for the computational details.

Rn Mass Balance

The final step is to calculate the indoor Rn concentration using a Rn mass balance. A transient mass balance equation was used for results presented in this paper, however, only a more simple steady-state equation is presented here

$$C_i = (S_d + S + (Q_v - Q)\, C_o/V)/(Q_v/V + \lambda) \qquad (10)$$

where: S_d is the entry rate of Rn by diffusion and from domestic water (which are assumed to be negligible), S equals S_{sg} or S_{cs} and Q equals Q_{sg} or Q_{cs} depending on the type of substructure, C_o is the outdoor Rn concentration (assumed to be 9 Bq/m^3), and λ is the radioactive decay constant for Rn which is assumed negligible.

Results and Conclusions

When mechanical ventilation is employed, construction or retrofit measures are generally also utilized to make the house more airtight. Thus, for comparisons, the ELAs and mechanical ventilation rates associated with each method of ventilation must be specified. For houses without mechanical ventilation, we use the average specific leakage area (i.e., ELA divided by floor area) for U.S. houses built between 1961 and 1983 without a vapor barrier as indicated by a data base of leakage areas.[4] For exhaust-ventilated houses, the average specific leakage area for houses with a vapor barrier but without other infiltration-reduction measures is selected and an exhaust flow rate corresponding to 0.50 air changes per hour (h^{-1}) is assumed. These assumptions yield average heating season (September 16 - April 30) air exchange rates of approximately 0.55 h^{-1} using hourly weather data for Spokane, WA. To obtain the same average air exchange rate with balanced ventilation, a mechanical ventilation rate corresponding to 0.4 h^{-1} is assumed and the ELA is adjusted as necessary.

The results of comparisons for a house with a basement are summarized in Table 1. A range of soil permeabilities and both typical and high soil gas Rn concentrations were used for calculations. For the following discussion, we consider a difference between any two Rn concentrations that is less than about 40 Bq m^{-3} (1 pCi/l^{-1}) to be unimportant. The calculations indicate that pressure-driven entry of soil gas and, thus, Rn should not be a problem when the soil surrounding the basement has a permeability of $10^{-12}m^2$ or less. Soil permeabilities in this range or lower are common -- for example, clays and silts have a permeability less then $10^{-13}m^2$. Thus, from the perspective of indoor Rn, any of these methods of ventilation should be acceptable if the soil has a low permeability. Even if the permeability is in the range of $10^{-11}m^2$, soil gas entry and the method of ventilation should not be important unless the soil gas has an unusually high concentration of Rn. However, if the soil permeability is in the range of 10^{-10} or $10^{-9}m^2$, our calculations indicate that exhaust ventilation, compared to infiltration at the same rate, could increase average indoor Rn concentrations by a factor of approximately 1.7 and by hundreds of Bq m^{-3}. In such situations, exhaust ventilation should be avoided unless other measures are taken to reduce Rn entry.

Table 2 contains results of comparisons for a house with a crawl space. Note that calculations were performed for three different distributions of leakage area: uniformly distributed, high floor ELA, and low floor ELA. Three crawl-space Rn concentrations were also used for calculations. It is interesting to note that a large fraction of the air that enters a house can come from the crawl-space, particularly when ventilation occurs by natural infiltration. In such instances, the indoor Rn concentration will be a substantial fraction (e.g., 50% to 100%) of the crawl-space Rn concentration. Control of crawl-space Rn concentrations (usually by crawl-space ventilation) is, therefore, more important than choosing a particular type or rate of ventilation for the house. The different techniques of ventilation do lead to substantially different Rn concentrations, in a house with a crawl space. Both the mechanical ventilation options, when combined with house tightening that includes reducing the ELA of the floor, lead to substantially lower indoor Rn concentrations than the traditional reliance on infiltration. Such results are expected, because with mechanical ventilation and house tightening a larger proportion of the air that enters the house will not pass through the crawl space. Balanced ventilation leads to the lowest indoor Rn concentrations -- about a factor of three lower than with natural infiltration.

The models have been used to investigate the effects of varying other parameters such as mechanical ventilation rate and wall-floor gap width. One particularly interesting result for a house with a basement, is a predicted increase in indoor Rn concentrations as the rate of exhaust ventilation is increased above approximately 0.5 h^{-1}. It is also interesting that increases in the wall-floor gap width above 0.002 m have only a slight effect on indoor Rn concentrations when the soil permeability is $10^{-11} m^2$ or lower.

Acknowledgments

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Table 1. Results of comparisons of ventilation strategies for a house with a basement. A gap width of 0.002 m was assumed.

Method of Ventilation --	Mechanical Ventilation Rate h^{-1}	Effective Leakage Area m^2	Soil Permea-bility m^2	Total Ventilation Rate h^{-1}	Soil Gas Entry Rate $m^3 h^{-1}$	Pressure* Difference Pa	Indoor Rn Conc. With: Csoil=26000+ Bq m^{-3}	Csoil=260000¤ Bq m^{-3}
Infiltration	0.0	0.134	10^{-9}	0.55	16.9	3.8	975	9670
"	"	"	10^{-10}	"	1.82	"	113	1050
"	"	"	10^{-11}	"	0.18	"	20	114
"	"	"	10^{-12}	"	0.02	"	10	20
Exhaust	0.5	0.054	10^{-9}	0.55	27.5	6.2	1660	16500
"	"	"	10^{-10}	"	2.96	"	187	1780
"	"	"	10^{-11}	"	0.30	"	27	188
"	"	"	10^{-12}	"	0.03	"	11	27
Balanced	0.4	0.038	10^{-9}	0.55	16.9	3.8	1000	9940
"	"	"	10^{-10}	"	1.82	"	116	1080
"	"	"	10^{-11}	"	0.18	"	20	117
"	"	"	10^{-12}	"	0.02	"	10	20
<------------------inputs to model			------------------------>	<-------------averages of hourly computations, Sept. 16 - April 30				------------->

*driving force for soil gas entry +typical soil gas Rn concentration ¤unusually high soil gas Rn concentration

Table 2. Results of comparisons of ventilation strategies for a house with a crawl space.

Method of Ventilation --	Mechanical Ventilation Rate h^{-1}	Effective Leakage Area Total m^2	Floor m^2	Total Ventilation Rate h^{-1}	Pressure* Difference Pa	Flow from Crawl Space to house h^{-1}	Indoor Rn Concentration with: C_{cs}=200 Bq m^{-3}	C_{cs}=400 Bq m^{-3}	C_{cs}=2000 Bq m^{-3}
Infiltration	0	0.067	0.023+	0.57	2.12	0.49	172	344	1710
"	"	"	0.035¤	0.55	1.77	0.55	198	396	1980
"	"	"	0.012§	0.58	2.41	0.26	96	188	917
Exhaust	0.50	0.027	0.009+	0.55	3.61	0.27	101	196	962
"	"	"	0.014¤	0.55	3.26	0.38	140	277	1370
"	"	"	0.005§	0.56	3.90	0.14	57	106	504
Balanced	0.40	0.018	0.006+	0.55	2.12	0.13	53	100	470
"	"	"	0.009¤	0.54	1.77	0.17	69	133	637
"	"	"	0.003§	0.55	2.41	0.07	33	58	256
<------------------inputs to model			------------------------>	<-------------averages of hourly computations, Sept. 16 - April 30					------------->

* pressure difference across floor
¤ high proportion of effective leakage area in floor
+ uniformly distributed effective leakage area
§ low proportion of effective leakage area in floor