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# A Coupled Multizone Flow and Radon Transport Model of Radon Entry and Concentrations in a Crawlspace House

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# A COUPLED MULTIZONE FLOW AND RADON TRANSPORT MODEL OF RADON ENTRY AND CONCENTRATIONS IN A CRAWLSPACE HOUSE

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## ABSTRACT

We have combined a numerical model of radon migration through soil with a multizone air flow model to predict radon entry and concentrations in crawlspace houses typical of those constructed in Florida, USA. The multizone air flow model simulates pressure differences between zones and the corresponding zone-to-zone air flows in response to meteorological data, while a building energy simulation model was used to estimate 'on-times' for the forced-air furnace system. Radon concentration in the crawlspace is highest in the summer season, however the living space radon concentration for this season is quite low. This situation arises because the interzonal flow in summer is mainly from the living space to the crawlspace, thereby minimizing the radon transport from the crawlspace into the house. Based on a parametric analysis, changes in the crawlspace vent area had a larger effect on radon concentrations in both the crawlspace and living space, while changes in the leakage distribution of the building shell or the duct system produced only small effects on the radon concentration in either zone.

## INTRODUCTION

Building substructures in the US are typically one of three types -- basement, slab-on-grade, or crawlspaces -- or a combination of these. Among the US housing stock, approximately one-third are constructed with crawlspace substructures (1). Typically, crawlspaces are either enclosed (unvented) or ventilated by means of vent openings in the perimeter walls. In crawlspace houses, the living space is not directly coupled to the underlying soil and the dynamics of radon entry into this zone will therefore depend upon the crawlspace behavior.

Radon concentration in the crawlspace is governed by the diffusion rate of radon from the soil enclosed in the crawlspace, the pressure-driven flow of radon-bearing soil gas into the crawlspace, and the crawlspace ventilation rate. Radon concentrations within the living space of a crawlspace house depend upon the crawlspace concentrations and rates of air flow into the living space from both the crawlspace and outdoors. In order to better define and understand the interactions among these various parameters, a simulation method has been developed that couples a multizone airflow model with a model of radon migration through soil and across the soil/air boundary. This method has also permitted an examination of features important to the design and construction of crawlspace housing as part of a program conducted by the state of Florida (FL), USA, to reduce radon entry into buildings.

## DESCRIPTION OF THE SIMULATION METHOD

### Air Flow Modeling

Air flow models are used to simulate the rates of incoming and outgoing air flows for a building with known leakage under given weather and shielding conditions. The air flow distribution for a given building is driven by the pressure differences between the various zones. There are three main sources of pressures in buildings: a) the wind pressure distribution, which depends on the velocity and the direction of the wind, the terrain surrounding of the building, the shape of the building, and the location of leaks in the building envelope, b) differences in density of the air, due to differences between outside and inside air temperatures (the stack effect) or moisture content,

and c) pressures due to the operation of mechanical heating/cooling or ventilation systems, where the interconnecting duct system can be treated like the other flow paths in the building.

In order to model the air flows through the building shell and through the air distribution system, we have employed the public-domain COMIS (Conjunction Of Multizone Infiltration Specialists) multizone model that solves the set of non-linear equations describing the airflow network (2). A building is modeled by pressure nodes that are interconnected with air flow links. In addition, the user needs to specify the leakage distribution for the building shell, and for the duct system. The interaction of the building with the surrounding temperature and wind environment is an important component of the air flow model. Typically, the model is driven by weather data, which includes outdoor dry- and wet-bulb temperatures, and wind speed and direction. Usually, the weather data is given at hourly intervals, which in turn specifies the maximum time-step resolution of the simulation.

## Thermal Simulation Model

Because the space conditioning system for a building affects the interior environment, which in turn alters the air flows and pollutant distributions, it is necessary to account for the thermal behavior of the building. As with airflows in a multizone structure, the thermodynamic behavior of a building is complex and involves non-linear energy flows between various zones. We have used the DOE-2 simulation program to solve the set of coupled integral-differential equations having complex boundary and initial conditions (3). The weather data provides input on outdoor conditions, including solar insolation. The user specifies the heat transfer coefficients for the various components of the building shell and the relevant interior membranes and the energy capacity and performance of the heating and cooling system.

## Radon Transport and Entry

A three-dimensional finite-difference model is used to determine the pressure and radon-concentration fields in a block of soil that extends horizontally 10 m beyond the foundation footer of the house in all directions and vertically from the soil surface to 10 m below the footer. one quadrant. Given a knowledge of the soil-gas velocity and the radon concentration at the boundary between the soil and the crawlspace, the radon entry rate into the crawlspace may be calculated. Initially the crawlspace concentration is assumed to be zero. After the first and each subsequent iteration, the radon entry rate is calculated, accounting for both advective and diffusive radon transport across the soil-crawlspace air boundary. Details of the model are given in refs (4-6).

Predictions for total radon entry rates were made for several combinations of crawlspace pressure and air-exchange rate, and based on an initial soil permeability of $10^{-11}$ $m^2$. The entry rates are based upon iterative solutions continued until the largest radon concentration residual is $10^{-3}$ beyond which no significant change in entry rate occurs. Advective radon entry rates for other soil permeabilities may be found by exploiting the fact that soil-gas velocities are linear with the product of permeability and pressure, that is, the entry rate for a soil permeability of $10^{-12}$ $m^2$ and a crawlspace pressure of -5 Pa is identical to that for values of $10^{-11}$ $m^2$ and -0.5 Pa, respectively. Diffusive entry depends primarily upon the radium content of the soil and the subsequent radon concentration gradient.

## Model Integration

In parallel with the development of the multizone air flow model COMIS, a multizone transport model, POLTRANS, was developed that determines the mass balance of each pollutant in each zone of a building. It is assumed that the pollutant is well mixed in a zone and is transported from zone to zone by the flow of air. In the case of radon in the living space of a crawlspace house, the principal source is the airflow from the crawlspace itself, and because radon is inert, the dominant removal term is the airflow out of the living space (the radioactive decay time constant is much smaller than the ventilation time constant). We have neglected other sources of radon, such as emanation from building materials, or the contribution to indoor concentrations from radon in

outdoor air. We have also assumed that diffusive transport of radon from the crawlspace into the living space is negligible.

The results from COMIS yield hour-by-hour pressures and flows between the three zones (crawlspace to outside; crawlspace to living space; living space to outside) run for two cases -- the distribution fan for the heating/cooling system off (so the only driving forces for the pressures and flows are wind and thermal effects), and the same weather with the distribution fan on 100% of the time. Use of the building energy simulation code DOE-2 provides the demand for the heating/cooling system, either in heating or cooling mode. DOE-2 incorporates the operation of a standard thermostatic switch, so that a fan-on fraction is computed for each hour of the year, based on demand for heating or cooling. This fraction is then used to provide the net hourly interzonal flows, which result from the combination of the two output files -- fan-on and fan-off, weighted by the fan-on fraction. The POLTRANS version used for this exercise has been modified to calculate the air flows for the house based on the air flows in the fan-off and fan-on mode and the fan-on time.

## Description of Model Inputs and Assumptions

The residential building used for the simulation is a one-story house with an attached garage. The building is typical of current construction practices for residential buildings in Florida. The air distribution system consists of a furnace/air conditioner unit, ten supply ducts and a single, central return duct. The details of this configuration were adapted from a previous study of residential air distribution systems (7). The furnace/ac unit, including the supply plenum and one third of the return duct run, is located in the garage, which is not part of the conditioned space. The supply and return ducts are placed in the attic, which conforms with the current Florida building code prohibiting placement of ducts within crawlspaces. The supply ducts are assumed to be insulated, circular ducts with a diameter of 0.15 m and a total combined length of 87 m. The insulated return duct is 0.45 m in diameter and 9 m long.

The leakage through the house envelope, the crawlspace walls and the garage walls is assumed to be uniformly distributed with respect to surface area. The heat transfer coefficient (insulation) values for the exterior walls and the floor of the building were chosen to conform to the requirements of the Florida energy code. Values for the key parameters used in the analysis are given in Table 1.

Table 1. Summary of key inputs and assumptions

| Key Parameter | | Value |
|---|---|---|
| Building Size: | | 1 story; 144 $m^2$ area |
| Heat transfer coefficients - exterior wall; ceiling; ducts | | 0.30; 0.19; 1.42 W $m^{-2}$ $K^{-1}$ |
| Air leakage - building shell (6.2 ach @ 50 Pa): | | total = 429 $cm^2$ (96 $m^3$ $h^{-1}$ at 1 Pa) |
| leakage distribution (base case): | | leakage ratio = (floor + ceiling)/walls = 1.26 |
| Air leakage - ducts: | | total = 140 $cm^2$ (50 $m^3$ $h^{-1}$ at 1 Pa): |
| leakage distribution (base case) | | leakage ratio = (return/supply) = 1.73 |
| Crawlspace venting (base case): | | vent area/floor area = 1/150 |
| Parametric analysis: | | |
| Crawlspace venting: | Case A | 0.5 x base case vent area ratio (= 1/300) |
| | Case B | 2 x base case vent area ratio (= 2/150) |
| Duct leakage distribution: | Case C | 0.5 x base case return/supply ratio (= 0.86) |
| | Case D | 2 x base case return/supply ratio (= 3.46) |
| Shell leakage distribution: | Case E | 0.5 x base case leakage ratio (= 0.63) |
| | Case F | 2 x base case leakage ratio (= 2.52) |

The hourly weather data for the annual simulations is taken from the Typical Meteorological Year (TMY) file for Tallahassee, Florida (8). The parameters given from the weather data file are outside temperature (dry bulb), humidity ratio, wind velocity, wind direction and solar insolation. The wind velocity is assumed to be measured at a height of 10 m. Pressure coefficients ($C_p$-

values) for relating the wind induced over- or under- pressure at the outer surfaces of the building to the dynamic pressure of the undisturbed wind at roof height were obtained from the ASHRAE Handbook (9, chapter 14). The terrain parameters which describe the wind profile, relate the wind velocity measured to the undisturbed wind velocity at the roof level of the building. The building is assumed to be located in an area of an urban character. The shielding effect due to the impact of surrounding buildings, trees etc. on the wind is taken into account by modifying the pressure coefficients to correspond to a shielding class of three as defined in the ASHRAE Handbook (9, chapter 23).

We have also examined, to a limited extent, the effects of variations in some key parameters thought to affect the estimated radon concentrations. Three of the leakage parameters - the crawlspace vent ratio, the duct leakage distribution, and the shell leakage distribution - were varied individually, holding the other two, along with those parameters not varied, at base case values as described previously. The values for these parameters are also summarized in Table 1.

## RESULTS AND DISCUSSION

### Radon Entry and Concentration Dynamics

Radon concentrations in the crawlspace are determined by the balance between the radon entry rate and the removal rate due to crawlspace ventilation. We have assumed that the stack effect within the crawlspace does not contribute significantly to radon entry. The hourly weather data provide the basis for calculating the radon entry rate into the crawlspace. These results are combined with the simulations of the interzonal pressure differences and air flows to yield hourly ventilation rates and radon concentrations for the crawlspace and living space zones.

The weekly average radon concentrations in the two zones and the zone-to-zone air flows are shown in Figure 1, which best illustrates and explains the dynamics of the soil - crawlspace - house system. When the computed pressure in the living space is lower than that in the crawlspace, air flows from the crawlspace to the living space , bringing with it radon from the crawlspace. When the pressures are reversed, and the living space is at a higher pressure than the crawlspace -- as would be the case when the heating/cooling system operates, or in the case of a reverse stack effect (temperatures in the living space are lower than outside) -- air flows from the living space to the crawlspace . When this occurs, the living space radon concentrations are very low, since there is now no radon entry into the living space. This effect mainly arises, as can be seen in Figure 1, during the air conditioning periods (weeks ~20 to ~40), when the fan operation time is greater and the indoor air temperature is cooler than that outdoors, leading to a reverse stack effect. During other times of the year, large fan "on" times correspond to heating periods. During this time, the fan will tend to pressurize the living space (due to the fact that the model assumes the return duct leakage is larger than that in the supply ducts), but the stack effect in the living space dominates the overall pressure balance, and the resulting flows are still mainly from the crawlspace to the living space .

### Parametric Results

The results of the parametric analyses are summarized Table 2, where the seasonal- and annual-average radon concentrations for the crawlspace and living space, respectively, are displayed as ratios to the comparable base case results. As can be seen, the largest single change in the radon concentration in either zone arises from changes in the crawlspace vent area ratio. Changing the leakage parameters -- return/supply duct leakage distribution or the building shell leakage distribution -- has only a minor effect on the resulting average radon concentration.

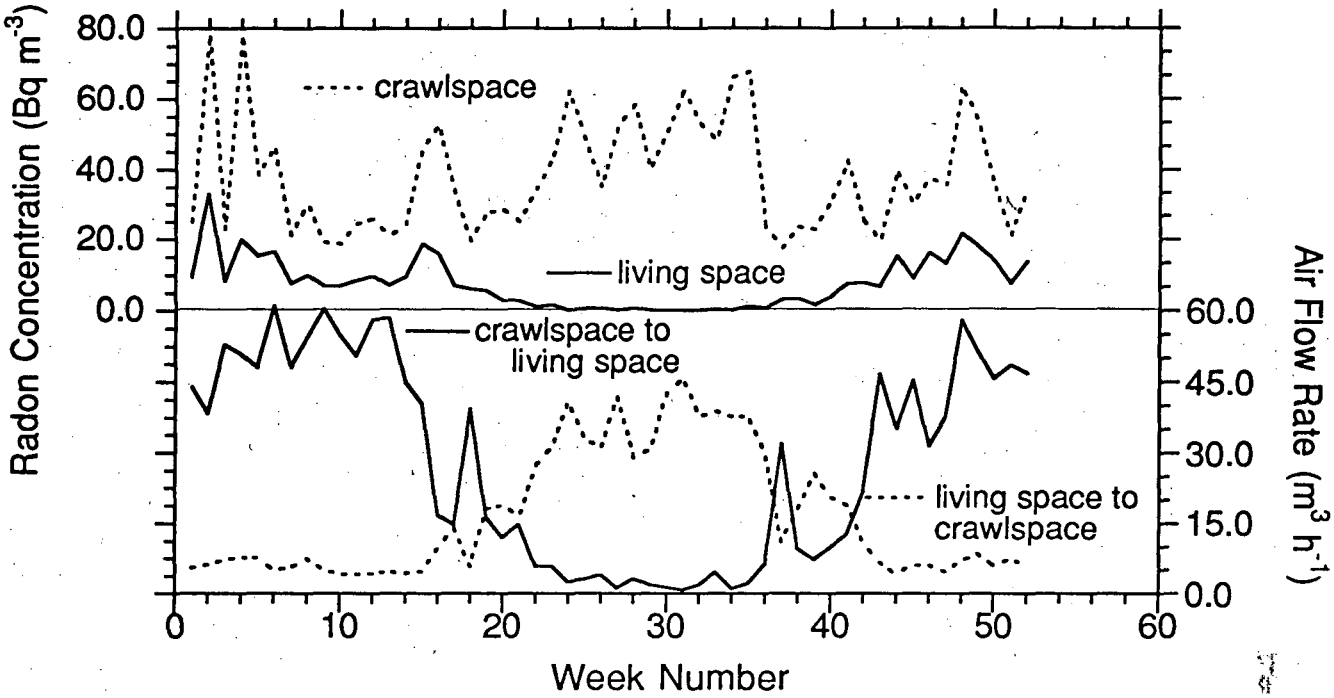


Fig. 1. Weekly average radon concentrations in the crawlspace and living space (top half) and interzonal flows (bottom half) for the base case simulation.

Table 2. Results of parametric analyses compared with base case.

| | winter | spring | summer | fall | annual |
|---|---|---|---|---|---|
| **Base case** | | | | | |
| crawlspace (CS) ventilation (ach) | 8.62 | 10.74 | 6.08 | 9.19 | 8.65 |
| living space (LS) ventilation (ach) | 0.39 | 0.31 | 0.31 | 0.30 | 0.33 |
| CS Rn (Bq $m^{-3}$) | 41.41 | 28.18 | 52.91 | 30.19 | 38.18 |
| LS Rn (Bq $m^{-3}$) | 14.85 | 8.08 | 0.57 | 7.66 | 7.75 |
| **Case A: 0.5 x CS vent rate** | | | | | |
| CS Rn ratio | 1.51 | 1.66 | 1.51 | 1.67 | 1.57 |
| LS Rn ratio | 1.61 | 1.76 | 2.23 | 1.79 | 1.71 |
| **Case B: 2 x CS vent rate** | | | | | |
| CS Rn ratio | 0.73 | 0.66 | 0.73 | 0.65 | 0.70 |
| LS Rn ratio | 0.67 | 0.60 | 0.47 | 0.60 | 0.63 |
| **Case C: 0.5 x duct leakage** | | | | | |
| CS Rn ratio | 0.94 | 0.99 | 1.01 | 0.99 | 0.98 |
| LS Rn ratio | 1.11 | 1.08 | 1.15 | 1.08 | 1.10 |
| **Case D: 2 x duct leakage** | | | | | |
| CS Rn ratio | 0.93 | 0.99 | 1.00 | 0.99 | 0.98 |
| LS Rn ratio | 0.90 | 0.96 | 1.00 | 0.96 | 0.94 |
| **Case E: 0.5 x floor leakage** | | | | | |
| CS Rn ratio | 1.09 | 1.03 | 1.05 | 1.04 | 1.05 |
| LS Rn ratio | 0.78 | 0.72 | 0.67 | 0.73 | 0.75 |
| **Case F: 2 x floor leakage** | | | | | |
| CS Rn ratio | 0.96 | 0.98 | 0.97 | 0.98 | 0.97 |
| LS Rn ratio | 1.07 | 1.13 | 1.26 | 1.12 | 1.10 |

## CONCLUSIONS

Radon concentrations in crawlspace houses result from a set of complex interactions within the soil - crawlspace - living space system, and a multizone airflow analysis is necessary to reveal the dynamics of this system. The zone-to-zone flows change as a function of temperature differences and mechanical system operation, and due to these changes, the radon concentrations in the crawlspace and in the living space are not well correlated. Based on the limited parametric analysis performed here, the largest single effect on living space radon concentration arises from changes in the crawlspace vent area. Changes in the duct leakage distribution or the leakage ratio of the building shell had much smaller effects on living space radon.

It should be noted also that overall, the predicted average living space radon concentrations are not very high. However, since the radon entry rates and resulting concentrations scale with the radon source term, increased soil radium concentrations and, to a more limited extent, increased soil permeability could lead to more significant radon entry rates and concentrations. In particular, homes in regions with elevated soil gas radon concentrations near the surface, coupled with poorly ventilated crawlspaces (which would not meet the current FL building code), could have elevated average living space radon concentrations.

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