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K.L. Revzan
Indoor Environment Program
Applied Science Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, CA 94720

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Abstract

The ^{222}Rn (radon) concentrations in the living areas and basements of two New Jersey houses and the concentration in the underlying soil of one of the two have been measured at half-hour intervals over the course of 10 months. Indoor and outdoor temperatures, wind speed and direction, and indoor-outdoor, basement-subslab, and basement-upstairs pressure differences have been measured at both locations at the same interval. Periods of forced air heater and air conditioner (HVAC) operation have been logged. The dependence of the pressure differences on the temperature differences, wind speed, and HVAC operation is demonstrated and its mathematical form described. Models of soil gas, basement, and radon concentrations are then developed using the same independent variables. The models contain parameters which are dependent on geological, structural, and human factors which have not been measured or otherwise determined; the parameters are determined by a weighted least-squares fitting technique to three-day averages of the data. For the first house, the RMS errors in the three calculated concentrations are 15% or less; for the second, the RMS error in the basement concentration is 17%; the RMS error in the living area concentration is 22%, although two distinct sets of parameters must be used because of a change in the mode of operation of the house. The modeling attempts make it clear that occupant behavior is a major influence on radon concentrations in houses. In particular, the operation of furnaces and air conditioners plays a large part in the distribution of radon between basement and living area. The large number of factors involved, the complexity of their relationships, and the impossibility of finding mathematical expressions of some of them make the development of predictive models of indoor radon problematical.

Nomenclature

Symbol	Name	Units
C	Radon concentration	Bq m^{-3}
C_b	Radon concentration, basement	Bq m^{-3}
C_l	Radon concentration, living area	Bq m^{-3}
C_o	Radon concentration, outdoor	Bq m^{-3}
C_s	Radon concentration, soil gas	Bq m^{-3}
f	Flow rate	$m^3\ h^{-1}$
f_{bo}	Flow rate, basement to outside	$m^3\ h^{-1}$
f_{bl}	Flow rate, basement to living area	$m^3\ h^{-1}$
f_{HVAC}	Flow rate, HVAC	$m^3\ h^{-1}$
f_{mech}	Flow rate, net, due to operation of mechanical systems	$m^3\ h^{-1}$
f_{lb}	Flow rate, living area to basement	$m^3\ h^{-1}$
f_{lo}	Flow rate, living area to outside	$m^3\ h^{-1}$
f_{ob}	Flow rate, outside to basement	$m^3\ h^{-1}$
f_{ol}	Flow rate, outside to living area	$m^3\ h^{-1}$
HVAC	Fractional heating, ventilation, or air conditioning operation	-
k	Soil permeability	m^2
l	Distance along streamline	m
N	Number of data points used in regressions and least-squares fits	-
p	Parameter (various subscripts)	(see text)
R	Correlation coefficient	-
q_{ob}	Flow rate, soil gas, outside to basement	$m^3\ h^{-1}$
q_{os}	Flow rate, soil gas, outside to subslab	$m^3\ h^{-1}$
q_{sb}	Flow rate, soil gas, subslab to basement	$m^3\ h^{-1}$
R_b	Resistance to flow of the basement shell	Pa h m^{-3}
R_s	Resistance to flow of the soil	Pa h m^{-3}
S	Radon entry rate	Bq h^{-1}
S_b	Radon entry rate, basement	Bq h^{-1}
T_s	Integrated soil temperature	C
u	Wind speed	m s^{-1}
v	Magnitude of velocity of soil gas	m s^{-1}
ΔP	Pressure difference	Pa
ΔP_{lb}	Pressure difference, living area and basement	Pa
ΔP_{ob}	Pressure difference, outside and basement	Pa
ΔP_{os}	Pressure difference, outside and building shell, across soil	Pa
ΔP_{sb}	Pressure difference, building shell and basement	Pa
ΔT	Temperature difference	K
ΔT_{bo}	Difference between basement and outside temperatures	K
ΔT_{lo}	Difference between living area and outside temperatures	K
ΔT_{bs}	Difference between basement and integrated soil temperatures	K
ϵ_{MAX}	Ratio of maximum residual to mean of data	-

ϵ_{RMS}	Ratio of root-mean-square residual to mean of data	-
λ	Air exchange rate	h^{-1}
λ_R	Radon decay rate	h^{-1}

Introduction

In a previous paper (Revzan *et al.*, 1988), the author and his colleagues reviewed our current understanding of the factors determining radon concentrations in houses, wrote down the differential equations governing those concentrations, and employed a least-squares technique to fit parameterized steady-state solutions of the equations (the "model") to the data from approximately a year of measurements in a northeastern New Jersey house with a basement. The use of the measurement period of a year was based on the belief that the factors which influence radon levels, assumed to be principally environmental, exhibit their full range of variation over that period. The model comprises three elements, expressed in the following three equations, the latter two of which are coupled: first, the equation describing the transport of air from the outside, where it is essentially radon-free, through the pore spaces of the radium-bearing soil, into the depressurized basement; second, the mass-balance equation describing the the diffusive and convective transport of radon into and out of the basement, assuming a soil gas concentration determined by the transport equations; third, the mass-balance equation describing the theory of the transport of radon into and out of the upper levels of the house, hereinafter referred to as the "living area". The latter two equations incorporate a model of air exchange through the building shell.

If the success of a parametric model may be judged by its ability to predict the outcome of measurements and by the confidence which may be placed in its parameters, the work described in Revzan *et al.* (1988) could be said to be successful only in describing the relationship between the radon concentrations in the basement and the upper floors of the house. It was shown that this relationship could be modeled by an equation with just two free parameters, one of which was determined by the flow rates of air from the basement to the living area and from the living area to the outside and the other by the extent of HVAC (heating, ventilation, and air conditioning) system operation. The nature of the two parameters emphasizes the importance of *both* environmental and human factors in determining the exposure of the occupants of the house to radon.

In the first and second elements of the model, the work of Revzan *et al.* (1988) was considerably less successful. Because of the complexity of the equations of mass transport through a porous medium, a greatly simplified model of the transport process was developed, and a rough fit to the measured soil gas concentrations below the basement slab was obtained. However, little confidence could be placed in the best values of the relatively large number of parameters used in the model and it was implied that greatly simplified models could fit the data with equal or even greater success. Although the model used to describe the entry of soil gas into the basement was one that used the actual steady-state solutions of the relatively simple first-order mass-balance equations involved, the outcome was similar in that the predictions of the model were only roughly correct and that little confidence could be placed in the parameter values. It was also shown that the fit of the model to data from different seasons produced sharply different parameters, which implied that the usefulness of the model as a predictive tool was limited.

In this paper, the models are employed not as a potential predictive tool, but as means of identifying the areas of the process of radon entry and distribution in houses which are well understood and of illuminating the areas in which further investigation is needed. The relationship between measured pressure differences across the walls, floor, and ceiling of the basements and the measured wind speed and temperature differences that produce the pressures is discussed. The dependency of the soil gas, basement, and living area radon concentrations on the pressure differences and on the environmental factors is described. The influence of human factors, in particular the operation of mechanical devices which cause air movement, on the pressure differences and on the distribution of radon between basement and living area is considered. In the absence of direct measurements of the air exchange rate, the validity of a widely used air exchange model is examined using data from an earlier study. In some areas, empirical relationships based on our understanding of the behavior of house occupants are used to simplify complex equations which are not amenable to statistical analysis.

The data comprise the measurements from the house described in Revzan *et al.* (1988), hereinafter referred to as House 14, and those from a second house located in the same area of New Jersey, hereinafter referred to as House 2; the houses were the controls in a 14-house study of mitigation techniques. In order to compare the two houses, the period covered is limited by the available data from House 2 to 10/16/86 through 07/09/87. House 14 has a basement of height 2.08 m, of which 1.78 m is below grade. House 2 has a basement with one wall fully above grade and the opposite wall approximately 1.5 m below grade. The basement walls of both houses are constructed of hollow-core concrete or cinder block. Further information on the characteristics of the houses and on data acquisition techniques is given only as required by the discussion; details on House 14 may be found in Sextro *et al.* (1987) and details on House 2 in Dudney, *et al.* (1989). Data for each house were taken at 30 min intervals.

The period chosen as the basis of the analysis is three days, which appeared, after examination of the variability in the data, to be a satisfactory compromise between the desire to filter out fluctuations which are irrelevant to the study of long-term tendencies and the desire to ensure that all major variations were preserved. The free parameters occurring in the models are determined by least-squares fits to the three-day averages of the data. For the pressures, the fits are unweighted; for the radon concentrations, they are weighted by the inverse variances, which, since the data are Poisson-distributed count rates, are just the count rates themselves. The quality of the fit is indicated by the 90% confidence limits of the parameters, the R^2, and the RMS and maximum fractional errors in the predicted values. The fitting procedure does not necessarily minimize R^2, which is not directly comparable to the R^2 of linear regressions.

General Theory

Figure 1 depicts a house with a subsurface basement as a two-zone air exchange system. The flows through the basement walls are directly determined by the pressure differences across those walls, which are, in turn, determined by the temperature differences between the inside air and the outside air or soil (stack effect), the wind speed, the operation of mechanical appliances such as furnaces, air conditioners, and fans, and human activities such as the opening and closing of doors and windows. The pressure difference across a wall will generally vary with height. Mass balance requires that there will be a neutral pressure level: above that level, assuming the basement to be warmer than the outside, the direction of the flow is inside to outside; below the neutral level, the pressure difference is positive and the flow direction is reversed. The neutral level may be at or above the ceiling, in which case all air flowing into the basement passes into the living area. The flow though the subsurface part of a basement wall is normally much less than that through the upper part, so that the neutral level in a heated building must generally be above the soil surface and the pressure difference between soil and basement is positive everywhere. When the wind speed is negligible and the outdoor temperature greater than the indoor, the neutral level may be below the soil surface and the flow of air through the wall from the soil reduced much below that which would be expected from examination of the temperature differences alone. (The soil temperature at slab depth is almost invariably lower than the basement temperature, so that some soil gas flow occurs even when the outside temperature exceeds that of the basement.)

The pressure difference between the basement and the outside draws air through the soil and thence through openings in all or part of the walls and in the floor. The air collects radon, a decay product of the radium in the soil, as it passes through the pore spaces, and this radon then enters the basement. Radon present in the pore space air will also diffuse through the walls and floor into the basement. The relative magnitude of the contributions of convective and diffusive entry to indoor radon concentrations is discussed by Nazaroff (1988); convection usually dominates in houses with high concentrations. Once having entered the basement, the radon is removed by radioactive decay and by the air flows from basement to outside and from basement to living area. A part of the latter flow may be due to a furnace or air conditioner drawing air from the basement and distributing it throughout the house. Radon, once having been transported to the first floor, may re-enter the basement due to the flow of air through openings in its ceiling and through the furnace ductwork. A mass-balance determines the radon concentration in the basement air; a similar balance determines the concentration in the living area.

The concentration of radon in the air entering the basement from the soil will be determined by the radium content of the soil, the fraction of the radon produced by the soil which actually enters the pore spaces, the porosity of the soil, the moisture content of the soil, and by the velocity of the air passing through the soil, the velocity being in turn determined by the pressure differences which produce the air flow and by the permeability of the soil. A large pressure difference between house and soil or a high soil permeability will produce a relatively high flow of radon-bearing air into the house, but it will also diminish the concentration of radon in that air.

An exact solution of the problem of radon entry and removal requires that the house and the surrounding and underlying soil be treated as a unit, creating a time-dependent mass transport problem of considerable difficulty. The approach taken here is to average the data over a time period long enough that steady-state solutions of the equations are an acceptable approximation and to separate the question of mass transport through the soil from that of the radon mass balances in the two zones of the house. Though the pressure difference across a wall, as a function of height, will be affected slightly by the balance of above- and sub-surface flows, and therefore by the soil characteristics, the loss in accuracy in ignoring this influence is small in comparison with that due to other simplifications which must be made. Given this approach, the environmental, mechanical, and human factors that produce pressure differences across the building shell and the underlying soil are taken as independent variables. The pressure differences then determine, given a theory of flow through wall openings, the air exchange rate of the house. Similarly, the pressure field in the soil determines the concentration of radon in the soil gas and the amount of radon entering the house. Knowledge of the radon entry rate and the various flows occurring in the two zones of the house allows us to determine the radon concentration in each of the zones.

Much of the theory is suitable for slab-on-grade houses, except that the structure can be treated as a single air exchange zone and the soil temperature will have a negligible effect on the depressurization. Houses with crawl spaces, however, require a somewhat different treatment. Much of the radon will enter by diffusion from the open soil. The magnitude of convective entry and the air exchange rate of the crawl space will vary widely, depending on the degree of isolation of the crawl space from the outside. The entry rate of radon into the living area depends, in large measure, on the latter quantity, and is typically, though not invariably, much lower than the entry rate from a basement.

Results and Discussion: General

Figures 2 and 3 show the three-day averages for the principal variables of interest for House 14 and House 2, respectively, for the period between 10/16/86 and 7/09/87. For House 14, figure 2 shows, from top to bottom, the basement and first floor radon concentrations, the soil gas radon concentration, measured at a central location below the slab, the basement-outside temperature difference, an average of readings at two locations, the integrated basement-soil temperature difference, a weighted average of readings at 5, 15, 28, 69, 107, 145, and 183 m depth, the fraction of the period during which the HVAC system (furnace only) is in operation, the pressure difference between first floor and basement, taken at a central location across the ceiling, and the pressure differences across the slab at a central location and across the south wall at a level 15 cm above the slab. The latter data is typical of the four wall pressure measurements made in this house, each of which was taken between a point near the basement floor and one some distance away from the outside wall at ground level. These data were subsequently corrected for temperature variations in the sampling lines so that the data represent the pressure differences between the outside and the basement, i.e., the driving force of radon entry.

For House 2, figure 3 shows the basement and first floor radon concentrations, the basement-outside temperature difference, the fractional HVAC (furnace and central air conditioner) operation, the pressure difference between basement and first floor, and the pressure differences between basement and soil and between basement and outside. The basement-outside pressure difference is an average of the differences across the four walls, which was obtained by a single sensor through the use of a manifold. It should be kept in mind that this pressure was not measured in the same manner as ΔP_{ob} for House 14, although the same nomenclature is used. The absence of basement-soil pressure differences during the first part of the year is due to sensor failure. Soil gas radon concentrations and soil temperatures are not available for House 2. A large peak in basement radon concentration in late May and early June has been truncated to allow clarity in the depiction of the radon concentration data; its height is approximately 2600 Bq m^{-3}.

From a qualitative examination of the depicted data we see that, in House 14, the radon concentrations exhibit no clear correlation with any of the other data, that the first floor radon concentration follows the basement concentration closely, with the gap between the two somewhat greater in the warmer seasons, that the variability in the radon concentration in both the basement and the first floor is significantly greater in the warmer months than in the colder, that the soil gas concentration diminishes with decreasing outside temperature, and that the pressure differences are correlated with the basement-outside temperature difference. In House 2, the basement radon concentration appears to be correlated somewhat more closely with the temperature difference, the first floor concentration seems to be almost bimodal, being on the order of two thirds of the basement concentration during the first period and approximately equal to the basement concentration during the second part, except for the period of the large peak, when the first floor concentration remains considerably lower than that of the basement. The pressure difference between first floor and basement also appears almost bimodal, with an apparent correlation with HVAC operation. However, only one of the two periods of intensive air conditioner operation (May-June) shows a peak in basement radon concentration, although both exhibit high basement-first floor pressure differences. It is apparent that the two houses exhibit quite different relationships between basement and first floor radon concentrations and between the radon concentrations and the factors on which those concentrations depend. It is also apparent that there are certain anomalies which are difficult to account for on the basis of our present understanding. Among these are the large fluctuations in soil gas concentration at House 14, which are unrelated to any known driving force, and the peak in the basement radon concentration of House 2 during late May, which is unrelated to any driving force and not reflected in the first floor concentration.

Having made these preliminary observations, we will discuss the following subjects in more detail: first, the dependence of the pressure differences in each house on the temperature differences, the wind speed, and the HVAC operation; second, the dependence of the soil gas concentration below House 14 on the same variables; third, the nature of the likely errors in the estimation of the air exchange rate, based on data from a previously studied house; fourth, the dependence of the basement radon concentration in each house on the variables determining the radon flux into the basement and on those determining the air exchange rate; fifth, the dependence of the first floor radon concentration in each house on the basement radon concentration and the variables determining the air exchange rate.

Results and Discussion: Pressures

The pressure difference across any part of a building shell is given by an algebraic sum of the temperature difference across the wall and the squares of the flow rate produced by wind and the net flow due to mechanical ventilation, f_{mech} (Mowris and Fisk, 1987), where the coefficients are dependent on the characteristics of the structure, the density of air, and, for a wall, the position with respect to the neutral level. If we are averaging over a period during which the f_{mech} is either on or off, but does not vary, the average pressure difference due to f_{mech} is just a multiple of the fraction of the period during which the flow is on, so that

$$\Delta P = p_t \ \Delta T + p_w \ u^2 + p_h \ HVAC. \tag{1}$$

In fitting this model to the data, we must test all the combinations of the variables for statistical significance, except that HVAC may not appear alone on the r.h.s. because pressure differences are known to have been present in both houses when furnaces and air conditioners are off.

For House 2, wind speed and soil temperature data are not available. We have used the data from House 14, which is taken to be representative of the area. No significant dependence of any of the ΔP on ΔT_{bs} was found and we have accordingly used ΔT_{bo} as the ΔT of equation 1. Analysis shows that the outside-basement pressure is dependent on ΔT_{bo}, HVAC, and u, in order of decreasing importance. The best fit of equation 1 to the 85 data yields $p_t = 0.144$ Pa K^{-1} (90% confidence limits 0.132, 0.156), $p_h = 5.18$ Pa (4.59, 5.78), $p_u = 0.115$ Pa m^{-2} s^2 (0.097, 0.133), $R^2 = 0.91$, $\epsilon_{RMS} = 0.16$, and $\epsilon_{MAX} = 0.58$. Similarly, the best fit to the 51 available basement-subslab pressure data gives $p_t = 0.080$ Pa K^{-1} (0.072, 0.088), $p_h = 2.10$ Pa (1.79, 2.40), and $p_u = 0.043$ Pa m^{-2} s^2 (0.031, 0.055); $R^2 = 0.91$, $\epsilon_{RMS} = 0.16$, and $\epsilon_{MAX} = 0.58$. Both HVAC operation and wind speed are less significant determininants of ΔP_{sb} than they are of ΔP_{ob}, which suggests that the wind has a limited effect on flow through soil.

There is no good fit to the basement-first floor pressure data. The most significant variable is HVAC, which confirms that there is basement depressurization due to furnace and air conditioner operation. The relatively poor fit is partly due to errors involved in measuring pressures on the order of 0.1 Pa and partly due to the influence of human factors, e.g., the opening and closing of doors, on the flow of air between basement and first floor. The primary factor is, however, the change in the character of ΔP_{1b} beginning at the end of January, 1987 (figure 3). This is confirmed by the statistical analysis, which shows that, for the period from 11/16/86 through 1/26/87, the best fit to the 33 data is

$$\Delta P_{lb} = 0.35\ HVAC\,, \qquad (2)$$

with the 90% confidence limits of p_h being 0.34 and 0.36, $R^2 = 0.91$, $\epsilon_{RMS} = 0.14$ and $\epsilon_{MAX} = 0.83$. For the period from 1/27/87 through 5/17/87, i.e., the period between the end of January and the beginning of the use of air conditioning (N=34), no combination of variables produces an R^2 greater than 0.32. The influence of HVAC operation on ΔP_{ob} also diminishes after January; data for ΔP_{sb} do not exist for the earlier period. It would appear that the furnace ceases to depressurize the basement after January, 1987, a fact that will prove important in the analysis of the relationship between basement and first floor radon concentrations. The reason for the change is not clear.

In the case of House 14, the results are less satisfactory. It is not possible to distinguish statistically among the various possible combinations of variables, so that it cannot be determined with certainty whether the basement is depressurized by the furnace. Since ΔT_{bo} must be a factor, and since HVAC adds nothing to the R^2, it is likely that the furnace contributes little or nothing to the depressurization. The replacement of ΔT_{bo} by ΔT_{bs} in equation 1 does not produce satisfactory results, and the linear combination of the two does not produce an improvement over the result with ΔT_{bo} alone, so that soil temperature does not appear to be a determining factor in basement depressurization. The pressure differences may be modeled by equation 1 with p_u and p_h taken as zero. For ΔP_{ob} at the east (N = 84), south (88), west (82), and north (79) walls, for the average ΔP_{ob} (58), and for ΔP_{sb} (86), p_t has the values 0.19 (0.17, 0.20), 0.23 (0.22, 0.24), 0.25 (0.24, 0.26), 0.28 (0.26, 0.30), 0.24 (0.22, 0.25), and 0.094 (0.091, 0.097), respectively. The R^2 values are, respectively, 0.51, 0.75, 0.82, 0.56, 0.71, and 0.82; the ϵ_{RMS} values are 0.57, 0.34, 0.29, 0.52, 0.39, and 0.27; the ϵ_{MAX} values are 68, 9, 3, 3, 4, and 13. The causes of the very poor results for two of the ΔP_{ob} (by comparison with the other ΔP_{ob}, with ΔP_{os}, and with the results from House 2) are not clear, but it may be related to differences in measurement techniques. The large values of ϵ_{MAX} occur when ΔP is very small and are not indicative of the general quality of the fit.

For House 14, there is no good fit to the ΔP_{lb} data. The most significant variable is HVAC, which indicates some influence of the furnace on the basement pressure, although such an effect was not sufficiently large to be of statistical significance in the analysis of ΔP_{os} and the ΔP_{os}. The highest R^2 is just 0.39.

We see that, for both houses, the degree of basement depressurization is determined principally by the stack effect, i.e., by the temperature difference between basement and outside. There is no evidence of any additional dependence on the basement-soil temperature difference and the substitution of ΔT_{bs} for ΔT_{bo} leads to relatively poor results. There is an indication of depressurization due to HVAC operation in both of the houses, although the effect is slight in House 14. There is some indication of the influence of wind in the case of House 2, but it is not highly significant; there is little indication of any dependence of the House 14 pressure differences on wind speed. The wind speed measurement was made at a point near the roof of House 14; wind speeds at ground level are much lower, so that it is possible that, given sufficient isolation of the basement from the living area, that the wind could affect the pressures in the two zones differently and could, therefore, have an influence on the air exchange rate of the house as a whole.

However, the absence of any statistically significant influence of the wind speed on ΔP_{lb} for either house suggests that the effect may not be large.

Results and Discussion: Soil Gas

The flow of air through the soil into a depressurized ($\Delta P_{ob} > 0$) basement is given by Mowris (1987) as

$$q_{ob} = \Delta P_{ob} \;/\; (R_s + R_b), \tag{3}$$

where R_b is the resistance of all subsurface openings in the walls and floor of the basement. Since the flow through the building shell must equal that through the soil, i.e., $q_{sb} = q_{os}$, we have

$$q_{os} = \Delta P_{os} \;/\; R_s, \tag{4}$$

and the velocity of the soil gas at any point is proportional to ΔP_{os}. Whatever the representation of the boundary conditions at the basement and soil, the solution of the mass-transport equation must have the exponential form (Nazaroff, 1989)

$$C_s = p_\infty\{1 - \exp(-\lambda_R \int dl/v)\}, \tag{5}$$

where the integral is a path integral along the streamline l. If we now absorb all of the influence of the soil and soil-basement interface characteristics into parameters and use equation 4, we have

$$C_s = p_\infty \{1 - \exp(-p_s/\Delta P_{os})\}. \tag{6}$$

The parameter p_∞ is just the soil gas concentration infinitely far away from the influences of the house and atmosphere. The parameter p_s depends on the geometry of the openings in the basement walls and floor, the nature of the material, if any, lying between the slab and the soil, the size of the gaps between the walls and the soil, and the permeability of the soil; the value of p_s will generally be dependent on the point at which C_s is measured, so that no single parameter can represent the soil gas concentration at every point of entry into the basement.

The pressure difference ΔP_{os} does not correspond to any of our measured pressures: the pressure difference across any wall is dependent on the difference between the basement and soil temperatures at a given height outside that wall and is not normally a constant multiple of the basement-outside temperature difference; the measured pressure difference across the slab is not necessarily proportional to the difference across the soil. It is possible, then, that a model based on the factors which produce the pressure differences will provide a better representation of the actual flow of soil gas into the basement than will one based on any combination of the measured pressures. However, the best estimate of ΔP_{os} is given by the average ΔP_{ob}. When equation 6 is fit to the 58 available data for House 14 (no soil gas data are available for House 2), we find that p_∞

= 154000 Bq m^{-3} (90% confidence limits 141000, 167000), p_s = 0.32 Pa (0.26, 0.37), R^2 = 0.63, ϵ_{RMS} = 0.16, and ϵ_{MAX} = 0.94.

The analysis of the pressure data suggests that ΔP_{os} in equation 6 be replaced by ΔT_{bo}. When this is done, the best fit to the data yields an R^2 of 0.54. Examination of the measured and predicted values of C_s indicates that a wind speed term must be included in the model, so that the predicted C_s is given by

$$C_s = p_\infty \{1 - \exp(-p_s/(\Delta T_{bo} + p_u u^2)\}. \quad (7)$$

The best fit of equation 7 to the 77 data gives R^2 = 0.64, which is a considerable improvement over the result when p_u is taken to be zero. The parameters are p_∞ = 143000 Bq m^{-3} (90% confidence limits 135000, 151000), p_s = 25.0 K (20.4, 29.6), and p_u = 1.05 K m^{-2} s^2 (0.62, 1.48); ϵ_{RMS} is 0.15 and ϵ_{MAX} is 1.17. The results are comparable to those obtained from the use of the average ΔP_{ob} as the independent variable. The measured soil gas data and the values predicted by equation 7 are shown on figure 4.

The model is clearly deficient or incorrect in that the best value of p_∞, which represents C_s at points remote from the influence of the house or the soil-air boundary, is actually less than the largest measured value of C_s. Attempts to constrain the model so that p_∞ is greater than 170,000 Bq produce results which are inferior to those of the unconstrained model, except for the period of late May and early June. The predictions of the model also contain a number of peaks and valleys that are not reflected in the data; the local minimum of the data in early April is not predicted by the model. The local minimum of the data in January is simultaneous with a peak in the wind speed, which suggests that wind is an important factor in radon entry into houses, despite the absence of evidence of its influence on depressurization.

Discussion: Air Exchange Rate

The absence of continuous data on the air exchange rates of the two zones of each of the two test houses forces us to make the assumption that the rates are dependent on pressure differences, and thus on environmental variables, in a manner suggested by an accepted model of infiltration (Sherman and Grimsrud, 1980), with the possible addition of algorithms dealing with mechanical ventilation (Mowris and Fisk, 1987). However, the infiltration model is strictly suitable only for single-zone buildings and may exhibit fractional errors as large as 0.75, depending upon the relative importance of stack- and wind-driven air flow, the wind direction, the infiltration rate, and, possibly, other factors (Sherman and Modera, 1984).

The magnitude of the errors which may be expected can be indicated by re-examining the data from the house described in Nazaroff *et al.* (1985), hereinafter referred to as the Chicago house. Fitting the model

$$\lambda = p_\lambda (| \Delta T_{bo} | + p_u u^2)^{1/2}, \quad (8)$$

to the 100 one-day average measured air exchange rates, we find p_λ = 0.055 hr^{-1} $K^{-1/2}$

(90% confidence limits 0.051, 0.059) and p_u = 0.11 K m^{-2} s^{-2} (0.06, 0.17). R^2 is 0.37, ϵ_{RMS} is 0.39, and ϵ_{MAX} is 1.08. The measured and predicted one-day average air exchange rates are shown in figure 5.

It is apparent that there are a number of large peaks in the exchange rate which are not predicted by the model; these are likely to have been produced by some variation in the use of the house by the occupant. Let us first attempt to eliminate the influence of warm weather behavior on the exchange rate by eliminating all data for which ΔT_{bo} is less than 10° C. The results of the fit to the 52 remaining data are p_λ = 0.054 hr^{-1} $K^{-1/2}$ (0.050, 0.058) and p_u = 0.14 K m^{-2} s^{-2} (0.06, 0.22). R^2 is now 0.20, which is lower than the previous result, but ϵ_{RMS} is 0.26, and ϵ_{MAX} is 0.58, which are marked improvements. The parameters p_λ and p_u have not changed significantly.

If we further remove those data which are identified as being measured during periods of fireplace operation (which increases the exchange rate), we find (N = 47) p_λ = 0.051 hr^{-1} $K^{-1/2}$ (0.047, 0.054) and p_u = 0.16 K m^{-2} s^{-2} (0.09, 0.23). R^2 is 0.34, ϵ_{RMS} is 0.19, and ϵ_{MAX} is 0.52. The statistical indicators are somewhat improved and the parameters are essentially unchanged. The model of equation 8 does not appear capable of predicting the air exchange rate even when data collected at times when human activities are known to have altered the rate have been eliminated. Although failure in the case of a single house does not invalidate the model, it indicates that problems may occur when it is used to predict radon concentrations; it is possible that simple schematic models of air exchange can be used with little loss of accuracy.

Results and Discussion: Basement Radon

The balance of flows into and out of the basement and living area of a house requires that

$$C_b = \frac{S_b + f_{lb}\, C_l}{f_{bl} + f_{bo}}, \tag{9}$$

and

$$C_l = \frac{f_{bl}\, C_b}{f_{lb} + f_{lo}}, \tag{10}$$

where it has been assumed that soil gas does not enter the living area directly and where the entry of radon with water and outside air, which is generally an insignificant factor in houses with high radon concentrations, has been ignored. Substitution of equation 10 into equation 9 and rearranging terms then gives

$$C_b = \frac{S_b + f_{lb}\, C_l}{f_{bo} + \dfrac{f_{bl}\, f_{lo}}{f_{lb} + f_{lo}}}. \tag{11}$$

When f_{lb} is small, which is the case during cold weather with the furnace off, or when f_{bl}

vanishes, which may occur during warm weather, the denominator of equation 11 becomes just $f_{bo} + f_{bl}$, i.e., the total flow out of the basement. When a a furnace or air conditioner is on, we have, on the other hand, $f_{lb} = f_{bl}$ and $f_{lb} >> f_{lo}$, so that the denominator is $f_{bo} + f_{lo}$, i.e., the total flow out of the entire house, which is to say that the house appears to be a single zone.

If we now assume that each of the non-mechanical flows has an identical dependence on environmental factors, an assumption which is reasonable in circumstances where wind is not a major factor in air exchange, we may write each as a constant multiple of some generalized flow, f. The flows f_{lb} and f_{bl} may be written as linear combinations of f and the mechanical flow f_{HVAC}, so that we have

$$C_b = \frac{p_s \; S_b \; (1 + p_{h1} \; f_{HVAC} / f \;)}{f \; (1 + p_{h2} \; f_{HVAC} / f \;)}, \tag{12}$$

where all parameters are dimensionless. During periods of furnace operation, the average f_{HVAC} will be, very roughly, a constant multiple of the air exchange rate and, hence, a constant multiple of the general flow, f. Thus the quotient f_{HVAC}/f will be a constant when the furnace is in operation and zero otherwise and the average of this quotient will be a constant multiple of the fractional HVAC operation. We then have

$$C_b = \frac{p_s \; S_b \; (1 + p_{h1} \, HVAC)}{f \; (1 + p_{h2} \, HVAC)}, \tag{13}$$

where the parameters p_{h1} and p_{h2} differ by a constant factor from those in equation 12. This equation simply expresses C_b as a source divided by a flow rate. The flow is just f when HVAC operation is zero and becomes $p_{h2}f/p_{h1}$ when the HVAC system is in operation 100% of the time, assuming that the HVAC flow is much greater than the pressure driven flow. It is generally the case that p_{h2} is greater than p_{h1}, since the effect of the HVAC system will be to mix the basement and living area air, causing a dilution of C_b. The argument leading from equation 12 to equation 13 is not necessarily applicable to situations in which an air conditioner rather than a furnace is in operation; there is insufficient data available to examine this question.

The source comprises a diffusive and a convective component. Since the convective term depends on the pressure differences across the soil and those across the various elements of the building shell, and since the pressure differences have been shown to depend primarily on the basement-outside temperature difference, we may express the source as a multiple of the soil gas concentration and a linear combination of a constant and ΔT_{bo}. Because the soil gas concentration has been shown to be dependent on the wind speed, we shall also include a term involving u in the source. If we now incorporate the air exchange model, i.e., equation 8, we are led to the equation

$$C_b = \frac{C_s \; \{p_d + p_c \; (\Delta T_{bo} + p_{u1} \, u^2)\} \; (1 + p_{h1} \, HVAC)}{(\,|\, \Delta T_{bo} \,|\, + p_{u2} \, u^2)^{1/2} \; (1 + p_{h2} \, HVAC)}, \tag{14}$$

where p_d and p_c are of dimension $K^{-1/2}$, p_{u1} and p_{u2} are of dimension $K \, m^{-2} \, s^2$, and p_{h1}

and p_{h2} are dimensionless.

Because it is uncertain that a spot measurement of soil gas radon is representative of the average concentration of the gas entering the house, we shall consider the model of equation 14 with the source term containing both measured and modeled soil gas concentrations. In the former case, data is available only from House 14; the period of the large peak in C_b in May has been excluded as unrepresentative of the usual operating condition of the house in that the occupants were absent on vacation. After fitting the model to the 72 acceptable data, we find that the parameters p_{u2}, p_{h1}, and p_{h2} cannot be determined with any confidence. This is a consequence of the very high correlation of HVAC and the air exchange rate during cold weather and of the appearance of terms involving HVAC in both numerator and denominator. The fitting algorithm produces solutions for which p_{h1} and p_{h2} are essentially equal and may take on any value whatsoever and for which p_{u2} is much higher than the physics of air entry into a basement would permit.

The model can be simplified by avoiding the use of the air exchange model for the warm weather period, when it is likely to be inaccurate, and using the correlation of furnace operation and air exchange during cold weather to create the following model:

$$C_b = \frac{C_s \, \{p_d + p_c \, (\Delta T_{bo} + p_u \, u^2)\}}{(1 + p_h \, HVAC)}. \tag{15}$$

The best values of the parameters are p_d = 0.0024 (90% confidence limits 0.0021, 0.0028), p_c = 0.00035 (0.00030, 0.00040), p_u = 0.39 K m^{-2} s^2 (0.21, 0.56), p_h = 1.02 (0.62, 1.43). R^2 is 0.66, ϵ_{RMS} is 0.15, and ϵ_{MAX} is 0.39. Because of the many simplifications and approximations involved in the development of the model, it cannot be inferred that the ratio of p_c and p_d reflects the actual ratio of convective to diffusive entry. At a ΔT_{bo} of 20° K and a wind speed of 5 ms^{-1}, the predicted ratio would be roughly 4:1, which is somewhat low but not unreasonable. The value of p_u is physically acceptable and of the same order of magnitude as a similar parameter discussed in the section on soil gas. There is no means of determining whether p_h, an empirical parameter, is reasonable. The three-day averages of the data and the predictions of the model are shown in figure 6.

When the measured C_s in equation 15 is replaced by the expression of the soil gas model, we have

$$C_b = \frac{\{1 - \exp[-p_s/(\Delta T_{bo} + p_u \, u^2)]\} \, \{p_d + p_c \, (\Delta T_{bo} + p_u \, u^2)\}}{(1 + p_h \, HVAC)}, \tag{16}$$

where it has been assumed that the coefficients of the wind speed in the source and soil gas terms are identical. Fitting this model to the data from House 14, we find that p_u cannot be predicted with any assurance. Removing the wind speed terms from the model and fitting the simplified model to the data gives the coefficients p_d = 433 Bq m^{-1} (400, 463), p_c = 40.7 Bq m^{-1} (32.6, 49.2), p_s = 30.9 K (15.7, 46.1), and p_h = 1.19 (0.36, 2.03). R^2 is 0.52, ϵ_{RMS} is 0.15, and ϵ_{MAX} is 0.66. The results are shown on figure 7;

comparison with figure 6 shows that the absence of soil gas data greatly diminishes the ability of the model to fit the data. The value of p_s is similar to the value of the equivalent parameter obtained from the soil gas model; p_h and the ratio of p_d and p_c are roughly equal to the values obtained from the use of equation 15.

The fit of equation 16 to the House 2 data leads to essentially unpredictable values of both p_d and p_u. It leads, furthermore, to a value of p_s which is so large as to have no effect on the calculated C_b. The best values of the two remaining parameters are p_c = 137 Bq m^{-1} (105, 170) and p_h = 5.77 (3.87, 7.67), with $R^2 = 0.59$, $\epsilon_{RMS} = 0.17$, and $\epsilon_{MAX} = 0.63$. The measured and predicted values of C_b are shown on figure 8. The overwhelming dependence of C_b on the furnace activity is consistent with the ΔP_{lb} data, which was previously discussed. The inverted peak in the calculated data (figure 8 at 6/1) would suggest that the effect of the HVAC flow is reversed when the system is operating as an air conditioner rather than a furnace, but that would not be consistent with the pressure data (figure 3), which shows similar effects from furnace and air conditioner. The cause of the May-June peak remains obscure. Lacking soil gas data, it is not possible to say more about the validity of the model of equation 15 as applied to House 2.

Results and Discussion: Living Area

In the same way that equation 13 was developed from equation 9, we find, beginning with equation 10, that the dependence of C_l on C_b may be expressed by

$$C_l = \frac{(p_{lb} + p_{lh}\ HVAC)\ C_b}{1 + p_{lh}\ HVAC}, \tag{17}$$

where C_b represents the measured basement concentration. In the absence of HVAC activity, C_l is the product of C_b and the transfer parameter p_{lb}, which is largely determined by the air exchange rates of living area and basement. When the HVAC system is on, the basement and living area radon concentrations are equal.

Determining the dimensionless parameters by a weighted least-squares fit to the 82 data for House 14 gives, as previously described in Revzan *et al.* (1988), $p_{lb} = 0.19$ (90% confidence limits 0.18, 0.20) and $p_{lh} = 5.7$ (5.3, 6.3) with $R^2 = 0.94$, $\epsilon_{RMS} = 0.11$, and $\epsilon_{MAX} = 0.97$. Apart from the relatively large ϵ_{MAX}, which occurs at a point of very low measured concentration, these are outstanding results for work of this nature. The measured and predicted values are shown on figure 9.

When we attempt to apply the theory to the 66 data from House 2, however, we are considerably less successful, the R^2 being only 0.53, which is insignificantly larger than the value, 0.52, obtained from a regression through the origin, i.e., a model in which C_l is simply a constant multiple of C_b. It is not difficult to determine the reason for the failure. The model was developed on the basis of an examination of the House 14 data, which showed two modes, namely a "summer" mode, during which C_l was roughly a constant multiple of C_b, and a "winter" mode, during which C_l and C_b were roughly equal. Equation 17 clearly reflects the existence of the two modes, with the HVAC operation being the "switch". (The possibility of using ΔT_{bo} or ΔT_{lo} in place of HVAC in equation 17 was investigated; the original equation is clearly preferable.)

In contrast to that from House 14, the data from House 2 suggests three modes of operation. During the period from October through January, C_l is less than, and somewhat correlated with, C_b; during the period from January through June, exclusive of the period of the large and unexplained peak in C_b, the two concentrations are much more nearly equal; during May, C_l remains normal, while C_b attains values more than twice as great as those attained in winter. Using the equation $C_l = p_{lb} C_b$, we find that $p_{lb} = 0.58$ for the first period and $p_{lb} = 0.73$ for the second, with comparable values of R^2, i.e., 0.58 and 0.60, respectively. The existence of the three modes is also reflected in the ΔP_{lb} data: when ΔP_{lb} is positive, a gap develops between C_l and C_b; when it is nearly zero, the gap disappears.

From the least-squares fit of equation 17 to the 66 data from House 2, we find $p_{lb} = 0.58$ (90% confidence limits 0.53, 0.64), and $p_{lh} = 0.67$ (-0.09, 1.43), with $R^2 = 0.53$, $\epsilon_{RMS} = 0.22$, and $\epsilon_{MAX} = 0.90$. When the data are divided, we find, for the 34 data from the period up to and including 1/26/87, $p_{lb} = 0.48$ (0.44, 0.51), and $p_{lh} = 1.12$ (0.74, 1.50), with $R^2 = 0.64$, $\epsilon_{RMS} = 0.09$, and $\epsilon_{MAX} = 0.23$. For the 32 data from the period between 2/7/87 and 5/17/87, we find $p_{lb} = 0.52$ (0.38, 0.65), and $p_{lh} = 8.0$ (0.7, 15.4), with $R^2 = 0.72$, $\epsilon_{RMS} = 0.22$, and $\epsilon_{MAX} = 0.72$. These results, together with the results of the analyses of the pressure data, appear to indicate that the furnace has ceased to depressurize the basement after January, 1987, and that, therefore, the flow of air from basement to first floor has increased and the basement and first floor radon concentrations have become more nearly equal. On figure 10, we show the predictions of the independent fits to the two parts of the data.

It is logical to carry the modeling process to its conclusion by substituting the expression for the modeled C_b, equation 16, for the measured C_b in equation 17. The resulting equation provides a model of living area radon concentration in which the only independent variables are the indoor and outdoor temperatures and the fractional HVAC operation. The result of fitting this equation to the C_l data proves to be better than the result of fitting equation 16 to the C_b data, suggesting that the model is so complex that cancellation of errors has occurred. Since a valid physical model must be capable of predicting *both* C_b and C_l, the full model will not be discussed further.

Conclusions

For the two houses of this study, it has been possible to develop a relatively simple model of radon entry and removal which, after determination of parameter values by statistical means, has produced calculated basement and living area radon concentrations that are generally within 20% of three-day averages of measured concentrations for all periods except those where conditions are clearly abnormal, e.g., absence of the occupants. The independent variables of the model are the temperatures inside and outside the house and in the underlying soil, the wind speed, and the flow rates of mechanical systems such as furnaces, exhaust fans, and air conditioners. For application of the model to periods longer than a day, the mechanical flow rates may be replaced by variables representing the fraction of the period of interest the system has been in operation. The discrepancies between the calculated and measured values are due to errors inherent in the use of a series of steady-state solutions of differential equations to represent a time-dependent process and to errors arising from inadequacies in our representation of the radon entry, removal, and distribution process itself. Errors of the former type cannot be eliminated. Errors of the latter type arise from inadequacies in our representation of the pressures which control the flow of soil gas and outside air into and out of the house and from the limitations in the model of soil gas transport. An improved model might result from more accurate treatment of the mechanical flows, which would reduce the errors involved in the development of the empirical equations 13 and 17, and from better air exchange and soil gas transport models.

We have illustrated, in the discussion of the Chicago house, how difficult it is to model the pressures which produce air exchange; since the same pressures control soil gas entry rate and, in part, concentration, the discussion is applicable to the source strength and soil gas transport models as well. The difficulty lies in the necessary assumption that the human beings occupying the house will not alter those aspects of their behavior that influence air and soil gas flows or, at least, will confine themselves to easily modeled changes. In the case of House 14, the identifiable change in house operation resulted from the occupants simply departing on a vacation; the failure of the model in this case is irrelevant, since the ultimate purpose of the model is to predict exposure. In the case of House 2, however, there are three distinct periods, the first two of which may be modeled, albeit with significant changes in parameter values, and the third of which (the period of the late May and early June peaks in basement radon) remains unexplained. In both houses, many of the discrepancies between calculated and measured concentrations for all periods may result from day-to-day changes in opening doors and windows, fireplace use, and use of appliances such as portable fans and heaters. Since it is beyond our capacity to model human behavior, it seems unlikely that even greatly improved models will be able to represent all houses at all times with any success.

Since predictive models of the physical processes involved in radon entry and removal can be developed only with considerable difficulty and since the development of predictive models of the human factors influencing radon concentrations is more difficult still, it is unlikely that accurate predictions can be made for individual houses. It is possible, however, that statistical distributions may be found for both the physical and human factors, and that a very simple model of the dependence of soil gas entry rate, air movement and exchange, and soil gas concentration on those factors may be found, so that the *probable* radon concentration in a house of a given type, situated on a given soil, in a given environment, may be determined. Further research is necessary, then, to determine the distribution of air exchange rates of the basements and living areas of houses under various conditions of occupancy, with a variety of HVAC systems, under a range of climatic conditions. The development of a statistical model would enable us to determine those circumstances in which high radon concentrations would be expected, allowing *in situ* measurements of an appropriate type to be made where most useful, and thus enabling remedial action to be taken where needed.

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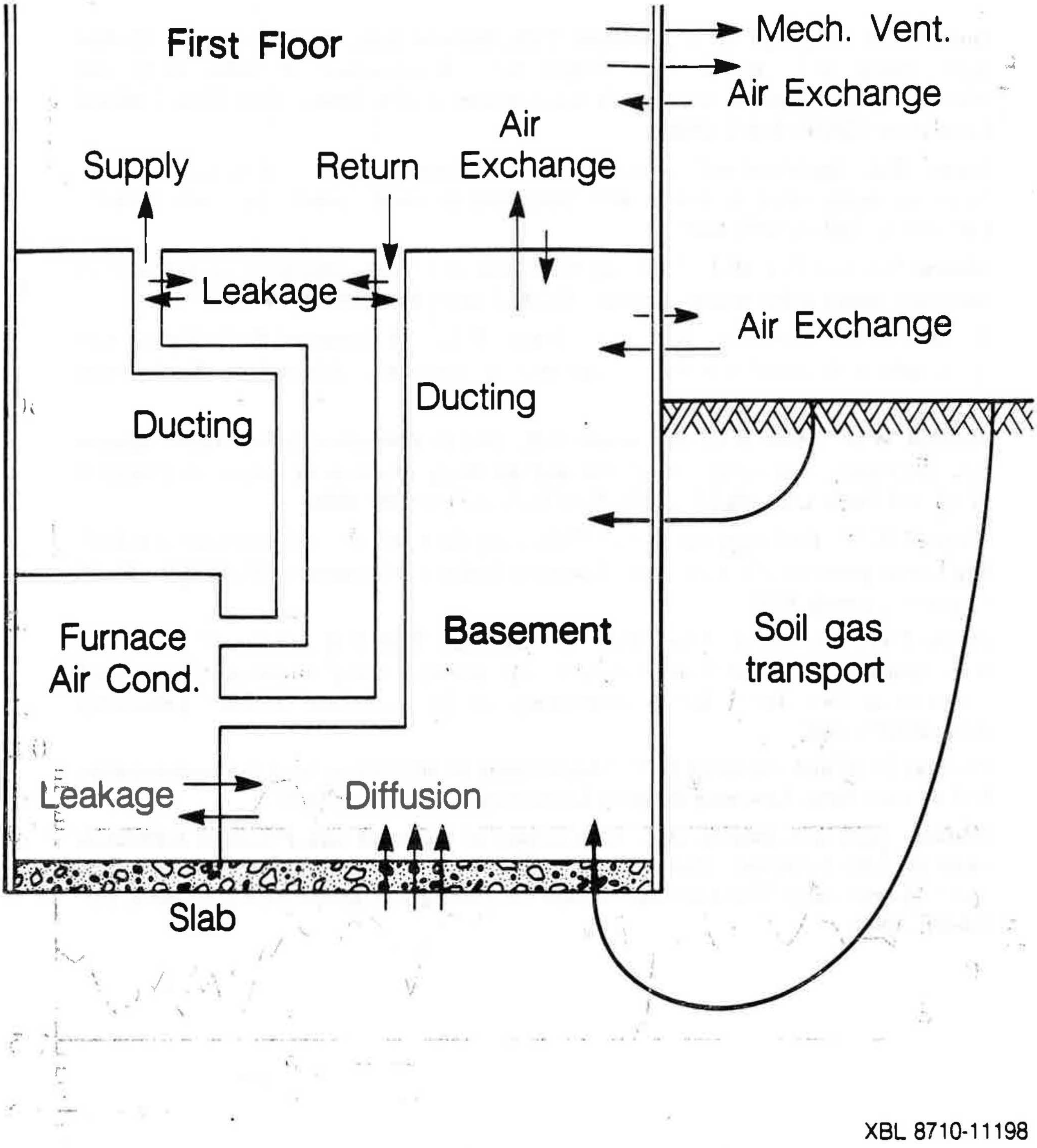

Figure 1.
Schematic depiction of factors affecting radon entry, removal, and distribution in a house with a basement.

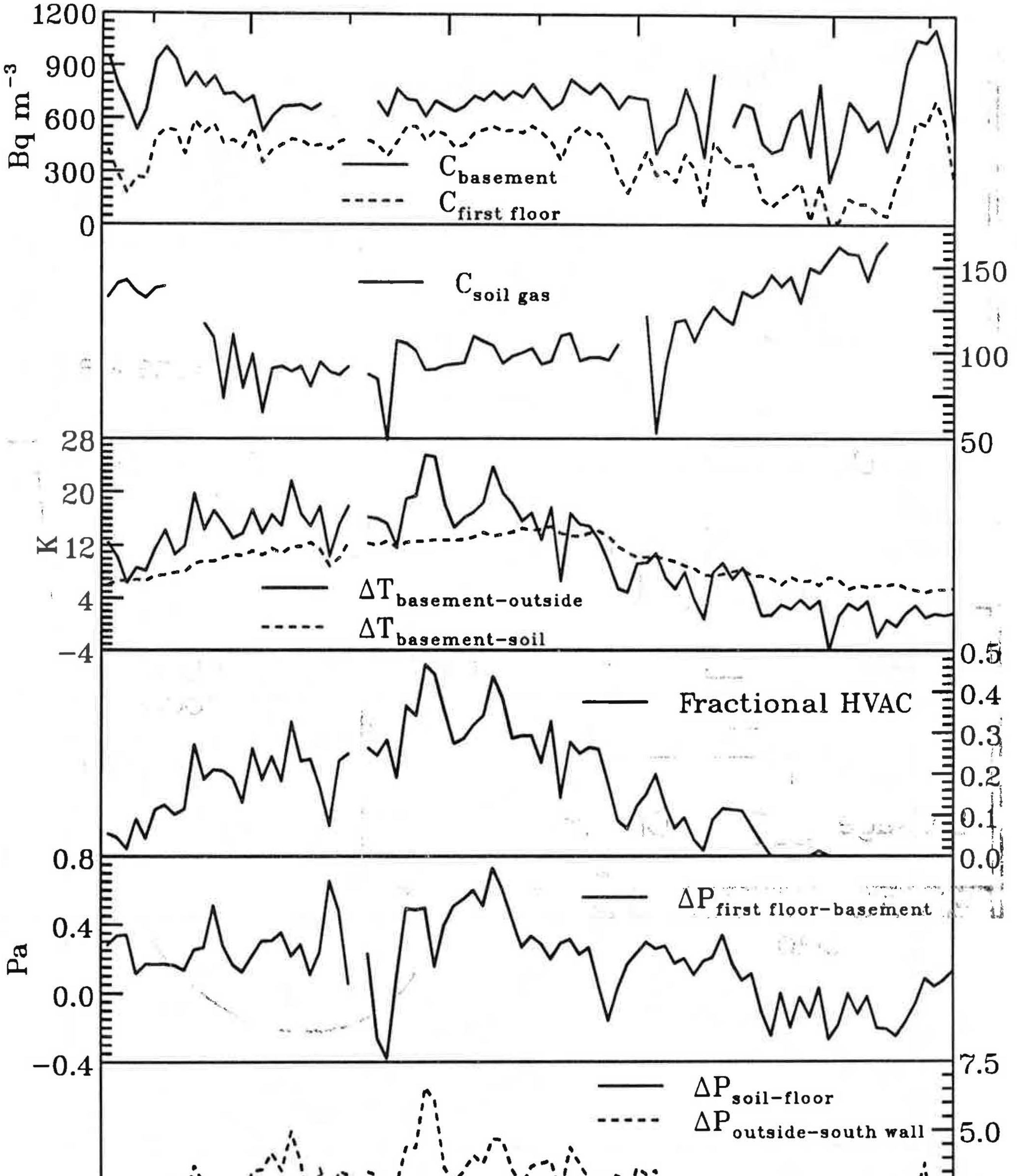

Figure 2.
Radon concentrations and factors influencing those concentrations, House 14.

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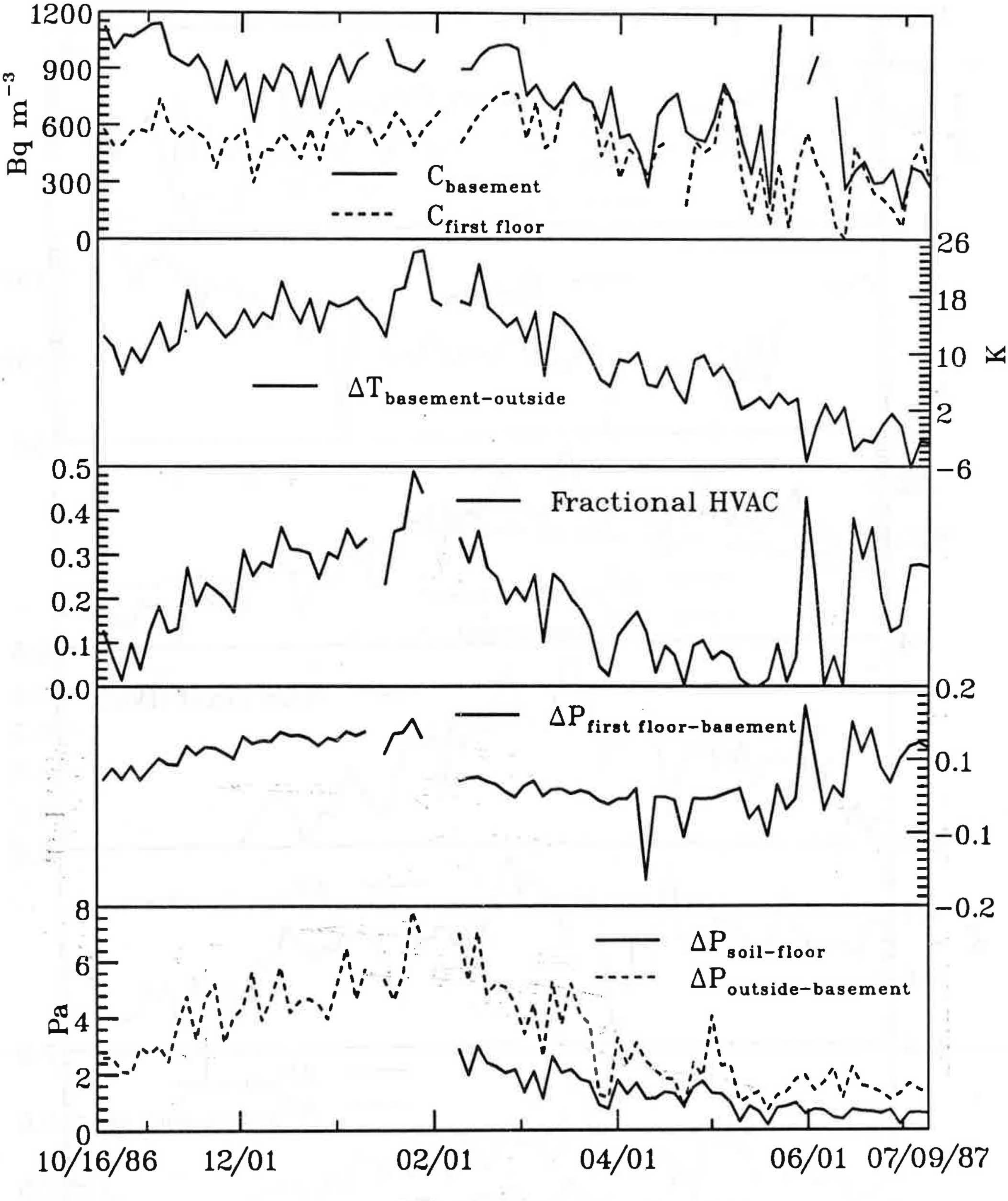

Figure 3.
Radon concentrations and factors infuencing those concentrations, House 2.

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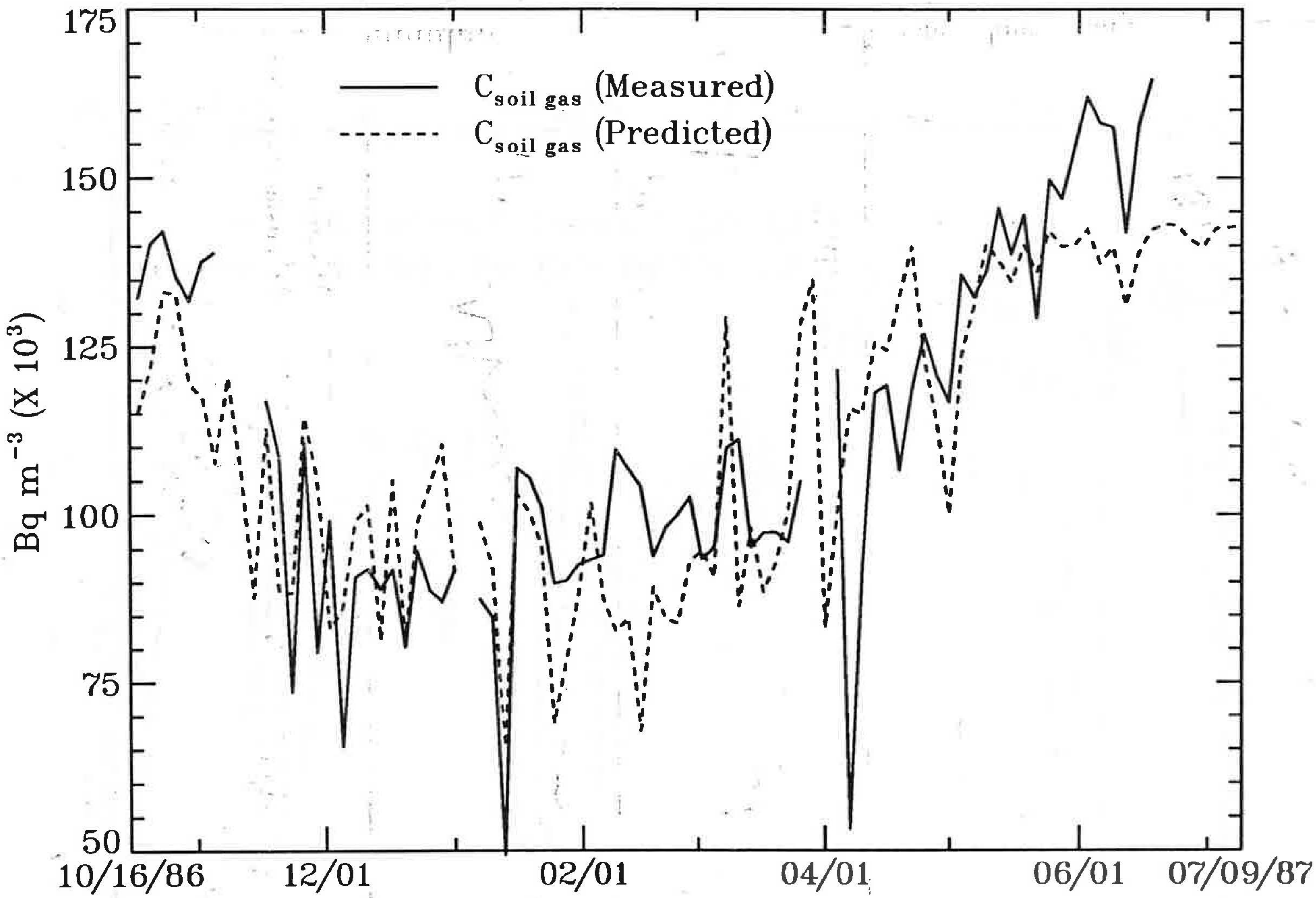

Figure 4.
Three-day average soil gas concentrations and calculated values from equation 7, House 14.

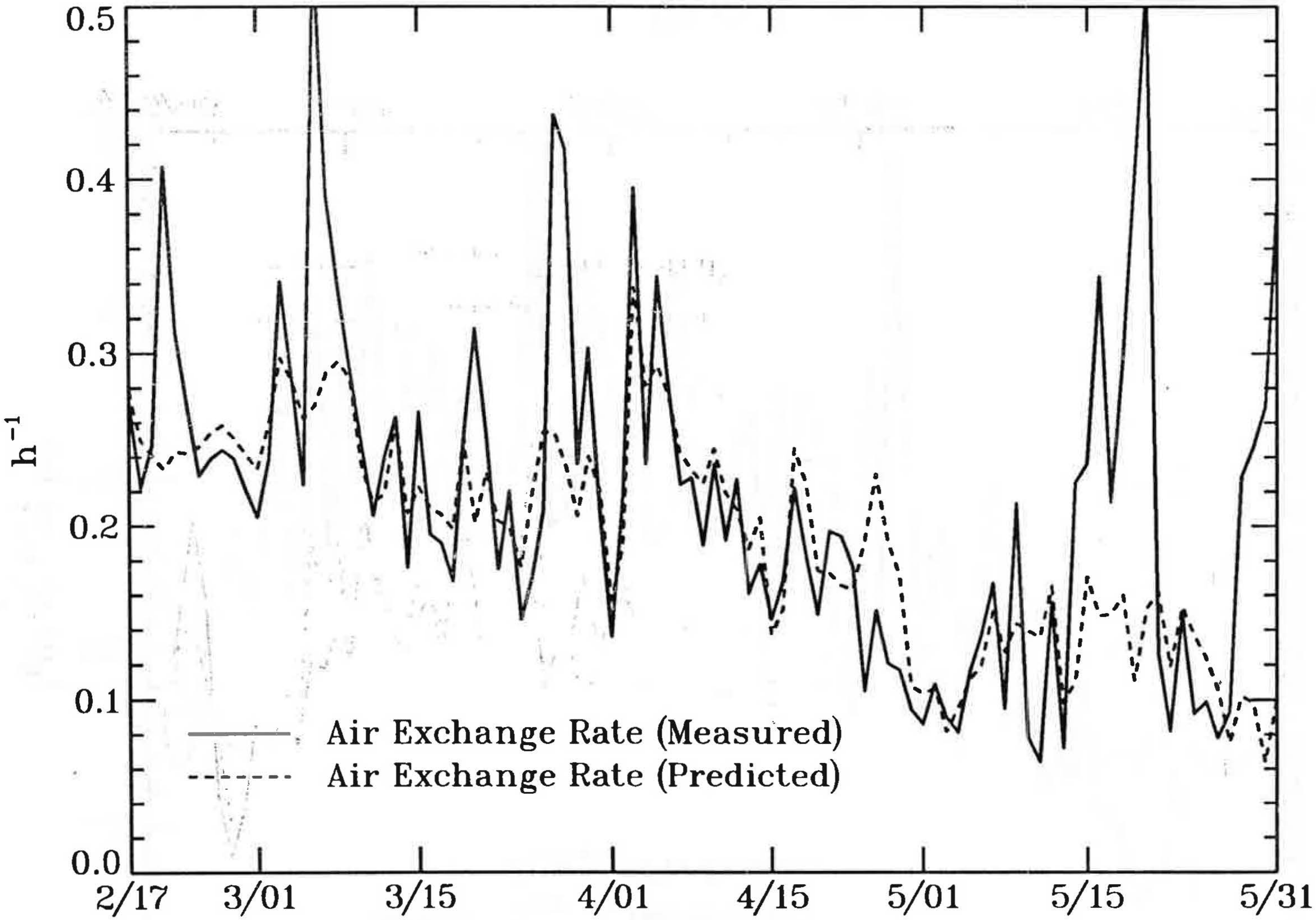

Figure 5.
One–day averages of measured air exchange rates and predictions of equation 8 for the house described in Nazaroff et. al. (1985).

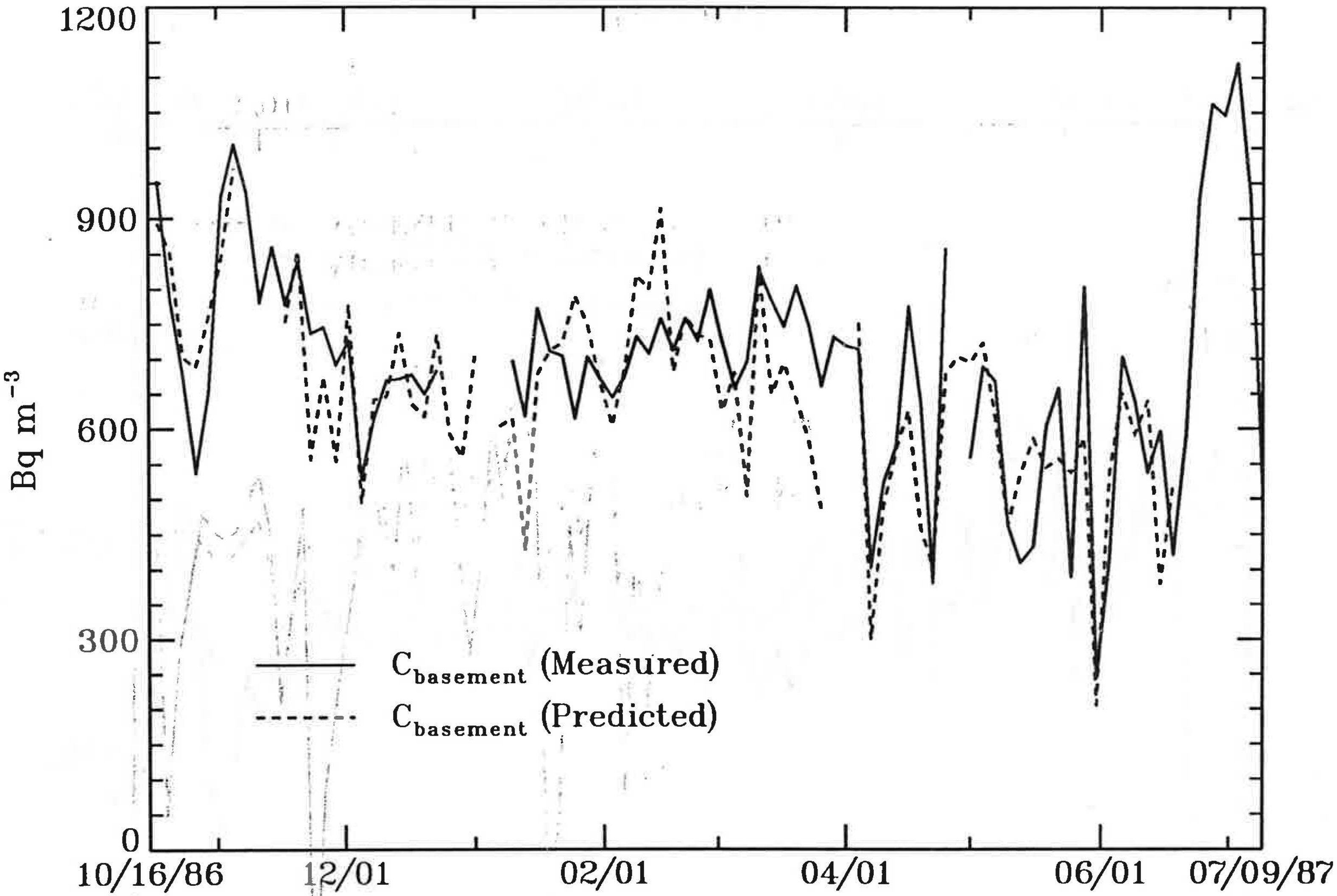

Figure 6.
Measured and predicted values of basement radon concentration, House 14, using measured values of soil gas concentration.

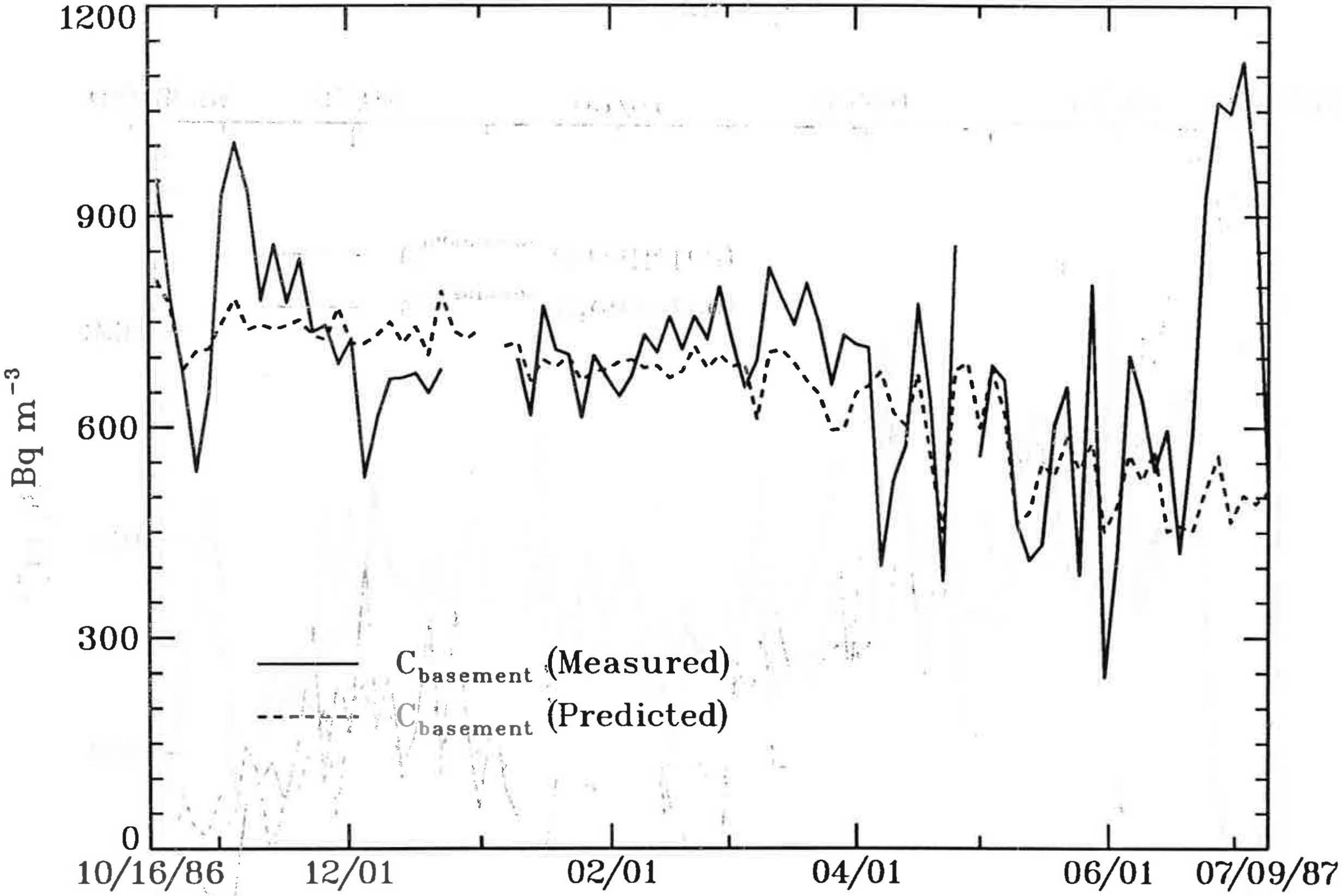

Figure 7.
Measured and predicted values of basement radon concentration, House 14, based on a model which does not use measured soil gas concentrations.

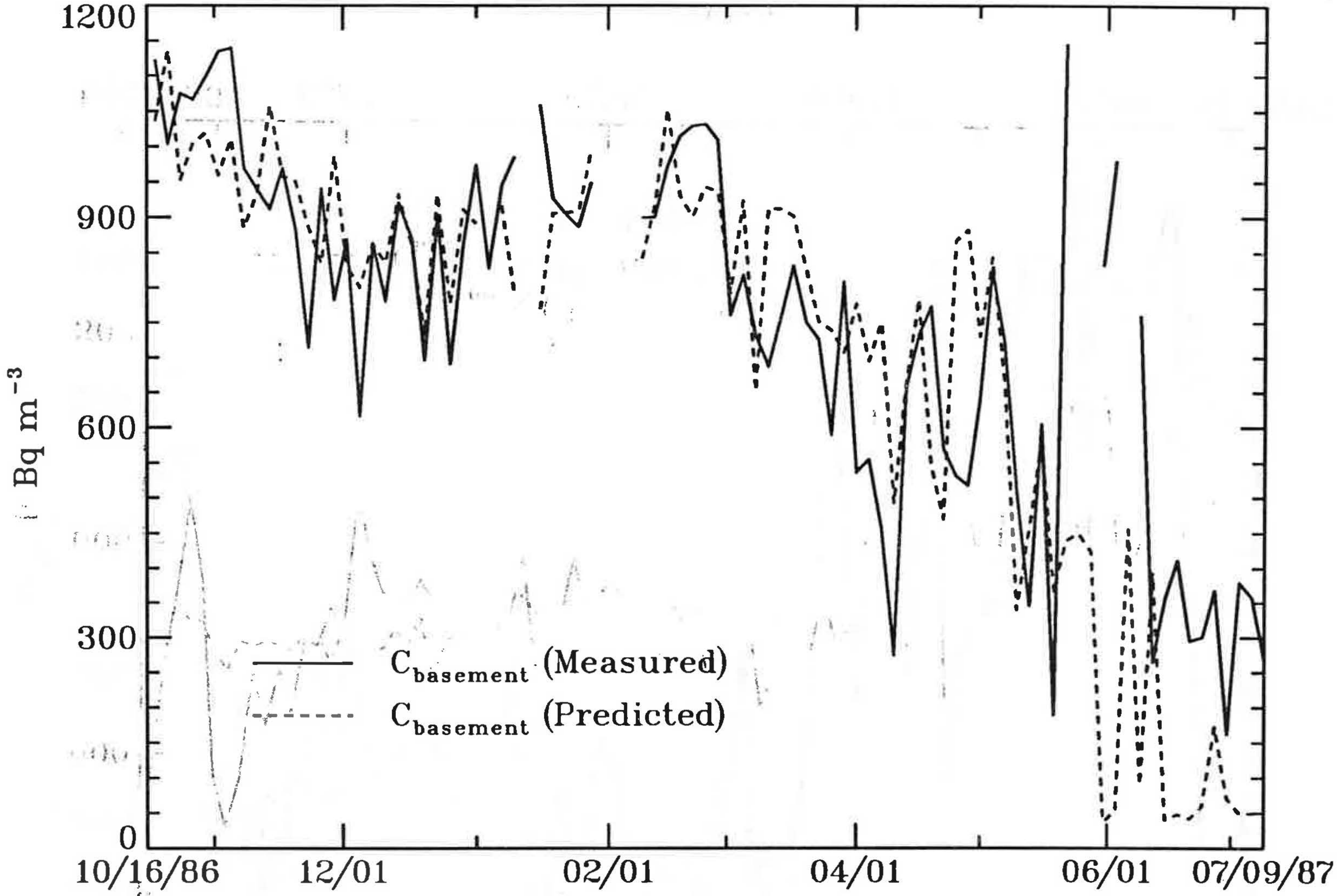

Figure 8.
Measured and predicted values of basement radon concentration, House 2, based on a model which does not use measured soil gas concentrations.

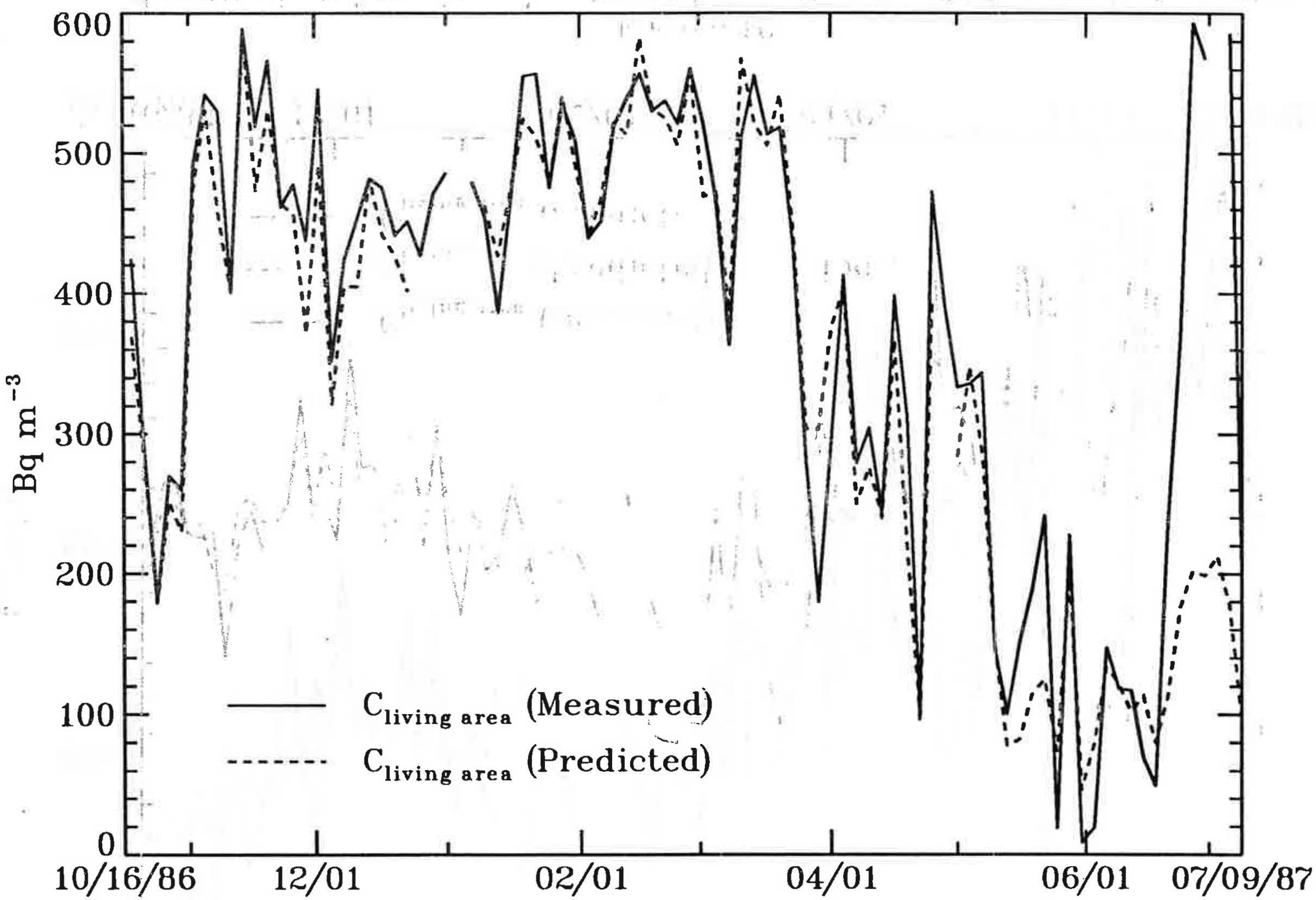

Figure 9.
Measured and predicted values of living area radon concentration, House 14, based on measured basement concentrations.

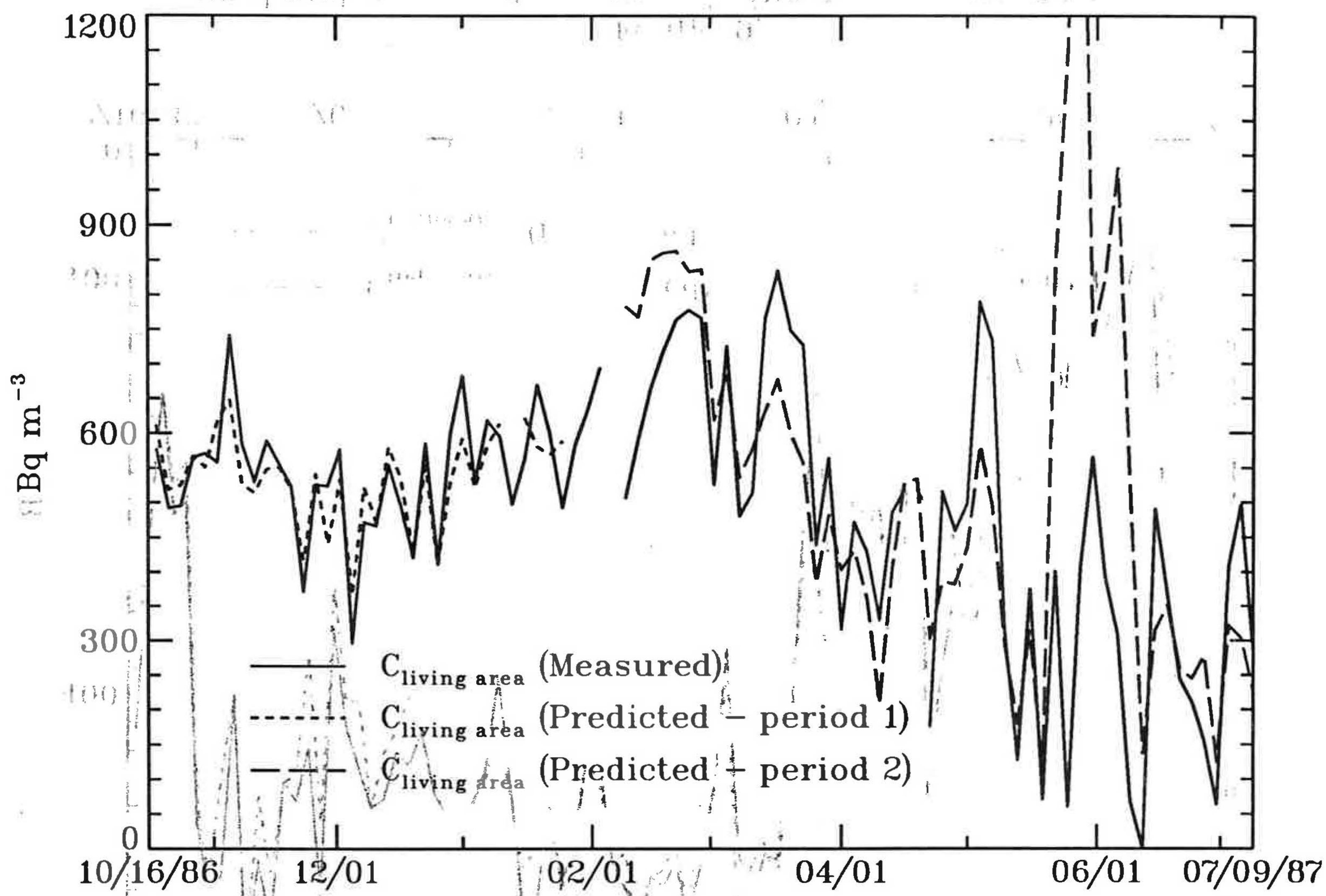

Figure 10.
Measured and predicted values of living area radon concentration, House 2, based on measured basement concentrations.