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Discussion of RADON TRANSPORT INTO A DETACHED ONE-STORY HOUSE WITH A BASEMENT

(Nazaroff, W.W. et al., Atmos. Environ., 19, No. 1, pp. 31-46, 1985)

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We would like to commend the authors on presenting such a unique and comprehensive set of physical and chemical data relating to the indoor radon concentrations of a single family house. In our discussion, we extend the interpretation of the data presented in this paper by developing what we feel is an improved model that can be used to predict radon concentrations in this house and possibly in others as well. In particular, we concentrate on the more complete set of low sump activity data which we have replotted in Fig. 1.

A steady state mass balance for radon in a house that is considered a single, well-mixed zone yields

$$V \frac{dC}{dt} = R_I C_o + R_s C_s + \sigma_d' - R_E C = 0 \qquad (1)$$

where

- V = volume of the house (L)
- C = indoor radon concentration (pCi/L)
- C_o = outdoor radon concentration (pCi/L)
- C_s = soil gas radon concentration (pCi/L)
- R_s = rate of soil gas entering the house (L/hr)
- R_I = rate of outdoor air entering the house (L/hr)
- R_E = rate of indoor air leaving the house (L/hr)
- σ_d' = diffusive emission of radon into the house (pCi/hr)

The diffusive component, σ_d', consists of radon emission from concrete, radon diffusion from soil through the concrete and emission from radon dissolved in water.

Using $R_I = R_E - R_s$, equation (1) can be solved for C to find

$$C = \frac{R_s}{R_E} C_s + \frac{\sigma_d'}{R_E} + C_o \left(1 - \frac{R_s}{R_E}\right)$$

The item in parentheses is equal to unity since $R_s/R_E \ll 1$. Thus

$$C = f_s C_s + \frac{\sigma_d}{\lambda_v} + C_o \tag{2}$$

where $f_s = R_s/R_E$ is the fraction of air entering the house from soil gas, $\sigma_d = \sigma_d'/V$, and $\lambda_v = R_E/V$ is the air exchange rate for the house.

Equation (2) says that the indoor radon concentration is the sum of three components:

1. $f_s C_s$ - radon entering via soil gas flow.
2. σ_d/λ_v - diffusive radon emission into the house.
3. C_o - radon in outdoor air.

Implicitly using this model, the authors make two simplifying assumptions: 1) the radon contribution from outdoor air is small and can be neglected and (2) the soil gas flow component, $f_s C_s$, can be considered constant. Therefore, they find $C = k_f + \sigma_d/\lambda_v$, where σ_d and $k_f = f_s C_s$ are constants. Using this model, their best fit to the data is shown by curve B of Fig. 1. Curve C shows a best fit to the data assuming the radon emission into the house is constant, independent of the ventilation rate λ_v.

We feel that neither of the above assumptions are valid and present a third model. The measured average outdoor radon concentration in the test house was 0.3 pCi/L while the indoor radon concentration ranged from 0.7-2.0 pCi/L. Therefore, outdoor radon contributed 15-43% of the radon in this house during the low sump activity periods and cannot be neglected.

We will now show that $f_s C_s$ is not constant and can be related to the ventilation rate as follows. First, consider the soil gas radon concentration C_s. The data presented by the authors in Table 4 show that over the range of indoor-outdoor temperature differences (ΔT), wind speeds (u) and barometric pressure changes (B'), the soil gas radon concentration varied from 251-484 pCi/L. In fact, a very nice equation of the form $C_s = f(\Delta T, u, B')$ can be developed from the following model.

Although many factors such as wind direction and soil permeability may cause the soil gas radon concentration to be greater on one side of the house or the other, we will assume that the concentration of soil gas which actually enters the house is fairly uniform. If we now consider a unit volume of soil near the surface of the house, a steady-state mass balance for the radon in that soil is given by

$$\frac{dC_s}{dt} = E - \lambda_d C_s - \lambda_w C_s = 0$$

where

E = emission of radon from radium decay (pCi/hr-Lsoil).

λ_d = loss due to radon diffusion and radioactive decay (hr^{-1}).

λ_w = loss due to weather induced dilution (hr^{-1}).

Solving for C_s,

$$C_s = \frac{E}{\lambda_d + \lambda_w} = \frac{E/\lambda_d}{1 + \lambda_w/\lambda_d} = \frac{C_{so}}{1 + \lambda_o}$$

where $C_{so} = E/\lambda_d$ is the soil gas radon concentration if there is no weather-induced flow and $\lambda_o = \lambda_w/\lambda_d$.

We now assume that C_{so} and λ_d are constant and that $\lambda_o = \lambda_w/\lambda_d$ can be modeled as $\lambda_o = a\Delta T + bu^{1.5} + cB'$. A best fit to the low sump activity data presented in Table 4 yields

$$C_s = \frac{C_{so}}{1 + a\Delta T + bu^{1.5} + cB'} = \frac{671}{1 + .0729\,\Delta T + .0777u^{1.5} + .00294B'} \quad (3)$$

Fig. 2 of this communication shows a comparison of the actual radon soil gas concentration and the computed concentration using equation (3). As can be seen, the agreement is excellent and makes a strong case for the existence of weather induced soil gas flow.

We now look at the term f_s, the fraction of air entering the house from soil gas. Rearranging equation (2), we can solve for f_s to find

$$f_s = \frac{\lambda_v(C-C_o) - \sigma_d}{\lambda_v(C_s-C_o)} \tag{4}$$

Using C_o = 0.3 pCi/L, the authors estimated value of σ_d = 0.06 pCi/L-hr and the data presented by the authors in Table 4 and Fig. 5 over the range of λ_v, C, and C_s values, we compute a value of $f_s = 0.0020 \pm 0.0003$. Therefore, 0.20% $\pm$ 0.03% of the air entering the house comes through the soil.

Equation (2) combined with the values for f_s and C_s we have just developed yields

$$C = \frac{f_s C_{so}}{1 + \lambda_o(\Delta T,u,B')} + \frac{\sigma_d}{\lambda_v} + C_o \tag{5}$$

where f_s, C_{so}, σ_d, and C_o are all constants.

We now try to relate λ_o and λ_v by assuming that λ_v can be modelled as $\lambda_v = \lambda_v(\Delta T,u) = a\Delta T + bu^{1.5}$, where a and b are constants. Using the data presented by the authors in Table 2, we find

$$\lambda_v\,(\Delta T,u) = 0.0106\ \Delta T + 0.0257u^{1.5},$$

Values of λ_v computed using this equation are plotted against the actual values in Fig. 3. The plot shows some scatter, but is fairly typical for this type of correlation.

We now define $\alpha = \lambda_o / \lambda_v$. Neglecting the barometric pressure term in λ_o (which is usually small),

$$\alpha = \frac{\lambda_o}{\lambda_v} = \frac{.0729\,\Delta T + .0777 u^{1.5}}{.0106\,\Delta T + .0257 u^{1.5}}$$

This term will not, in general, be constant. In particular, it is interesting to note that the ΔT term is a much larger contributor to λ_o than it is to λ_v. This seems reasonable since the wind would tend to cause less pressure induced flow through the soil than into the house.

However, to a fairly good approximation, we can consider α constant. For the range of ΔT and u listed in Table 4 by the authors ($4\ ^oC \leq \Delta T \leq 16\ ^oC$, 1.0 m/s $\leq u \leq 3.5$ m/s), we find $\alpha = 5.3 \pm 1.0$ ($\pm 19\%$). If we now let $\lambda_o = \alpha\lambda_v$ in equation (5) and substitute all the known values for the constants we find

$$C = \frac{f_s C_{so}}{1 + \alpha\lambda_v} + \frac{\alpha d}{\lambda_v} + C_o = \frac{1.34}{1 + 5.3\,\lambda_v} + \frac{0.06}{\lambda_v} + 0.3 \qquad (6)$$

This equation is plotted in Fig. 1 (curve A). The agreement with the observed data is very good, even at the extremes in ventilation rate. This is particularly interesting since most of the constants were derived from the Table 4 data which spans only an intermediate range of ventilation rates. Comparison of curves A and B to the data shows that curve A results in an average standard deviation of $\pm 12\%$ while curve B yields a standard deviation of $\pm 24\%$.

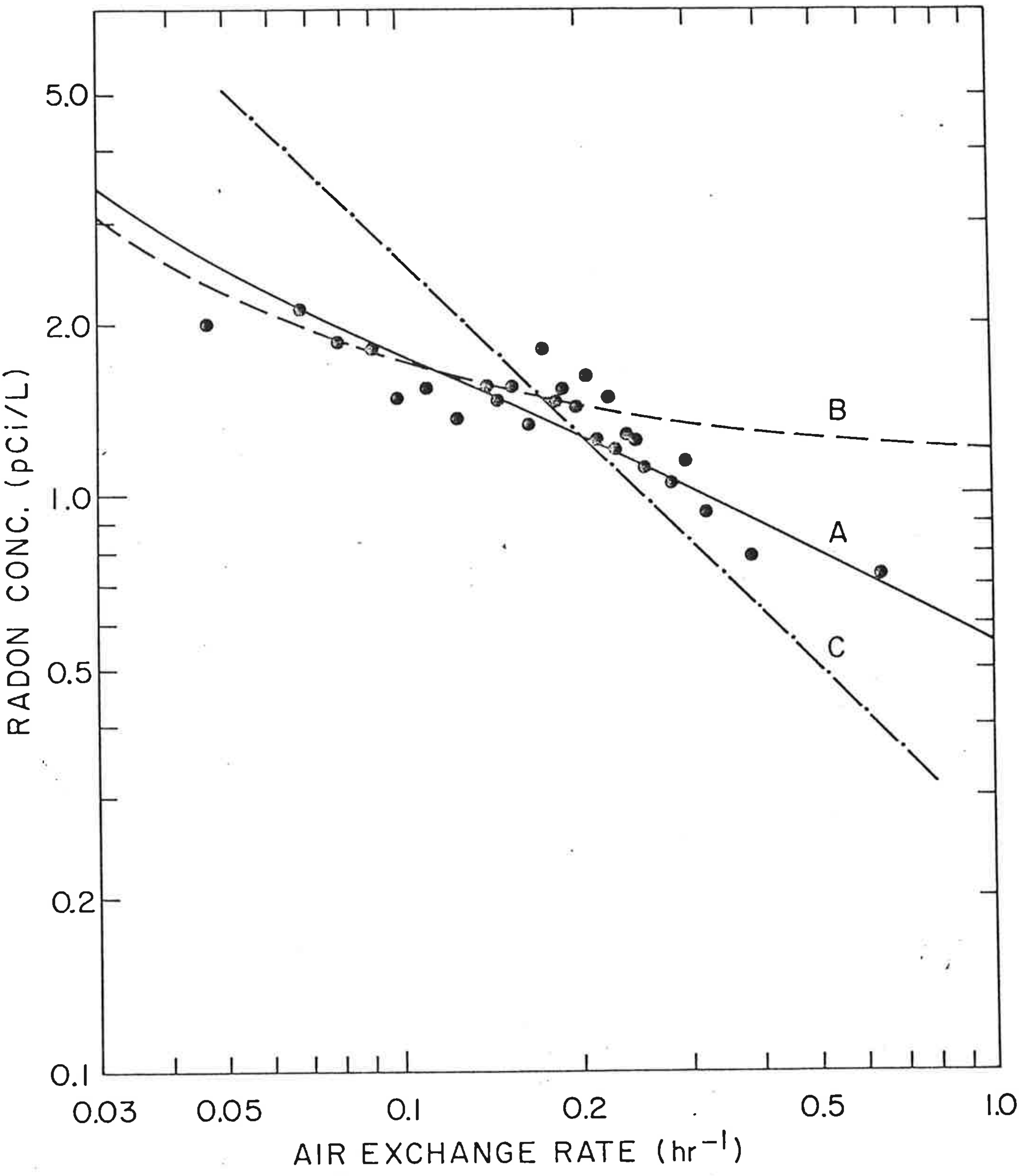
Very little data of the type presented in the authors' paper is available. If nothing else, this modeling exercise points toward a need for more of the same since it is becoming increasingly clear that the mechanisms causing radon entry into homes are more complicated than had previously been recognized.

FIGURE CAPTIONS

Fig. 1. The low sump activity data along with the two models (curves B and C) presented in Fig. 5 of the authors' paper. Curve A represents the model presented in this discussion.

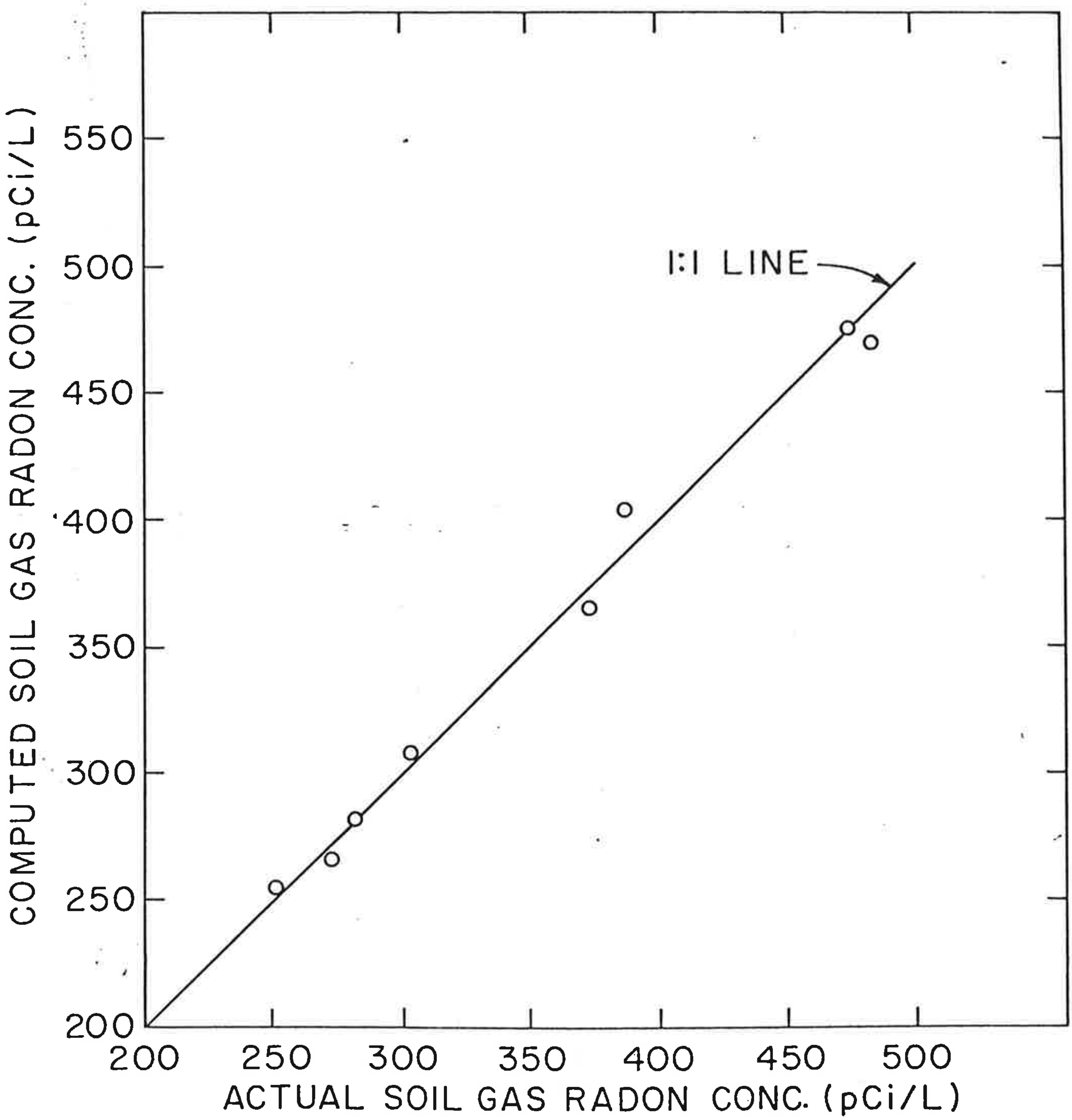
Fig. 2. A comparison of the radon soil gas concentrations presented in the authors' paper with those computed from a model in this discussion which correlates the soil gas concentration to indoor-outdoor temperature differences, wind speed, and barometric pressure changes.

Fig. 3. A comparison of the actual air exchange rates in the test home with those computed in this discussion from a model correlating air exchange rate with indoor-outdoor temperature differences and wind speed.



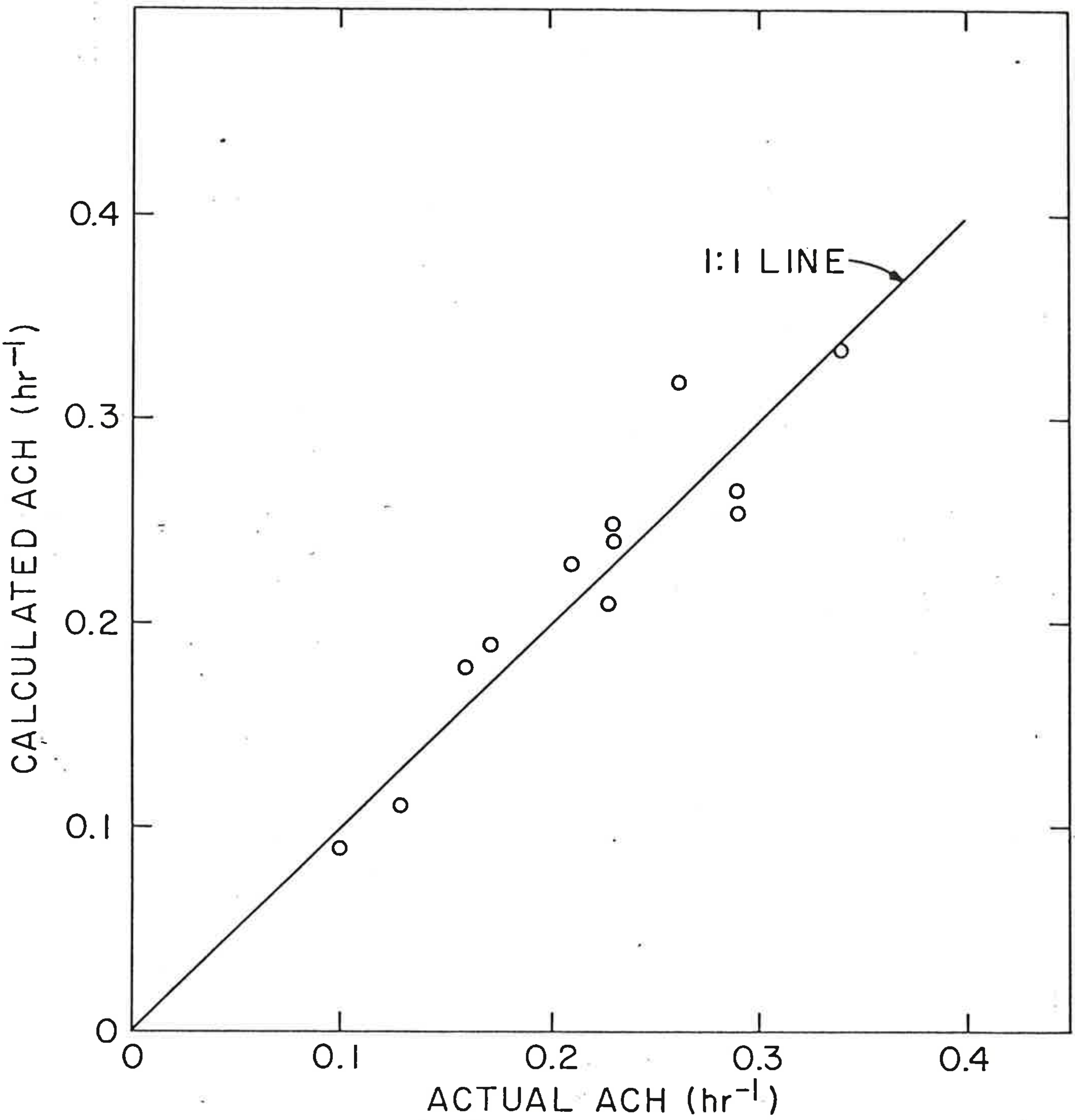
RADON CONC. (pCi/L)
5.0
2.0
1.0
0.5
0.2
0.1
0.03
0.05
0.1
0.2
0.5
1.0
AIR EXCHANGE RATE (hr^{-1})
A
B
C

Figure 1



COMPUTED SOIL GAS RADON CONC. (pCi/L)
550
500
450
400
350
300
250
200
1:1 LINE
200
250
300
350
400
450
500
ACTUAL SOIL GAS RADON CONC. (pCi/L)

Figure 2



0.4
0.3
0.2
0.1
0
CALCULATED ACH (hr^{-1})
1:1 LINE
0
0.1
0.2
0.3
0.4
ACTUAL ACH (hr^{-1})

Figure 3