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RADON CONCENTRATION, SOURCE STRENGTH AND VENTILATION RATE: HOW WELL DO WE KNOW THE CONNECTIONS?

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Abstract. The simple steady state model which is frequently used to relate radon concentration (C), source strength (S) and ventilation rate ($1/\tau$) is expressed in the equation $C=S\tau$. The assumptions of this model are given and their validity explored in this paper. In particular the assumption of steady state conditions for the ventilation rate is studied experimentally in a simple one chamber building, the Solar Classroom at Hamilton College. Even in this simple case variations are found of a factor of three or more in τ which can be attributed to wind and stack effects. Studies of other houses are cited which show that variations of τ between houses can be as large as a factor of sixty or more. The implications of these results for developing ventilation standards or for mitigating the indoor radon problem are suggested. Individual houses can be understood and mitigating strategies implemented in them on a case by case basis but a statistical treatment of houses in general does not seem to be a fruitful approach.

The Simple Model and its Assumptions. The relationship among the three quantities, radon concentration (C), source rate (S) and ventilation rate ($1/\tau$) is given in this simple model by $C=S\tau$. The assumptions of this model are: 1) uniform concentration of radon throughout the enclosed space, 2) negligible outside ambient concentration, 3) the time constant of radioactive decay of radon is much longer than the ventilation rate time constant (τ), 4) steady state conditions hold, i.e. source rate (S) equals disappearance rate (C/τ) with both being constants.

Validity of Assumptions. For most houses the uniform concentration assumption seems implausible on the face of it. A paper by Hernandez and Ring (1982) shows that in test houses of many chambers this assumption is off by close to a factor of two in some instances when a two chamber model is used to make a more accurate analysis.

The negligibility of the ambient concentration is open to question also. Generally outside concentrations are lower than those inside (see Prichard et al. (1982)) but not so low (sometimes only a factor of two) that this level is always negligible.

The time constant of radioactive decay of radon is about 5 days and τ is typically of the order of hours. This assumption is thus generally valid.

The steady state assumption is open to question on two counts. First, the source of radon may itself be varying in time, i.e. there may be variations in the supply rate. Examples are the observations of Hess et al. (1982) on radon from ground water and Hernandez et al. (1982) on the variation of radon concentration with barometric pressure. And second, the ventilation rate ($1/\tau$) itself may be varying. It is this second point with which this paper will mainly be concerned. It should be clear, however, that variation in ventilation rate is only one important part of a more complex problem.

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Experiment at the Solar Classroom. In order to study ventilation rate variability for a very simple one room house, tracer gas experiments were carried out in the Solar Classroom at Hamilton College. This house and its performance have been described and analyzed in two papers, one by Ring and Hamilton (1979) and the other by Ring (1981).

Introduction of an unusual non-toxic gas into the building and measurement of the concentration of that gas as a function of time allows ventilation rate to be measured directly. We used SF_6 as the gas and an infrared absorption detector tuned to a part of the vibration-rotation spectrum of the SF_6 molecule at 10.7 μm. The rate of flow of SF_6 gas was controlled and monitored by a flow meter and the volume of gas in the Solar Classroom was mixed by a low speed fan while the experiments were being run.

Three different kinds of experiments are possible with this arrangement. They are growth, steady state and decay experiments. For growth and decay experiments an analysis of the data in terms of exponential transients yields the characteristic time, τ, which is the reciprocal of the infiltration rate. In the case of a true steady state if the injection rate is known then the infiltration rate can be found from the steady source concentration, i.e., $C_{ss} = S\tau$, where C_{ss} = steady source concentration and S = steady source (or injection) rate. Figure 1 is a strip chart record with all three kinds of behavior shown. The steady state behavior shows as a constant value of SF_6 concentration. A change in this level would indicate a proportional change in τ and thus a departure from the steady state.

These experiments are designed to directly measure infiltration. However, they have experimental problems associated with them. Prominent among these are zero drift, temperature dependence of the gas analyzer response and, most important for us, changes in τ during the course of the experiment. The first two effects can be observed and to a large extent corrected for. The changes in τ can be directly observed in the steady source experiments and it is these changes which are of interest in testing the steady state assumption. In the transient experiments a consistency requirement linking τ and S or C_o, the initial concentration, checks that τ is a constant over the period of growth or decay. A similar check can also be done roughly by looking at the strip chart records where abrupt changes in τ are very obvious.

Experiments were run in January, February and March of the 1983 heating season and in July during the non-heating season. The results for the steady source experiments are given in Figure 2 and those for the transient experiments in Figure 3. ΔT is the temperature difference (inside-outside).

Interpretation of the Experiment. The two variables ΔT and wind are intuitively important. Both theoretical studies, e.g., Sinden (1978) and experimental ones, e.g., Keast (1978), show that a pressure differential across a building's exterior shell will produce an air flow which obeys a law: $A = K (\Delta p)^\alpha$, where K and α are determined by the shapes and sizes of the openings which permit the air flow A.

If the flow is laminar $\alpha = 1$, if it is turbulent $\alpha = 4/7$ and entrance and exit effects can mean that $\alpha = 1/2$, Sinden (1978). Experimentally the exponent has been found to vary for various wall elements from .296 for a mail slot, to .678 for door frame trim, to .824 for a sealed test wall, Keast (1978).

The pressure differential can be produced by either the stack effect (ΔT) or by wind or by a combination of these two effects. It can be shown that the combined effect will always be less than or equal to the sum of the two effects, Sinden (1978). An interesting point which Sinden develops is that in some circumstances the two effects may work to cancel each other. This effect has been observed and reported by Blomsterberg and Harrje (1979).

Other authors make special assumptions about the way in which the two effects should be combined, e.g., Sherman and Grimsrud (1980) assume that they can be added in quadrature, i.e., $((\Delta p_t)^2 + (\Delta p_w)^2)^{\frac{1}{2}}$.

For the Solar Classroom data which includes only qualitative wind observations we have chosen to try a linear regression of $1/\tau$, the ventilation rate of air flow, versus ΔT and these results are shown in Figure 3.

We have run a similar linear regression on the steady source data using $1/C_{ss}$ as the variable proportional to air flow. These results are shown in Figure 2. Note that C_{ss} is the average daily SF_6 concentration.

It can be shown that the stack effect, e.g., Sinden (1978), produces a Δp which is proportional to ΔT so that in the above regressions we have assumed $\alpha = 1$. We have, however, run the regressions against $(\Delta T)^{\frac{1}{2}}$, or $\alpha = \frac{1}{2}$, and have found about equally good correlations.

For the purposes of comparison it is worthwhile looking at the much more extensive measurements and analysis reported by Malik (1978) on two similar town-houses in Twin Rivers, New Jersey. When the temperature difference and wind velocity (and direction) are combined in multiple linear regression very good fits are found over the entire range of ventilation rates from .2 to 2.2 air exchanges per hour. Of perhaps even more interest, however, is the result that the two houses have different fits and the wind-stack combined effect appears to be a cancelling one under some circumstances for one house but not for the other.

Larger Scale Studies Covering Many Houses. The results given above for the simple one chamber house show a factor of three variation in τ and the results of Malik show a factor of ten for a multi-chambered residence. Since the Solar Classroom is much tighter than the Twin Rivers houses the over-all variation for both houses is from about .07 to 2.2 exchanges/hr. or an extreme outside variation of a factor of thirty in ventilation rate. But what of other houses and comparisons between them?

Two studies of many houses, one by Nero and Nazaroff (1981) of 98 and the other by Persily and Grot (1983) of 50, show ventilation rates ranging from .02 to 1.5 exchanges/hr. for the first and from .05 to 3.0 exchanges/hr. for the second.

In the case of the Nero and Nazaroff study it should be noted that radon concentration was also measured and it ranged over three decades from about .04 to about 30 pCi/l or even a greater range than that of ventilation rates which varied by a factor of 75. Furthermore no strong correlation shows up in the scatter diagram when radon concentration is plotted against ventilation rate.

Conclusions. To make measurements of radon concentration and ventilation rate at one time in one house (or worse, one measurement at one time and the other at a different time) does not necessarily tell you much about the average radon level in that house. This is so since, from what we have seen, we might expect for a multi-chambered house a factor of ten variation in ventilation rate and thus, even if the source rate doesn't change, a factor of ten in radon concentration.

Thus it is better to use integrating monitors such as track etch (Alter and Fleischer, 1981) for radon and PFT (Dietz, 1982) for ventilation rate. In these measurements a time averaged $\overline{C}$ and $\overline{\tau}$ may be found and such values ought to be much closer to the over-all time-averaged steady state values. Also the value of $\overline{S}$ thus found ($\overline{S} = \overline{C}/\overline{\tau}$) will be more nearly a representative value.

The drawback of this method is that the fluctuations, and hence the maximum and minimum values, are not recorded. This lack means that the dynamic behavior of the house can not be followed in time, possibly dangerous periods can not be identified and, furthermore, there is little evidence with which to elucidate the mechanisms by which radon is entering and collecting in the house.

Finally, it should be obvious that to apply the one shot measurements to a set of houses is only to compound the difficulties. Such treatment will tend to obscure even more thoroughly the mechanisms operating in individual houses and will produce a broad distribution of results which will not be useful for either setting standards or resolving the problem.

To claim, for example, that ventilation rates in houses ought never to be lower than some figure, say 1/3 of an exchange/hr., is to ignore many important facets of the problem, namely: 1) that it is difficult (although not impossible) to establish that a given house has such a mean ventilation rate and it is even more difficult to show that there are no dangerous periods for that house, 2) that the ambient level may be sufficiently high so that increasing the ventilation actually worsens rather than helps the problem, 3) that the source rate may be changing greatly with time and thus override the ventilation rate, 4) that the source strength though constant may be so great that even a wide-open house would not be adequately ventilated, 5) that different neighboring houses may behave differently even though of similar construction, and experiencing similar weather conditions, 6) that differences in houses in construction, weather and source conditions are much greater than those suggested in (5) above and thus what serves as an adequate standard for some set of houses will be far from adequate for all.

To establish that there is an indoor radon problem is one thing but to resolve that problem is quite another. The former seems to have been accomplished and statistical studies have been useful here. But the latter requires careful study and understanding of individual houses and does not seem amenable to a statistical treatment.

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FIGURE CAPTIONS

Fig. 1. Strip chart record showing response of SF_6 IR detector on vertical scale (approx. proportional to concentration) with time of day on horizontal. Note the effects caused by wind, sun and thermostat turning on and off the heaters. The three regions of growth, steady state and decay are clearly to be seen.

Fig. 2. The reciprocal of C_{ss} the daily average SF_6 concentration derived from steady source experiments is shown plotted against ΔT, the average difference in temperature between inside and outside over the day of the experiment. The least squares best fit straight line is shown with its slope, intercept and correlation coefficient.

Fig. 3. Ventilation rates derived from growth and decay experiments is shown plotted against ΔT, the average difference in temperature between inside and outside over the day of the experiment. The least squares best fit straight line is shown with its slope, intercept and correlation coefficient.

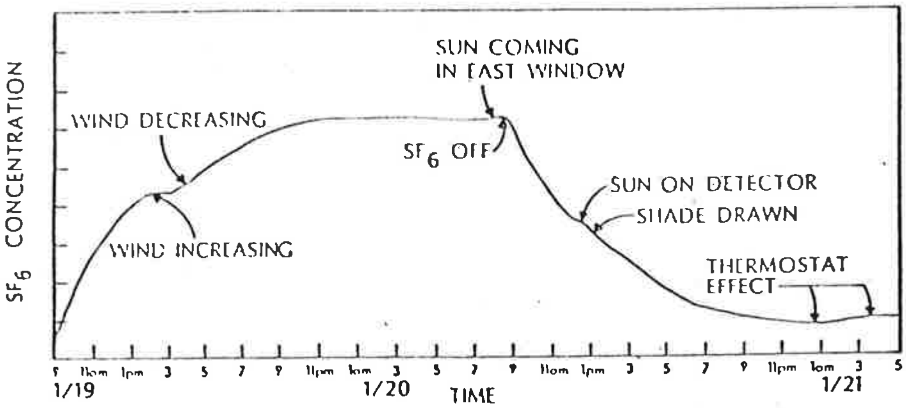

FIG. 1

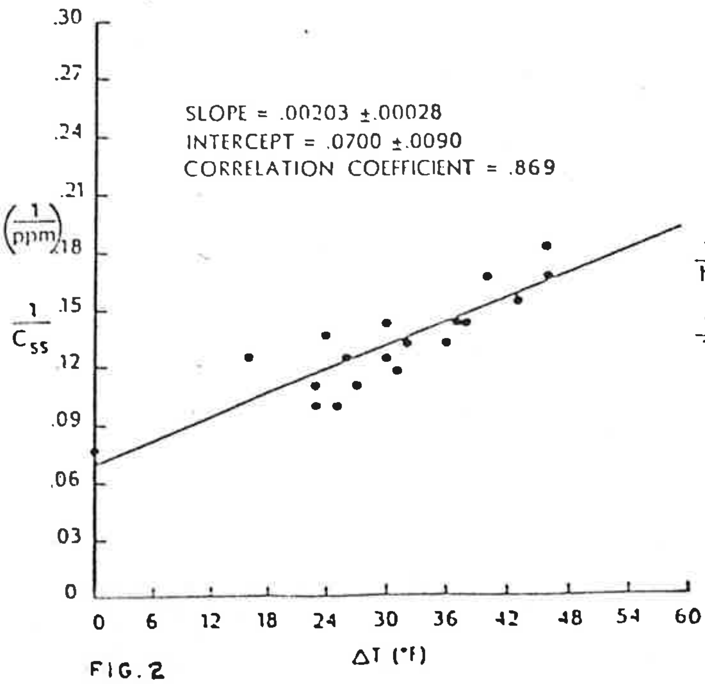

FIG. 2

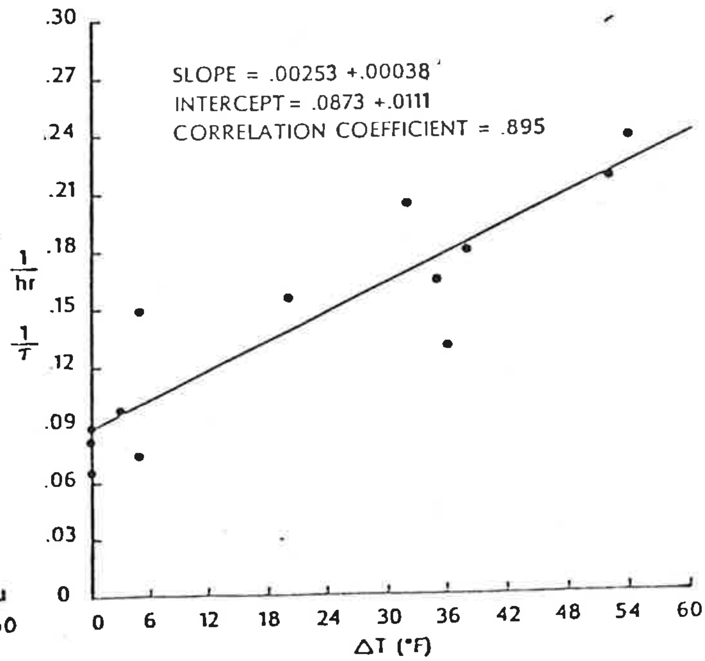

FIG. 3