A New Look at the Twelve Hour Dynamic Equilibrium Protocol

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Abstract

Both the 1992 and 1993 EPA protocols for the radon testing of homes specify a 12 hour delay time between the inception of closed-house conditions and the beginning of a radon test, when the test duration itself is two or three days long. The authors develop a simple model of a dwelling that includes radon entry, house ventilation and radon decay.

$$\frac{dn(t)}{dt} = N_{in} - N_{ex}\, n(t) - n(t)\, \lambda e^{-\lambda t}$$

The model is solved using numerical integration for a large range of variation of radon entry and ventilation rates. It is determined that the 12 hour delay time is indeed sufficient for most values of the two variables. Exceptions are noted for very tight homes (around 0.1 air changes per hour). The authors also conclude that the radon decay term makes only a small correction to the 12 hour delay allowing the 12 hour delay, therefore, to also be used for establishing house equilibrium when measuring non-radioactive pollutants entering via the soil gas.

Introduction

The United States Environmental Protection Agency (U.S. EPA) codified radon testing in homes in a series of documents during the 1980's, finalizing these protocols in 1992 and 1993 (EPA 1992, EPA 1993). These latter documents specify a 12 hour delay between the beginning of closed-house conditions and the start of a radon or radon decay product test when the sampling period is set at, or greater than 48 hours and less than 96 hours. This delay was based upon research conducted on homes in the 1980's by many (Harris, J. 1987; Hubbard, L. et al, 1987; Nagday, N. et al, 1984; Nitschke, I., et al., 1985, to name a few).

Although radon dynamics within dwellings have been well explored, the authors wished to focus on a very practical aspect of radon dynamics that may deserve a renewed investigation. Of interest is whether the 12 hour delay time is a reasonable protocol given the large variation of radon entry rates and house ventilation rates that are known to exist.

A Mathematical Model

It is well established that the final radon concentration in a dwelling is the combination of several factors; radon entry rate (from diffusion, convective soil gas flow, release from water-borne radon and emanation off of building materials), exfiltration out of the dwelling and, to a smaller extent, the radioactive decay of the radon into radon decay products. Each of these three factors can be written as a variable in a differential equation, resulting in:

$$\frac{dn(t)}{dt} = N_{in} - N_{ex}\, n(t) - n(t)\, \lambda e^{-\lambda t} \quad \text{(Equation 1)}$$

where: N_{in} is the rate at which radon particles enter the building air space

N_{ex} is the fraction of the house air exchanged every hour

$n(t)$ is the concentration of radon in the building at any time, and

λ is the radioactive decay rate appropriate for radon. (.693/91.68 hrs.)

The differential equation, given in equation 1, can be numerically integrated, giving $n(t)$, the radon concentration in the building at any time, t.

Solving equation 1, shows that N_{in}, the rate at which radon particles enter the building air space, scales the solution exactly, so that doubling the rate of incoming radon simply doubles the final radon concentration, for example (for a fixed air exchange rate). For that reason, N_{in} is set equal to 1, for simplicity, in the following graphs.

Results

Radon Concentration as a Function of Time

Figure 1, below, demonstrates the radon concentration over time for three different air exchange rates, 0.1, 0.2 and 0.4 air changes per hour (ACH). It can be seen that for an ACH of 0.4 (graphed), the radon concentration levels off at, or around, 12 hours.

However, for an ACH of 0.1, the radon concentration has not leveled off at 20 hours. A continuation of figure 1 to the right would show that it eventually levels off at hour 37. Such ventilation rates are not unknown (see Nazaroff and Nero, 1984, for example).

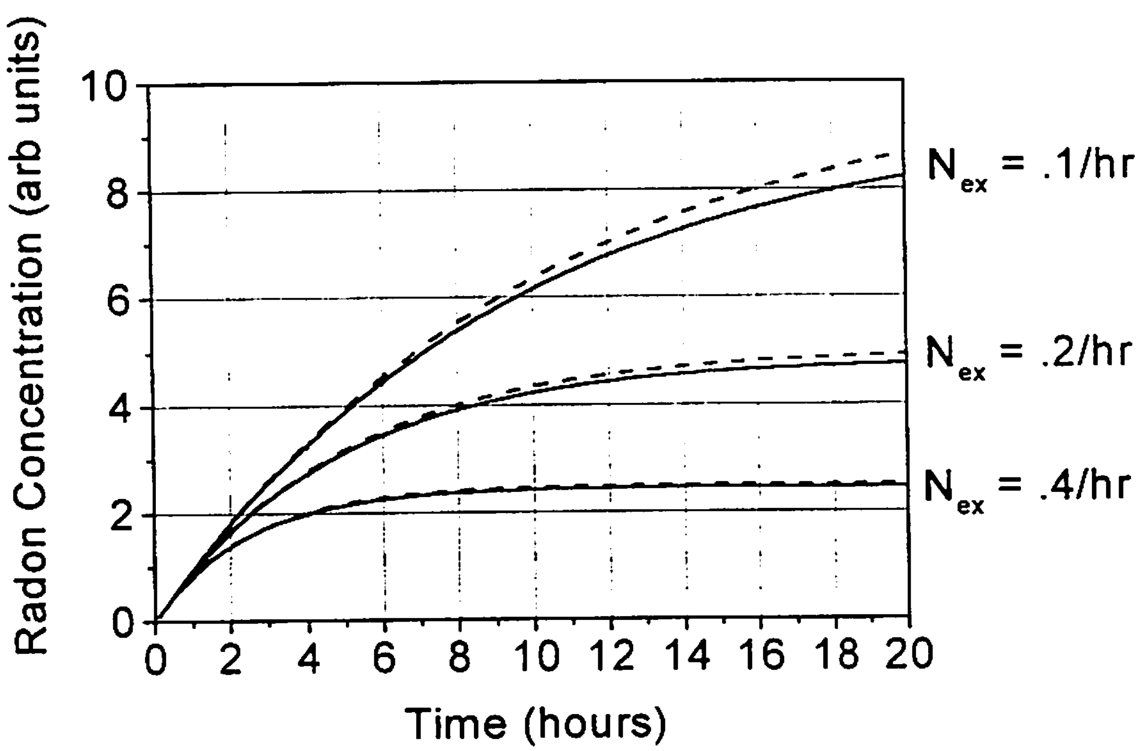

Figure 1: The radon concentration as a function of time for various exchange rates. The dashed lines give the results when the radioactive decay of radon is neglected.

Changing the radon entry rate in Figure 1 does not change the time it takes for the radon concentration to level off. It simply changes the final radon concentration.

Equilibrium Time as a Function of Air Exchange Rates

Figure 2 graphs the saturation time, defined as the amount of time, in hours, it takes for the radon concentration to achieve 98% of its final value, as a function of air exchange rates.

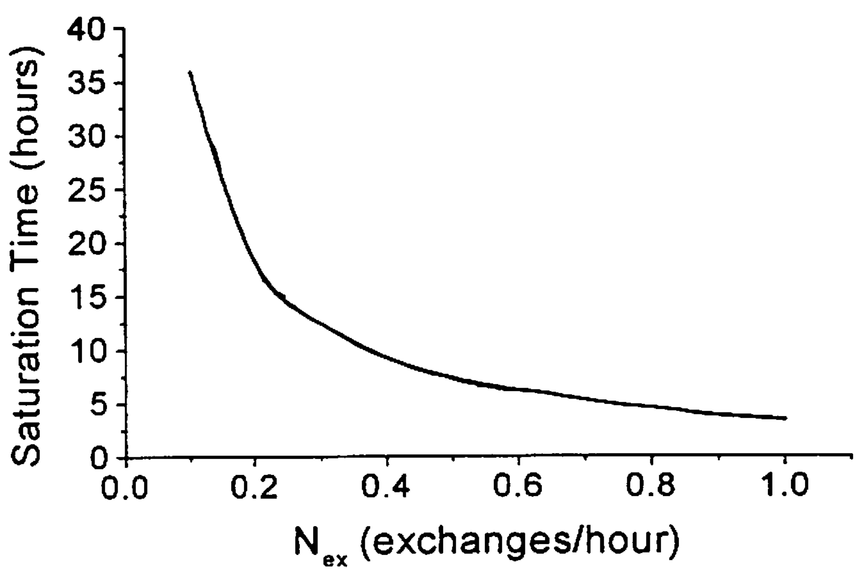

Figure 2: The time to reach 98% of the saturation value as a function of exchange rate. Saturation time is independent of radon entry rate, N_{in}.

Figure 2 shows that for air changes greater than roughly 0.4, the 12 hour dynamic equilibrium time is sufficient. Indeed, many homes would seem to be in dynamic equilibrium in much less than the 12 hours used in the EPA protocols. Figure 2 also shows that for some values of N_{ex}, those less than 0.4 ACH (approximately), the 12 hour delay is not sufficient.

Testing Error Resulting from Using 12 Hour Protocol

Using the 0.1 ACH curve, which is presumably a worst case scenario, one can calculate the error introduced by beginning a radon or radon decay product test 12 hours post closed-house conditions instead of waiting for dynamic equilibrium (in this case, approximately 35 hours) before beginning a 48 hour sample. This error is calculated by determining the area under the $N_{ex} = 0.1$ curve in Figure 1 from hour 12 to hour 60 and dividing that by the area found by multiplying 48 hours times the final radon concentration. This error is approximately 5%. This assumes the measuring device integrates accurately. This percentage error does not depend upon the radon influx nor the final radon concentration.

An Analytical Expression for Radon Concentration

In the limit that the radioactive decay can be ignored we can get the following analytic formula for the radon concentration as a function of time:

$$n(t) = \left(1 - e^{-N_{ex}t}\right)\frac{N_{in}}{N_{ex}} \quad \text{(Equation 2)}$$

For t very large, the expression for n(t) becomes simply N_{in}/N_{ex}, allowing one to quickly calculate the final radon concentration once dynamic equilibrium has been achieved. For example, setting N_{in} equal to 1 and N_{ex} equal to 0.4, gives the final radon concentration as 2.5, reproducing the value found in figure 1. For other values of t, equation 2 can be quickly evaluated (assuming N_{ex} is known, or can be estimated) to determine the dynamic equilibrium time for a specific dwelling. Since no radioactive decay term is present, this expression is also suitable for non-radioactive pollutants entering the dwelling.

Conclusions

A differential equation which describes the rate of change of radon can be easily numerically integrated to give the radon concentration as a function of time. Using this equation, it is shown that for a typical dwelling, the 12 hour dynamic equilibrium time used by the EPA in its testing protocols is sufficient. There are dwellings, however, in which the 12 hour delay between closed-building conditions and commencement of testing is not sufficient, but the error introduced by not waiting until true dynamic equilibrium is achieved is not large (5 %). It is further shown that the radioactive decay term in the differential equation can be safely ignored, allowing an analytical expression to be developed. This analytical expression, which can be solved on a small calculator, may prove useful in the determination of concentrations (as a function of time) of other indoor air contaminants for various values of house air changes.

References

Indoor Radon and Radon Decay Product Measurement Device Protocols, EPA 402-R-92-004. July, 1992.

Protocols for Radon and Radon Decay Product Measurements in Homes, EPA 402-R-92-003, June, 1993.

Harris, J., "Radon and Formaldehyde Concentrations as a Function of Ventilation Rates in Residential Buildings in the Northwest", Proceedings of the APCA annual meeting, 1987.

Hubbard, L., et al., "Radon Entry into Detached Dwellings: House Dynamics and Mitigation Techniques", submitted to Radiation Protection Dosimetry, 1987.

Nagda, N., et al, "Energy Use, Infiltration and Indoor Air Quality in Tight, Well Insulated Residences", final report for EPRI, 1984.

Nitschke, I., et al., "Indoor Air Quality, Infiltration and Ventilation in Residential Buildings", NYSERDA Report No. 85-10, 1985.

W.W. Nazaroff and A.V. Nero, "Transport of Radon from Soil into Residences", Proceedings of the Third International Conference on Indoor Air Quality and Climate, Stockholm, Sweden, 1984.