# USING A MODEL TO ESTIMATE THE EFFECTS OF VENTILATION AND EXHAUST APPLIANCES ON THE ACCURACY OF A 48 HOUR RADON TEST

J.F. Burkhart and R.E. Camley
Physics Department
University of Colorado-Colorado Springs 80918

## Abstract

Under ideal circumstances, a 48-hour radon test is conducted following U.S. EPA closed-house guidelines. However, it is not uncommon for a test to have violations of the closed-building guidelines. This paper presents a mathematical model for predicting indoor radon concentrations when the house has been ventilated or appliances (which exhaust indoor air) have been run during a radon test. The following equation,

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

has been numerically integrated with the variables set to mimic ventilation (open windows and/or doors) and exhaust appliance parameters found in actual radon test conditions. The results, given in chart form, indicate that a 48 hour test of a typical house (ACH = 0.35 $h^{-1}$) can tolerate small violations of the closed-house guidelines without there being a significant degradation in test results although tighter homes are much more sensitive to these violations in protocols.

## Introduction

Professional radon testers well understand the need for standardized testing conditions for a short-term (48 hour) radon test. The United States Environmental Protection Agency (U.S. EPA) has designed a protocol establishing these standardized conditions, the so called "closed-house" conditions (EPA 1992, EPA 1993). When following closed-house conditions, it is required that the house be closed 12 hours prior to the beginning of a 48-hour test to ensure dynamic equilibrium is achieved, that is, that the radon concentration in the house has come to a value reflective of a steady-state condition where the radon coming into the home and the radon leaving the home are time independent. Violations of this 12-hour rubric were looked at previously (Burkhart and Camley, 1999), where it was found that the 12 hours was indeed a sufficient time to guarantee dynamic equilibrium in all but the tightest of houses (exceptions being houses with hourly air changes (ACH) less than 0.4 $h^{-1}$.)

In this paper, the authors expand their previous model to include the effects on indoor radon concentrations when doors and/or windows are opened (for any time duration) and fans or other appliances which exhaust indoor air are turned on (again, for any time duration) during a 48 hour radon test. Although relatively straight forward, the model is sufficiently complex to allow for interactions between the exhaust appliances and the radon entry rate as well as allowing variations in hourly air changes in order to better describe the actual variability of hourly air changes found in homes.

## Description of Model

Several previous attempts at modeling the indoor radon concentration have been made (see, for example, Sherman, M. 1992; Nazaroff, W.W. 1988; Revzan, K.L. et al., 1990; Loureiro, C., 1987). The model presented in this paper, however, is comparatively simple in that it ignores such parameters as radon soil gas concentrations, radon depletion in the soil, soil porosity and permeability, effects of wind direction and speed on the air infiltration and pressure changes within the home and any building shell parameters other than the entry rate for radon and the air exchange rate. Clearly, this model would not suffice in describing the effects on indoor radon in the event that any of the above parameters were individually varied during a modeled radon test.

However, this same lack of complexity makes the model particularly useful in predicting gross effects on indoor radon concentrations as long as only air exchange rates, ventilation rates and exhaust rates are changed during the modeled test. Assuming that the entry rate for radon remains constant during a radon test (with the exception that the entry rate is affected by exhaust appliances), the following equation describes the incremental change in radon concentration, in time, in a house with windows/doors being opened and closed and exhaust appliances being run during a test. Numerical integration of this equation gives the radon concentration at any time, t:

$$\frac{dn(t)}{dt} = N_{in} + (N_{ex} + N_v + N_f)n(t) - n(t)\lambda e^{-\lambda t} \qquad \text{(Equation 1)}$$

$$\text{where } N_{in} = N_o(1 + k\frac{N_f}{N_{ex} + N_f}) \qquad \text{(Equation 2)}$$

and where: n(t) is the radon concentration within the building at any time t,

$N_{in}$ is the rate at which radon enters the building,

$N_o$ is the rate at which radon enters without exhaust appliances being run,

$N_{ex}$ is the fraction of the house air exchanged every hour (in units of ACH),

$\lambda$ is the decay rate for radon (.693/91.68 hours),

$N_v$ is the increase in the house air exchange rate caused by ventilation from an open window or door (in units of ACH),

$N_f$ is the exhaust rate (in cubic feet per minute converted to units of ACH) caused by exhaust fans and appliances, and

k is a parameter that will be found by fitting this model to actual airflow measurements.

Equation 2 describes the effect on the radon entry rate of turning on an exhaust appliance (such as a bathroom fan, a ventilated stove hood, or a wood burning stove). This expression links the exhaust rate to an increase in the radon entry rate by assuming that the supply air necessary to replace the exhausted air ($N_f$) comes partly from the soil ($N_o$) and partly from the outside ($N_{ex}$) in the ratio of $N_f/(N_{ex} + N_f)$. This ratio says that the tighter the house, the more the make-up air comes from the soil. The proportionality constant, k, in equation 2, has a value on the order of 1 as can be seen by comparing the results of this model to that of Sherman's model (Sherman, M. 1992) for a house of 0.21 $h^{-1}$ ACH during the winter. The actual value of k probably varies somewhat depending upon a variety of factors (season of the year, house construction, sub-slab communication, etc.) However, the choice of k = 1 should give the general behavior of the exhaust/soil gas entry rate correctly.

Equation 1 uses the $N_{in}$ found in equation 2. In addition, equation 1 incorporates the effect of the total air changes (made up of the normal air exchange rate for the house, $N_{ex}$, the additional air exchanges caused by open doors and windows, $N_v$, and exhaust appliances, $N_f$). The final term in equation 1 calculates the loss of radon because of radioactive decay. This last term is kept in the differential equation although its effect on the final average radon concentration can be shown to be minimal.

It is been established in an earlier paper (Burkhart, J.F. and Camley, R.E., 1999) that the radon concentration found by integrating equation 1 is simply proportional to the radon entry rate. As a result, radon units are not necessary in the resultant analysis. Since the following discussion estimates percentage error (from violating the closed-house testing conditions), one can apply this estimated percent error to any house regardless of the actual measured radon concentration.

## Results

Equation 1 is first solved to find the effect of opening a single window on the final average radon concentration in houses of various air exchanges. In order to track a typical homeowner error, it is assumed that a 20-inch wide window is fully opened (or, equivalently, a sliding window is opened to a width of 20 inches) for 4 hours during the test, after the house was properly prepared by being under ideal closed-house conditions for the 12 hours prior to the commencement of the test. Such a situation might be encountered if, for example, a well-intentioned person (living in the house being tested) inadvertently ventilates one room for a brief period (4 hours) and then, discovering their error, closes the window for the duration of the test.

The incremental increase in ventilation, caused by the window being open, was calculated using:

$$N_v = 0.12 h^{-1} / in \qquad \text{(Equation 3)}$$

where the linear length (in inches) of the window opening is used (Wallace, L.A. and Ott, W.R., 1996). Table1, below, gives the percentage error (decrease) in final average radon concentrations (in arbitrary units) for four different houses (ACH = 0.1, 0.35 and 1.0 and 2.0 $h^{-1}$) under the above described conditions.

| ACH ($h^{-1}$) with house closed | Radon concentration with house closed (arbitrary units) | Radon concentration with window open (for 4 hours) | Resultant percent error |
|---|---|---|---|
| 0.1 | 9.282 | 6.648 | -28.3 |
| 0.35 | 2.795 | 2.468 | -11.7 |
| 1.0 | 0.992 | 0.924 | - 6.9 |
| 2.0 | 0.498 | 0.474 | - 4.8 |

Table 1: Percentage decreases in final average radon concentrations in four different houses with a window open 20 inches wide in each house for four hours during a 48-hour test

From table 1, it is seen that the final average radon concentration in a house with an ACH of around 1.0 $h^{-1}$ (or larger) is not greatly affected by fully opening a window (20 inch opening) for 4 hours during the test. The error introduced by such a violation of closed-building protocols is less than 7 %. Such an error is within the well-documented accuracy of most common radon measuring devices. However, a very tight house (ACH = 0.1 $h^{-1}$) would show a error close to 30%. It may be instructive to see why this is so.

In figure 1, below, the radon concentration in three houses (ACH = 0.1$h^{-1}$, 0.35 $h^{-1}$ and 1.0 $h^{-1}$) is shown as a function of time. It can be seen that because of the low air exchanges, the radon concentration in the tightest house (ACH = 0.1 $h^{-1}$) does not ever rise to its equilibrium value after the 4 hour ventilation. For that reason, the average value of the radon for the tightest house is well below the potential equilibrium value of 9.282 (in arbitrary units). For the other two houses, however, the rise in the radon back to the equilibrium value is sufficiently quick so that equilibrium is achieved within a few hours. In those cases, the final average value for the radon is close to the equilibrium value.

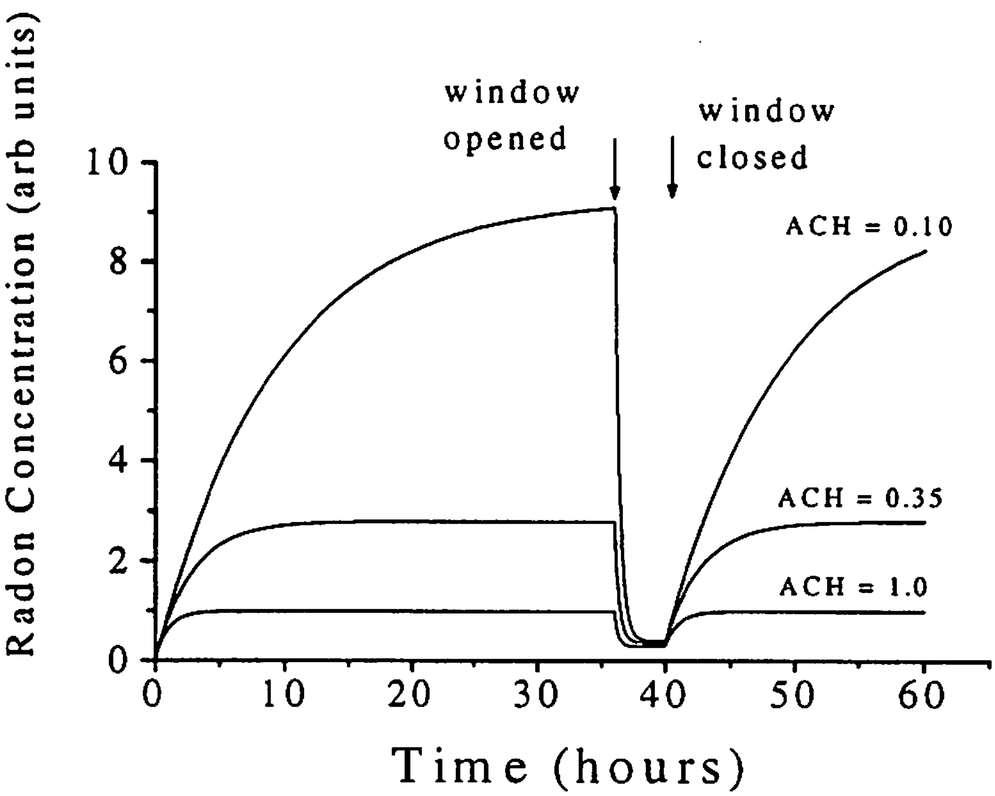


Figure 1: Radon concentration (arbitrary units) as a function of time in three different homes with a window being open for four hours during a 48-hour test

Equation 1 is now solved to find the effect of opening a single window on the final average radon concentration in houses of various air exchanges under a "worse case scenario". It is assumed that a 20-inch wide window is opened for the full 48 hours of the test, after the house was properly prepared by being under ideal closed-house conditions for the 12 hours prior to the commencement of the test. Such a situation might be encountered if, for example, a person (living in the house being tested) decided to ventilate one room for the duration of the test, deciding that the closed-house conditions were too stringent (for personal comfort or for other reasons.) Since our model does not divide the house into separate zones of any kind, it must be assumed here that the room being ventilated is completely open to the rest of the house and, indeed, all parts of the interior of the house are in perfect communication which each other. Under these ideal circumstances, the percentage decrease in final average radon concentrations is shown in table 2:

| ACH ($h^{-1}$) with house closed | Radon concentration with house closed (arbitrary units) | Radon concentration with window open (for 48 hours) | Resultant percent error |
|---|---|---|---|
| 0.1 | 9.282 | 0.451 | -95.1 |
| 0.35 | 2.795 | 0.380 | -86.4 |
| 1.0 | 0.992 | 0.298 | -70.0 |
| 2.0 | 0.498 | 0.228 | -54.2 |

Table 2: Percentage decreases in final average radon concentrations in four different houses with a window open 20 inches wide in each house for the full 48-hours of a 48-hour test

Table 2 suggests that fully opening a window during the total duration of a radon test has a substantial impact on the final average radon concentration for most houses.

How much ventilation (by opening doors and windows) can a typical house tolerate before there is an appreciable drop in the measured radon value? In Figure 2, various window openings are graphed versus the percentage error in measured radon. In this instance, only one house is looked at and the air exchanges (not including the additional effects of the window ventilation) are held constant at 0.35, the recommended air exchanges for a home (ASHRAE Standard 62, 1989) and close to the actual measured average value for homes (Wallace, L.A. and Ott, W.R., 1996). The greatest air exchange (caused by the windows and/or doors being open), 10 $h^{-1}$, is when the entire house is completely open (Wallace, L.A. and Ott, W.R., 1996.) However, as can be seen from figure 3, our model suggests that one does not need to open all the doors and windows to effectively ruin any chance of obtaining a reasonably accurate radon test result. Indeed, even a sliding window opened 10 inches, for four hours, will produce a 10% error (decrease) in the final average radon concentration if a house is truly at an air exchange rate of 0.35 $h^{-1}$ when the window is closed.

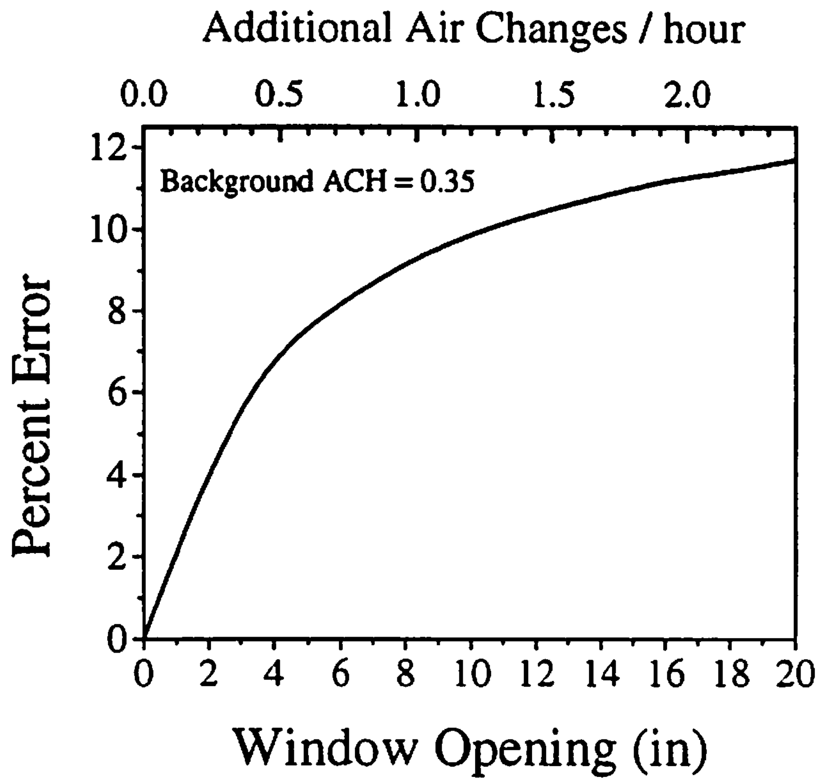


Figure 2: Percentage decreases in final average radon concentrations caused by various size window openings for 4 hours during a 48-hour test. Graph shows the effect in a home with ACH of $0.35h^{-1}$.

It can be concluded from figure 2 that ventilation of a house (with ACH = $0.35\ h^{-1}$) during testing may result in measurable errors, unless the window is only open a few inches for a few hours during the test period.

In order to estimate the effect of running exhaust appliances, equation 1 is integrated after setting $N_v$ equal to zero, representing the case of no ventilation (other than that caused by the exhaust system.) $N_f$ in equation 2 is then set to various actual known exhaust values, in cubic feet per minute (cfm) as shown in table 3. The right hand column of table 3 shows the exhaust rate in ACH ($h^{-1}$) determined by converting the center column of figure 1 from cfm to ACH by assuming a typical house has a volume of 20,000 cubic feet. Since this is a relatively small house in some areas, it should be assumed that the actual air exchanges in a larger house might be less than those shown in table 3.

| Appliance | Exhaust rate (cfm) | Exhaust rate (ACH) |
|---|---|---|
| Bathroom fan | 25 | 0.075 |
| Clothes dryer | 100 | 0.30 |
| Range hood | 225 | 0.675 |
| Wood fireplace | 170 | 0.51 |

Table 3: Typical exhaust rates for home appliances. The right hand column assumes a house with a total interior volume of 20,000 cubic feet.

In an attempt to mirror actual testing circumstances, table 4 shows the percent error (of average indoor radon concentration) caused by each of these appliances being run for four hours, commencing in the middle of the test. This would reflect a typical circumstance where the people living in the house occasionally used the bathroom, did laundry, cooked food or had a fire in an open fireplace during a 48 hour test. The house is assumed to be under closed-house conditions in all other aspects.

| Appliance | Radon concentration with appliance off (arbitrary units) | Radon concentration with appliance on (arbitrary units) | Percent error |
|---|---|---|---|
| Bathroom Fan | 2.795 | 2.788 | -0.3 |
| Clothes dryer | 2.795 | 2.733 | -2.2 |
| Range hood | 2.795 | 2.651 | -5.2 |
| Wood fireplace | 2.795 | 2.683 | -4.0 |

Table 4: Percentage decreases in final average radon concentrations caused by running various exhaust appliances for 4 hours during the 48 hours of a radon test. The results are for a home with ACH of $0.35h^{-1}$

The results of table 4 suggest that the exhaust appliance results in a slight decrease in radon concentrations. That is, even though the exhaust appliance is providing an additional negative pressure differential between the house and the soil (causing the entry rate of radon to increase), this is offset by the increased ventilation and make-up air coming from the outside. Table 4 also suggests that none of the appliances, run separately, would cause an appreciable error in the results of a 48-hour test.

Finally, table 5 shows the estimated percent error (in average indoor radon concentrations) caused by running each appliance for the full 48 hours of the test. In this example, it is assumed that the 12-hour secular equilibrium has been properly achieved prior to the beginning of the test. The house modeled has an air exchange rate of 0.35 $h^{-1}$.

| Appliance | Radon concentration with appliance off (arbitrary units) | Radon concentration with appliance on (arbitrary units) | Percent error |
|---|---|---|---|
| Bathroom Fan | 2.795 | 2.722 | - 2.6 |
| Clothes dryer | 2.795 | 2.240 | -19.9 |
| Range hood | 2.795 | 1.630 | -41.7 |
| Wood fireplace | 2.795 | 1.858 | -33.5 |

Table 5: Percentage decreases in final average radon concentrations caused by running various exhaust appliances for the full 48 hours of a 48 hour radon test. Graph shows the effect in a home with ACH of 0.35 $h^{-1}$

Table 5 predicts that running a typical bathroom fan during the entire 48 hours of a radon test would have no appreciable deleterious effect on the final average radon concentration. Having a fire going in an open fireplace, does, however, appreciably lower the expected measured radon concentration.

## Conclusions

First, given the assumptions built into this model, the results suggest that radon test results are greatly affected by relatively small amounts of increased ventilation. Indeed, opening a single window by as little as 10 inches for four hours during a test may cause an error as much as 10 percent in the measured radon value. The analytical equation, given by equation 3, predicts the ventilation caused by opening windows. Equation 3 may, or may not, be appropriate for use in our model. Further work needs to be done to resolve this issue.

Second, the model strongly suggests that increased ventilation is much more effective at lowering expected measured radon results in tighter homes. This would imply that professional radon testers must be especially vigilant about monitoring closed-house conditions in newer, tighter, homes.

Third, radon test results seem to be less sensitive to the running of exhaust appliances, it these appliances are only operated for 4 hours, or less, during a radon test. However, the use of a wood-burning fireplace or even running an exhaust hood (225-cfm) during the entire test seriously impacts the resultant measured radon value.

## Disclaimer

The mathematical model used in this paper has been fit to "real-world" parameters as much as possible. However, the model is not sufficiently complex to take into account many variables found in "real-world" situations such as effects of wind direction, duration and speed. Neither does the model incorporate the effects of rain or ice/snow during the radon test. Although the model allows a variability in soil gas radon concentrations (with a commensurate variability in the rate of radon entry), the radon entry rate was held constant during the 12 hours prior to the test and during the 48 hours of the test (with the exception that the entry rate was increased by the running of exhaust appliances) in all of the above examples. For these reasons, the results shown here should be used as general guidelines only. The authors are not recommending that closed-house protocols be violated under any circumstances.

## References

Burkhart, J.F. and Camley, R.E., "A New Look at the Twelve Hour Dynamic Equilibrium Protocol", Proceedings of the 1999 International Radon Symposium, Las Vegas, Nevada, 1999.

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

Loureiro, C., "Simulation of the Steady-State Transport of Radon from Soil into Houses with Basements under Constant Negative Pressure". Ph.D. Thesis, University of Michigan, Ann Arbor, 1987.

Nazaroff, W.W., "Predicting the Rate of 222Rn from Soil into the Basement of a Dwelling Due to Pressure-Driven Air Flow", Radiation Protection Dosimetry, Vol. 24, pp 199-202, 1988.

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

Revzan, K.L., Fisk, W.J., and Gadgil, A.J., "Modeling Radon Entry into Houses with Basements: Model Description and Verification", Proceedings of the 1990 Indoor Air Symposium, Toronto, Canada, 1990.

Sherman, M., "Simplified Modeling for Infiltration and Radon Entry", Volume 3, Session 6, Proceedings of the 1992 International Radon Symposium, Minneapolis, Minnesota, 1992.

Wallace, L.A. and Ott, W.R., "Air Exchange Rate Experiments in a Detached House Using a Continuous Monitor", 1996 Annual Meeting of the Society for Risk Analysis and International Society of exposure Analysis, New Orleans, LA. 1996.