# Modeling of Radon and Its Daughter Concentrations in Ventilated Spaces

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**In order to predict indoor radiation levels due to radon daughters at low building ventilation and air leakage rates, differential equations governing the decay and venting of radon (Rn–222) and its daughters were used. A computer program based on the equations was written to predict radon and daughter concentrations, total potential alpha energy concentration and equilibrium factor. The program can account for time dependence of ventilation and emanation rates and is readily used by building designers.**

**Sample calculations using the program showed that potential alpha energy levels in tightened buildings can commonly reach about 0.01 working level (WL), a level more than twice as high as concentrations currently found in most houses.**

Reduction of ventilation and infiltration can save energy used in heating and cooling buildings. It is well established that very little outside air is needed to supply sufficient oxygen for respiration or to keep carbon dioxide within acceptable levels.[1] Recent studies have shown, however, that limiting air exchange could raise indoor CO, $NO_2$, respirable particulate, hydrocarbon, and aldehyde levels above already high levels in many homes with gas appliances and smokers; high CO and $NO_2$ levels in these homes may be responsible for increased respiratory and other disease.[2–8]

Similarly, evidence has been accumulating in the last 25 years that alpha particles emitted by radon (Rn–222) daughter products may also need consideration in the design of ventilation systems.[9–18] While radiation levels and thus risk within buildings are usually low compared to those occurring in mining and other occupational settings,[9] the size of the exposed population is so much greater that excess lung cancer may, nevertheless, be a problem. It has been estimated, for example, that exposure to radon decay products in older, well ventilated buildings is responsible for 500 to 1100 lung cancer deaths annually in Sweden (4 to 22.5% of total lung cancer mortality) and exposure in newer, tighter buildings constructed of materials containing greater quantities of radium is expected to increase lung cancer mortality by 100 to 600 annual deaths.[15]

It is likely that prediction of indoor radiation levels will be required under American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Ventilation Standard 63-72R[19] as concern increases about radiation levels in tightened buildings. Prediction requires reliable emanation rate data and a mathematical model to serve as a framework for the designer. Some emanation rate data[9] on building materials are currently available and more should be available soon. Mathematical models heretofore used have either neglected to include the effect of ventilation[20] or have assumed steady-state conditions.[21–22] Steady-state conditions are rapidly approached only when ventilation or infiltration rates are high, as in well-ventilated uranium mines or leaky buildings. Deviation from steady state increases with decreasing air exchange rate. Thus, while steady-state solutions of radioactive decay of radon and its daughters are often adequate, time-dependent solutions which account for ventilation may yield more accurate predictions of indoor radon and daughter concentrations for tightened buildings, especially when used in conjunction with more reliable emanation rate data than are currently available.

## Radon and Its Daughters

Rn–222 is produced by the radioactive decay of Ra–226, which is part of the decay chain of U–238. Thus any material containing radium or uranium—for example, soil and mineral deposits—is a potential source of radon. Since Ra-226 has a half-life of over 1600 years, its concentration is practically invariant with time and it decays to Rn+222 at a constant rate. Since Rn+222 is an inert gas it can diffuse relatively undiminished except by radioactive decay through the porous material in which it was formed and emanate into the surrounding air or water. It decays into its daughters which have short half-lives and exist either as free atoms or ions ("unattached fraction") in the air or attached to aerosols ("attached fraction"). The decay chain is effectively terminated with the appearance of Pb+210 because of its 22-year half life. Table I lists the decay chain of Rn+222 into Pb+210.

Table I. Potential alpha energy of $^{222}Rn$ and its short-lived decay products.[9]

| Radionuclide | $i$ | Radioactive half-life | Radioactive decay constant $\lambda_i$ ($min^{-1}$) | Number of atoms/ picocurie | Potential alpha energy (MeV) Per atom | Per picocurie | Conversion factor $C_i$ $\frac{MeV \cdot L^{-1}}{pCi \cdot L^{-1}}$ | $\frac{WL}{pCi \cdot L^{-1}}$ |
|---|---|---|---|---|---|---|---|---|
| $^{226}Ra$ ↓ | | | | | | | | |
| $^{222}Rn$ | 0 | 3.8d | $1.258 \times 10^{-4}$ | 17488 | | | | |
| $^{218}Po(RaA)$ | 1 | 3.05 min | 0.2272 | 9.77 | 13.68 | 134 | 134 | 0.00103 |
| $^{214}Pb(RaB)$ | 2 | 26.8 min | 0.02586 | 85.3 | 7.68 | 659 | 659 | 0.00507 |
| $^{214}Bi(RaC)$ | 3 | 19.7 min | 0.03518 | 63.1 | 7.68 | 485 | 485 | 0.00373 |
| $^{214}Po(RaC')$ | 4 | $1.6 \times 10^{-4}$ s | $3.75 \times 10^{-5}$ | $10^{-5}$ | 7.68 | $7.68 \times 10^{-5}$ | $7.68 \times 10^{-5}$ | $6 \times 10^{-10}$ |
| ↓ $^{210}Pb$ | | | | | | | | |

There are five identifiable sources of radon in buildings:

1. Radon can diffuse through earth, basement walls, and floors from soil in contact with a residence.
2. Construction materials such as concrete, brick, stone, plaster, sand, and gravel contain radium in varying concentrations. Wood, in contrast, contains little radium.
3. Untreated ground water contains dissolved radon which can outgas in the residence as it is used[17,23–25] in bathing, clothes and dish washing, and especially showering.
4. Natural gas is usually a minor source of radon compared to the previous three sources. Radon concentration is proportional to its concentration at the wellhead and inversely related to pipeline transit time and storage time.[26] Gas cooking and unvented heating could release radon into the building but properly ventilated appliances should remove most of the radon from the residence.
5. Outdoor radon can enter buildings through openings. Ambient concentrations in the U.S. are usually in the range 0.04 to 1 pCi/L (1.5 to 40 Bq/m$^3$)* depending on local soil emanation rates, humidity, and wind. Indoor concentrations—due mainly to sources 1 through 3 above—are generally much greater than those outdoors.[9,14,27]

The reader is referred to Reference 9 for an excellent review of the current state of knowledge of radon, its daughters, and their health effects, including more detailed source data.

## Radon and Daughter Levels and Ventilation

Commonly accepted building construction in the past has resulted in infiltration rates of approximately 0.5 to 1.5 air changes per hour (ach or simply $h^{-1}$),[28] high enough so that health hazards due to radon and its daughters were not usually of concern except in houses built on reclaimed phosphate lands or over uranium mill tailings. Anticipated practice, however, is to make buildings more airtight. Air exchange rate depends on wind speed and indoor-outdoor temperature difference. When these are small, even leaky houses have low air exchange rates, but low air exchange rates are less common in leaky than in tight houses. Some builders are now constructing residences with air leakage rates as low as 0.1–0.2 ach in order to save energy.[29]

Average radon levels in residences increased from about 0.9 pCi/L (32 Bq/m$^3$) to about 2.9 pCi/L (107 Bq/m$^3$) since 1940 in Sweden as air exchange rates were reduced from 0.8–0.9 to 0.3–0.45 ach and as aerated concrete increasingly replaced wood and brick in home construction.[15] Partly out of concern about increasing radon levels, the Swedish Building Code of 1975 required that homes with mechanical ventilation—and this includes nearly all homes built in Sweden today—maintain air exchange rates of at least 0.5 ach.

* Concentrations of Rn+222 and its daughters have usually been expressed in picocuries per liter (pCi/L) but this unit should soon be completely replaced by the SI unit, becquerels per cubic meter (Bq/m$^3$). One Bq = 1 s$^{-1}$; 1 pCi/L = 37 Bq/m$^3$.

In order to predict accurately indoor radon and daughter levels at low air exchange rates, it is necessary to have a physical model which includes ventilation and indoor sources, and which shows the time dependency of the various radionuclide concentrations. Haque and Collinson[21] presented the equations that need to be solved in a paper in 1967 but didn't solve them for time dependency; instead they used only steady-state solutions to predict radiation dose to the respiratory system in various London residential and occupational surroundings. While this is acceptable for highly ventilated spaces like mines and leaky houses, it may not suffice for tight buildings because steady state is rarely reached before the air exchange rates or the emanation rate changes. Water containing elevated amounts of radon is usually used for short periods of time, and emanation by building materials and soil vary with atmospheric conditions.[9] The air exchange rate changes with atmospheric conditions and when windows and doors are opened and closed. The U.S. Environmental Protection Agency used these steady-state solutions to study control measures[30] and the effects of ventilation on radon and daughter levels in buildings.[31] Jacobi generalized the steady-state solutions to predict levels of unattached daughters—daughters unattached to aerosol—in uranium mines and exposure of miners to this fraction.[22] Raabe in his study of the interactions of radon daughters and aerosols actually derived time-dependent solutions of these equations, generalized to include particle settling, but did not include ventilation.[20] In the present paper, the equations, including a ventilation term, are solved for time dependency. The solutions may be iterated over suitable time intervals to account for time dependence of ventilation and emanation rates. The solutions can also be easily modified to take into account particle settling and the division of daughters into attached and unattached fractions. Illustrated in the figures are time dependence of total potential alpha energy concentration and equilibrium factor for several different sets of conditions.

## Physical Model of Radon Decay and Ventilation

The decay chain of radon and its daughters is shown in Table I. In addition to decay, concentrations are decreased by dilution with less contaminated air. Also, particle settling and adsorption onto surfaces may remove daughters. It is planned to treat these clearance mechanisms in the future. They are not completely independent of ventilation.

In the present treatment, let subscript $i$ = 0 through 4, denote Rn+222, Po+218, Pb+214, Bi+214, and Po+214 respectively, $A_i$ = activity concentration of the $i$th radionuclide (pCi/L) at time $t$, and $\lambda_i$ = its decay constant ($min^{-1}$); the absence of a superscript on the $A_i$ refers to indoor values while superscript "o" refers to outdoor values; $I$ = air exchange rate (air changes/min or simply $min^{-1}$), and $Q$ = source strength, the entry rate of Rn+222 into the building per unit volume (pCi/L·min). Note that $I$, $\lambda_i$, and $Q$ must be consistently expressed in terms of the same unit of time, in this case $min^{-1}$. Although $I$ and $Q$ are held constant in these equations, the solutions may be iterated with new values of $I$ and $Q$ used for each interval. The following differential equations characterize radioactive decay and convective dilution of radon and its daughters:

$$\frac{dA_O}{dt} = Q - (\lambda_O + I)A_O + IA_O^\circ \quad (1)$$

$$\frac{dA_i}{dt} = \lambda_i A_{i-1} - (\lambda_i + I)A_i + IA_i^\circ \quad \text{for } 1 \le i \le 4 \quad (2)$$

In each equation, enhancement of the $i$th radionuclide indoors is due to decay of its parent (Rn+222 results from Ra+226 decay) and admission from outside, while removal is due to decay of the radionuclide itself and venting outdoors. To account for settling, $I_sN_i$ would be subtracted from the right side of Eq. (2), where $I_s$ = settling rate (min$^{-1}$ in this treatment). ($I_sN_O$ would not be subtracted in Eq. (1) since radon, a gas, does not settle under normal building conditions).

The solutions are found in Appendix A. Values of $\lambda_i$ can be found in Table I (and are related to radioactive half-lives by $\lambda_i = \ln 2/t_{1/2}$). As mentioned above, $I$ is usually in the range of 0.1 to 1.5 ach (converted to min$^{-1}$) but can be much higher when windows and doors are open or mechanical ventilation is used. The least known of all the parameters in the equations is $Q$, which depends on the types of construction materials used, the sources of water, the ground over which the building is erected, and on atmospheric conditions. Reference 9 gives an average radon emanation rate for soil of 0.42 pCi/m$^2$·s (0.016 Bq/m$^2$·s) with range $6 \times 10^{-3}$ to 1.4 pCi/m$^2$·s ($2.2 \times 10^{-4}$ to 0.052 Bq/m$^2$·s). Assuming a one-story building of height 2.5 m, one obtains a source strength of 0.01 pCi/L·min ($6 \times 10^{-3}$ Bq/m$^3$·s) with range $1.4 \times 10^{-4}$ to 0.033 pCi/L·min ($8.7 \times 10^{-5}$ to 0.020 Bq/m$^3$·s). This value is used for computational purposes below but it should be borne in mind that in real buildings radon entry rates are reduced by concrete floors. Actual source strengths may be higher or lower because of sources other than soil. As mentioned above $A_O^o$ is usually 0.04 to 1 pCi/L (1.5 to 40 Bq/m$^3$),[27] with the most common concentrations in the range 0.1 to 0.2 pCi/L (4 to 7 Bq/m$^3$).[32]

It has been found useful in calculating dose to the lungs to use a measure of the total potential alpha energy concentration ($E$) of the daughters, the working level ($WL$).[9] One working level is defined to be any combination of short-lived radon daughters ultimately yielding $1.3 \times 10^5$ MeV of potential energy per liter of air upon decay to Pb+210. In general:

$$E = \sum_{i=1}^{4} C_iA_i \quad (3)$$

where the coefficients $C_i$ are given in Table I, and represent potential alpha energy per pCi of each daughter.

Let $\overline{E}$ = value of $E$ at radioactive equilibrium; since $A_O \simeq A_i$ for each $i$ for radon daughters at equilibrium:

$$\overline{E} = \sum_{i=1}^{4} C_iA_O = (0.01\ WL/\text{pCi} \cdot \text{L}^{-1})A_O = \frac{A_O}{100\ \text{pCi} \cdot \text{L}^{-1}}\ WL \quad (4)$$

The ratio $E/\overline{E}$, called the equilibrium factor ($F$), is a measure of the deviation from equilibrium of radon and its daughter concentrations.

$$F = \frac{E}{\overline{E}} = \frac{(100\ \text{pCi} \cdot \text{L}^{-1}/WL) \sum_{i=1}^{4} C_iA_i}{A_O} \quad (5)$$

($E^o$ and $F^o$ refer to outdoor values of $E$ and $F$ respectively.) The equilibrium factor is also important for estimating potential alpha energy concentration given radon activity and vice versa.

### Sample Calculations

A computer program was developed to obtain $A_i$ (and hence $E$ and $F$) for any ventilation rate $I$, source strength $Q$, outdoor radon and daughter activity concentrations $A_i^o$ and initial indoor concentrations $A_i(O)$. In the calculations presented here $A_i(O)$ were usually set equal to $A_i^o$.

Figure 1 shows potential alpha energy concentration dependence on air exchange rates from 0.2 to 6 ach (the latter simulating open windows). The source strength is 0.01 pCi/L·min ($6 \times 10^{-3}$ Bq/m$^3$·s) and the outdoor radon concentration is 0.2 pCi/L (7 Bq/m$^3$), both typical values. Notice that at 1 ach (around the average for existing homes), $E$ changes from about $10^{-3}$ to $5 \times 10^{-3}$ $WL$ over time, in good agreement with the normal range of $E$ of $10^{-4}$ to $5 \times 10^{-3}$ $WL$ with an average of about $2 \times 10^{-3}$ $WL$.[11] If the air exchange rate is reduced to 0.5 ach (characteristic of currently built homes), then $E$ changes from $10^{-3}$ to 0.01 $WL$ over time. Values of $E$ above 0.005 $WL$ are not common unless there is little ventilation or a high source strength.[11,30,32] Thus ventilation rates below 0.5 ach might produce potential alpha energy concentrations higher than are currently typical. At 0.2 ach (probably

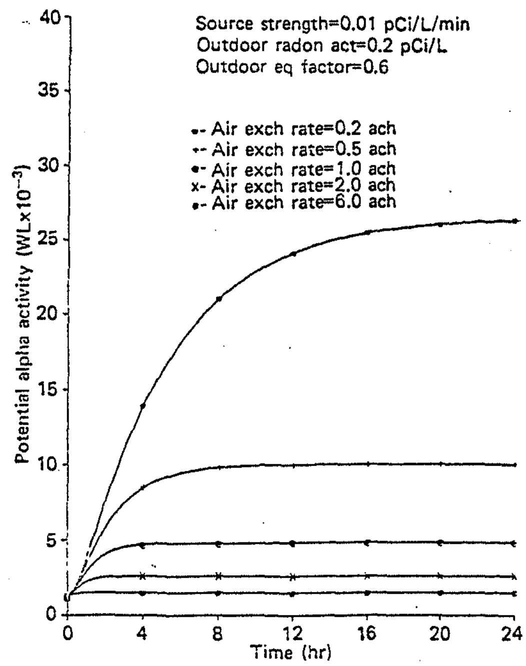


**Figure 1.** Potential alpha activity ($E$) for various air exchange rates. $A_{iO} = A_i^o$, $i = O–4$).

near the lower limit of current construction practice), $E$ increases from $10^{-3}$ to 0.026 $WL$ over time. Even conservatively assuming that the 4 h level of 0.014 $WL$ will not normally be surpassed, this is well above typical current levels. Even in homes built on reclaimed Florida phosphate lands,[11] over half the houses had potential alpha energy levels below 0.01 $WL$. Note also that source strengths can easily surpass 0.01 pCi/L·min ($6 \times 10^{-3}$ Bq/m$^3$·s)[33] so that levels of 0.02 and even 0.03 $WL$ can be reached.

Figure 2 shows the effect of ventilation in clearing building air of high radionuclide levels. Conditions are identical to those in Figure 1 except that initial concentrations are 20 pCi/L. Of course, the source strength must have been considerably higher than assumed in this calculation for radon daughter concentrations of 20 pCi/L to be reached. (Radon concentration exceeded 30 pCi/L and potential energy concentration reached 0.18 $WL$ in an experimental energy-efficient residence when the air exchange rate was maintained at

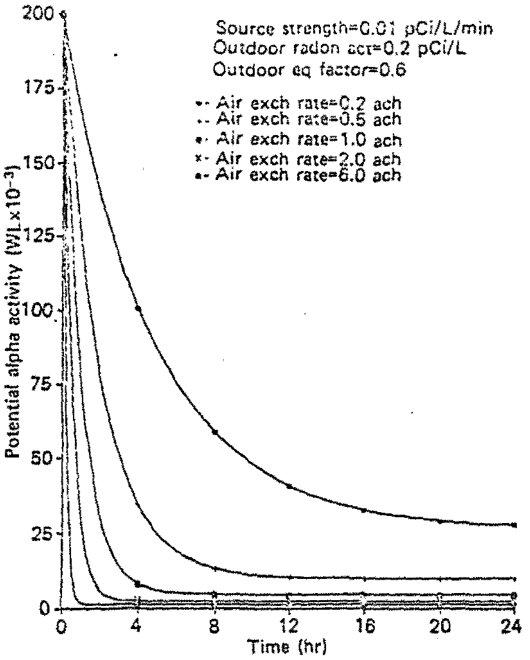


**Figure 2.** Potential alpha activity ($E$) for various air exchange rates. $A_{io}$ = 20 pCi/L, $i$ = 0–4.

0.07 ach for two days.[34]) For an extremely tight house (0.2 ach), potential alpha energy concentration is still 0.1 $WL$ after 4 h and is always at least 0.027 $WL$. Potential alpha energy is over 4 times greater at 0.5 ach (0.035 $WL$) than at 1 ach ($8 \times 10^{-3}$ $WL$) after 4 h. For well-ventilated houses (2+6 ach), near-outdoor levels are reached in 1 to 3 h.

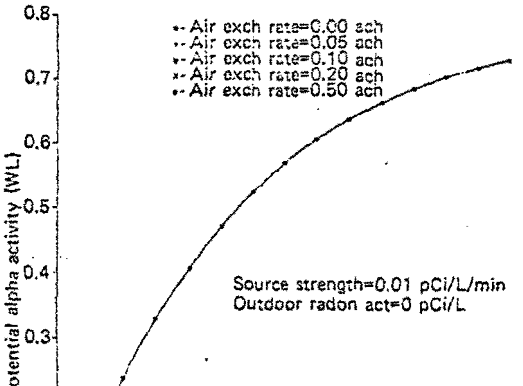


**Figure 3.** Potential alpha activity ($E$) for various air exchange rates. $A_{io} = A_i^o$ = 0 pCi/L, $i$ = 0–4.

Figure 3 shows the effects of even lower air exchange rates (outdoor radon levels are neglected here). Equilibrium is not quite reached even after 2 weeks for the extreme case of 0 ach, which was included to show the drastic effect of even a slight change in air exchange at low air exchange rates. For example, the radon removal rate at 0.05 ach is 7.6 times as great as at 0 ach. A further minute increase of 0.05 ach nearly doubles the radon removal rate. Thus the model predicts that data scatter would make it difficult to correlate measured radon and radon-daughter concentration with low measured infiltration rates.

Figure 4 is similar to Figure 1, except that the outdoor radon concentration was raised to 0.5 ach from 0.2 ach. It shows that at a source strength of 0.01 pCi/L-min ($6 \times 10^{-3}$ Bq/m$^3$-s) there is an approximately uniform increase in $E$ of $2 \times 10^{-3}$ to $3 \times 10^{-3}$ $WL$ at the higher outside radon concentration.

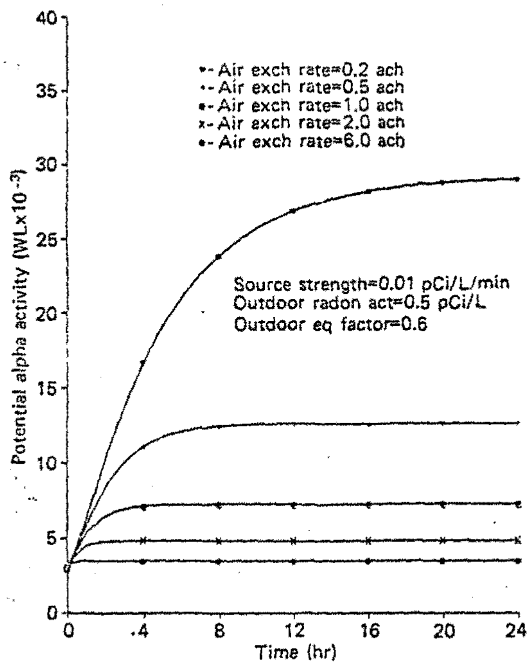


**Figure 4.** Potential alpha activity ($E$) for various air exchange rates and high outdoor radionuclide concentrations. $A_{io} = A_i^o$, $i$ = 0–4.

Figure 5 shows the dependence of $E$ on source strengths for $10^{-4}$ to 0.05 pCi/L-min ($6 \times 10^{-5}$ to 0.03 Bq/m$^3$-s), closely bracketing soil emanation rates,[9] for 0.5 ach and an outdoor radon concentration of 0.2 pCi/L (7 Bq/m$^3$). The figure shows that at common source strengths near 0.01 pCi/L-min ($6 \times 10^{-3}$ Bq/m$^3$-s), changes in source strength are highly signifi-

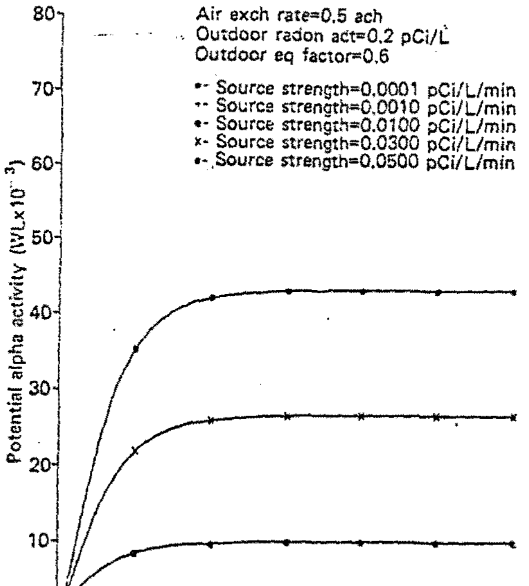


**Figure 5.** Potential alpha activity ($E$) for various source strengths. $A_{io} = A_i^o$, $i$ = 0–4.

cant, unlike the case of source strengths below $10^{-4}$ pCi/L-min ($6 \times 10^{-5}$ Bq/m$^3$-s). The results shown in Figures 4 and 5 generalize conclusions reached using steady-state assumptions to the non-steady-state situation.

Figure 6, derived in Appendix B, shows the dependence on each other of the steady-state equilibrium factor and the clearance rate of a space, defined to be the removal rate of a substance from the space by all mechanisms other than radioactive decay. The clearance rate includes the air exchange rate, and deposition on walls and surfaces. If radon activity outside the space is zero, then the clearance rate is simply the sum of these factors.* In particular, outdoors may be considered such a space, and a clearance rate calculated from the equilibrium factor. The clearance rate may then be used to calculate daughter activities corresponding to any radon activity (as is done by the subroutine described in Appendix B).

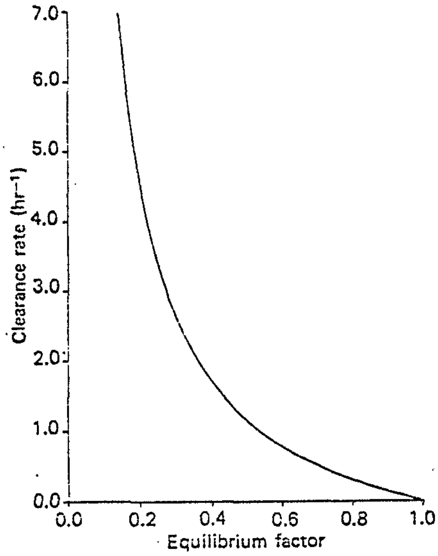


Figure 6. Equilibrium factor vs. clearance rate for $A_i^o = 0$ pCi/L, $i = 0$–4.

For indoor use, the curve in Figure 6 would have to be modified for particular outdoor radon activities and indoor source strengths but can still be used as a good approximation when the outdoor activity is low, as it usually is. It is interesting to note that the relationship shown in Figure 6 suggests an experimental basis for obtaining components of the clearance rate for a building once the air exchange rate has been determined. Radon and its daughters are never at equilibrium, even at steady state, as long as the clearance rate is not zero. Equilibrium would be reached for a completely sealed building in 2–3 weeks (illustrated for a source strength of 0.01 pCi/L-min ($6 \times 10^{-3}$ Bq/m$^3$-s) in Figure 3).

Figure 7 shows radon and daughter concentrations for a ventilation rate of 0.5 ach and source strength of 0.01 pCi/L-min ($6 \times 10^{-3}$ Bq/m$^3$-s). Steady state is not reached before 8 h, and radionuclide concentrations are constantly changing in the first few hours. Figure 8 shows the effect of various air exchange rates on equilibrium factor. While equilibrium factor clearly varies inversely with air exchange rate at steady state, increasing from 0.61 at 1 ach to 0.73 at 0.5 ach and 0.86 at 0.2 ach, no clear relationship is apparent during the first 2 h when conditions are changing. It is thus difficult to predict, on theoretical grounds, the value of the equilibrium factor in actual buildings.

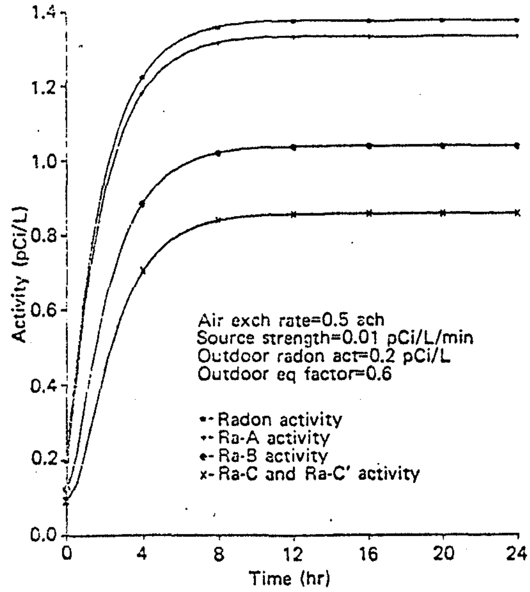


Figure 7. Radon and daughter activities ($A_i$, $i = 0$–4). $A_{i0} = A_i^o$, $i = 0$–4.

## Discussion

Differential equations were solved that show the time dependence of radon, daughter, and potential alpha energy concentrations in buildings (Appendix A). These equations are more appropriate than steady-state solutions for tighter buildings since steady-state conditions are rarely attained because of changing conditions. A computer program was developed using these equations that requires the user to supply source-strength data, air exchange rate, initial radon and daughter levels, and outdoor radon concentration. The user may supply outdoor daughter levels or may have a subroutine calculate them from the outdoor radon concentration and equilibrium factor (Appendix B), which may be more readily available. The subroutine may prove useful in calculating daughter activity concentrations from potential alpha energy when using instant working level monitors that measure only potential alpha energy.[35]

Sample calculations in this paper showed that potential alpha energy levels in buildings tightened to 0.2 to 0.5 ach can surpass 0.01 *WL* at common source strengths, and reach much higher levels at greater source strengths, in contrast to normal current levels of below $5 \times 10^{-3}$ *WL*[11,32] in ordinary homes. The Surgeon General of the U.S. Public Health Service rec-

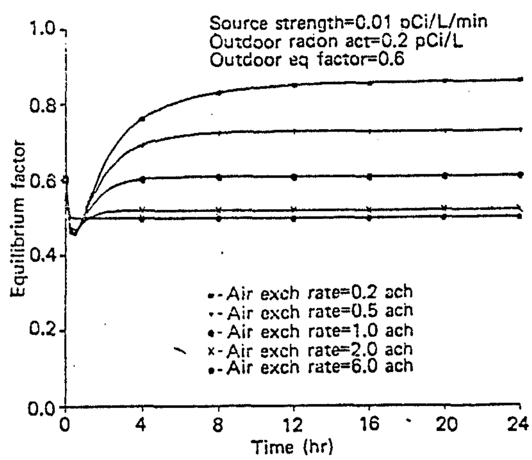


Figure 8. Equilibrium factor (E/Ē) for various air exchange rates. $A_{i0} = A_i^o$, $i = 0$–4.

* But recall that radon, an inert gas, neither normally settles in buildings nor reacts with surfaces. This was ignored in Appendix B since the contribution to the outdoor clearance rate of its components is not known.

ommended that remedial action may be suggested for houses built on or near uranium mill tailings in Grand Junction, CO when potential alpha energy concentration is between 0.01 and 0.05 *WL* above background.[36] Remedial action is indicated above 0.05 *WL*. The EPA recommended remedial action in Florida phosphate lands when the total potential alpha energy concentration exceeds 0.02 *WL*.[37] Remedial action required to reduce concentration between 0.005 and 0.02 *WL* to as low as reasonably achievable should be taken after considering such factors as cost and normal indoor background.

Simulations of actual changing conditions can be performed by changing source strength and/or air exchange rates every hour or other suitable time interval and setting initial radon and daughter levels equal to those at the end of the previous period. Changes in air exchange rate can be related to changes in indoor-outdoor temperature difference and wind speed. Iteration could be especially useful when windows are frequently opened and closed, or if there are sporadic but large releases of radon, for example from water. This method could then be compared with the use of steady-state equations and average air exchange and emanation rates. If it is shown to be more accurate it can be used by building designers to ensure that radon and radon-daughter concentrations are not permitted to increase over present levels.

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## References

1. T. Kusuda and P. E. McNall, "Opportunities for Energy Savings in Buildings through Ventilation Management," Proceedings for Engineering Foundation Conference, Hennikers, NH, 1977.
2. T. D. Sterling and E. Sterling, "Carbon monoxide levels in kitchens and homes with gas cookers," *JAPCA* 29: 238 (1979).
3. D. J. Moschandreas, J. W. C. Stark, J. E. McFadden, and S. S. Morse, "Indoor Air Pollution in the Residential Environment," (2 vols.), U.S. Environmental Protection Agency Report EPA-600/7-78-229a and b, Research Triangle Park, NC, 1978.
4. C. D. Hollowell, R. J. Budnitz, and G. W. Traynor, "Combustion-Generated Indoor Air Pollution," Lawrence Berkeley Laboratory report LBL-5918, Berkeley, 1976.
5. J. R. Goldsmith, "Contribution of motor vehicle exhaust, industry, and cigarette smoking to community CO exposure," *Ann. N.Y. Acad. Sci.* 15: 122 (1970).
6. "Smoking and Health—A Report of the Surgeon General," U.S. Department of Health, Education and Welfare report (PHS) 79-50066, Washington, 1979.
7. J. S. Kelley and G. J. Sophocleus, "Retinal hemorrhages in subacute carbon monoxide poisoning," *J. Am. Med. Assoc.* 239: 1515 (1978).
8. R. J. W. Melia, C. du V. Florey, D. G. Altman and A. V. Swan, "Association between gas cooking and respiratory disease in children," *Br. Med. J.* 2: 149 (1977).
9. "Sources and Effects of Ionizing Radiation," United Nations Scientific Committee on the Effects of Atomic Radiation 1977 Report to the General Assembly, with Annexes, United Nations Publication, New York, 1977.
10. "Recommendations of the International Commission on Radiological Protection," ICRP Publication 26, *Annals of ICRP* 1: 3 (1977).
11. R. J. Guimond, W. H. Ellett, J. E. Fitzgerald, Jr., S. T. Windham, and P. A. Cuny, "Indoor Radiation Exposure due to Radium-226 in Florida Phosphate Lands," U.S. Environmental Protection Agency report EPA-520/4-78-013, Washington, revised 1979.
12. G. Hultquist, "Studies on Naturally Occurring Ionizing Radiations, with Special Reference to Radiation Doses in Swedish Houses of Various Types," Svenska ventenskapsakedemiens handlingar, fjärde serien, 6 (3), Stockholm, 1956.
13. F. Steinhausler, "Long-term measurement of radon daughter concentrations in the air of private and public buildings and their dependence on meteorological parameter," *Health Phys.* 29: 705 (1975).
14. H. B. Spitz and M. E. Wrenn, "The Diurnal Variation of the Radon-222 Concentrations in Residential Structures in Grand Junction, Colorado," Second Workshop on the National Radiation Environment, U.S. Department of Energy, New York, 1974.
15. G. A. Swedjemark, "Radon in Dwellings in Sweden," Symposium on Natural Radiation Environment III, Houston, 1979.
16. G. A. Swedjemark, "The Ionizing Radiation in Dwellings Related to Building Materials," National Institute of Radiation Protection report SSI-1977-04, Stockholm, 1977.
17. T. F. Gesell and H. M. Pritchard, "Measurement of Radon-222 in Water and Indoor Airborne Radon-222 Originating in Water," Radon Workshop, U.S. Department of Energy report HASL-325, New York, 1977.
18. H. Horiuchi, "Radon-222 and its Daughters in Buildings at Uranium City, Saskatchewan," Radon Workshop, U.S. Department of Energy Report HASL-325, New York, 1977.
19. "Standards for Ventilation Required for Minimum Acceptable Indoor Air Quality," ASHRAE Standard 62-73R, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., in preparation.
20. O. G. Raabe, "Concerning the interactions that occur between radon decay products and aerosols," *Health Phys.* 17: 177 (1969).
21. A. K. Haque and A. J. Collinson, "Radiation dose to the respiratory system due to radon and its daughter products," *Health Phys.* 13: 431 (1967).
22. W. Jacobi, "Activity and potential alpha-energy of $^{222}$Rn and $^{220}$Rn daughters in different air atmospheres," *Health Phys.* 22: 441 (1972).
23. H. Kahlos and M. Asikainen, "Natural Radioactivity of Ground Water in the Helsinki Area," Institute of Radiation Physics Report SFL-A 19, Helsinki, 1973.
24. J. O. Snihs, "The content of some natural radioactive elements, especially radon-222, in some potable waters in Sweden," *Nord. Hydrol.* 4: 256 (1973).
25. C. T. Hess, S. A. Norton, W. F. Brutsaert, R. E. Casparius, and E. G. Coombs, "Levels of $^{222}$Rn in Maine and New England Buildings Arising from Potable Water Supplies," in "Radon in Buildings," National Bureau of Standards Special Publication 581, Washington, 1980. p. 81.
26. R. H. Johnson, Jr., D. E. Bernhardt, N. S. Nelson, *et al.*, "Assessment of Potential Radiological Health Effects from Radon in Natural Gas," U.S. Environment Protection Agency report EPA 520/1-73-004, Washington, 1973.
27. "Natural Background Radiation in the United States," National Council on Radiation Protection and Measurements report 45, Washington, 1975.
28. T. H. Handley and C. J. Barton, "Home Ventilation Rates: A Literature Survey," AEC report ORNL-TM-4318, 1973.
29. B. Adamson and B. Eftring, "Design of Low Energy Houses," (6 vols.), Lund Institute of Technology Department of Building Science report BKL 1979: 3 to 8 (E), Lund, Sweden.
30. J. E. Fitzgerald, Jr., R. J. Guimond and R. A. Shaw, "A Preliminary Evaluation of the Control of Indoor Radon Daughter Levels in New Structures," U.S. Environmental Protection Agency report EPA-520/4-76-018, Washington, 1976.
31. S. T. Windham, E. D. Savage and C. R. Phillips, "The Effects of Home Ventilation Systems on Indoor Radon-Radon Daughter Levels," U.S. Environmental Protection Agency report EPA-520/5-77-011, Washington, 1977.
32. A. C. George and A. J. Breslin, "The Distribution of Ambient Radon and Radon Daughters in Residential Buildings in the New Jersey-New York Area," Symposium on the Natural Radiation Environment III, Houston, 1978.
33. P. E. McNall, Jr. and S. Silberstein, "Residential Building Technology Trends and Indoor Radon and Radon Daughter Concentrations," in "Radon in Buildings," National Bureau of Standards Special Publication 581, Washington, 1980. pp. 45–52.
34. W. W. Nazaroff, M. L. Boegel, C. D. Hollowell and G. D. Roseme, "The Use of Mechanical Ventilation with Heat Recovery for Controlling Radon and Radon-Daughter Concentrations," Lawrence Berkeley Laboratory report LBL-10222, Berkeley, 1980.
35. R. Rolle, "Rapid working levels monitoring," *Health Phys.* 22: 233 (1972).
36. 10 CFR 12, 1972.
37. *Fed. Reg.* 44: 38664-70 (1979).

## Appendix A

### Solution of Radon and Daughter Decay Equations

$$A_i(t) = A_i(\infty) + \sum_{j=0}^{i} \alpha_{i,j} e^{-(\lambda_j + I)t}$$

$$\text{for } 0 \le i \le 4 \quad \text{(A-1)}$$

where:

$$\alpha_{ij} = \frac{\lambda_i}{\lambda_i - \lambda_j} \alpha_{i-1,j}$$

$$\text{for } i \ge 1 \text{ and } j < i \quad \text{(A-2)}$$

$$\alpha_{ii} = A_i(O) - A_i(\infty) - \sum_{j=0}^{i-1} \alpha_{ij}$$

$$\text{for } i \ge 1 \quad \text{(A-3)}$$

$$\alpha_{OO} = A_O(O) - A_O(\infty) \quad \text{(A-4)}$$

$$A_i(\infty) = \lim_{t \to \infty} A_i(t)$$

$$= \frac{\lambda_i \cdot A_{i-1}(\infty) + I \cdot A_i^o}{\lambda_i + I} \quad \text{for } i \ge 1 \quad \text{(A-5)}$$

$$A_O(\infty) = \frac{Q + I \cdot A_O^o}{\lambda_O + I} \quad \text{(A-6)}$$

## Appendix B

### Outdoor Daughter Activities

A subroutine is described here that calculates radon daughter concentrations from radon concentrations and equilibrium factor. The same equations described for indoor air are assumed to apply for decay and dilution outdoors. The exact nature of the clearance processes is not well understood and they are subsumed in a single "clearance factor" $I_O$, cor-responding to the air exchange rate, I, of a building. (In these equations $I_O$ is expressed in $min^{-1}$.) Radon and daughter levels external to "outdoors" are assumed equal to zero. Further, outdoor activities are assumed to be steady states.

The steady-state concentrations of radon daughters can be written as follows:

$$A_1^o = \frac{A_O^o \lambda_1}{\lambda_1 + I_O} \quad \text{(B-1)}$$

$$A_2^o = \frac{A_O^o{}_1 \lambda_2}{(\lambda_1 + I_O)(\lambda_2 + I_O)} \quad \text{(B-2)}$$

$$A_3^o = \frac{A_O^o \lambda_1 \lambda_2 \lambda_3}{(\lambda_1 + I_O)(\lambda_2 + I_O)(\lambda_3 + I_O)} \quad \text{(B-3)}$$

$$A_4^o = \frac{A_o \lambda_1 \lambda_2 \lambda_3 \lambda_4}{(\lambda_1 + I_o)(\lambda_2 + I_o)(\lambda_3 + I_o)(\lambda_4 + I_o)} \quad \text{(B-4)}$$

The potential alpha activity ($E^o$, in $WL$) for outdoor air is then, according to Eq. (5):

$$E^o = \sum_{i=1}^{4} C_i A_i^o \quad \text{(B-5)}$$

The equilibrium factor for outdoor air, $F^o$ is then:

$$F^o = \frac{100\, E^o}{A_O^o} = 100 \left( \frac{C_1 \lambda_1}{\lambda_1 + I_O} + \frac{C_2 \lambda_1 \lambda_2}{(\lambda_1 + I_O)(\lambda_2 + I_O)} + \frac{C_3 \lambda_1 \lambda_2 \lambda_3}{(\lambda_1 + I_O)(\lambda_2 + I_O)(\lambda_3 + I_O)} + \frac{C_4 \lambda_1 \lambda_2 \lambda_3 \lambda_4}{(\lambda_1 + I_O)(\lambda_2 + I_O)(\lambda_3 + I_O)(\lambda_4 + I_O)} \right) \quad \text{(B-6)}$$

The value of $I_O$ can be solved from this relationship if $F^o$ is known. Since $\lambda_4 \ll I_O$ so $\lambda_4/\lambda_4 + I_O \simeq 1$, and $C_4 \ll C_3$, the last term may be neglected in Eq. (B-5) and (B-6). The value of $I_O$ can then be used in Eq. (B-1) through (B-5) to solve for the activity concentrations of each radon daughter and the total potential alpha energy. (A solution is shown in Figure 8.)

Figure 6 shows the solution of Eq. (B-6); $F^o = 0.6$ (as in most of the figures) corresponds to a clearance factor of 0.77 ach.

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