LBL-9560 c.2
EEB-Vent 79-16
Preprint

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

Submitted to Science

RADON IN ENERGY-EFFICIENT RESIDENCES

C. D. Hollowell, J. V. Berk, M. L. Boegel,
J. G. Ingersoll, D. L. Krinkel and W. W. Nazaroff

March 1980

TWO-WEEK LOAN COPY
This is a Library Circulating Copy which may be borrowed for two weeks. For a personal retention copy, call Tech. Info. Division, Ext. 6782.

RECEIVED
LAWRENCE
BERKELEY LABORATORY
JUL 9 1980
LIBRARY AND
DOCUMENTS SECTION

LBL-9560 c.2

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Submitted to
Science

LBL-9560
EEB-Vent 79-16

Radon in Energy-Efficient Residences

C.D. Hollowell, J.V. Berk, M.L. Boegel, J.G. Ingersoll,
D.L. Krinkel and W.W. Nazaroff

Energy Efficient Buildings Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

March 1980

The work described in this report was funded by the Office of Buildings and Community Systems and the Office of Solar Applications for Buildings, Assistant Secretary for Conservation and Solar Energy of the U.S. Department of Energy under contract No. W-7405-ENG-48.

ABSTRACT

Radon concentrations were measured in seventeen houses incorporating energy-saving features, most of which included specific measures to achieve low infiltration rates. Ventilation rates in these houses ranged from 0.04 to 1.05 air changes per hour; corresponding radon concentrations were found to range from 0.6 to 22 nCi/m^3. In general, radon concentration tended to increase with decreasing ventilation rate. In one house, a mechanical ventilation system with an air-to-air heat exchanger was installed, and radon concentrations were measured at selected ventilation rates. The correlation between increasing ventilation and decreasing radon concentration was confirmed, and it appears that mechanical ventilation with air-to-air heat exchangers can maintain air quality as well as energy efficiency in many houses where air quality problems exist.

Keywords: energy conservation, heat recovery, indoor air quality, infiltration, mechanical ventilation, radon, residential buildings

Radon and its decay products have always been present as part of the earth's natural radiation burden. Radon emanates from soil, rock, and earth-derived building materials, and can gain entry to buildings through cracks and openings in the structure or around the foundation. Buildings serve to contain any contaminants that enter or are generated within the building itself and, for this reason, these pollutants typically reach higher concentrations indoors than outdoors. Limited surveys in ordinary houses have found mean concentrations of indoor radon ranging from 0.2 to 1.3 nCi/m^3[1] -- five to ten times the outdoor background levels. Prolonged exposure to high concentrations of the radioactive decay products of radon is known to pose a health risk; it is possible that the concentrations in existing houses in the United States may cause thousands of cases of lung cancer each year.[2] Unless special care is taken, indoor concentrations of radon and radon daughters could be further increased by energy-conserving measures that reduce ventilation rates.

Infiltration -- the uncontrolled leakage of air through cracks and gaps in the building envelope -- is the dominant mechanism for ventilating houses during seasons when doors and windows are normally kept closed. In conventional U.S. houses, infiltration rates range from 0.5 to 1.5 air changes per hour (ach)[3], but construction techniques have been developed and are now being used to achieve infiltration rates as low as 0.1 ach. Reducing infiltration is a cost-effective way to reduce home heating requirements, and a trend toward construction of low-infiltration houses is rapidly developing in response to the rising cost of energy.

This building trend, while supporting national efforts to conserve energy, may lead to increased human exposure to radon and radon daughters as well as to other indoor-generated contaminants, such as carbon monoxide, nitrogen oxides and particulates from combustion appliances and tobacco smoke; formaldehyde from urea formaldehyde foam insulation, particleboard and plywood; and other organic contaminants from various chemicals used indoors. Because reducing infiltration clearly affects indoor air quality and poses potential health risks to occupants, it is important that the impact of making houses more energy-efficient be studied carefully so that appropriate preventive and/or contaminant control measures can be developed and incorporated into building construction practices.

The concentration of radon-222 in a given house depends on the outdoor levels, the indoor radon sources, and the ventilation rate in the house. Radon source strengths vary significantly from house to house and, in any given house, may vary with time. A steady-state radon concentration is achieved in a house when both the radon source strength and the ventilation rate are held constant for a time long enough for several air changes to have occurred. Based on these assumptions, the steady-state radon activity is represented by the following equation:

$$I = \frac{\sigma + I_o \lambda_v}{\lambda + \lambda_v} \tag{1}$$

where

I = indoor radon concentration (nCi/m^3)

I_o = outdoor radon concentration (nCi/m^3)

σ = radon source strength ($nCi/m^3/hr$)

λ = the radioactive decay constant of radon (0.0076/hr)

λ_v = ventilation rate (hr^{-1})

Under typical conditions, $I >> I_o$ and $\lambda_v >> \lambda$, so that equation (1) reduces to

$$I = \frac{\sigma}{\lambda_v} \tag{2}$$

Thus, under steady-state conditions, indoor radon concentration is inversely proportional to ventilation rate. Because both radon source strength and infiltration rate can also vary significantly with changes in weather conditions, it is not always accurate to assume that they remain constant during a buildup to steady-state conditions, especially when the ventilation rate is very low and the time required to achieve steady state is correspondingly long. This fact contributes to the uncertainty in our results.

In this study, we measured radon concentrations and infiltration rates in seventeen houses in the U.S. and Canada. Three of the houses selected are research or demonstration energy-efficient houses and four are privately owned residences built to assure very low infiltration rates. Eight houses of passive solar design and one conventionally heated house were studied because of the possible significance of rock-bed heat storage as an additional radon source.[4] Some of the passive

solar houses did not have low infiltration rates but most incorporated such energy-conserving measures as weatherstripping and caulking, along with typical passive solar design features. One house was an underground structure having a potential for high radon influx because of its large surface contact with soil.

Sampling was performed under conditions designed to permit the radon concentration to achieve, as nearly as possible, the steady-state levels that would exist if infiltration were the only air-exchange mechanism. To approximate this correspondence, we had the occupants close windows and doors the night before sampling. Grab samples of air were collected in Tedlar[5] bags and returned to our laboratory for analysis with a zinc sulfide scintillation counting system using 100 ml scintillation cells.[6] This method allows accurate measurement of radon in concentrations as low as 1 nCi/m^3 with counting times of several hours. We also modified Jonassen's method[7] of concentrating air samples so that a three-liter sample could be counted, thus reducing statistical uncertainty to 10% for radon concentrations as low as 0.2 nCi/m^3 with 30-minute counting periods.

Infiltration was measured by a tracer gas technique.[8] A volume of gas (either ethane or sulfur hexafluoride) was injected into the house and dispersed by means of fans to achieve a homogeneous concentration of about 100 ppm. An infrared analyzer and a chart recorder were used to detect and record the dilution of the gas with time. From the dilution rate, we determined the infiltration rate of the house. The infiltration rate and radon concentrations measured in each house are given in Table 1 and plotted in Figure 1a.

As the plot reveals, radon concentrations tend to be higher in houses having very low infiltration rates. The figure also demonstrates that radon concentrations in these energy-efficient houses exceed the indoor levels in conventional houses (on the order of 1 nCi/m^3) and, in some cases, reach very high levels -- exceeding 10 nCi/m^3. The scatter in the plot reflects variations in radon source strength (σ); the variations could result from temporal fluctuations in the radon source, from differences in the nature of the sources from house to house, or from differences in design and construction among the houses. There are no obvious design features which account for the differences in source magnitude among these houses. If σ were constant and identical for each house and only the ventilation rate differed, the plot of log(I) versus log (λ_v) would result in a straight line, following equation (2).

To reduce radon-daughter exposure in such tightly constructed houses, three basic measures can be adopted: the first is to reduce the indoor radon source by blocking routes of radon entry into the interior space. For example, cracks and openings in basement floors and walls can be sealed to prevent radon-bearing soil gas from leaking into the structure. This technique has proved effective in houses located in some communities in Canada.[9] The second measure is to remove radon daughters, along with particulates, from the air by means of filtering devices or electrostatic precipitators. The effectiveness of these devices in reducing radon daughter concentrations has yet to be evaluated. A third method is to install a mechanical ventilation system to increase air exchange and thereby reduce the concentrations of radon and radon daughters as well as those of all other indoor-generated contaminants. A potentially cost-effective means of maintaining adequate ventilation

without losing the energy benefits gained by tight construction is to equip the mechanical ventilation system with an air-to-air heat exchanger.[10]

The effectiveness of such a system for controlling radon levels in a tightly constructed building was studied in detail at one energy-efficient house.[11] In the initial survey we measured a radon concentration of 22 nCi/m^3 under steady-state infiltration conditions of about 0.1 ach. During a later study, a heat exchanger was installed and operated for several days at each of four different ventilation rates. Continuous radon measurements were made at these four rates. The radon measurements were also repeated under natural infiltration conditions with the heat exchanger off. The average steady-state radon concentrations measured under these five ventilation conditions, plotted as a function of ventilation rate in Figure 1b, are well fitted by a straight line corresponding to a constant radon source of 2.5 $nCi/m^3/hr$. These data demonstrate that increasing ventilation is an effective means of reducing high radon concentrations in tight houses.

These preliminary findings confirm that reduced ventilation rates lead to increased radon concentrations in residential buildings. Where radon source strengths are naturally low, the increased exposure due to reduction in ventilation may be very small, but in houses having high radon source strengths, energy-conserving measures that lower overall infiltration may pose a serious health risk to occupants.

References and Notes

1) 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," Presented at the DOE/UT Symposium on the Natural Radiation Environment III, Houston, Texas, April 23-28, 1978; W.M. Lowder, A.C. George and C.V. Gogolot, et al., "Indoor Radon Daughter and Radiation Measurements in East Tennessee and Central Florida," U.S. Atomic Energy Commission Report HASL TM-71-9, New York, 1971; United Nations, Report of the U.N. Scientific Committee on the Effects of Atomic Radiation to the General Assembly with annexes. Volume I: Levels, Volume II: Effects, United Nations No. E 72.IX.17 and 18, New York (1972).

2) R.J. Budnitz, J.V. Berk, C.D. Hollowell, W.W. Nazaroff, A.V. Nero, and A.H. Rosenfeld, Energy and Buildings, 2, 209 (1979).

3) D.T. Grimsrud and R.C. Diamond, Building Energy Performance Standards: Infiltration Issues, Report No. LBL-9623 (Lawrence Berkeley Laboratory, University of California, Berkeley, 1979).

4) J.E. Johnson and H.G. Olson, Measurement of Rn-222 Build-up in Solar Heated Buildings and Calculation of Radiation Doses, Report No. COO-4546-2, (Colorado State University, Fort Collins, October 1978).

5) Trademark, E.I. Dupont. Sampling bags available from Environmental Measurements, Inc., 215 Liedesdorff St., San Francisco, CA 94111.

6) H.F. Lucas, Jr., in Workshop on Methods for Measuring Radiation in and around Uranium Mills, E.D. Harward, Ed., vol. 3, No. 9 (Atomic

Industrial Forum, Washington, D.C., 1977), pp. 69-96.

7) N. Jonassen and J.P. McLaughlin, Radon in Indoor Air 1, Research Report 6 (Laboratory of Applied Physics, Technical University of Denmark, Lyngby, 1976).

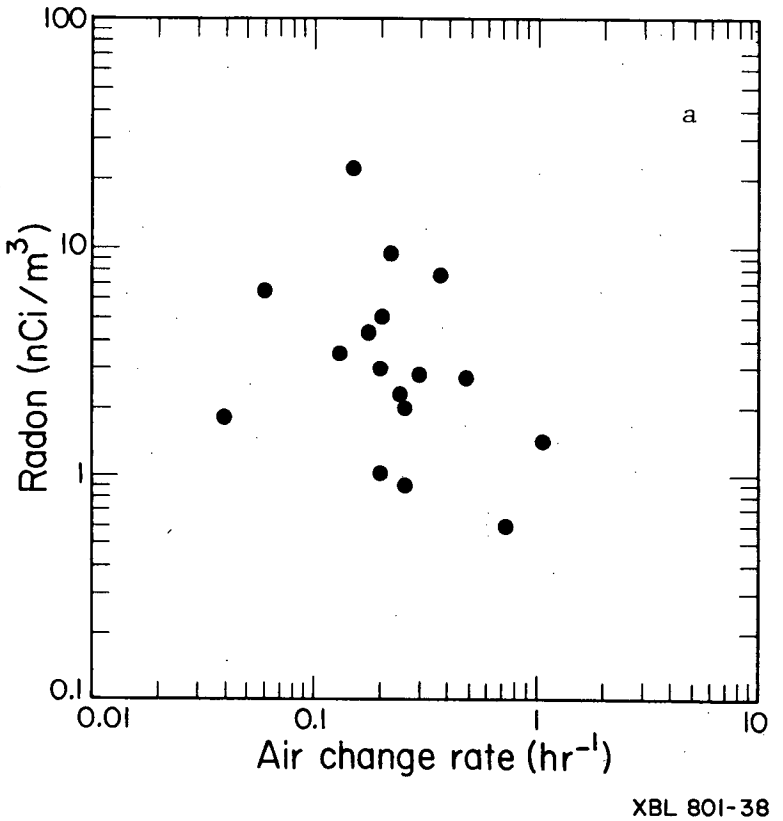
8) Proposed Standard Practice for Air Leakage Measurements by the Tracer Dilution Method. Under consideration by American Standard Testing Methods Committee E6-41.

9) P.J. Manley, "Remedial Techniques for Radiation Reduction in Inhabited Structures" (Paper presented to the Second Workshop on Radon and Radon Daughters in Urban Communities Associated with Uranium Mining and Processing, Bancroft, Ontario, 12-14 March 1979, sponsored by the Atomic Energy Control Board of Canada under the aegis of the Federal Provincial Task Force on Radioactivity).

10) G.D. Roseme, J.V. Berk, M.L. Boegel, C.D. Hollowell, A.H. Rosenfeld, and I. Turiel, Residential Ventilation with Heat Recovery: Improving Indoor Air Quality and Saving Energy, Report No. LBL-9749 (Lawrence Berkeley Laboratory, University of California, Berkeley, February 1980).

11) 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, Report No. LBL-10222 (Lawrence Berkeley Laboratory, University of California, Berkeley, February 1980).

12) We thank J. Woods and R. Rasmussen of the Energy Research Institute at Iowa State University and R. Dumont of the National Research Council, Division of Building Research (Canada), who measured air infiltration rates at the houses tested in Iowa and Saskatchewan, respectively; R. Kammerud of LBL, who made arrangements for measuring passive solar houses; and P.A. Hillis of LBL, who assisted in analyzing air samples. The work described in this report was funded by the Office of Buildings and Community Systems, Assistant Secretary for Conservation and Solar Energy of the U.S. Department of Energy under contract No. W-7405-ENG-48.



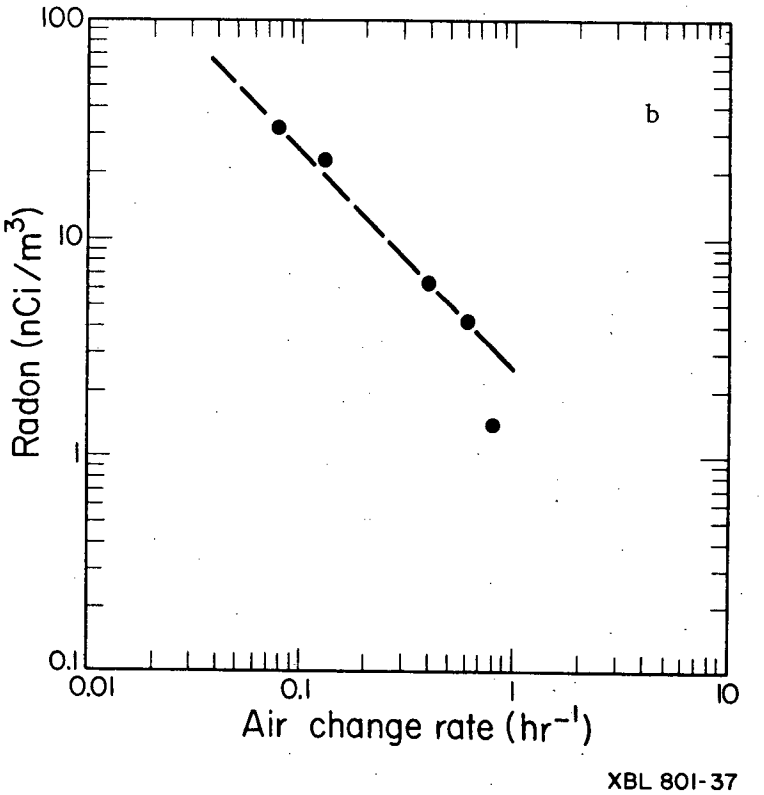


Fig. 1. Radon concentration vs. ventilation rate in (a) seventeen energy-efficient houses where infiltration was the only ventilation mechanism and (b) a single house with a mechanical ventilation system where ventilation rate was varied.

Table 1. Radon Concentration and Infiltration Rates in Various House Types

House Location	House Type	Radon Concentration (nCi/m^3)	Infiltration Rate (ach)
Minnesota	Infiltration reduction measures	1.8	0.04
Minnesota	Infiltration reduction measures	6.5	0.06
Texas	Underground	3.5	0.13
Maryland	Energy research house	22	0.15
Illinois	Infiltration reduction measures	4.3	0.18
Iowa	Energy research house	1.0	0.20*
Saskatchewan, Canada	Infiltration reduction measures	3.0	0.20†
California	Energy Research House	5.0	0.20
New Mexico	Passive Solar	9.3	0.22
New Mexico	Passive Solar	2.3	0.24
New Mexico	Passive Solar	2.0	0.26
New Mexico	Passive Solar	0.9	0.26
New Mexico	Conventional heating	2.8	0.30
New Mexico	Passive Solar	7.6	0.37
New Mexico	Passive Solar	2.7	0.48
New Mexico	Passive Solar	0.6	0.73
New Mexico	Passive Solar	1.4	1.05

*Infiltration rate measured by researchers at Iowa State University.

†Infiltration rate measured by researchers at the National Research Council, Division of Building Research (Canada).

This report was done with support from the Department of Energy. Any conclusions or opinions expressed in this report represent solely those of the author(s) and not necessarily those of The Regents of the University of California, the Lawrence Berkeley Laboratory or the Department of Energy.

Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720