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Extended Summary

DISTRIBUTION OF INDOOR RADON CONCENTRATIONS AND SOURCE MAGNITUDES: MEASUREMENTS AND POLICY IMPLICATIONS

A.V. Nero and W.W. Nazaroff

Building Ventilation and Indoor Air Quality Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

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INTRODUCTION

Substantial effort has been devoted in recent years to studying radon 222 and its daughters in U.S. residences. As a part of our study of the effect of ventilation on indoor concentrations, our group has carried out surveys in conventional and energy-efficient houses, measuring airborne radon concentrations and air-exchange rates concurrently. These surveys have been complemented by measurements of radon emanation rates from building materials commonly used in the United States. Based on this earlier work, this paper examines the frequency distribution of indoor radon concentrations and air exchange rates found in these studies, discusses radon source magnitudes extracted from our data, compares the distribution of source magnitudes with information on emanation rates from source materials, and, finally, considers the ways in which variability in source magnitude might affect regulatory efforts to control indoor concentrations of radon and its daughters.

RESULTS

Radon concentrations and air-exchange rates

Three housing groups--consisting of 17 "energy-efficient" houses in the United States and Canada (Hollowell et al., 1980), 29 conventional houses in the San Francisco area (Berk et al., 1979) and 52 houses in a community in rural Maryland (Moschandreas et al., 1981)--were surveyed. In each case radon (and usually radon daughter) concentrations were measured simultaneously with infiltration rate, radon in grab samples and infiltration by a tracer gas decay technique. To establish a correspondence between the radon concentration and the ratio of source magnitude to air infiltration rate, we asked occupants to close windows and doors for the night prior to measurements. Our results are presented in Figure 1, which shows clearly that radon concentrations do not correlate strongly with air exchange rates in any of these survey groups. Moreover, it is evident that in these houses radon concentrations are distributed over a much broader range than are infiltrations rates. From these observations, we suggest that the wide distribution of radon concentrations found in this and other work (e.g., George and Breslin, 1978) arises largely from variations in source magnitude.

Distribution of radon source magnitudes

For steady-state conditions, the radon source magnitude, i.e., the radon entry rate per unit house volume, may be estimated by taking the product of the radon concentration and the air-exchange rate. Figure 2 displays a frequency distribution of the source magnitudes

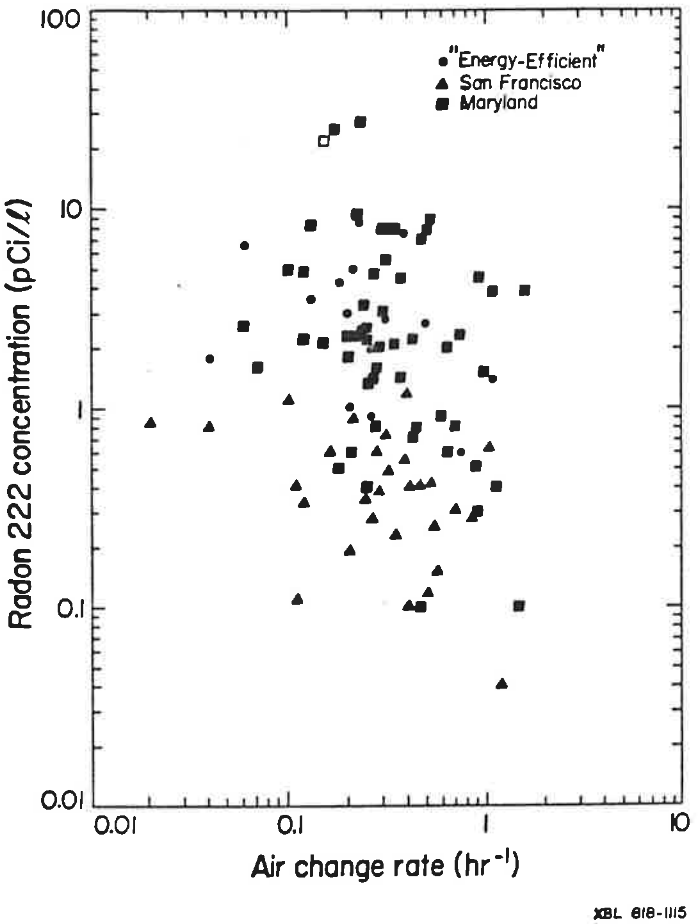
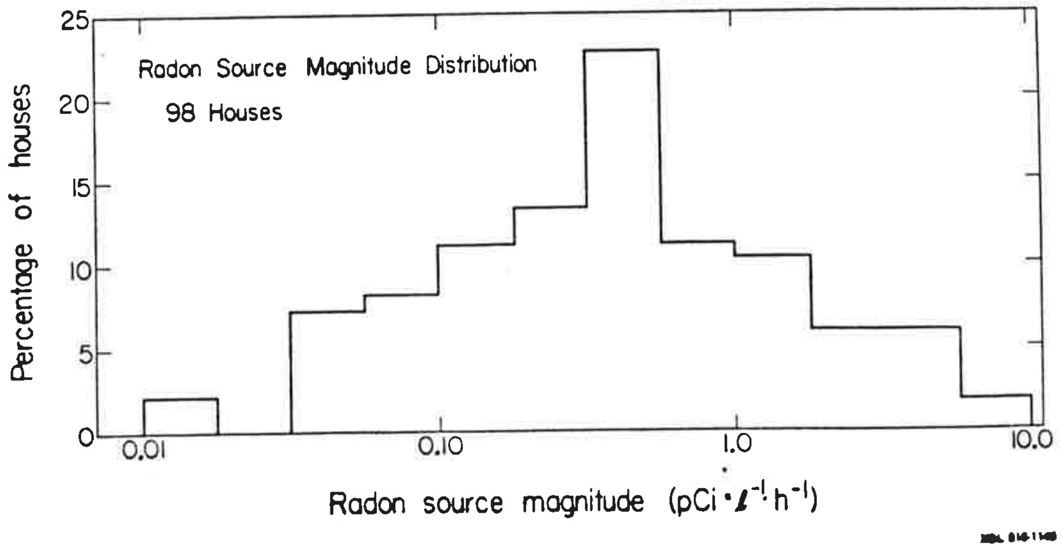


Figure 1. Radon Concentrations and Air Change Rates in U.S. Residences. The Figure is a composite of results from three survey groups: "energy-efficient" houses in the United States and (one) in Canada; conventional houses in the San Francisco area; and conventional houses in a community in rural Maryland

Figure 2. Frequency Distribution of Radon Source Magnitude. For each of 98 houses, the radon entry rate per unit volume is calculated from the radon concentration and air change rate given in Figure 1.



calculated from the data of Figure 1. Values range over almost three orders of magnitude. The geometric standard deviation of the distribution is similar to that for the radon concentrations in these houses and much larger than that for the infiltration rates. This distribution is similar to that obtained for residences in England (Cliff, 1978).

Because this distribution of source magnitudes is based on analysis of grab samples, it contains some uncertainty associated with the assumption that measured parameters are constant before sampling, which may not be the case. This uncertainty aside, the source magnitudes measured represent instantaneous values only. When measurements are repeated in a single house, the source magnitudes are found to vary significantly, although not nearly as widely as the distribution seen in Figure 2. The distribution of time-averaged source magnitudes can therefore be expected to have a mean and standard deviation similar to those for Figure 2. Furthermore, in an individual house, the source magnitude may correlate with infiltration rate in such a way that the indoor radon concentration does not vary as much with time as the source magnitude (Nazaroff et al., 1981). Hence, our observation that most of the variation in radon concentration arises from variations in source magnitude (when derived from grab-sample measurements) may also apply to time-averaged values of these parameters.

Contribution of building materials and soil to source magnitudes

The major sources of radon in most buildings are thought to be building materials or underlying soil and rock. Table 1 (adapted from Ingersoll, 1981) presents radon emanation rates and radionuclide concentrations for concrete samples from nine metropolitan areas in the United States. The average radon emanation rate from all samples tested was 0.8 pCi $kg^{-1}hr^{-1}$. A concrete slab 0.2 m thick with an average emanation rate and a typical density of 2000 kg/m^3 would have an emanation rate, expressed per unit area, of approximately 0.04 pCi $m^{-2}s^{-1}$. For a one-story house, interior height 2.4 m, placed on this concrete slab, the corresponding source magnitude would be 0.07 pCi $l^{-1}hr^{-1}$ -- an order of magnitude below the average source magnitude of 0.9 pCi $l^{-1}hr^{-1}$ for our 98-house sample.

TABLE 1. EMANATION RATES AND RADIONUCLIDE CONCENTRATIONS IN ORDINARY CONCRETE

Origin	No. of Samples	Emanation Rate per Mass ($pCi\ kg^{-1}\ h^{-1}$)			Elemental Concentrations (mean)			Average Escape-to-Production Ratio (%)
		Range	Mean	S.D.	U (ppm)	Th (ppm)	K (%)	
Albuquerque, N. Mex.	12	0.70-1.95	1.22	0.35	2.5	6.0	1.5	22
Kansas City, Mo.	12	0.40-0.65	0.53	0.07	1.0	2.0	0.7	25
Philadelphia, Penn.	7	0.35-0.55	0.42	0.08	0.6	1.5	0.7	17
Salt Lake City, Utah	9	0.50-0.75	0.64	0.08	2.0	4.0	0.6	14
San Francisco - Oakland, Cal.	21	0.65-1.10	0.83	0.12	1.5	3.0	0.6	24
Austin, Texas	8	0.60-0.92	0.73	0.12	1.3	1.5	0.8	24
San Antonio, Texas	8	0.27-0.72	0.46	0.14	3.0	7.5	1.5	8
Chicago, Ill.	12	0.25-1.39	0.66	0.36	1.5	2.0	0.5	25
St. Paul - Minneapolis, Minn.	5	0.54-0.75	0.62	0.09	1.5	4.0	1.5	19
Knoxville, Tenn.	6	0.46-0.78	0.59	0.12	1.0	1.2	0.5	23

In contrast to concrete, the soil can contribute a large portion of the observed radon source magnitude. A typical radon flux from the soil is 0.4 pCi m^{-2} s^{-1} (Wilkening et al., 1972), which would contribute 0.7 pCi l^{-1} hr^{-1} to the house postulated above, assuming this typical flux gained entry to the interior. Our group has recently begun to study the specific question of radon transport, important if the source of indoor radon is to be understood and if information on radionuclide concentrations or radon fluxes is to be used as a basis for identifying geographic areas where high indoor radon concentrations may be endemic.

Risk assessment and control strategies

The considerable effort now being devoted to assessing the risk from indoor exposure to radon daughters should take explicit account of the wide variation in indoor concentrations. Whereas average exposures are the basis for estimating population risks, knowledge of the frequency distribution is necessary for estimating individual risks. Data presently available suggest that millions of the U.S. population are exposed to concentrations ten times the average. It appears appropriate that regulatory efforts be designed to avoid such excessive exposure of individuals, at the same time achieving an acceptable average exposure of the population as a whole (Nero, 1981).

Controlling average exposures and avoiding excessively high individual exposure requires attention to major factors affecting indoor concentrations, i.e., ventilation rates and source magnitudes. Because variations in the latter appear to be the principal cause of variations in indoor concentrations, examination of the geographic distribution of source magnitudes and of its relationship to population distribution may be a critical requirement for identifying the portion of the population subjected to excessive exposures and for designing programs to reduce such exposures.

CONCLUSIONS

Indoor radon concentrations measured by our group vary over a large range and do not correlate well with infiltration rate. Calculation of source magnitudes for the houses monitored yields values ranging over three orders of magnitude, and this variation appears to be the main cause of the variation in indoor concentrations. Radon emanation rates from building materials such as concrete do not account for the source magnitudes observed; on the other hand, the radon flux from soil averages ten times as much as that from concrete, and could account for the source magnitudes observed. The observed distribution in indoor concentrations suggests that a significant portion of the population is subject to unusually high risks, and variations in source magnitude need to be considered in developing strategies for identifying this portion of the population and for reducing indoor concentrations.

ACKNOWLEDGEMENTS

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