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Author
Nero, A.V.

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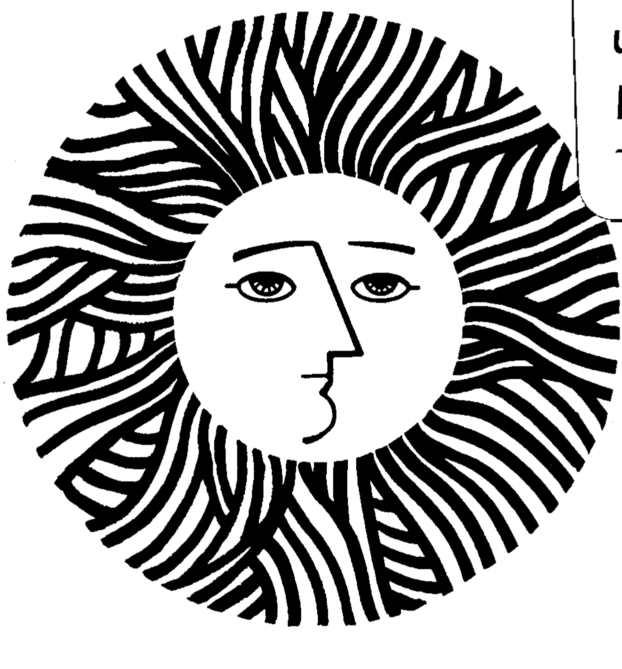

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Building Ventilation and Indoor Air Quality Program
Energy and Environment Division
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Berkeley, CA 94720

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ABSTRACT

To elucidate any connection between high radon concentrations and low-infiltration houses, we have concurrently measured the ^{222}Rn concentration and the infiltration rate in U.S. houses. Three housing surveys have been undertaken: one in "energy-efficient" houses located throughout the United States and two in "conventional" houses in the San Francisco area and in Maryland. In each of the groups surveyed, no clear correlation was observed between ^{222}Rn concentrations and infiltration rate, although each parameter varied over a wide range. Infiltration rates for the entire sample, numbering 98 houses, ranged between 0.02 and 1.6 air changes per hour, and radon concentrations ranged from 0.1 to 27 pCi/l. It appears that the major cause of the observed differences in ^{222}Rn concentration is variation from one house to another in the rate at which ^{222}Rn enters houses from its sources.

Keywords: energy conservation, indoor air quality, infiltration, radon, residential buildings

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INTRODUCTION

Buildings tend to contain contaminants that originate within or under the building, causing them to reach higher concentrations indoors than outdoors. Radon is one such pollutant, since it emanates from earth-derived building materials, and can also gain entry to buildings by transport through cracks and openings in the structure or around the foundation. Limited surveys in ordinary U.S. houses have found mean concentrations of indoor ^{222}Rn ranging from 0.1 to 1.2 pCi/l (Ne81)--typically several times the outdoor background levels. Prolonged exposure to high concentrations of the radioactive decay products (daughters) of ^{222}Rn is known to pose a health risk; the concentrations now found in U.S. houses may cause thousands of cases of lung cancer each year (Bu79, Ne81b). Unless care is taken, indoor concentrations ^{222}Rn and its daughters could be increased by energy-conserving measures that reduce ventilation rates of U.S. buildings.

For a given radon entry rate, the indoor radon concentration depends on the ventilation rate. 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 0.3 to 1.5 air changes per hour (ach) (Gr79), 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. In addition, more modest reductions in infiltration rates can be expected to result from programs now beginning for reducing energy use in existing houses.

This trend may lead to increased human exposure to ^{222}Rn and its daughters as well as to other indoor-generated contaminants: 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 affects indoor pollutant concentrations, potentially affecting the health of occupants, it is important to examine the range of indoor concentrations and the effect of energy-saving measures and pollutant control techniques.

We have measured indoor ^{222}Rn concentrations and infiltration rates in conventional and "energy-efficient" houses in the United States. Our purpose has been to examine any correlation between indoor concentrations and infiltration rates from one house to another. We performed measurements in three survey groups: "energy-efficient" houses located throughout the United States (as well as one Canadian house); conventional houses in San Francisco area; and primarily conventional houses in a rural community in Maryland.

MONITORING STRATEGY AND TECHNIQUES

Measurements in the three survey groups consisted of single grab samples taken for ^{222}Rn analysis and concurrent measurement of air exchange rates. The concentration of radon in a house depends on the radon entry rate and the ventilation rate. A steady-state concentration is approached if the entry rate and the ventilation rate are approximately constant long enough for several air changes to have occurred. Under these conditions, the indoor radon concentration will approach

$$I = (\sigma + I_0 \lambda_v) / (\lambda_v + \lambda),$$

where σ is the volumetric source strength (the rate, expressed per unit volume, at which radon enters from indoor materials and from underlying soil and rock), I_o is the outdoor radon concentration, λ_v is the ventilation rate, and λ is a radioactive decay constant. For ^{222}Rn, λ is $0.0076\ hr^{-1}$, much less than a typical value of λ, so that I equals σ/λ_v plus I_o, which is ordinarily a small additive term.

In our survey, sampling was performed under conditions designed to permit the radon concentration to achieve, as nearly as possible, the steady-state level that would exist if infiltration were the only air-exchange mechanism. To approximate this correspondence, occupants were asked to close windows and doors the night before sampling. However, both radon source strength and infiltration rate can vary significantly with changes in weather conditions, so that they cannot be assumed to remain constant during the period prior to our measurements. Such variation must be considered in examining possible correlations between measured radon concentrations and infiltration rates.

Grab samples of radon were obtained in one of two ways in each of the surveys. One technique was to collect grab samples of air in Tedlar (Trademark, E.I. DuPont) bags or metal cans and return them to our laboratory for analysis with a zinc sulfide scintillation counting system using 100-ml scintillation cells (Lu77). This method allows accurate measurement of radon in concentrations as low as 1 pCi/l with counting times of several hours. We also modified Jonassen's method (Jo76) of concentrating air samples so that radon in a three-liter sample could be transferred to a 100-ml scintilation cell for counting, thus reducing statistical uncertainty to 10% for radon concentrations as low as 0.2 pCi/l with 30-minute counting periods. The alternative technique was to use a commercially available portable instrument incorporating a scintillation cell. The calibration of this instrument was checked by comparison with our laboratory system. However, because the sample of air collected was only 170 ml and counting times were 30 minutes, the sensitivity of these measurements was poorer, i.e., 50% relative standard deviation at 0.5 pCi/l or 20% at 2 pCi/l.

Infiltration was measured by a tracer gas technique in each survey (cf. Sh80). 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 concentration of the gas in the living space as a function of time. From the rate at which the concentration decreased, we determined the infiltration rate of the house.

SURVEY GROUPS AND MEASUREMENT RESULTS

The "energy-efficient" survey group consisted of 17 houses in the United States and one in Canada. Three of the houses selected are research or demonstration energy-efficient houses (located in California, Iowa, and Maryland) and four are privately-owned residences (in Illinois, Minnesota, and Saskatchewan) built to assure very low infiltration rates. Eight houses of passive solar design and one conventionally heated house, all in New Mexico, were studied because of the possible significance of rock-bed heat storage as significant radon source. 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 in Texas was an underground structure having a potential for high radon influx because of its large surface contact with soil. Measurements in these houses were performed during May-August of 1979. The results are shown in Figure 1, where ^{222}Rn concentration is plotted versus air change rate.

The second survey was performed during the summer of 1979 in homes of Lawrence Berkeley Laboratory employees. The 29 houses monitored were located in several San Francisco area communities. Approximately half of the houses had crawl spaces, the others having a concrete slab, basement, stilts, or some combination of these understructures. Results of these measurements are shown in Figure 2.

The third survey group consisted of 55 houses located in the same general area as the Maryland energy-efficient research house where measurements had yielded the highest ^{222}Rn concentration shown in Figure 1. This survey was designed by our group and conducted by Moschandreas et al., who selected houses and performed the measurements during April-October 1980 (Mo81). One group of houses was selected from the neighborhood in which the energy research house was located. A second group was selected from the remainder of the town. A third group consisted of houses in the surrounding rural area and neighboring towns. Results of these measurements, are summarized in Figure 3 (which omits 3 houses that nominally yielded radon concentrations of 0.0 pCi/l).

DISCUSSION

Results from none of the groups surveyed showed a strong correlation between ^{222}Rn concentration and air change rate. If the radon source strength σ were constant and identical for each house and only the ventilation rate affected the ^{222}Rn concentrations, the data is each of the figures would fall on a straight line. The scatter in each plot reflects variations in σ, a variation that is illustrated by plotting a frequency distribution of source magnitudes for the total of 98 houses, as is done in Figure 4. Such variations could result from temporal fluctuations in the radon source, from differences in the nature of the sources from house to house, and from differences in design and construction among the houses. There are no obvious design features, in any of these survey groups, that alone account for the differences in source magnitude among these houses.

For a given source magnitude, the indoor concentration can be expected to depend largely on the ventilation rate. This has been confirmed by intensive measurements in the energy-efficient house in Maryland, mentioned above, where ventilation rates were varied using a mechanical ventilation system with an air-to-air heat exchanger, yielding a ^{222}Rn concentration that was inversely proportional to the ventilation rate (Na81a). On the other hand, examination of other data taken by our group indicates that - in some houses - the source magnitude may correlate with air exchange rate for changes that depend on meteorological conditions (Na81b).

CONCLUSIONS

The high indoor ^{222}Rn concentrations in some U.S. homes can arise from either high source magnitudes or low ventilation rates. Our surveys of U.S. housing indicate little correlation from one house to another, between ^{222}Rn concentration and infiltration rate and, in fact, show a substantially wider range in ^{222}Rn concentrations, indicating the important influence of differences in source magnitude. Measures are available for controlling indoor concentrations, either by reducing the rate of radon entry or by removing radon or its daughters from indoor air using measures such as mechanical ventilation with heat recovery. A key factor in implementing such measures is identification of houses with large source magnitudes.

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Building Ventilation and Indoor Air Quality Program
Energy and Environment Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720
U.S.A.

A.V. Nero,

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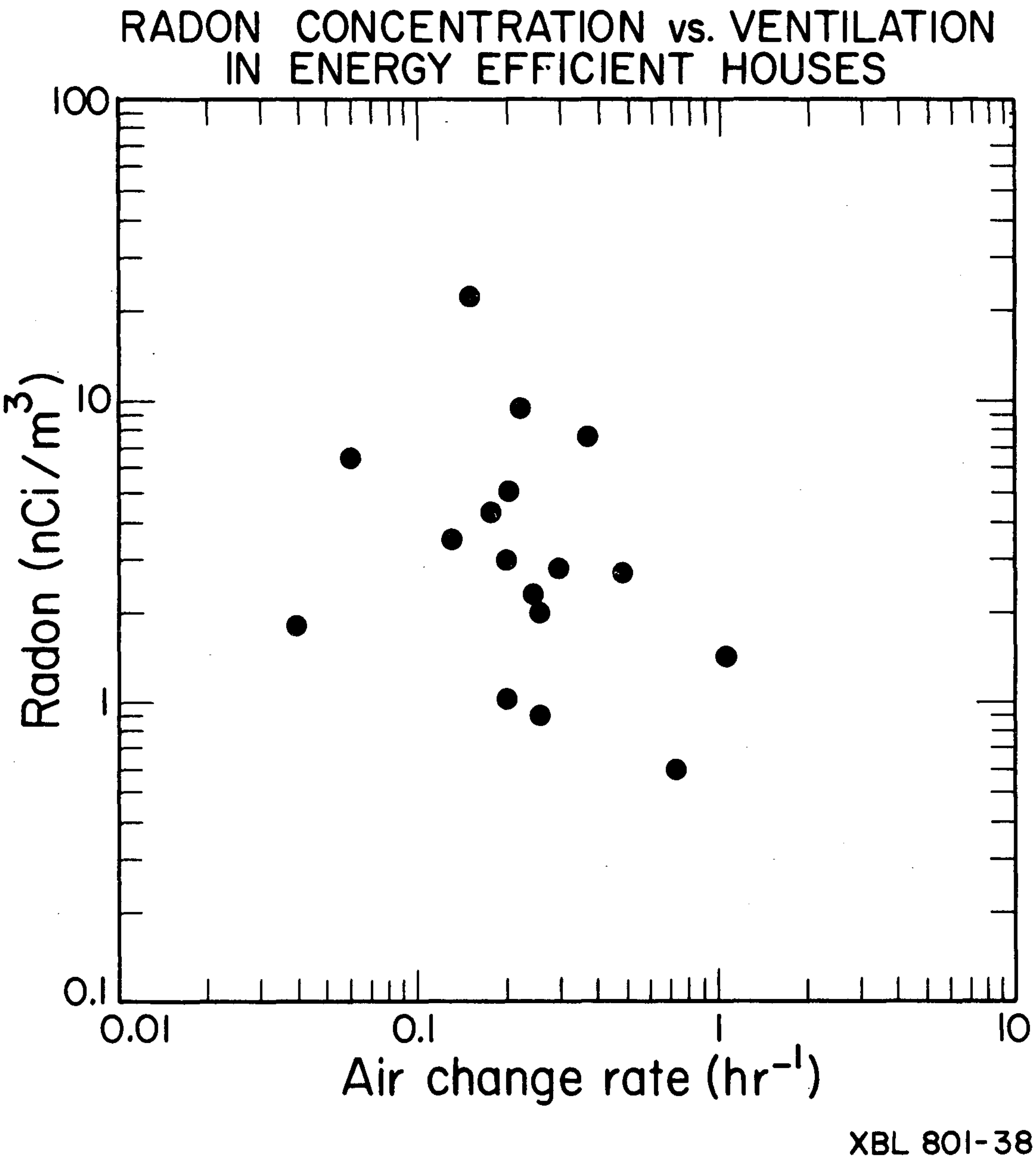

Figure 1. Radon 222 concentrations versus ventilation rates in 17 "energy-efficient" houses, 16 in the United States and one in Canada.

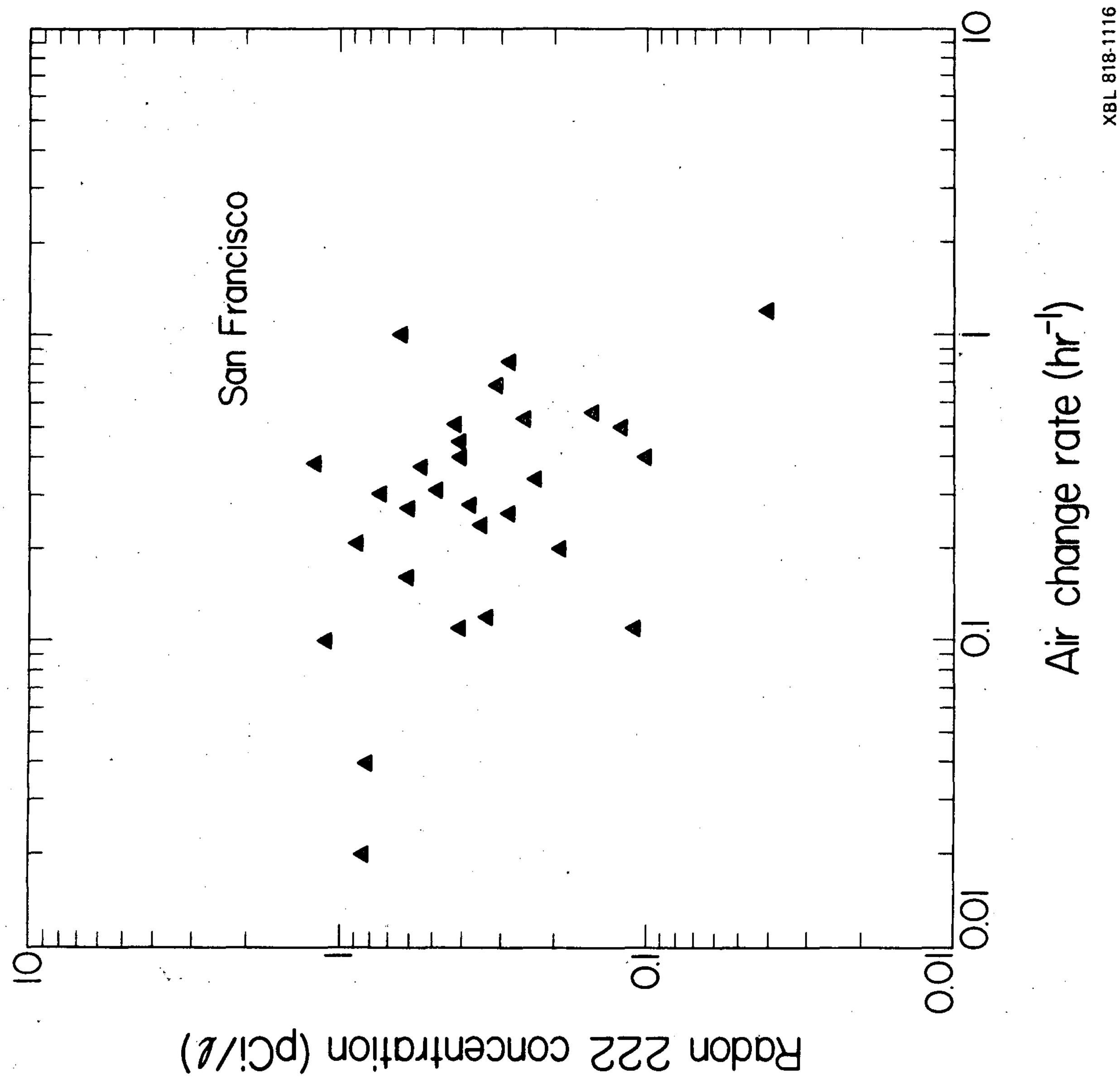

Figure 2. Radon 222 concentrations versus ventilation rates in 29 houses in the San Francisco area.

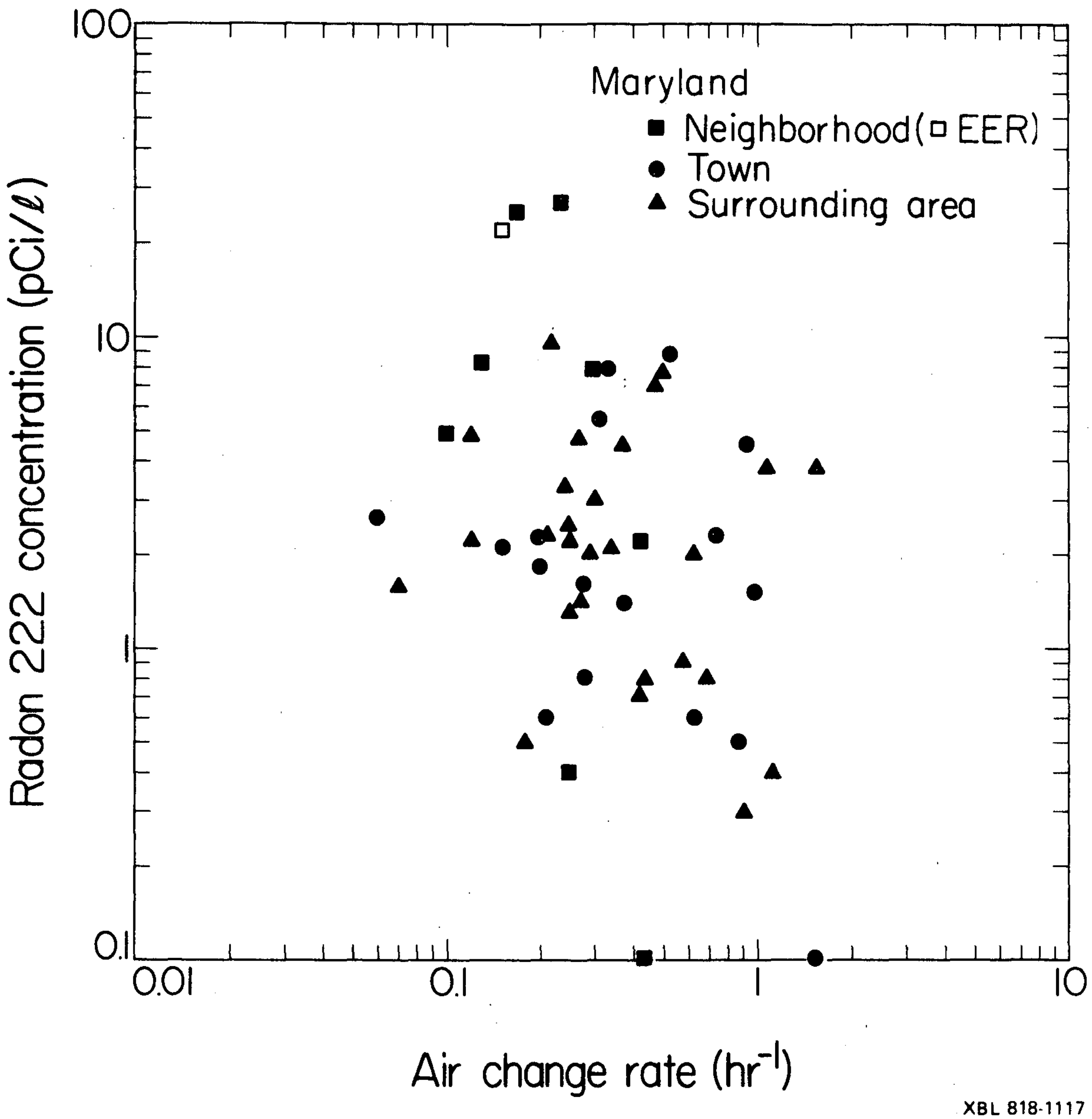

Figure 3. Radon 222 concentrations versus ventilation rates in 52 houses in a community in rural Maryland. The 53rd house (open square), also located in rural Maryland, is one of the energy-efficient houses indicated in Figure 1.

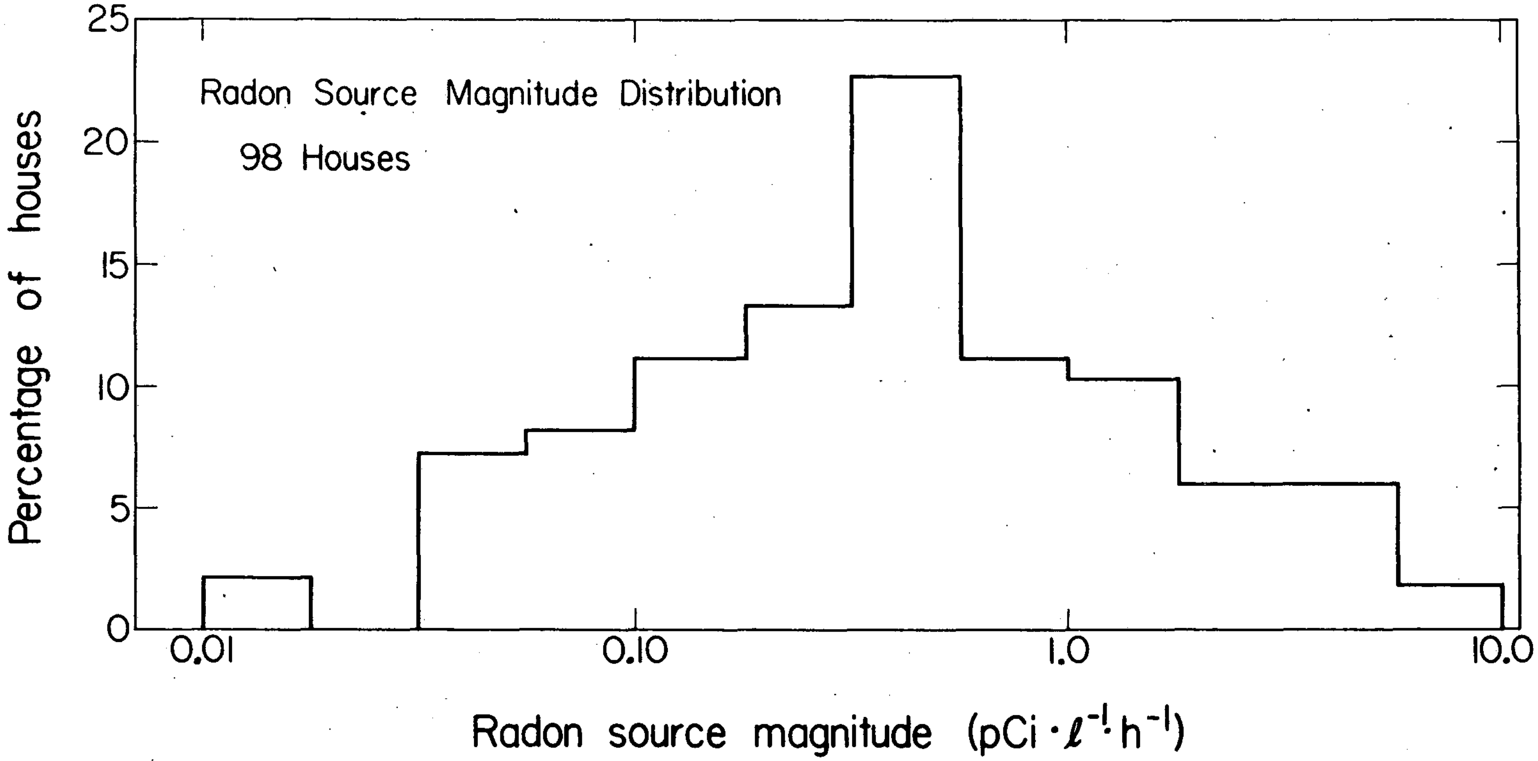

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Figure 4. Frequency distribution of radon source magnitudes calculated from the data in Figures 1-3 by taking the product of ^{222}Rn concentration and ventilation rate.

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LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720