Radon Concentrates and Ventilation Rates in Eastern Pennsylvania Houses

H.M. Sachs, Ph.D. D. Harrje H.W. Prichard K. Gadsby D.I. Jacobson

INTRODUCTION

The distribution of radon in houses is an important issue for both public health and energy conservation, making it crucial that the factors governing the distribution of radon in houses be discovered and understood through careful analysis.

The amount of radon daughter exposure is proportional to the rate of excess lung cancer development in uranium miners (Beir, 1980), and most workers feel that environmental exposures account for a large fraction of the lung cancer observed in nonsmokers. Because environmental exposures usually have been at low dose rates, there is divergence among authorities on the appropriate extrapolations from miner data to environmental risk. Published estimates range from 100 to 1,000 lung cancers per million working level months of radon daughter exposure (Table 1). Martell (1983) suggests further that much lung cancer among smokers also involves radon daughters causally.

Determining the distribution of exposure for large populations would be feasible with available passive monitors but has not been carried out. Instead, based upon the observation that most people spend 80-90 percent of their time indoors, investigators have chosen to measure concentrations in buildings, particularly houses.

The most striking characteristic of the distribution of radon concentrations is its extremely wide dispersal, typically two or three orders of magnitude within a region and more between regions. As stressed by Sachs and others (1982), the lognormal distribution typical of these studies implies control by a number of factors interacting multiplicatively. That analysis of variability stressed that geologically controlled variables (soil, soil permeability, water supply) would exhibit this great variability, while other potential contributors (ventilation rate, building materials) usually show less variability.

H.M. Sachs, Technical Director, National Indoor Environmental Institute, 5200 Butler Pike, Plymouth Meeting, PA 19462
D. Harrje and K. Gadsby, Senior Research Engineers, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ 08544
H.W. Prichard, Assistant Professor, Environmental Sciences, University of Texas, School of Public Health, P.O. Box 20186, Houston, TX 77225

If geological variables govern the distribution of those areas in which high values are likely, such areas should exhibit the spatial coherence (on a scale of 1-100 km) characteristic of most geological outcrop belts and most aquifers (which supply subterranean water).

It is well-established that ground water can be a major source of radon in houses (Hess et al., 1979, 1980). It is also well-established that trends of high radon concentration in houses are sometimes correlated with geological features. Hess et al. (1979) noted the association of high radon concentrations with location on granites and high-grade metamorphic rocks in Maine, a relationship that is expected to hold for much of northern New England and probably for other regions as well. Sachs et al. (1982) stressed the strong association of high concentrations with specific sedimentary rock "belts" in eastern Pennsylvania. Statistically, location is an important variable in predicting radon concentrations for these houses (Gross and Sachs, 1982).

In contrast, neither building materials nor ventilation variability appears to account adequately for the broad distribution of radon concentrations in houses. As reviewed in several articles in the Third Natural Radiation Environment and in Nero and Lowder (eds, 1983), building materials generally a narrow range of emanation variability.

Ventilation is best considered as a modulator or amplifier of an underlying source, since it has a fairly narrow distribution, with most houses apparently having long-term ventilation rates between 0.5 and 1.5 air changes per hour (ACH), (Nero, 1983). For some hypothetical steady radon source strength, a decrease in ventilation rate will increase the concentration of radon in a dwelling; this relationship has been demonstrated in an instrumented house. Among energy-efficient houses, there seems to be a general inverse relationship between ventilation rates and radon concentrations, but the data are quite scattered (Nero et al., 1983). Indeed, LBL data for 99 houses of various construction styles show no simple relationship between radon concentration and ventilation rate.

With this background, our goals in this prototype study were clear: We wanted to specify as many components of the radon budgets of conventional houses as possible, to examine the magnitude of the contributing factors. We chose a representative panel of 37 houses in eastern Pennsylvania. Each house was located with respect to its geological formation (the underlying substrate) by Sachs and A. van Assendelft. Harrje and Gadsby coordinated and took responsibility for the blower-door ventilation measurements by Princeton personnel. Prichard analyzed the concentration of radon in the domestic water supplies from samples gathered by Sachs and Gadsby. Prichard also arranged for the use of Terradex Track-Etch (R) Type F passive radon detectors (Alter and Fleischer, 1981). Field difficulties in deploying the detectors in frozen ground prevented large-scale radon concentration study.

METHODS

The time-varying concentration of radon in a house is given by

$$\frac{dN}{dt} = S + \frac{N_a}{T_a} - \left[\frac{N(t)}{T_r} + \frac{N(t)}{T_a} \right]$$

where N is concentration, S is source strength, N_a is the outdoor (ambient) concentration, T_a is the ventilation constant of the building, and T_r is the mean life of a radon-222 atom.

This equation is valid for the extreme situation in which the structure can be treated as comprising only a single, well-mixed chamber. In real houses, radon concentrations in basements are often two to ten times higher than in living areas above the basement (e.g., Sachs and others, 1981; Table 2 of this paper), so that the one-chamber approximation is not completely appropriate. Nonetheless, even in these cases one can consider the living area to be modeled by a single-chamber situation. The 2-chamber situation has been investigated by Hernandez and Ring (1982).

Steady-state conditions are not reached in houses of conventional design. Among other factors, barometric pressure gradients can cause short-term but large-scale variation of the source strength (Hernandez, et al., in pres). The ventilation rate of conventional houses is also a strongly varying function of indoor-outdoor temperature gradients and the local wind field (Persily, 1982).

On the other hand, we are interested in exposure, which will be linked to long-term average concentrations. For this reason, the use of long-term integrating monitors of radon concentration is most appropriate, and it is important to select ventilation measurement methods that can approximate long-term average ventilation rates as well.

The goal of approximating long-term ventilation measurements led us to choose blower-door pressurization methods to approximate ventilation rates instead of using tracer gas dilution methods. It is generally accepted that the tracer gas systems are more accurate, but of limited applicability until integrating monitors become more widely available (Dietz et al., 1983). Short-term tracer gas methods yield information only on instantaneous ventilation rates, except where expensive continuous monitors are employed. This is prohibitive for large field studies.

In contrast, the blower door methods measure the flow of air induced by a calibrated door-mounted fan as a function of the pressure difference between the inside (affected by the fan) and the outside (Blomsterberg and Harrje, 1979). The pressurization or depressurization profile, in conjunction with knowledge of the house volume and flow rates can be used to determine a tightness value at 50 pascal (pa) or an Effective Leakage Area (ELA) at 4 pa differential pressure for the building. From this, the ventilation rate can be approximated (Sherman and Grimsrud, 1980). Alternatively, a useful empirical relationship is that the seasonal average ventilation rate is strongly linked to the 50 pascal pressure difference flow rate divided by 20 (Persily, 1982; Kronvall, 1978). In this study, we have used both the Effective Leakage Area values and the Princeton approximation, respectively labeled as LBL and PK ACH on Table 2.

As noted above, all radon measurements for air were made with Terradex Track-Etch type F integrating passive monitors, exposed for at least two months. These devices were placed in the houses by the occupants, and generally were picked up by Princeton staff at the time the ventilation measurements were made for each house.

15 mL water samples were collected by Princeton field personnel at the time of blower door measurements. In each case, water was drawn into a plastic syringe from a cold-water tap running freely. The water was then injected under 10 mL of scintillator in a 25 mL scintillation flask. Duplicate samples were taken for each location. All houses served by private wells were sampled; only representative samples were taken in houses served by the same community water supply. Analysis by Prichard followed the alpha scintillation methods of Prichard and Gesell (1977).

Because we do not expect large-scale temporal variability in radon concentrations of water supplies, and because all water supplies in this region that have been measured have had concentrations no higher than 20,000 picocuries per liter (pCi/L), we feel that this sampling strategy served the project needs adequately.

As indicated above, the location of each house was interpolated on the largest scale available geological map to determine the underlying substrate; this approach led to very specific assignments in almost every case. This system led to the recognition of 11 different geological categories largely equivalent to those of van Assendelft and Sachs (1982). This is too many for analysis of a data set of this size. In addition, the relative frequencies were very highly skewed, with two categories having 10 houses each, and no other categories having more than three houses. Consequently, we clustered the geological variables into four categories: Group 1, All Great Valley formations, a group dominated by the Leithsville and Allentown rocks; Group 3, comprising houses on the Mauch Chunk Formation; Group 4, houses on the Marcellus; and Group 5, all others of Silurian to Triassic age. Our original Group 2, Beekmantown of the Great Valley, was combined with Category 1 because there were only two Beekmantown houses.]. [There were no houses located on igneous or metamorphic rocks in this study.

Participants in this study were all uncompensated volunteers. In the Allentown and Bethlehem region, participants were recruited from the members of the Geology Department, Lehigh University, and their friends. We also studied houses in two much smaller towns, referred to as "C" and "D" in this report. In each of these towns, the volunteers were members of the faculty of local schools or their friends. In this report, information that might lead to the identification of these participants has been aliased to preserve confidentiality. In each case, the relevant location and contact data for each house are recorded at the Center for Energy and Environmental Studies, Princeton University. A duplicate file is maintained by the senior author.

RESULTS

As noted above, the potential "supply" terms in the radon budget are the local geological conditions (soil, soil permeability, substrate), the building materials, and the supply water. The "sink" is limited to dilution by ventilation and a much smaller (ca. 100x) elimination by radioactive decay.

We elected not to study the emanation of radon from building materials, either in situ or in the laboratory, for three reasons: (1) This study was designed to be as unintrusive as possible. (2) There were severe restrictions on available manpower. (3) There have been no indications of building material problems in prior studies in the region.

In this report, we will first address the findings by variable, and then consider the results for computed variables and variable interrelationships.

1. RADON IN AIR. Data for thirty houses are given in Table 1 and summarized in Table 3. Several characteristics of the data set require comment. First, the logarithmic average concentration in the living areas is 4.7 pCi/L, an uncommonly high value. The corresponding cellar logarithmic average is 6.5 pCi/L. Clearly, the data for new houses (less than 10-15 years old) are quite distinct from those for the older houses. For 16 older houses, the living area and cellar concentrations had logarithmic averages of 2.9 and 4.0 pCi/L, respectively, while the 12 newer houses had

comparable values of 10.6 and 13.7 pCi/L. These values are comparable to those found by Gross and Sachs (1982) in an analysis of the 36-house Pennsylvania Power and Light cohort analyzed by Sachs and others (1983). The implications for human exposure in the future are discussed below.

The living area radon concentrations were almost always lower than those in the cellar in this study. Of 30 houses with complete radon data, cellar values were lower in only 8 (27%). As shown in Table 3, in six of these cases, the values were very close (within 1 s.d.); the two remaining cases are marginally further separated.

We infer from this pattern that the predominant sources throughout the region are in the basement. Important living area sources (much greater than cellar sources) would be marked by living area concentrations consistently higher than those in the basements (this is strictly true only if the volumes and ventilation rates are comparable). This implies that the local geology is likely to be a strong control element. We also infer that water is at best an infrequent major source of radon in these houses (see also the discussion below) and that building materials used upstairs (e.g., gypsum drywall board) are relatively unimportant as well.

2. RADON IN WATER. The study included 15 houses served by private wells; the average radon concentration for water drawn from these supplies was 1550 pCi/L, (935 to 2540 pCi/L, 1 s.d., arithmetic average concentration). It is clear that conventional houses have enough ventilation and interior volume that no likely water use pattern will allow water at these concentrations to be a significant source.

3. VENTILATION RATES. As noted in the Methods section, we have computed two different ventilation indices, referred to on the ventilation summary table (Table 4) as LBL and PK. The LBL index is the air change rate calculated from the equivalent leakage area, which in turn is computed from the pressurization profile. The PK value is based on the empirical relationship of dividing the flow (ACH) at 50 pascal depressurization by the constant value 20.

Overall, the LBL figures indicate that the houses are more well-ventilated than the PK estimates (by 32%, a value that is significant). Thus, it is clear that the two indicators are not equivalent. However, they are highly correlated, with a Pearson correlation coefficient of 0.84 ($p<0.001$).

The data set comprises roughly two-thirds older (greater than 10-15 years) and one-third newer houses, and it is interesting to compare the two data sets (Table 4). First, by either of the two measures, the younger houses are much tighter than the older ones. Air change rates for the older ones are 1.7-2.0 times higher than for the newer houses in this panel. As important, the younger houses show much less variability in their ventilation rates, as measured by the 1 standard deviation errors given on Table 4. On average, the variability of the ventilation rate of the newer houses is half that of the older ones. We infer from this that since the 1973 oil crisis builders have learned to construct houses that are much tighter than the old average, which included some rather tight and many rather leaky houses.

4. SOURCE STRENGTH. Estimated source strengths for each of 26 houses have been computed from the computed ventilation rates, integrated living area radon concentrations, and measured house volumes (determined by Princeton field personnel while doing blower-door determinations). The data are presented in Table 2.

   As noted above, two different ventilation measures are available, the PK and LBL estimates. Both are presented in Table 2. We have chosen to work with the simpler PK approach to air change estimates in the succeeding comparisons.

5. THE CONTROLS OF RADON CONCENTRATION. The "General Linear Model" of the Statistical Analysis System (SAS, 1979) was used to predict radon concentrations from the measured variables of Table 2. In separate runs, the radon concentration in the living area and in the cellar (both logarithmic and linear) was estimated from combinations of variables including the radon in the water supply, house age (old vs. young), the LBL and PK air change values, the LBL and PK computed source strengths, geology, and the number of floors in the house. In these analyses, continuous variables (e.g., radon in water) are treated as independent variables in a regression, while classification and dichotomous variables are included in a form equivalent to analysis of variance. Classification variables like geology can take several distinct states which cannot be ordered. Dichotomous variables can have one of only two possible values.

   As indicated in Table 5, the computed relationships between the dependent variables (radon concentrations) and the independent variables (location, age, etc.) were all highly significant. The general linear models account for over 80% of the variance, or information, of the data set. Unfortunately, the data set is very small, since only 22 houses had complete information, and thus no single component stands out as a significant contributor to the regressions. This contrasts with the results of Gross and Sachs, who found a very strong "location" (geology) signal in their analysis of a somewhat larger data set from the same region.

DISCUSSION

This study can only be considered as a small pilot program to demonstrate that effective methods are available to examine the variables controlling radon distribution in large groups of houses. From the high fraction of the variance accounted for (greater than 80%), we believe that we have measured most of the important variables in this region, or linearly correlated "proxies" for them.

Despite its very small size, this study has again shown the strong association of a particular suite or group of sedimentary rocks with elevated radon concentrations. Because these and similar rocks are very widespread, we believe that this conclusion is extremely significant.

With a much larger study, it will be possible to identify specific formations within the region that are strongly associated with high radon concentrations, and begin the process of rational control of radon through revisions of the building codes to assure that radon is precluded from houses or can be readily eliminated where found.

Because radon concentrations in the living area were almost always lower than in cellars, we believe that it is unlikely that living area materials (e.g., drywall) are significant contributors of radon in this region. It is possible that basement materials, such as the concrete, do contribute;

this remains to be measured. However, it is unlikely that this material will be found to be a significant source (Ingersoll 1983). Unless there was a change in the source of concrete about 10 years ago throughout the region, there is another reason to doubt that the concrete used in this region is a particularly strong source: Almost all the older houses show relatively low radon concentrations, in the range seen in other regions.

Indeed, the role of ventilation in this region is very large. We have seen (Table 4) that the older houses are much more leaky than the newer ones, and that their leakiness is much more variable. We stress that the houses in this study are entirely conventional; none were designed as solar or energy-efficient buildings. On average, the older houses had about double the air change rates of the newer ones, and the variability from house to house was twice as great.

The inferences from this are clear: Since energy prices began to escalate, builders have responded by a variety of measures designed to improve energy efficiency, including additional insulation and careful weatherstripping. This led to significant decreases in natural infiltration. Still, only 3 of the 12 newer houses with ventilation data had PK ventilation rate estimates lower than the tightest of the old houses. Most of the change has been in making all houses as tight as the best of the old houses, rather than in the introduction of measures that would allow houses to be made extremely tight (Elmroth and Levin, 1983).

Source strengths tend to fall into two discrete groups. Houses with high radon concentrations (greater than 10 pCi/L) have source strengths in excess of 3 microcuries per hour, while those with radon concentrations less than 4 pCi/L have low radon source strengths. Clearly, in a larger data set there would be a continuous gradation in source strength values, but this type of data exploration is essential to begin searching for regions and conditions that favor high radon accumulations.

The data set from eastern Pennsylvania, fewer than 75 houses studied to date, is too small for strong health and policy inferences. However, it is very suggestive of strong health implications. Because the average radon values in the newer houses are so high (greater than 10 pCi/L logarithmic average winter values in two data sets), we would expect an increase in the lung cancer over the next few decades. However, because the latency period of lung cancer induced by radon exposure is long (decades) and the dose rate in the newer houses is still fairly small in most houses, we do not expect a lung cancer "signal" in the present death rate data for the region. Simply put, it will not be until after the turn of the century that enough people will have lived long enough in post-1970 housing for an epidemic of excess lung cancer to begin.

Because so few other regions have been adequately studied, we do not know where else similar patterns will be found. We do feel that it is imperative that we begin to work now to assure that exposures in this region are controlled, that similar regions are identified, and that we learn to avoid radon contamination in houses.

SUMMARY AND CONCLUSIONS

1. This pilot study of 37 houses has confirmed that the sedimentary strata of eastern Pennsylvania have the potential to support significant amounts of excess radon in houses. Values in excess of 80 pCi/L were found in conventional houses. Our data convince us that the radon in these houses arises largely from the soil and is introduced into the houses through their foundations.

2. Newer houses have more radon, experience lower ventilation rates, and show less ventilation variability from house to house than the older houses in this study.

3. It is unlikely that the excess radon is caused by contributions from building materials.

4. No single house in this study had high enough radon concentrations in its water supply to account for more than a small fraction of the radon in the house; peak values were less than 5000 pCi/L. On the other hand, at least one municipal water supply, at 1600 pCi/L, might be thought by conservative authorities to pose some additional risk to the population using it.

5. If this problem is not addressed, and if the BEIR (1980) estimates are correct, then we expect to begin to see excess lung cancer due to radon exposure after the beginning of the twenty-first century. Until then, there will not have been enough population-years of exposure, since the older houses in this region have relatively low radon concentrations.

6. Because the radon is introduced through the foundations, relatively simple engineering changes and precautions at the time of construction should suffice to assure that radon can be controlled without sacrificing energy efficiency. In affected areas, the appropriate requirements should be added to the building codes as soon as feasible, and occupancy should be contingent on satisfying a radon concentration criterion.

Acknowledgements

The initial impetus for this study was provided by the opportunity to analyze data generated by the Pennsylvania Power and Light Company. We are grateful to Dr. A. George for introducing us to the problem. Field ventilation studies were supported by U.S. Department of Energy; Building Systems, Conservation and Renewable Energy, Contract DE-AC02-77CSZ0062. R. Crosby and D. Jacobson assisted in data generation and analysis, Dr. D. Strawn provided SAS analytical assistance. Track-Etch (R) radon detectors were provided by Mr. Mike O'Connell of the Office of Radiation Programs of the US EPA. Dr. R. Oswald compiled Table 1.

References

Alter, H.W., and Fleischer, R.L. 1981. "Passive integrating radon monitor for environmental monitoring." Health Physics Vol. 40, pp. 693-702.

Assendelft van, A.C.E., and Sachs, H.M. 1982. "Soil and regional uranium as controlling factors of indoor radon in eastern Pennsylvania." Princeton University, PU/CEES Report #145, 68 pp.

Beir, 1980. "The effects on populations of exposure to low levels of Ionizing Radiation: National Academy Press, Washington, D.C., 524 pp.

Blomsterberg, A. and Harrje, D.T. 1979. Approaches to evaluation of air infiltration energy losses in buildings. ASHRAE Transactions 1979

Dietz, R.N., and Cote, E.A. 1982. "Air infiltration measurements in a home using a convenient perfluorocarbon tracer technique." Environment International Vol. 8, pp. 419-433.

Elmroth, A. and Levin, P. 1983 (eds). Air infiltration control in housing: A guide to international practice. Swedish Council for Building Research, Stockholm, Document D2:1983.

Gross, S., and Sachs, H.M. 1982. "Regional (location) and building factors as determinants of indoor radon concentrations in eastern Pennsylvania." Princeton University Report PU/CEES #146, 117 pp.

Hernandez, T.L., and Ring, J.W. 1982. "Indoor radon source fluxes: experimental tests of a two-chamber model." Environment International Vol. 8, pp. 45-57.

Hernandez, T.L., Ring, J.W., and Sachs, H.M. In press. "The variation of basement radon concentration with barometric pressure or the curious case of the breathing basement." In press in Health Physics.

Hess, C.T., Casparius, R.E., Norton, S.A., and Brutseart, W.F. 1980. "Investigation of natural levels of radon-222 in groundwater in Maine for assessment of related health effects." The Natural Radiation Environment III, Vols. 1 and 2, T.F. Gesell and W.M. Lowder, eds., pp 529-546.

Hess, C.T., Norton, S.A., Brutseart, W.F., Casparius, R.E., Combs, E.G., and Hess, A.L. 1979. "Radon-222 in potable water supplies in Maine: The geology, hydrology, physics and health effects." A-045-ME Completion Report. Office of Water Research Project.

Ingersoll, J.G. 1983. "A survey of radionuclide contents and radon emanation rates in building materials used in the U.S." Health Physics Vol. 45, pp. 363-368.

Kronvall, J. 1978. Testing of homes for air leakage using a pressure method. ASHRAE Transactions Vol. 84, part 1.

Martell, E.A. 1983. "Alpha-radiation dose at bronchial bifurcations of smokers from indoor exposure to radon progeny." Proc. Natl. Acad. Sci. USA Vol. 80, pp. 1285-1289.

Nero, A.V. 1983. "Indoor radiation exposures from Rn-222 and its daughers: A view of the issue." Health Physics 45, pp. 277-288.

Nero, A.V., Boegel, M.L., Hollowell, C.D., Ingersoll, J.G., and Nazaroff, W.W. 1983. "Radon concentrations and infiltration rates measured in conventional and energy-efficient houses." Health Physics Vol. 45, pp. 401-405.

Persily, A. 1982. "Understanding air infiltration in homes." Princeton University Report PU/CEES #129, p. 335.

Prichard, H.M., and Gesell, T.F. 1977. "Rapid measurements of radon concentrations in water using a commercial liquid scintillation counter." Health Physics Vol. 33, pp. 577-581.

Sachs, H.M., Hernandez, T.L., and Ring, J.W. 1982. "Regional geology and radon variability in houses." Environment International Vol. 97, pp. 97-103

Sherman, M.H. and Grimsrud, D.T. Infiltration - pressure correlation: Simplified physical modelling. ASHRAE Transaction Vol. 86, part 2, 1980.

Table 1
LUNG CANCER RISK ESTIMATES
(compiled by R. Oswald)

UNSCEAR, 1977 200-450/(10^6xWLM) "United Nations Scientific Committee on the Effects of Atomic Radiation, 1977" Report to the General Assembly, Annexes, G&B (United Nations, New York, 1977).

BEIR, 1980 10-50/(10^6x person year x WLM)
BIER Report "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation" 372-397 (National Academy of Sciences, National Research Council, Washington D.C. 1980).

EVANS, 1981 100/(10^6xWLM) EVANS, R.D., Marley, J.H., Jacobi, W., McLean, A.S., Mills, W.A., Stewart, C.G. "Estimate of Risk From Environmental Exposure to Radon-222 and its Decay Products" Nature 290, March 12, 1981.

JACOBI, 1979 100-500/(10^6xWLM) JACOBI, W. "Proceedings of NEA Specialist Meeting on Personal Dosimetry and Area Monitoring Suitable for Radon and Daughter Products" Paris, 223-230 (Nuclear Energy Agency, OECD, Paris, 1979).

ARCHER, 1979 1000/10^6xWLM) ARCHER, V.E. Trans. Am. Nucl. Soc. 33, 145-145-146 (1979).

MEYERS & STUART 21-54/(10^6xWLM) MEYERS, D.K. & Stewart, C.G., AECL 5970 (Chalk River Nuclear Laboratories, 1979).

Table 2

House Identi-fication	Radon Concentrations Air Living area	Air Cellar	Water	House Age 1= >younger 0= >older	Calculated Air Changes/hr LBL (ELA)	(PK)	Geological Class	No. of Floors	1-Chamber Calculated Source Strength, microcuries per hour
A4	1.2	2.7	10	.	1.56	1.03	1	2	1
A6	1.8	4.1	10	.	1.04	0.63	.	2	1
A9	.	.	.	.	1.65	1.07	1	1	
A2	1.8	2.0	10	0	0.92	0.58	1	2	1
A7	2.2	1.0	10	0	.	.	1	.	.
B1	5.1	4.7	10	0	1.09	0.73	1	2	4
B3	3.0	5.6	540	0	1.82	0.84	.	2	2
C2	7.4	7.4	1740	0	0.58	0.51	3	2	4
C3	4.1	6.8	10	0	1.25	0.89	5	2	4
C4	5.9	3.8	4600	0	1.45	1.06	3	2	6
C5	6.0	14.8	1900	0	0.97	0.89	3	2	5
C6	2.8	8.9	2485	0	1.17	0.41	3	2	1
C8	0.8	2.6	1045	0	1.02	0.67	3	1	1
C9	5.0	7.8	1955	0	1.63	1.05	3	2	5
L4	2.8	0.8	65	0	1.59	1.06	5	2	3
L5	0.5	1.9	10	0	0.89	1.10	5	2	1
L8	1.9	3.0	65	0	1.38	1.60	5	2	3
L9	1.6	4.4	65	0	1.18	0.90	5	2	1
L10	6.5	8.9	65	0	.	.	5	2	
A1	32.4	55.1	945	1	0.46	0.34	1	1	11
A3	7.1	11.4	1375	1	0.58	0.44	.	2	3
A5	3.2	4.2	10	1	0.93	0.71	1	2	2
A8	7.9	10.4	10	1	0.84	0.69	1	1	5
B2	1.2	2.5	10	1	0.76	0.52	1	2	1.
C1	16.0	43.0	1640	1	0.82	0.44	3	2	7.
C7	7.5	6.2	1400	1	0.74	0.42	3	2	3.
L1	84.0	113.0	1990	1	0.48	0.39	4	1	33.
L2	13.1	12.4	1355	1	0.45	0.28	4	2	4.
L3	1.6	0.5	65	1	1.16	.	5	2	.
L6	80.0	204.0	2215	1	0.79	0.67	5	1	54.
L7	17.3	16.6	955	1	.	.	4	1	.

TABLE 3

SUMMARY OF RADON DATA

		M	Radon in Air, pCi/L Living Area		Outer Cellar	
			Geometric Mean	1 s.d. span	Geometric Mean	1 s.d. span
I.	All houses studied	30	4.6	1.4-15.8	6.5	1.7-24.8
II.	Houses <10-15 yr old	12	10.6	2.7- 4.0	13.7	3 -73
III.	Houses >10-15 yr old	16	2.9	1.3- 6.2	4.0	1.8-9.1

TABLE 4

SUMMARY OF VENTILATION DATA

	Variable	Mean	Error Estimate (±1 s.d.)	Sample Size
I. All data				
	LBL air Change rate	1.10	±0.59	32
	PK air change rate	0.83	±0.53	33
II. Older houses (age > 10-15 years)				
	LBL air Change rate	1.27	±0.68	18
	PK air change rate	0.99	±0.60	
III. Newer houses				
	LBL air Change rate	0.73	±0.22	11
	PK air change rate	0.49	±0.15	10

Table 5

Dependent (predicted) Variable:	Living area		Cellar	
	Linear	Logarithm of Radon	Linear	Logarithm of Radon
% Variance accounted for by prediction	95%	82%	98%	86%
Probability >F (all highly significant)	0.0001	0.0027	0.0001	0.0006

Independent variables included radon in water supply (linear and logarithmic transform values), house age class (dichotomous), air change rate estimates (LBL and PN), geology (classes 1,3,4, or 5), 1-chamber source strength estimates (based on LBL and PN estimates), and the number of floors in the house. Data for 22 houses are included.