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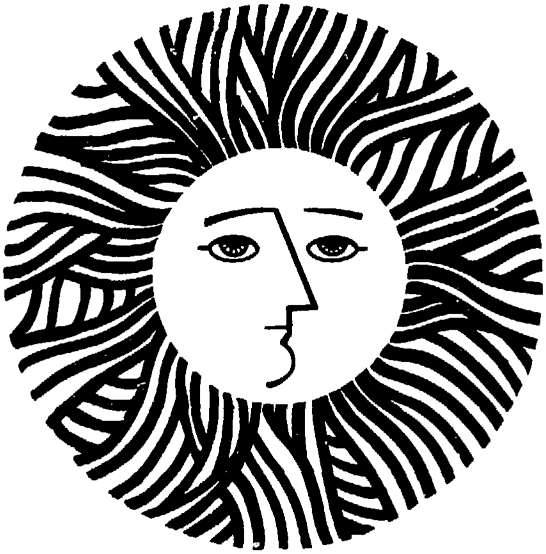

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ABSTRACT

A radon concentration of 1 pCi/l (37 Bq/m^3) appears to lie in the range that is typical for air inside U.S. residential buildings. Moreover, some U.S. residences have concentrations higher than 1 pCi/l, sometimes by an order of magnitude, implying significant individual risk to occupants. For typical radon daughter equilibrium ratios, this concentration corresponds to a radon daughter exposure rate of 0.2 working level months (WLM) per year. This exposure rate may account for a significant lung cancer incidence if data on lung cancers per unit exposure in miners are applicable to such low exposures. Reductions in air exchange rates may raise the typical exposure rate and even increase it to unacceptable levels in some cases. Measures that reduce energy use by reducing natural infiltration or mechanical ventilation in new or retrofit buildings are therefore undergoing severe scrutiny. Lawrence Berkeley Laboratory has performed measurements in buildings specifically designed to use energy efficiently or utilize solar heating. In many of these buildings radon concentrations appear to arise primarily from soil underlying the buildings. Measures to control higher levels, e.g., by mechanical ventilation with heat recuperation, appear to be economical. However, to evaluate energy-saving programs adequately requires a much more comprehensive characterization of radon sources (for example, by geographical area) and a much fuller understanding of the dynamics of radon and its daughters indoors than now exist.

Keywords: energy-efficient buildings, health risk, indoor air quality, radon concentrations, radon daughters.

PRESENT INDOOR CONCENTRATIONS AND THEIR SIGNIFICANCE

Radon concentrations in U.S. residences are typically on the order of 1 pCi/l. Measurements in 21 New York and New Jersey residences by George and Breslin (1) yielded annual average radon concentrations of 0.3 - 3.1 pCi/l in living spaces, with a geometric mean of about 0.8 pCi/l. The mean annual average daughter concentration was about 0.004

WL. Similar results have been obtained in studies in other countries. Higher indoor concentrations have been reported in communities associated with uranium and phosphate mining in the U.S. and elsewhere. As Rundo and co-workers (2) have shown, however, high concentrations are also found in houses in ordinary areas; in grab-sample measurements in 22 houses, six yielded radon concentrations of 10 pCi/l or more.

Even typical indoor radon concentrations of 1 pCi/l may be a significant risk factor in lung cancer, if data from radon daughter exposures of miners are applicable. The 1977 UNSCEAR report, which summarized information on the lung cancer incidence of miners, adopted 200 to 450 x 10^{-6} per WLM as the lifetime risk of lung cancer from exposure to radon daughters (3). A house with 0.006 WL (i.e., 1 pCi/l radon concentration and an equilibrium factor of 0.6) causes an annual exposure of approximately 0.2 WLM to an occupant present two-thirds of the time. Direct application of the UNSCEAR data to such low doses among the general population yields an estimated annual lung cancer incidence of 40 to 90 per million people. However, this estimate may be altered by consideration of differences between the case of miners and that of the general population, including daughter particle-size distribution, breathing rate, age, sex, and smoking habits of the individuals exposed. The inclusion of such factors could broaden the risk estimate to approximately 10 to 100 per million per year. In any case, the estimated risk is significant, especially considering that some individuals may be receiving substantially higher than average exposures and that programs to reduce energy use in buildings may lead to an increase in exposures. The possibility of such increases has become a major consideration in formulating energy conservation programs in the U.S.

ENERGY CONSERVATION PLANS

For airborne contaminants that arise from indoor sources, a house acts as a container with a leakage rate proportional to the air exchange rate for the structure. In the United States, air exchange rates typically lie between 0.5 and 1.5 h^{-1}. Among measures used to reduce building energy use, several affect the air exchange rate by reducing infiltration; these measures include caulking, weatherstripping, and plugging of leaks in the building envelope. These ordinary measures can be expected to reduce the infiltration rate in existing housing by up to 25%. More elaborate procedures for identifying deficiencies or for reducing infiltration could reduce the infiltration rate by 50%. Improvements in construction techniques for new houses can result in even more substantial decreases in air exchange rates. Such improvements can save most of the energy lost via infiltration, estimated to account for about one-third of the energy requirement for space heating in U.S. residences.

With such reductions in air exchange rates, however, a corresponding increase in indoor air pollution must be expected. Pollutants of particular importance are: combustion-generated emissions, such as CO and respirable particles; organics, such as formaldehyde; and radon daughters. The average indoor concentrations for these contaminants are not known. However, the indoor concentrations and corresponding risk for radon can be estimated as indicated above. The increase of up to 25% in estimated radon-related lung cancer incidence that could be associated with ordinary infiltration-reducing measures in existing houses has prompted a re-examination of these measures. The larger risk increases that could occur in areas with high radon levels or in very "tight" new houses has prompted examination of techniques to control radon daughter exposures. New measurement programs have begun to characterize indoor radon and radon daughter concentrations.

MEASUREMENTS IN ENERGY-EFFICIENT BUILDINGS

Lawrence Berkeley Laboratory conducts a broad program on indoor air quality in close coordination with programs on measurement and analysis of building energy performance. One project in the program on indoor air quality examines indoor radon and daughter sources and concentrations, with particular attention to the effect of infiltration reduction on daughter exposures in residences. An important aspect of this project is measurement of concentrations in "energy-efficient" houses, most of which have infiltration-reducing features or some form of passive solar design. Other work of the project includes measurement of emanation rates from building materials, measurement of radon concentrations in conventional buildings, and development of measurement instrumentation and techniques.

One set of measurements in energy-efficient houses conducted grab-sample measurements of radon concentration and air infiltration rate in 17 houses in the U.S. and Canada. Most of these houses fit one of three descriptions: three were built as energy-efficient houses for demonstration or research purposes; four are privately owned residences built to assure low infiltration rate; and eight are passive solar houses with rock-bed heat storage.

Occupants were asked to keep windows and doors closed throughout the night prior to measurements to assure a degree of correspondence between the observed radon concentrations and infiltration rates. Concentration measurements were obtained by taking air samples in Tedlar sampling bags and analyzing the samples in a laboratory system based on ZnS(Ag) alpha scintillation counting. Infiltration was measured by releasing a tracer gas in the house and measuring its concentration as a function of time.

The results of these measurements, performed in mid-1979, are shown in Figure 1, which gives the radon concentration and air exchange rate for each house. Where the strength of indoor radon source is the same for these houses, the points on the figure would be expected to lie on a straight line, assuming the outdoor radon concentrations were small. However, substantial scatter is observed. The range of radon concentration is itself significant. Values in the vicinity of 1 pCi/l are in the typical range. But, based on the annual exposure estimates given above, the highest radon concentration observed (20 pCi/l), if sustained throughout the year, would correspond to an annual exposure of 4 WLM, the limit recommended for occupational exposures by the International Commission on Radiation Protection (4) and many national organizations. Recent measurements in certain of these houses have yielded even higher results.

In the demonstration house that had indoor radon concentrations of about 20 pCi/l, we have conducted a more extensive series of experiments. During a two-week period the air exchange rate was controlled by a mechanical ventilation system incorporating an air-to-air heat exchanger. For measured air exchange rates from 0.07 to 0.8 h^{-1}, continuous measurements of radon and frequent sampling for individual radon daughters were performed, yielding the data shown in Figure 2. The dynamic dependence of concentrations and equilibrium factor on ventilation rate, condition of the heating system, and smoking was examined in a preliminary way; more thorough analysis of the data is underway. Not unexpectedly, the steady-state radon concentration was found to be inversely proportional to the air exchange rate. However, the dependence of individual daughter concentrations appears to be much more complex. Study of the effect of both mechanical ventilation with heat recovery on radon concentrations and of such removal mechanisms as filtration or plateout on daughter concentrations is an important aspect of further work in this area.

Our program of measuring radon emanation rates from various U.S. building materials has emphasized concrete. For most of these measurements, a sample of the material was placed in a sealed container for a specified period, after which the radon in the container was transferred to a scintillation cell. In some cases radium contents and emanation rates were measured with a sodium iodide gamma spectrometer. For the concrete samples examined, obtained from five U.S. metropolitan areas, emanation rates per unit mass were found to be within the range 0.5 - 2 pCi kg^{-1} h^{-1}. For 0.2 m thick concrete, 1 pCi kg^{-1} h^{-1} corresponds to a rate of 0.05 pCi m^{-2} s^{-1}, which would contribute about 0.1 pCi/l to the indoor concentration of a house with an air exchange rate of 1 h^{-1} and an emanating surface to interior volume ratio of 0.5 m^2 per m^3. A few measurements of gypsum, wood, and rockbed samples have also been performed. In general, findings from these studies indicate that rates from building materials are not large enough to account for radon concentrations as high as those found in the measurements in energy-efficient buildings.

WHAT NEEDS TO BE DONE

For purposes of evaluating the health effect of, and possible control measures for, indoor radon daughter exposures, three broad areas require more detailed investigation: (1) the dependence of the indoor radon source strength on geographic area, building type, and source control measures; (2) the behavior of radon and daughter concentrations in the indoor environment and the dependence of concentration on various removal mechanisms; and (3) the dependence of health risk on exposure to radon daughters in the concentrations and particle size distribution in which they appear indoors.

The first two areas are being examined with great urgency in the United States by laboratories of the Department of Energy, the Environmental Protection Agency, and others. The possibility of surveys to find communities or houses with high indoor concentrations is being examined, as are means of more fully characterizing source strengths on a geographic basis and indoor radon and daughter behavior in controlled conditions. Should geographic areas be found in which high indoor levels are typical, it is even conceivable that indoor radon surveys could serve as a basis for epidemiological work. For the near future, however, it appears probable that decisions on maintaining indoor air quality will be made on the basis both of physical characterization of indoor levels and of what is now known about the health effects of indoor radon daughter exposures. It is imperative, therefore, that what is now known of the dose-response relationship be reviewed extremely carefully to ascertain its applicability to conditions inside residences and other buildings.

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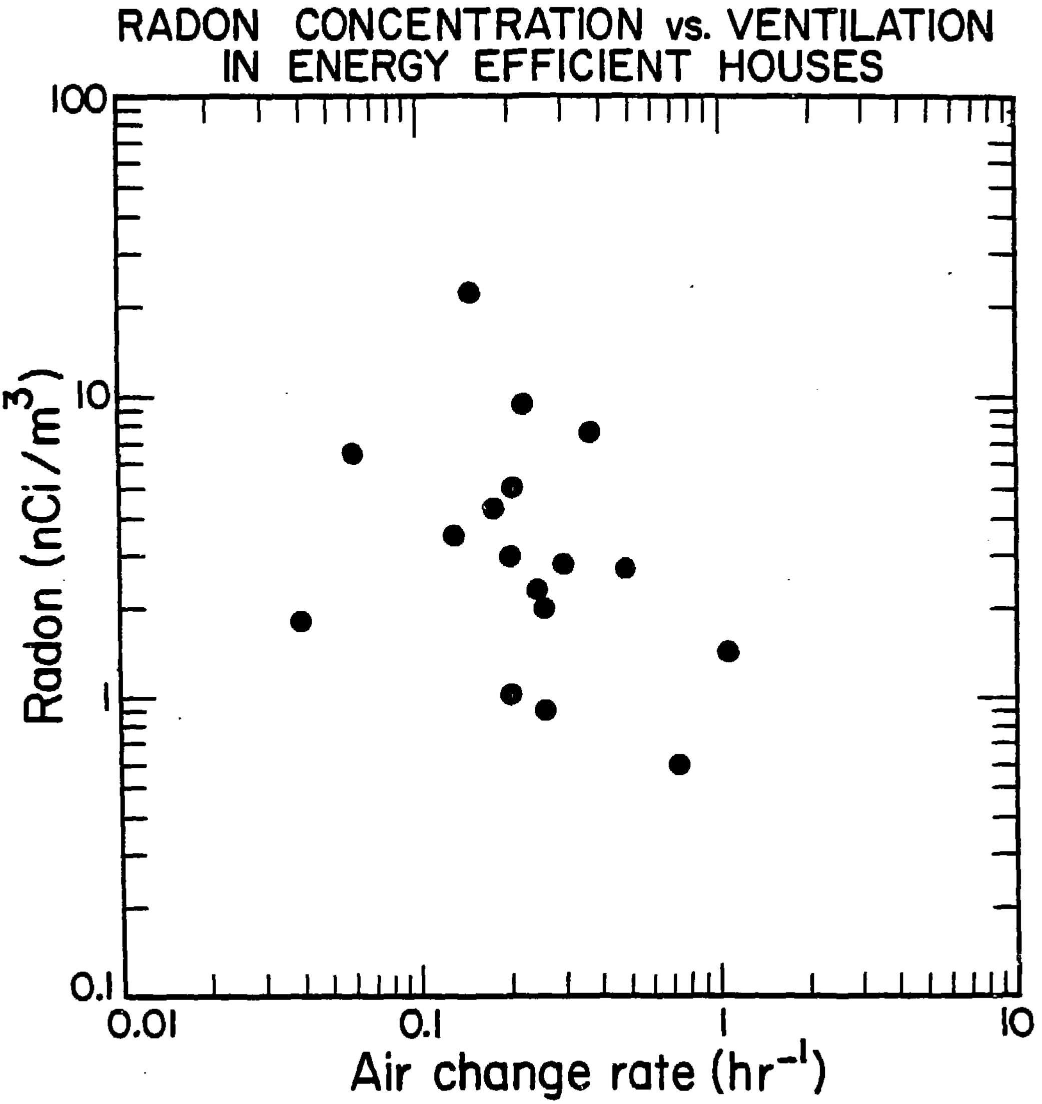

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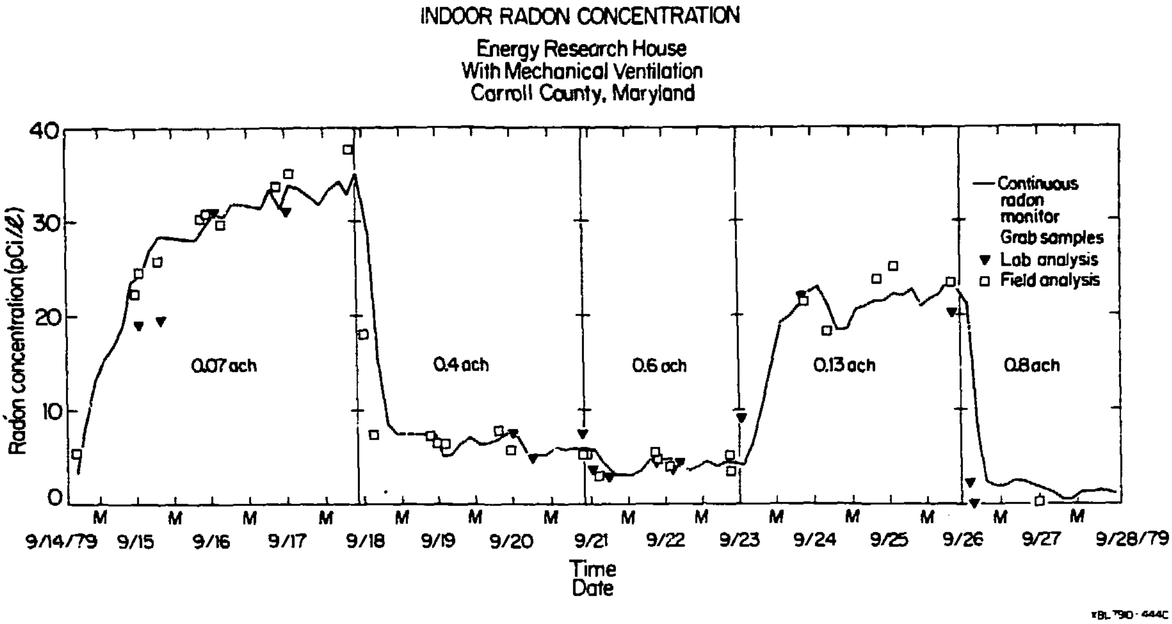
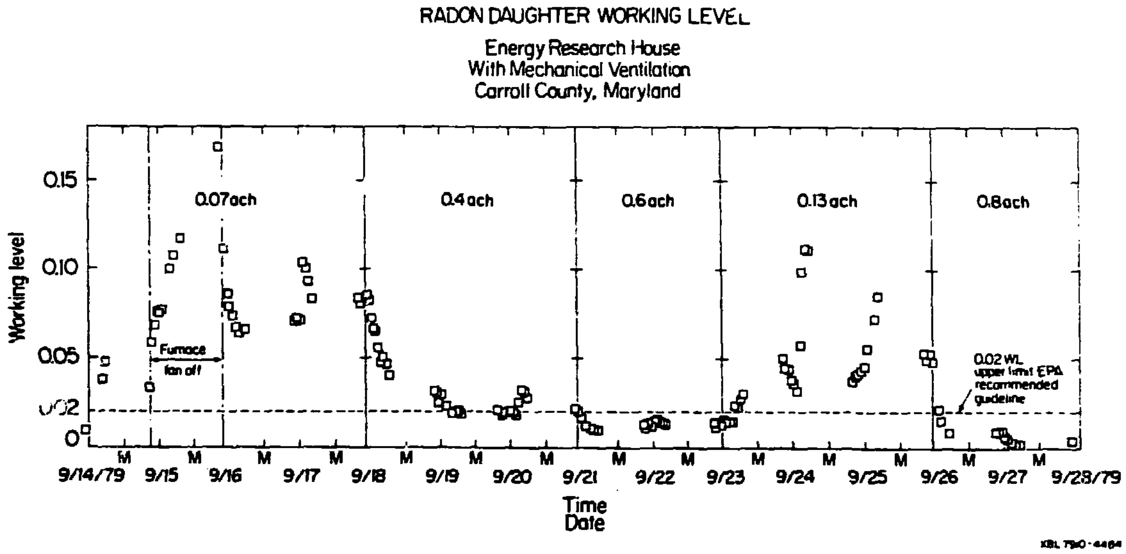
Figure 1. The figure shows results of "spot" measurements of indoor radon concentration and air exchange rate. In each case, windows and doors were kept closed during the night prior to the measurements. (nCi/m^3 = pCi/ℓ)



(a) Radon concentration versus time.



(b) Potential alpha energy concentration (Working Level) versus time.

Figure 2. In an energy research house, the air exchange rate was controlled using mechanical ventilation provided through an air-to-air heat exchanger. Both the radon-222 concentration (a) and the potential alpha energy concentration, in Working Level (b), were measured as functions of time during a two-week period.