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ABSTRACT

Exposure to the radioactive decay products of radon 222 that are present in indoor air constitutes the most significant radiation dose received by the general population in most countries. Indoor concentrations are found to vary greatly from one building to another, ranging from very low levels that can be regarded as insignificant to very high levels that cause radiation doses higher than those experienced by uranium miners (under present regulations). This wide range of concentrations is attributable to two factors: variability in the rate at which radon enters buildings, from whatever source, and differences in the ventilation rate, which determines the degree to which radon is removed from indoor air. In single-family dwellings, the major source of radon at the higher indoor concentrations is typically the ground underlying the structure. This source term varies greatly, depending both on the geographic variability of soil concentrations of radium 226, from which radon 222 arises, and on the type of structure. Earth-sheltered dwellings, because they are more completely surrounded by earth material than other structures, have an as yet unquantified potential for having radon entry rates that are higher than typical for other houses in the region. Moreover, measures that save energy by reducing ventilation rates (for example by reducing infiltration) can also raise indoor radon concentrations. For these reasons a significant effort is needed to determine the potential for ventilation-reducing measures and earth sheltering to increase radon concentrations, especially in regions where they are already high. Where necessary, proper attention to specific design features that affect radon entry rates or residence time indoors should be adequate to avoid undue risk to the public.

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Introduction

Exposure to the radioactive decay products of radon 222 that are present in indoor air constitutes the most significant radiation dose received by the general population in most countries. Indoor concentrations are found to vary greatly from one building to another, ranging from very low levels that can be regarded as insignificant to very high levels that cause radiation doses higher than those experienced by uranium miners (under present regulations). This wide range of concentrations is attributable to two factors: variability in the rate at which radon enters buildings, from whatever source, and differences in the ventilation rate, which determines the degree to which radon is removed from indoor air. In U.S. single-family dwellings, the major source of radon at the higher indoor concentrations is typically the ground underlying or surrounding the structure. This source term varies greatly, depending both on the geographic variability of soil concentrations of radium 226, from which radon 222 arises, and on the type of structure.

Earth-sheltered dwellings, because they are more completely surrounded by earth material than other structures, have an as yet unquantified potential for having radon entry rates that are higher than typical for other houses. Moreover, measures that save energy by reducing ventilation rates (for example by reducing infiltration) can also raise indoor radon concentrations. For these reasons a significant effort is needed to determine the potential for ventilation-reducing measures and earth sheltering to increase radon concentrations, especially in regions where they are already high. When necessary, proper attention to specific design features that affect radon entry rates or ventilation rates should be adequate to avoid undue risk to the public.

Background

The scientific and regulatory community has, over the years, focussed very substantial attention and resources on the problem of outdoor and occupational exposures to air pollutants. The impetus for this effort has been the demonstrated and imputed effects that such exposures can have on the general population and on workers. However the community has, until recently, tended to neglect a comparable, and perhaps even more important, component of the total exposure to air pollutants: the component that occurs in the ordinary indoor environment and primarily in our own homes. For many pollutants, indoor concentrations can considerably exceed those found indoors.

Indoor air pollutants include several classes of substances, among them combustion products, such as the nitrogen dioxide produced in substantial amounts by small, portable kerosene heaters; formaldehyde and other organics, which may arise from plywood, particleboard, and other products; and radon and its decay products (or "daughters"), naturally occurring radioactive elements present throughout the air we breath. Members of each of these pollutant classes have concentrations that vary over two or three orders of magnitude within even the ordinary building stock.[1]

For most pollutants, the major factor determining the indoor concentration is the source strength, i.e., the rate at which the pollutant enters the indoor space, but - for a given source strength - the ventilation rate and other factors have a direct effect on the concentration. Thus measures that save energy by reducing ventilation rates tend to raise indoor pollutant concentrations by amounts that depend - in first order - on the degree of ventilation reduction. Similarly, measures that raise the source strength tend to increase radon concentrations, and earth-sheltering features could increase the availability of sources of radon. However, as indicated below, certain aspects of earth-shelter construction techniques could also decrease the efficiency of radon entry, at least from the surrounding earth.

Radon is a noble, radioactive gas that arises from the uranium and thorium radioactive decay series, naturally present in small amounts throughout the earth's crust. As a noble gas, radon can migrate through earth, rock, or building materials derived therefrom and enter indoor or outdoor air. Because of its 4-day half life, the isotope of major concern is radon 222, which arises from radium 226 and decays to a series of four short-lived daughters (half lives less than 30 min.). The daughters are chemically active substances that can be collected in the lung, either directly or via airborne particulates to which they attach, thereby leading to irradiation of lung tissue as the daughters decay. This is precisely the exposure to which elevated incidence of lung cancer among uranium miners has been attributed, albeit from higher exposures than ordinarily occur indoors. The potential contribution of such exposures to lung cancer among the general population is the origin of the substantial interest in the question of indoor radon, as exemplified by a current special issue of Health Physics on this topic.[2]

Radon and Its Daughters in Conventional Dwellings

Substantial efforts have been devoted to characterizing concentrations of radon (hereafter referring to radon 222) and its daughters in indoor and outdoor air.[3] Indoor radon concentrations are found to range from less than 0.1 pCi/l to at least 100 pCi/l within the U.S. housing stock,[4, 5] with comparable variability found in other countries.[3, 6, 7] (The unit of radioactivity used here, the picoCurie, equals 0.037 Becquerel, in SI units, or 0.037 decays per second.) A major part of these characterization efforts has been devoted to buildings built with or on materials known to contain unusually high radium concentrations. Two notable examples are the use of tailings from uranium mills in the vicinity of Grand Junction, Colorado, U.S.A.,[8] and the use of alum-shale concretes in Sweden.[7] However, comparable efforts have been devoted to examination of the more general housing stock, where no such materials are known beforehand, and the full (0.1-100 pCi/l) range has been found.

One of the major reasons for the work in the general housing stock has been the expectation that higher radon concentrations would be associated with lower ventilation rates. In this context, several sets of data accumulated by our group are noteworthy, since we consistently measured both the radon concentration and the ventilation rate, typically where conditions had been permitted to stabilize over a period of time.[9] For a stable, well-mixed condition, with low outdoor radon concentrations, the indoor concentration, $I = \lambda^{-1} S/V$, were λ is the ventilation rate, S is the radon entry rate, and V is the house volume.

Figure 1 shows data from about 100 houses, plotted as radon concentration versus air exchange rate, using logarithmic scales. These data were taken in 16 "energy-efficient" houses in the United States and Canada, 29 conventional houses in the San Francisco Bay area, and 55 houses in a community in rural Maryland (cf. ref. 10). If the source strength, S/V, were the same for these houses, the data would fall along a straight line (with slope equal to -1) when plotted in this fashion. Neither the full data set nor any of the three subsets can be construed to show this behavior.

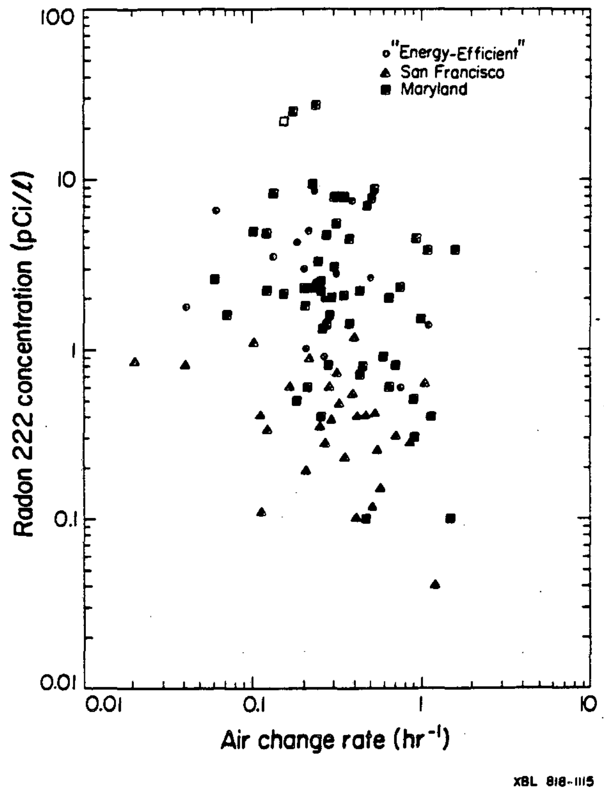

Fig. 1. Measured radon concentrations and ventilation rates.

It is significant, in fact, that the range of concentrations considerably exceeds that of the ventilation rate, suggesting the importance of variability in the source strength in this housing group. Again using the composite sample, Figure 2 shows a frequency distribution of source strengths, each calculated from a data point of Figure 1 by using $S/V = \lambda I$. The result is a nearly log-normal distribution, despite the rather happenstance makeup of the sample.

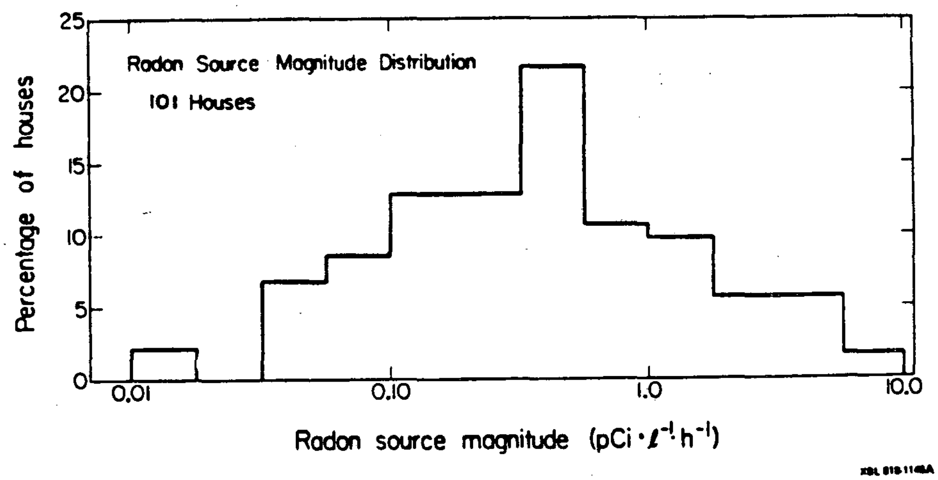

Fig. 2. Distribution of calculated radon source strengths.

The major sources of radon in most buildings are thought to be building materials or underlying soil and rock, except in cases (cf. ref. 5) where domestic water has unusually high radon concentrations. Of building materials used in the U.S., concrete constitutes the most significant potential source of radon. However, a survey of radon emanation rates from concrete samples from nine metropolitan areas yielded an average emanation rate of 0.8 pCi $kg^{-1}h^{-1}$.[11] For a one-story house on a 0.2-m thick concrete slab (with density 2000 kg/m^3), the corresponding source strength would be 0.07 pCi $l^{-1}h^{-1}$ -- an order of magnitude below the average source strength (0.9 pCi $l^{-1}h^{-1}$) found in our 100-house sample. On the other hand, the radon flux from soil that is often cited as average is 0.4 pCi $m^{-2}s^{-1}$,[12] and this would yield 0.7 pCi $l^{-1}h^{-1}$ if it gained entry to a one-story house. This is comparable to measured results, and -- although the question of how radon passes through understructures needs more work -- tends to corroborate the view that underlying soil and rock is typically the major contributor to indoor radon concentrations. However, because of the wide variability in radon emanation rates among each source class, either soil and rock, building materials, or water supplies can dominate the observed source strength, depending on the circumstances.

Turning to the question of health effects, it is useful to examine the implications of typical concentrations, then consider the significance of the wide variability. One pCi/l lies in the typical range for radon, and up to 1 pCi/l of each of its daughters can be associated. However, the amount of daughters varies, depending on removal rates (via ventilation or otherwise), and the health implications are associated specifically with the alpha radiation ultimately emitted by the daughters that are inhaled. For convenience, the concentration of daughters is therefore typically characterized by the associated "potential alpha energy concentration" (PAEC), given in units of "working level" (WL). This unit is defined so that, if none of the daughters are removed from the air, 1 pCi/l radon yields 0.01 WL, but only 20 to 80% of that possible is usually present. The usual unit for characterizing radon-daughter exposure (i.e., concentration x time) is the "working level month" (WLM), defined to be 173 WL-hours. Continuous exposure to 0.005 WL (roughly the daughters associated with 1 pCi/l of radon) therefore yields an exposure of 0.005 WL x (1 WLM/173 WL-h) x 8760 h/yr = 0.25 WLM/yr.

Assuming the population spends 80% of its time at this exposure rate, a consideration of the dose-effect data from studies of uranium miners suggests an associated incidence of lung cancer of 10 to 100 cases annually per million population.[13] For the U.S. population, this leads to an estimated 2000 to 20,000 cases of lung cancer annually if the indoor radon concentration averages 1 pCi/l, or 1000 to 20,000 if it is thought that the average concentration in U.S. housing lies between 0.5 and 1 pCi/l. The average individual risk is, of course, fairly small -- of the order of 0.1 to 1% for 1 pCi/l. The aggregate is, however, large as compared with virtually any well-characterized environmental hazard other than smoking or riding in automobiles.

Moreover, considering that a portion of the general population lives at much higher concentrations, including some in the 10-100 pCi/l range, some individuals are exposed to much higher risk. For example, the added risk associated with a 10 pCi/l concentration for 20 years (intermediate between a lifetime and the time usually spent in one house) is four times the usual risk (0.1 - 1%) just cited, and higher concentrations yield even larger individual risks.

Potential Effects of Energy Efficiency

Of measures to save energy in homes, the one with the most general implications for concentrations of indoor pollutants, including radon, is ventilation reduction. In most single-family homes, the ventilation rate (typically 0.5 to 1 h^{-1}) is dominated by infiltration, so that efforts to reduce ventilation-related energy losses tend to focus on uncontrolled ventilation processes, i.e., infiltration. Modest infiltration reductions can be obtained by rather ordinary means, such as weatherstripping, caulking, or leak detection and plugging. More substantial reductions can be accomplished by unusual construction measures, such as incorporation of an impervious barrier as part of the outer fabric of the building.

Ordinary infiltration-reduction measures, which can result in significant energy saving, typically yield rather modest reductions in the infiltration rate, yielding infiltration reductions averaging 10 to 30% for any given program.[14, 15] A 20% reduction in the average ventilation rate in U.S. housing, requiring a program of unprecedented scope and intensity, would raise radon and daughter concentrations by approximately 25%, yielding an estimated increase in lung cancer rates of 250 to 5000 per year, assuming no efforts to maintain indoor air quality. This increase could presumably be avoided partly or completely by identifying the portion of the population already exposed to high concentrations and reducing their exposures.

On the other hand, special construction techniques that substantially reduce infiltration rates, e.g., by a factor of two to five below the usual rate of 0.5 - 1 h^{-1}, can cause radically different concentrations and associated risks. This applies to risks arising, not only from radon and is daughters, but also from other indoor pollutants. Hence, in such houses, it is important to consider systems for providing adequate ventilation. One means to do this, while recovering energy that would ordinarily be lost thereby, is to use a mechanical ventilation system with an air-to-air heat exchanger. This approach has been shown to be effective for controlling radon concentrations in an unusually "tight" house.[16]

Certain earth-shelter designs can result in substantially lowered infiltration rates, notably lower than the usual range. As in, other houses with very low infiltration rates, design of such earth-sheltered houses should take account of the need for adequate indoor air quality, and awareness of this design consideration has already become evident in the earth-shelter community (see, for example, refs. 17 and 18). However, there are other ways in which earth-sheltering could affect indoor radon concentrations in an unusual way, i.e., by changing the radon source strength.

Potential Effects Specific to Earth Sheltering

As noted above, the principal source of the variability in indoor radon concentrations is the wide range of radon source strengths within the housing stock. Source strength differences arise from differences either in the rate at which radon emanates from the source material (i.e., the ground or building materials) or in the efficiency with which it enters the house interior. Earth sheltering can influence both the amount of source material and the transport efficiency.

Major radon sources and pathways for an ordinary house are indicated in Figure 3. As indicated, radon can arise from either the surrounding soil or the concrete floor and walls. In either case the house understructure constitutes the origin or point of entry.

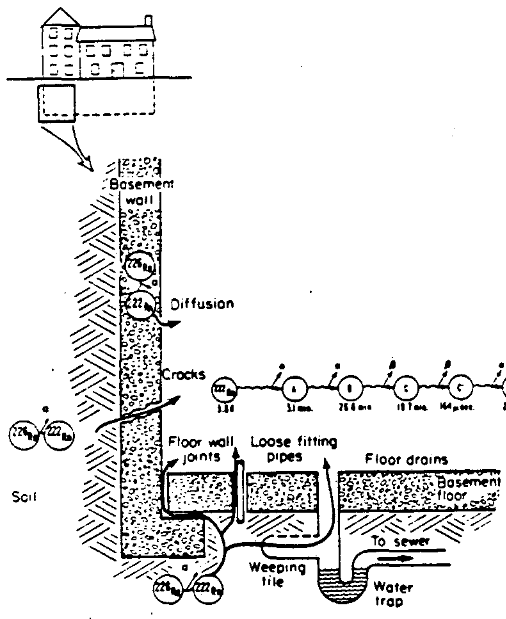

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Fig. 3. Primary pathways for radon entry into buildings.

The amount of source material in an earth-sheltered dwelling can increase both because earth surrounds more of the structure than is ordinarily the case and because larger-than-average amounts of concrete are often incorporated. To the extent that diffusion is the main mechanism for radon transport within the source material itself, the material within one or two diffusion lengths of the interior constitutes the main radon source. This accounts partially for the fact that soil is often the dominant radon source, i.e., the diffusion length in soil that is not saturated with water is about 1 m, substantially larger than the roughly 10-20 cm typical of concrete.[19, 20]

On the other hand, an equally important question is the transport efficiency across any barriers to radon movement that may exist. For an ordinary house, this is often only the concrete itself (as in Figure 3), and the effectiveness of this barrier may be compromised by cracks and designed openings. In contrast, an earth-sheltered house has barriers and drainage systems that are designed to control moisture,[18] and these may reduce transport substantially. Similarly, construction standards and quality control may typically be more stringent for earth-sheltered dwellings than for others, making it more likely that the earth-shelter barriers affect radon transport substantially.

It is therefore clear that some earth-shelter design features tend to increase the radon source strength, while others may cause a decrease. Unfortunately, it is not now known what the net effect of these opposing factors may be. It is therefore important that effort be devoted to investigating the effect of earth-sheltering on radon source strengths, an effect that has potentially great importance in areas where local materials (whether soil or concrete) have unusually high emanation rates, leading to high indoor concentrations even in ordinary housing.

Radon measurements in Earth-Sheltered Dwellings: Results and Prospects

As just suggested, little work has been done investigating radon concentrations in earth-sheltered dwellings. In particular, none has characterized the effect of earth-sheltering features in a controlled manner.

Data from seven earth-sheltered dwellings in Illinois[21] yielded average radon concentrations that ranged from 4.1 to 9.3 pCi/l, considerably higher than average but not characteristically higher than results from conventional dwellings in the same area. An oddity of this work is that, considering the measured radon concentrations, the daughter concentrations found in both the conventional and earth sheltered dwellings were roughly 5 to 20% of the equilibrium (i.e., maximum) values, significantly lower than the 20 to 80% cited above as typical. One of the houses in Figure 1 is an earth-sheltered house in Texas, with 9 ± 4 pCi/l radon at an air exchange rate of 0.35 h^{-1}, significantly higher than average but with no local conventional houses for comparison. From as yet unpublished data, it is clear that the range of concentrations in earth-sheltered houses is much larger than indicated by the results just discussed: two houses monitored in New York each yielded average radon concentrations of about 2 pCi/l,[22] while a house in Pennsylvania was found to have a radon concentration of 35 pCi/l at an air exchange rate of about 0.2 h^{-1}, yielding a source strength of 7 pCi $l^{-1}h^{-1}$.[23]

Radon Concentrations and Source Strengths Measured in Earth-Sheltered Houses

Number of Houses	Location	Radon (pCi/l)	Air Exchange Rate (h^{-1})	Source[a] Strength (pCi $l^{-1}h^{-1}$)	Ref.
7	Illinois	4.1-9.3	b	b	21
1	Texas	9 ± 4	0.35	3	9
1	Mass.	100	b	b	24
1	Penna.	35	0.2	7	23
2	New York	2.2	b	b	22

[a]Calculated by taking the product of the grab-sample radon concentration and the measured air-exchange rate, where applicable.
[b]Average radon concentrations were measured without comparable air-exchange measurements.

The few data that are available indicate higher than average radon concentrations in earth-sheltered dwellings. On the other hand, there is some indication (as in ref. 21) that ordinary houses in the same area also exhibit high radon levels. In fact, it is in just such areas that any elevation of radon concentrations by use of earth sheltering would be most significant. For example, a hypothetical doubling of the radon concentration from 5 to 10 pCi/l could raise individual risks by up to several percent, an amount that would be highly significant. This is not intended to suggest that earth sheltering actually does cause such added risks, but rather that it is possible and this prospect warrants further work. Moreover, earlier discussions of potential radon-related risks in the earth-shelter literature[21, 18] have been imprecise in their estimates of both aggregate and individual risks.

Our group is planning a modest survey of radon concentrations in earth-sheltered houses, conducted in collaboration with researchers at Oklahoma State University. While this effort would not directly investigate radon transport into earth-sheltered houses, it would perform long-term measurements with a modest degree of control imposed by performing comparable measurements in a conventional house in the neighborhood of each earth-sheltered house selected. In this way, we can take a practical step forward in ascertaining the degree to which earth-sheltering actually affects indoor radon concentrations.

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