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INDOOR RADON LEVELS: EFFECTS OF ENERGY-EFFICIENCY IN HOMES

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The expectation of elevated ^{222}Rn levels in modern homes that have low air interchange rates with the outdoor air caused us to survey both solar and conventional homes in northeastern New York State. As a group, homes that are more airtight have three times the ^{222}Rn levels of the conventional homes; they have other specific problems that are introduced or exaggerated by modern construction. For example, the highest two levels of radon in the solar homes give doses over 30 years that are known to produce lung cancer in 1% of uranium miners. Summer readings in more than one-half of the cases are different from winter ones by a factor of two or more, so that year-round measurements are necessary for precise dosimetry. The track-etching technique is ideally suited for such measurements. Radon emanation measurements on soils and sand demonstrate a considerable variety of release rates.

Introduction

^{222}Rn is significant in its role as a possible hazard to health, as an indicator of subsurface uranium, and as a potential aid to earthquake prediction. Suitably housed track detectors give quantitative measures of ^{222}Rn, free of other radon isotopes and daughter nuclides (Fleischer and Mogro-Campero, 1978). The technique is now calibrated and shows linear response over a wide range of radon concentrations, times of exposure, and doses down to 10 pCi/L days (Fleischer *et al.*, 1980). Dielectric track detectors are well suited for the long-term measurements at low radon concentrations that were desired in this study, since they are rugged, thermally insensitive, inexpensive, passive, require no supply of energy, and have the needed sensitivity.

The increase in the number of airtight, energy-efficient homes in the United States threatens to increase markedly the exposure of the occupants to ^{222}Rn and its decay products in two ways: (1) reduction of ventilation rates, thus causing ^{222}Rn to accumulate to a greater extent, and (2) in some solar homes, injection of additional radon from ^{226}Ra-containing heat-storage material. To test the effects in northeastern New York, integrated ^{222}Rn surveys are being done with long integrating times. The results of that work will be summarized and some of the considerations that control radon levels in homes will be described with the aid of a simple model and by some measurements on building materials.

Model of a Home

Figure 1 is a highly oversimplified one-dimensional model of the radon concentration in an airtight home. It allows the important considerations to be readily recognized. As sketched, the radon enters solely through the basement floor, and all walls are assumed to be impervious. As long as the mean diameter of the floor is large relative to the mean radon diffusion distance d in the medium below the floor, $\sqrt{D/\lambda}$ (D = diffusion constant, λ = radon decay rate, 2.1×10^{-6} sec^{-1}), the edge effects can be ignored and a purely one-dimensional model is appropriate.

Below the floor the diffusion of radon is governed by the relation

$$\frac{dc}{dt} = D\frac{d^2c}{dx^2} - \lambda c + a, \tag{1}$$

where c is the concentration and a is the production rate of radon. If a is constant within the earth and $c = c_a$ within the air in the house, the steady-state solution to Eq. (1) is

$$c = c_a + (c_\infty - c_a)\,[1 - \exp(-x/d)]. \tag{2}$$

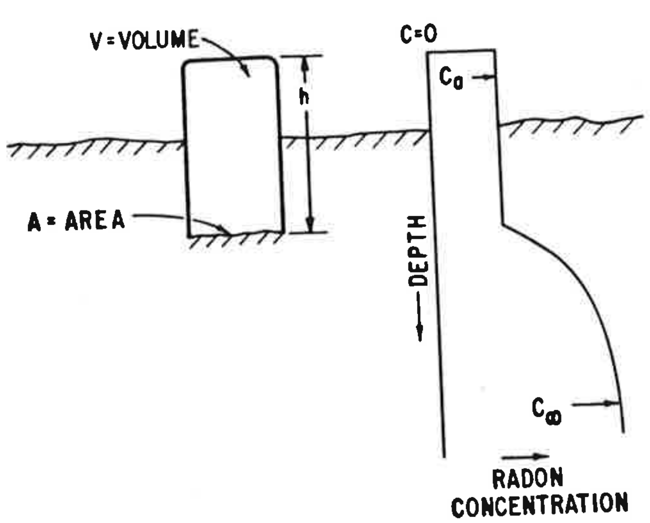

Fig. 1. Schematic of radon concentration in a home. The home accumulates radon to a concentration c_o that depends on the flux through the basement floor.

where $c_\infty = a/\lambda$. In the air within the home

$$\frac{dc_o}{dt} = -\lambda c_o + \frac{JA}{V}. \tag{3}$$

Using Eq. (1) the flux J into the house, $\epsilon D\, dc/dx$, is $\epsilon\sqrt{D\lambda}\,[c_\infty - c_o(t)]$, where ϵ is the porosity of the soil. Equation (3) can be solved to give $c_o = [\lambda' c_\infty/(\lambda + \lambda')]$ $[1\text{-}\exp(-[\lambda + \lambda']t)]$, where $\lambda'(= DA/dV = \sqrt{D\lambda}/h)$ is the fractional rate of filling of the home to its maximum concentration

$$\lambda' c_\infty/(\lambda + \lambda') = c_\infty/(1 + h/\sqrt{D/\lambda}) = c_\infty/(1 + h/d). \tag{4}$$

These same equations have been solved by Fleischer (1980) in describing a method of measuring radon flux from the ground.

In short the maximum concentration is intermediate between the value in the ground and that in the outside atmosphere, taken as zero for this calculation. Its level decreases according to Eq. (4) as the height h (volume-to-area ratio) increases, and it increases as the mean diffusion distance in the subbasement medium increases (and hence the effective thickness of the material that injects the radon). In an actual house there is escape of radon through windows, doors, and walls; there may be additional inputs through basement walls and the water supply. In addition, the basement floor is rarely a negligible barrier to radon, as assumed in these calculations. Nevertheless, the model indicates that radon will be elevated for a low, airtight house with a dirt floor, exposed crawl space, or highly permeable cellar floor and/or walls. Rundo *et al.* (1981) have recognized the effects of the crawl spaces, and we will document a somewhat similar problem from highly permeable cellar walls.

Measurement Methods

Homes were grouped into conventional "non-energy-efficient" and airtight "energy-efficient" structures, the selection of category being based on the owner's description of the home. Of 14 energy-efficient homes reported here, 11 were solar homes, three of which had solar collectors. Thirteen conventional homes have been surveyed.

Readings were carried out using the configuration of a solid-state track detector and cup-shaped enclosure (Fig. 2) described by Fleischer *et al.*, (1980). Our apparatus differed in the use of a high permeation (HP) membrane that enhanced the signal by allowing more complete entry of ^{222}Rn into the cup. The considerations in the use of HP membranes have been given by Ward *et al.* (1977) and Alter *et al.* (1981). Desiccants were used to prevent condensation problems (Likes *et al.*, 1979).

Since the soil surrounding the foundation of a home is the most usual source of the radon that enters from outside, it is important to know variability that exists in

Fig. 2. Detector cup used for track etching measurements of indoor ^{222}Rn. The high permeation membrane admits only the longest-lived radon isotope. The desiccant package restricts the condensation of moisture.

the construction materials used. In addition, the sand or soil that is often used inside solar homes as a heat-storage medium can also lead to the possibility of added injection of radon. Soils were examined using the experimental configuration shown in Fig. 3 (Fleischer and Mogro-Campero, 1978). Using exposures of several months, to insure that a steady-state radon level has been present over most of the monitoring time, the radon concentration is a measure of the emanating properties of the material in the enclosure. The membrane insures that only ^{222}Rn is recorded (Ward *et al.*, 1977; Fleischer and Mogro-Campero, 1978). When the membrane permeability is sufficiently high (Alter *et al.*, 1981), the radon concentrations will be equal above and below the membrane; and the emissivity per unit mass is given by $S_M = c\lambda\, V_a/\varrho\, V_s$, where V_a is the volume of the air space, including the porosity of the soil, and ϱ is the density of the soil having a volume V_s. A theory by Ward *et al.* (1977) allows the effect of a membrane that is a stronger barrier to be calculated.

Results

Homes

In most cases, 6-month-long readings were taken from October to April for the "winter" readings and April to October for the "summer" ones. Where both periods have been measured, the average provides a 1-yr reading. Table 1 compares the average of two pairs of these readings at different positions in the basement of non-energy-efficient home number 5 with the results of single exposures over the full year. Within the statistical uncertainties the expected agreement is present. The home-by-home results are given elsewhere (Fleischer *et al.*, 1982). Here we summarize what has been learned.

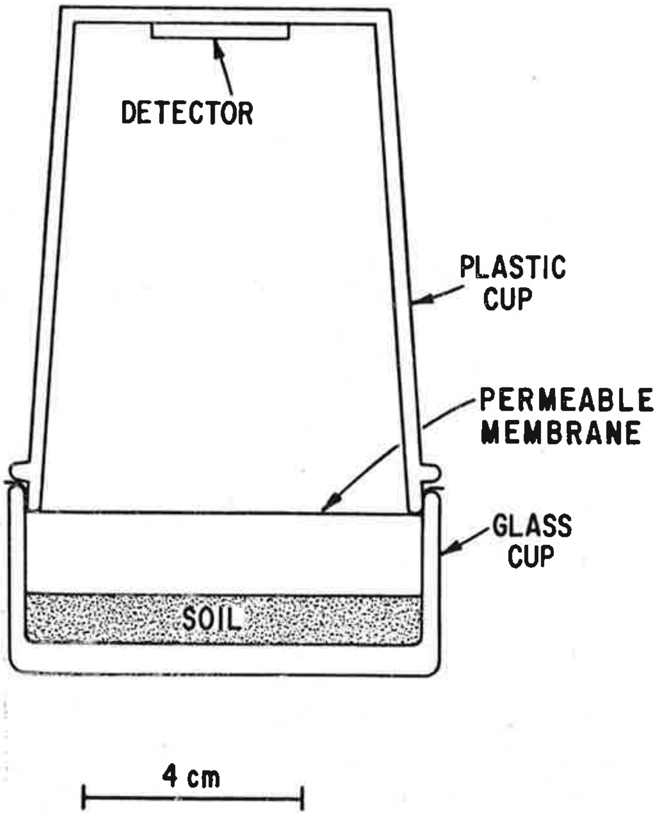

Fig. 3. Equipment used to measure emanation from soil sample in order to assess radon inputs. Use of the membrane insures that only radon is recorded.

Table 1. Full-year vs half-year radon concentrations [pCi/L].

Home 5	Winter	Summer	Average	Full Year
Basement				
A	1.64 ± 0.18	0.53 ± 0.09	1.09 ± 0.20	1.27 ± 0.09
B	3.06 ± 0.26	0.76 ± 0.11	1.91 ± 0.28	1.58 ± 0.12

Most noticeable in the results is the wide variability of values, but in general the higher typical values for the energy-efficient homes. During the winter, one-half of the energy-efficient homes have readings of 4 pCi/L or above, while only one room in one of the conventional homes has readings this high. Values of 3 pCi/L and above have been proposed by the U.S. Environmental Protection Agency as requiring remedial action (EPA, 1980).

The second observation (see Table 2) is that energy-efficient homes tend to be significantly more radon-rich than are the more conventional homes surveyed, particularly in the first- and second-story living areas that are most relevant to human exposure. First- and second-floor living areas are higher by 3.2 times in the energy-efficient homes in the winter and 2.2 times in the summer, as judged by the median values. One of the non-energy-efficient homes had a reading of 200 pCi/L in the basement, presumably due to venting of radon from well water. This reading biased the average basement ratio in Table 2.

A third observation is that, as shown by Table 3, summer radon levels are usually significantly different from winter ones in a variable manner, so that a full year of integration is required for careful monitoring. Table 4 gives the status of full-year values. Although the data are limited, again the values in airtight homes are typically several times those in conventional ones.

Table 2. Energy-efficient to non-energy-efficient home.

	Ratios of Radon Concentration			
	Basement	First Floor	Second Floor	Overall
Winter				
Average	0.3	3.0	2.6	2.0
Median	1.3	5.0	2.7	3.0
Summer				
Average	3.07	2.81	–	2.94
Median	1.41	2.23	–	1.82

Table 3. Winter/summer ratios.

	Home Number	Basement	First Floor	Second Floor
Non-energy-efficient	2	0.45		
	5	2.7		
		3.9		
	12	0.7	1.0	
	Average	1.48	1.0	
	Median	0.7	1.0	
Energy-efficient	2	2.8, 9.0	3.1, 3.8	
	5	4.5	8.5	4.6
	9	0.4	1.3	0.6
	10	0.9	0.5	0.3
	11	0.4	1.0	0.8
	12	0.3	0.4	
	13	2.4	1.8	1.4
	Average	2.1	2.4	1.5
	Median	0.9	1.3	0.8

Table 5. Radon emanation rates from sand, soil, and construction material.

Material	Sample Number	S_M (Emanation) (atoms/g sec)	Calculated Flux[a] (atoms/cm^2 sec)
Soil			
Thoreau, NM		0.0110	1.62
Scotia, NY		0.0094[b]	1.39
Northeastern New York	(E-5A)	0.0107	1.57
	(E-5A)	0.0108	1.59
	(E-5B)	0.0034	0.50
Sand	(E-2)	0.0040	0.59
	(E-2) (repeat)	0.0047	0.69
Northeastern New York	(L-1)	0.0034	0.50
	(L-2)	0.0027	0.40
	(P-1)	0.0017	0.25
Brick	(E-2)	0.00014	0.05
Wallboard	(E-5)	0.00014	0.03

[a] Flux from semi-infinite geometry into air with no radon.

[b] Relative to Thoreau, NM, using results of Fleischer (1980).

Construction materials

Radon emanation levels using the procedure sketched in Fig. 3 give the results shown in Table 5. The emanation rates are accompanied by flux values that are calculated for a thick slab of the material with a plane surface. The emanation rates and flux values range over a factor of 6.5 for the granular material, and the brick and wallboard that were tested were lower by a factor of 42 relative to the average for the sand and soil. The choice of materials for heat storage could have a profound effect on radon injection.

Specific cases

Three causes of unusually high readings have been recognized in this work, each connected with one of the three homes that had the highest radon concentrations. The highest level that we have observed indoors is 200 pCi/L in the basement of non-energy-efficient home number 14. It is fortunate that this is not one of the tighter homes, as evidenced by the much lower first-floor readings (3.2 pCi/L). The high reading occurs where air from a well vents into the basement, a situation that has now been eliminated. Further monitoring will clarify the extent to which the upstairs levels were raised by the original situation. The water in this house will be tested for radon.

Table 4. Full-year average radon [pCi/L].

	Home Number	Basement	First Floor	Second Floor
Non-energy-efficient	2	1.4 ± 0.2		
	5	1.0 ± 0.1	0.5 ± 0.1	
		1.6 ± 0.1		
	12	1.3 ± 0.2	0.21 ± 0	
	Average	1.33	0.36	
Energy-efficient	2	5.0 ± 0.3	3.0 ± 0.2	
	5	20.8 ± 1.0	7.6 ± 0.4	7.2 ± 0.3
	9	9.4 ± 0.5	3.7 ± 0.2	4.4 ± 0.2
	10	1.3 ± 0.1	1.7 ± 0.1	2.0 ± 0.1
	11	1.5 ± 0.1	0.48 ± .04	0.60 ± 0.05
	12	2.6 ± 0.1	0.45 ± 0.04	
	13	1.5 ± 0.1	0.87 ± 0.06	0.87 ± 0.06
	Average	6.01	2.54	3.01

Nine of the energy-efficient homes (numbers 2, 4, 7, 8, 9, 10, 13, 14, and 16) contain sand, crushed rock, or slabs of concrete as heat-storage materials. Any of these materials are potentially competent radon emitters and have probably contributed to the relatively high average radon concentration for this group (3.8 pCi/L in the living areas). Two of the heat-storage materials have been measured from energy-efficient home number 2, which had a basement value of 12.4 pCi/L during the first winter of monitoring. The sand and the brick used for heat storage emit 0.24–0.28 radon atom/g min and 0.0084 atom/g min, respectively (sand and brick E2). As Table 5 shows, this sand is comparable with other sands and soil; and, if it is not separated from the house by an effective barrier, it acts as a bare dirt floor, which has been shown to be an effective injector of radon (Rundo *et al.*, 1981).

Energy-efficient home number 5 is the third and final example. The progressive increase in radon observed in the winter, 12 to 18 to 36 pCi/L from the second story to the basement, marks it as the source of radon. No heat storage mass is present, and the well water is low in radium (2 pCi/L) and radon (20 pCi/L). Radium was assesed by evaporating a known quantity of water and then alpha counting the residue with allyl diglycol carbonate detectors (Cartwright *et al.*, 1978). Radon was measured by exposing a series of four detectors in a closed air space with stirred water samples for different periods of time.

The critical factor appears to be the basement walls. They are of an unsealed building block that constitutes a negligible barrier to radon. Experiments by Hart (personal communication) gave 166 (cm³/cm² sec)/(atm/cm) as the permeability. The emanating power of the natural soil outside the basement is 0.65 atom/g min, i.e., comparable to the New Mexico soil (Table 5). It is the probable source of the high radon indoors.

Conclusions

Three sources of unusually high radon levels in homes that we have documented are (1) ^{222}Rn released from well water containing a large concentration of radon, (2) injection of ^{222}Rn into living areas of solar homes by geological materials used for heat storage, and (3) injection of radon into a tightly sealed home from exterior soil through a highly permeable basement wall. In addition, Table 5 shows that construction materials vary widely in radon production. As illustrated in Table 3, summer radon levels are usually importantly different from winter ones in a variable manner, so that a full year of integration is required for careful monitoring. Finally, Table 2 indicates that energy-efficient homes tend to be significantly more radon-rich than are the more conventional homes studied, particularly in the first- and second-story living areas that are most relevant to human exposure.

The causes of the elevated radon are diverse; however, the chief reason is that airtight homes retain radon longer than well-ventilated ones and hence allow buildup to higher levels. Similarly, any inputs of radon are of greater concern in structures in which loss of radon is restrained. Therefore, the use of radon-emitting heat-storage materials such as sand or rock requires special care in solar homes.

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