RADIOACTIVITY (Radon and Daughter Products) AS A POTENTIAL FACTOR IN BUILDING VENTILATION

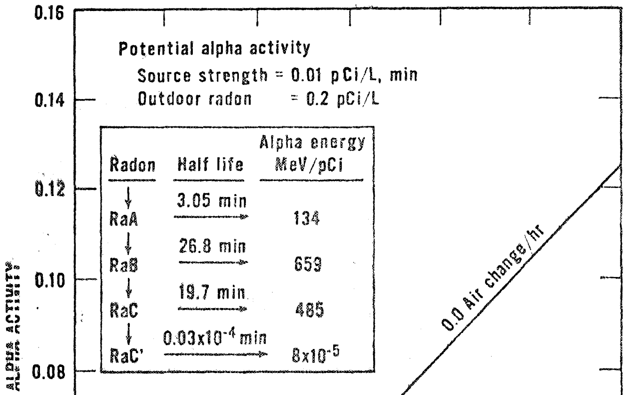

Fig. 1

Awareness has developed in the United States, particularly within the last five years, that traces of radioactive radon gas and its daughter products are present in varying amounts in the indoor air. Some of the existing literature on the subject is briefly reviewed and discussed. It is recommended that further attention be given to quantify radon concentration data pertinent to the environmental health aspects of ventilation requirements from the standpoint of indoor air quality consistent with building energy conservation.

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REDUCTION of ventilation is one of the strategies employed to save energy in the heating and cooling of buildings. Very little ventilation is needed to supply sufficient oxygen for respiration or to keep carbon dioxide within acceptable levels. Recent studies have revealed, however, that limiting of ventilation could cause high levels of air pollution, especially in homes with gas appliances. Tests at Lawrence Berkeley Laboratories[1] and by Geomet[2] have shown that concentrations of CO, NO, CO_2, non-methane hydrocarbons, and aldehydes in the residential environment are often higher than outdoors dues to the existence of indoor pollutant sources. Evidence has been accumulating, particularly within the last five years, that nuclear radiation from radon gas and its daughter products is also a factor which may need consideration in the design of buildings and their ventilation systems. The radiation levels within buildings are usually low, but it has not yet been determined whether indoor radiation can pose health problems. Although this issue is central to building ventilation in general and to the ASHRAE Ventilation Standard[3] in particular, most of the available information appears in

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Table 1—Selected Elements in Uranium Decay Chain*

NUCLIDE	HALF-LIFE (TIME)	MeV (abundance) ALPHA ENERGY	MeV (abundance) BETA ENERGY	MeV (abundance) GAMMA ENERGY
$^{226}_{88}\text{Ra}$	1622 years	4.60 (6%), 4.78 (95%)		0.186 (4%)
$^{222}_{86}\text{Em(rn)}$	3.825 days	5.486 (100%)		0.51 (0.07%)
$^{218}_{84}\text{Po(RaA)}$	3.05 minutes	5.998 (100%)	0.33 (0.022%)	0.186 (0.03%)
$^{218}_{85}\text{At(RaA')}$	2 seconds	6.65 (5%), 6.70 (94%)	unknown (0.1%)	
$^{218}_{86}\text{Em(RaA'')}$	0.019 seconds	7.127		
$^{214}_{82}\text{Pb(RaB)}$	26.8 minutes		0.65 (50%) 0.71 (40%) 0.98 (6%)	0.295 (19%) 0.352 (36%)
$^{214}_{83}\text{Bi(RaC)}$	19.7 minutes	5.45 (0.012%) 5.51 (0.008%)	1.0 (23%) 1.51 (40%) 3.26 (19%)	0.609 (47%) 1.120 (17%) 1.764 (17%)
$^{214}_{81}\text{Po(RaC')}$	1.64×10^{-4} seconds	7.68 (100%)		0.799 (0.014%)
$^{210}_{81}\text{T1(RaC'')}$	1.32 minutes		1.2 (25%) 1.9 (56%) 2.3 (19%)	0.296 (80%) 0.795 (100%) 1.310 (21%)
$^{210}_{82}\text{Pb(RaD)}$	19.3 years	3.72 (0.000002%)	0.017 (85%) 0.061 (15%)	0.0467 (0.045%)
$^{210}_{83}\text{Bi(RaE)}$	5.00 days	4.65 (0.00007%) 4.69 (0.00005%)	1.17 (100%)	
$^{210}_{84}\text{Po(RaF)}$	138.4 days	5.298 (100%)		0.802 (0.000012%)
$^{206}_{81}\text{T1(RaE'')}$	4.19 minutes		1.57 (100%)	
$^{206}_{82}\text{Pb(RaG)}$	Stable			

Radio active decay of radium (Ra 226) results in the daughter products in descending order as shown in Table 1. Most of the energy of the radioactivity is asalpha particles.

*Radiological Health Handbook, U.S. Department of Health, Education and Welfare, January 1970, p. 112.

physics publications which are not well circulated among, nor understood by, heating, air-conditioning and ventilating engineers. The purpose of the paper is to provide ASHRAE engineers with state-of-the-art information on radon and its daughter products in air within buildings.

RADON AND DAUGHTERS

Radon (Rn 222) is found in our atmosphere, because it is the first radioactive decay product of radium which is present in varying amounts in soil, masonry building materials, and ground water. Since radon is a gas, it can diffuse into the air. It can also be absorbed by solid surfaces and can be dissolved into water[4]. Radium (Ra 226), a radioactive decay product of uranium, having a half-life of 1622 years, is distributed in rocks and soils in concentrations which vary with location, but is relatively invariant with time. As it decays, by alpha particle emission, it becomes radon 222 (Rn), which is a gas. Radon gas can then diffuse through soils, concrete, etc. and enter the atmosphere either outside or inside a structure. Outside, the natural winds dilute its concentration. Inside, the dilution is less. Radon has a half-life of only 3.8 days, so within a relatively short time it decays to polonium 218 (RaA) and other daughter products, mostly by alpha emission. While polonium and the other daughter products of decay are solid atoms, it is hypothesized that they remain airborne and are likely to attach themselves to dust particles, due to their atomic charges. Table 1 shows the element transformations in the radium decay chain. After radon, the half-lives of all the daughter products are quite short until the lead isotope Pb 210 (RaD). As Table 1 shows, most of the daughter products are alpha emitters, and if these get into the respiratory system, alpha particle damage in the lung may result.

Atmospheric concentration of radon gas and its daughter products is reported to be influenced by barometric pressure, soil temperature, wind speed, diurnal temperature fluctuations, snow cover and rainfall, and possibly other factors.[5]

The concentrations or radon and radon daughters have been expressed in picocuries per litre of air (pCi/L), which is equivalent to 0.037 nuclear transformations per second per litre of air.* On the average, in the U.S., outdoor radon concentrations range from 0.05 to 0.13 pCi/L, and indoor concentrations are usually higher [6]. It should be pointed out that outdoor concentrations are influenced strongly by locations and meteorological parameters. These also play a role in determining indoor concentrations, but the nature of the building materials and ventilation rates is presumed to be of primary importance except in the few

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*This is because their rate of transformation is proportional to the concentration.

Table 2—Some Radon Concentrations Reported in the Literature

			Radon Concentration	
Authors	Locations	Buildings	Indoor pCi/L	Outdoor pCi/L
T.F. Gesell and A.M. Pritchard[9]	Houston, Texas	House	0.5-2.0	0.3
H. Horiuchi[10]	Saskatchewan, Canada	Primary school (ventilated)	15	
		One house in survey of 552 houses	250	
Noel Jonassen[11]	Denmark	House	5	
Henry Spitz and M.E. Wrenn[6]	Grand Junction, Colorado	Houses	7.8-290	0.10
G.A. Swedjemark[8]	Sweden	Single apartment dwelling	6-18	
L.T. Caruther and A.W. Waltner[12]	Raleigh, N.C.	Physics Building	1.8-3.9	0.2
F. Steinhausler[5]	Innsbruck, Austria	12 Houses	< 0.05-7.46 (extremes)	
J. Fitzgerald et al[13]	Reclaimed Phosphate-mining Land—Polk & Hillsborough Counties, Florida	1000 Houses	0.02~10.5*	

*Approximated from working level (WL) data.

Table 3—Radon Concentration and Corresponding Ventilation Rate in Modern Swedish Homes

			Radon Concentration pCi/L		
Type of House	Building Construction Material	Air Change/hr	min	av	max
Multifamily Apartment	Concrete	0.3 ~ 0.5	1	3	12
	Sand-based concrete	0.3 ~ 0.9	1	2	3
	Shale-based concrete	0.4 ~ 0.8	2	4	10
Single-family dwelling	Brick face; wood frame; rockwool insulation	0.4 ~ 0.7	0.5	1	3
	Wood construction: basement of shale-based concrete; rockwool insulation	0.4 ~ 0.8	0.5	4	8
	Shale-based porous concrete	0.2 ~ 0.5	3	6	19
	Sand stone; wood frame; rockwool insulation	0.1 ~ 0.4	5	9	12

known cases of residences built on soil containing unusually large concentrations of radioactive material. Building materials can also be important sources of radon. Materials such as granite, concrete blocks, bricks and gypsum boards often contain significant traces of radium[7,8] while wood and organic materials of construction usually do not. Some soils and ground water[9]* may be significant sources of radon. Building materials probably play two roles; one as a source or radon, and the other as a barrier (or non-barrier) for soil-produced radon diffusing into the structure.

PRIOR WORK ON INDOOR RADIATION LEVELS

It has been reported by several workers that radon and its daughter elements are present in measurable amounts in indoor environments. Table 2 summarizes some radon measurements reported in and around structures in the U.S., Canada and Europe. High radon concentrations are indicated at Grand Junction, Colorado[6] and in the province of Saskatchewan, Canada[10] due to the proximity of uranium mines and the high radium content of soil around and near the structures, including mining and milling tails, and/or other sources. Selected homes in these locations had levels as high as 250-300 pCi/L. In other locations listed in the table, indoor radon levels covered a range from < 0.05 to 18 pCi/L. A large scale measurement project was conducted in the State of Florida, where houses had been built on land reclaimed by employing phosphate-ore fill, which is high in radium[13].

A report by the Swedish National Institute for Radiation Safety (4) has shown that radon levels in a dwelling can vary depending on ventilation rate. A summary of some of their measurements on several types of dwelling units is given in Table 3. Air change rates are also given in the table, and a cursory glance at the results suggests a trend toward higher inside radon levels at lower ventilation rates. Swedjemark[8] has suggested that ventilation rates are more important than building materials in establishing radon concentration.

Preliminary measurements made by NBS personnel in the Washington, DC. area showed the indoor radon concentration to be more than 6 pCi/L in one of the houses, which was constructed to be as "tight" as current practical technology allows. The infiltration rate of this tight house was approximately 0.2 air change per hour. Even this very low infiltration in the house represents about 16 cfm/person

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*The contribution of radon from well-water to residential construction and indoor concentrations is not addressed in this paper, but should be considered in more detailed studies.

genies are attained, which is usually difficult in the field test condition. Careful experimental procedure, accurate knowledge of filter efficiency, sampling rate, and sampling time are needed, in conjunction with comprehensive mathematical procedures, to translate the radioactivity data of the filter paper into the original radon concentration[20].

Although a direct measurement technique of radon radioactivity, without relying upon the filter paper content of the daughter products, is availalbe (such as that of Lucas Chambers) it is usually not suitable for field measurements. An excellent review on the subject of radon instrumentation has been published by Budnitz.[21]

CONCLUSIONS AND RECOMMENDATIONS

The foregoing observations suggest that in some cases radon and its daughter products may be limiting factors in establishing ventilation rates in residences. Several reported measurements have exceeded the 3 pCi/L suggested Maximum Permissible Concentration (MPC). However, in the absence of a generally accepted standard for maximum permissible concentrations of these radioactive elements, and lack of source-strength data in residences, it is difficult to set ventilation standards. The data presented in this paper from the literature show considerable variations and are essentially spot checks. They cannot be well-correlated with infiltration measurements. There is need for a more broad-based survey to determine whether a problem exists and, if so, to what extent.

Swedjemark[7], as noted previously, has suggested that ventilation rates are more important than building materials in controlling inside radon concentrations. In buildings where windows and doors are closed, as during the heating season, natural air leakage normally changes only about 50% with time, wind velocity, and outside temperature. Mechanical ventilation with a heat exchanger may be needed to maintain acceptable levels of radon in many homes and minimize the energy requirement for heating or cooling the outside air.

There are a number of areas where more complete information and better measurement accuracy are needed. For example, it is necessary to know how radon concentrations in new construction can be minimized by better selection of building materials and pretreatment of water supplies. There is need for measurement methods which quickly pinpoint sources, both in existing buildings and in materials to be used in new buildings. There is need for a broad-based survey to determine typical existing radon levels in housing. It would also be desirable to know what architectural parameters could be optimized to design structures for minimum inside radon concentration.

Better determination of the accuracy of measurement methods is needed in order to permit better intercomparison of field studies made by different investigators. It would be desirable to have a better knowledge of the statistical variations in measurement methods.

Of particular concern in ventilation design is to determine whether fluctuations in radon level are primarily due to changes in ventilation rate or whether diffusion into air and absorption of the gas (which may vary in accordance with temperature, atmospheric pressure, relative humidity, etc.) play major roles.

Finally, there is the question of what remedial measures may be effective in reducing the level of radon and its daughter products in inside air. For example, could surface sealants be used which inhibit the diffusion of radon into room air? Also, since radioactivity in inside air may be associated with dust particles, is it possible to significantly reduce the level of alpha emitters by recirculating air through high-efficiency particulate filters? Higher ventilation rates with heat reclaim may also be one future answer. Although these points are discussed to some extent in a recent EPA (Environmental Protection Agency) report by Fitzgerald, Guimond and Shaw[13], more information based upon improved measurement accuracy and upon more extensive nationwide data is needed to resolve the radon problems, because reduction in ventilation to save energy use should be strongly influenced by this information.

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WIND REDUCTION BY A HIGHLY PERMEABLE TREE SHELTERBELT*

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ABSTRACT

Miller, D. R., Rosenberg, N. J. and Bagley, W. T., 1975. Wind reduction by a highly permeable tree shelterbelt. Agric. Meteorol., 14:321—333.

Vertical wind profiles above dryland wheat fields were measured simultaneously in the open and at horizontal distances of $2H$, $4H$, and $8H$ (H = shelterbelt height) in the lee of a highly permeable tree shelterbelt. Two-dimensional wind reduction patterns in the lee of the shelterbelt are presented. The effects of measurement height and atmospheric stability on the horizontal wind profiles (wind reduction curves) are presented. The wind reduction curves were most consistent during neutral atmospheric conditions. Drag coefficients for the shelterbelt were calculated utilizing the wind reduction curve data in a model by Seginer and Sagi (1972). Shelterbelt drag, characterized by the integrated wind reduction curve or a drag coefficient, is suggested as a practical basis for comparison of the effectiveness of different field shelterbelts. Utilization of the drag coefficients showed the 4-year old highly permeable windbreak was already 1/3 as effective as a fully grown shelterbelt.

INTRODUCTION

Only about 20% of the farms and ranches in the U.S. Great Plains that need shelterbelts have adequate ones (Ferber, 1969). This reluctance to plant and maintain field shelterbelts continues in spite of the usefulness of wind shelter for decreasing soil erosion, increasing crop yield (Stoeckeler, 1962; van Eimern, 1964; Bagley, 1964, and others) and decreasing water use (Miller et al., 1973; Brown and Rosenberg, 1971). A reason often given for not planting shelterbelts is the long period of time invested before the trees provide effective protection. This study was initiated to examine the effectiveness of a very young, rapidly growing tree shelterbelt.

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for average occupancy. There is still too much scatter in the test reported data to suggest a definite correlation between infiltration and inside radon levels.

RADON VS. VENTILATION (AIR LEAKAGE)

A suggested model for the radon concentration in the inside air with respect to radon generation and air infiltration may be

$$\frac{dN}{dt} = -I(N - N_o) - \lambda N + S$$

where

N = radon concentration, atoms/L
N_o = outside air radon concentration, atoms/L
I = infiltration rate, air change/hr
λ = radon decay constant = 1.258×10^{-4} min^{-1} = 0.0075 hr^{-1}
S = total radon/daughter source strength, atoms/L, hr
t = time, hr

Similar equation can be used for describing the disintegration and decay process for each of the radon daughters, namely for RaA, RaB, RaC and RaC′. The term for S in the daughter equations, however, would have to be replaced by the disintegration rate of the parent element.

The solutions for all of the radon daughters that satisfy a set of these equations can then be combined to yield a total alpha energy and expressed in the unit of WL, which will be explained later. A computer program has been developed at NBS to solve these equations for different ventilation rates and source strength levels. Fig. 1 illustrates one of the calculations showing selected potential alpha activity increase in the house with a few selected typical ventilation rates on the assumption that the radon strength is 0.01 pCi/L, min* and the outdoor radon concentration is 0.2 pCi/L.*

Although not shown in the figure, the alpha activity of a completely tight house could eventually increase to an equilibrium level as high as 0.7 WL after two weeks. The ventilated houses, however, quickly attain a steady concentration of much lower levels within one day.

It is seen that if the source strengths are known and remain constant, the increase of radon concentration is simply inversely proportional to infiltration rate I. Since infiltration rates, I, probably cannot be made practically less than about 0.2 air change per hour, and present-day levels are 0.5 to 1.0 for well-built recent houses, the radon levels for very tight houses cannot be expected to be more than 3 to 5 times those of conventional houses. Examination of the data in Tables 2 and 3 shows many variations far greater, and suggests uncertainties in measuring the radon concentration as well as the possible variation in the source strength with time, as atmospheric conditions change.

ACCEPTABLE LEVELS

Recognition that radon and its daughter products released into homes from building materials, soils, and water by outgassing can be a problem in many houses is comparatively recent in the U.S. There are no national standards for maximum allowable levels in the residential environment, nor are there standards for building materials. There are standards for occupational exposure[14,15,16,17,18], developed to protect the health of uranium miners. Here the allowable concentrations are higher than those which would be specified in a residence, but they provide a starting point for projections as to what levels should be acceptable in the living environment on a 24-hour-per-day basis. The concept of WL (working level) is used in the occupational standard. Working level is defined as any combination of radon daughters in a litre of air which will result in the ultimate emission of 1.3×10^5 million electron volts (MeV) of potential alpha energy. The numerical value of the working level is derived from the alpha energy released by the total decay of short-lived radon daughter products in equilibrium with 100 pCi/L of radon (222) in air[15]. The WL values were developed, in part, by considering statistical cancer data on mine workers who had worked approximately ten years in an environment containing approximately 100 picocuries per litre or more of radon[15]. Under these conditions, the statistical risk is one cancer per 1000 workers per year[4]. In 1968 a standard was issued by the Secretary of Labor[16] for the mining industry concerning the protection of mine workers, stating *occupational exposure to radon daughters in mines shall be controlled so that no individual will receive any experience of more thant two Working Level Month (WLM)* in any consecutive three-month period and not more than four WLM in any consecutive twelve-month period. Actual exposures shall be kept as far below these values as practicable.*

In 1969, the Department of the Interior issued a guideline[17] stating that if the air samples show an atmospheric concentration of radon daughters greater than one, but less than two WL, immediate corrective action shall be taken or the men shall be withdrawn. Atmospheric concentrations greater than two WL shall be reduced below one WL before resuming work.

In 1964, the International Commission on Radiological Protection (ICRP) presented a formula for estimating the Maximum Permissible Concentration (MCP) of radon based on the fraction of the equilibrium abount of RaA (see Table 1) which, if the fraction equals 10%, results in a maximum permissible concentration (MPC) in air of 30 pCi/L (occupational exposure)[14]. However, both the ICRP and National Council on Radiation Protection and Measurement (NCRP) recommend that individuals in the general public be exposed only to levels limited to one-tenth of the recommended MPC's for occupational personnel. Dr. J.A. Auxier[19], the Director of Oak Ridge National Laboratory, Health Physics Division, and the Swedish National Institute for Radiation Safety[4] generally concur. Thus it appears that if a criterion is to be applied today, the MPC for radon in homes should not exceed the suggested 3 pCi/L which is consistent with AEC regulations of 1966, as amended[18]. The Swedish National Institute for Radiation Safety estimates that a 1 pCi/L limit of radon corresponds to a cancer risk of 20 persons per million[4]. (This projection is based on data obtained at higher levels of exposure.)

MEASUREMENT PROBLEMS

Perhaps the major reasons for the data scatter of Tables 2 and 3 are the measurement errors for radon concentrations. The most common field measurement of radon concentration in the house is obtained through the measurement of the radioactivity of its daughter products by an air sampling technique. The air sampler collects the radioactive dust particles which have attracted the radon daughter products, which are strong alpha emitters, onto a filter paper. The filter paper is then in turn placed into an appropriate radioactivity counter to detect the total alpha activity of the sampled radon daughter products. Since the radon and its daughters are constantly transforming into their respective progenies, thus adding new alphas to them from radon, it is difficult to attribute the measured total alpha strength into the original concentration of radon in the air, unless the steady-state concentrations of all of the pro-

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*These data are derived from information provided in a United Nations publication entitled "Sources and Effects of Ionizing Radiation" Scientific Committee on the Effect of Atomic Radiation 1977, page 71.

*WLM is an extension of WL, to express a cumulative exposure. Inhalation of air containing a radon daughter concentration of one WL for 170 working hours (month) results in an exposure of one WLM.