BUILDING VENTILATION AND INDOOR AIR QUALITY

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DIVISION

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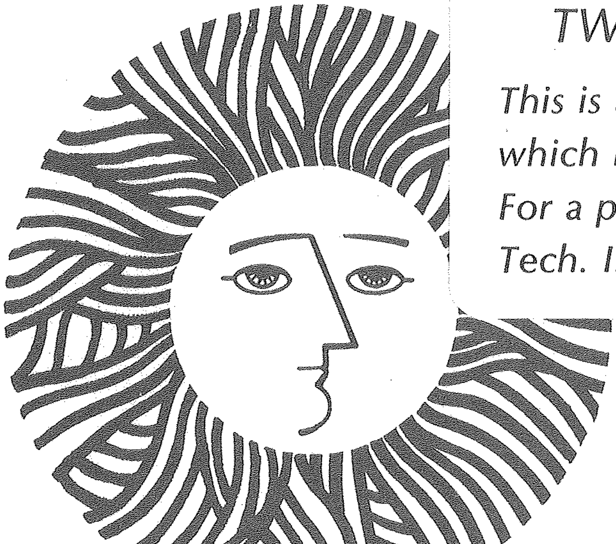

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Building Ventilation and Indoor Air Quality

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Abstract

Rising energy prices, among other factors, have generated an incentive to reduce ventilation rates and thereby reduce the cost of heating and cooling buildings. Reduced infiltration and ventilation in buildings may significantly increase exposure to indoor contaminants and perhaps have adverse effects on occupant health and comfort. Four indoor air contaminants -- carbon monoxide and nitrogen dioxide from gas appliances; formaldehyde from particleboard, plywood, urea-formaldehyde foam insulation, and gas appliances; and radon from building materials, soil, and ground water -- are currently receiving considerable attention in the context of potential health risks associated with reduced infiltration and ventilation rates. We have measured and analyzed these air contaminants in conventional and energy efficient buildings with a view to assessing their potential health risks and various control strategies capable of lowering pollutant concentrations. Preliminary findings suggest that further intensive studies are needed in order to develop criteria for maintaining acceptable indoor air quality without compromising energy efficiency.

Keywords: air pollution, carbon monoxide, energy conservation, formaldehyde, health, indoor air quality, nitrogen dioxide, radon

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INTRODUCTION

Out of national concern about the availability of conventional energy resources, a major effort is currently underway in the United States to make buildings more energy-efficient. Various energy-conserving measures -- tightening the building envelope to reduce exfiltration and infiltration, improving insulation, and reducing ventilation -- are being devised to reduce heating and cooling requirements.

Unfortunately, reducing infiltration and ventilation rates in buildings can lead to elevated levels of indoor-generated air contaminants which, in excessive concentrations, may impair the health, safety and/or comfort of the occupants. Indoor contaminants include gaseous and particulate chemicals from indoor combustion processes (such as cooking, heating, tobacco smoking), toxic chemicals and odors from cooking and cleaning activities, odors and viable microorganisms from occupants and a wide assortment of chemicals released from indoor construction materials and furnishings.

In conventional buildings, occupants are protected from undesirable indoor air contaminants in two ways: fresh air enters through cracks in the building envelope (uncontrolled) or by the opening of doors and windows or via mechanical ventilation systems (controlled), allowing contaminants to be diluted or to escape.

As infiltration is reduced, criteria must be developed for determining ventilation requirements that will assure acceptable indoor air quality without sacrificing energy efficiency. At present, there is little agreement in the United States, or elsewhere, on the amount of ventilation air required for the health, safety and comfort of building occupants. This information gap is due in large measure to the complex biological, chemical and physical mix of indoor air pollutants. Furthermore, earlier studies of indoor air pollution have assumed that indoor pollution arises from and is directly related to outdoor sources, whereas it is now recognized that numerous indoor air contaminants have their sources in the built environment itself.

Four indoor-generated contaminants are of particular concern in residential buildings: carbon monoxide (CO), nitrogen dioxide (NO_2), formaldehyde (HCHO), and radon (Rn). The health risks posed by exposure to these contaminants in conventional houses, as well as the added risks engendered by reducing infiltration and ventilation in new construction and in retrofitted houses are discussed below.

DISCUSSION

Gas Appliance Emissions: Carbon Monoxide, Nitrogen Dioxide and Formaldehyde

Several recent field and laboratory studies conducted at Lawrence Berkeley Laboratory (LBL) have focused on combustion-generated indoor air pollution in conventional residential buildings -- namely, air contaminants from gas stoves and heating systems. We have demonstrated that levels of several gaseous air pollutants (CO, NO, NO_2 and HCHO) and respirable particulates are elevated in indoor environments where gas appliances are used[1,2]. In the case of CO, NO_2 and HCHO, these levels often approach or exceed ambient air-quality standards adopted or proposed in the U.S. and other countries and, in the case of respirable particulates, the levels we have measured are often comparable to those present outdoors on a very smoggy day. Such high levels are clearly unacceptable in terms of human health, safety and comfort, and are of particular concern in energy-efficient residential structures where infiltration is reduced.

Using an experimental room (simulating a kitchen) with a volume of 27 m^3 (950 ft^3) and an air-exchange rate varying from 0.25 to 10 air changes per hour (ach), we have characterized the emissions from a new gas stove[3]. Our results indicate that gas stoves generate high emissions of carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), formaldehyde (HCHO), and respirable aerosols (size < 2.5 μm), and that the concentrations of these species become significant when the air-exchange rate is less than 1 ach. The results for CO, NO_2 and HCHO are summarized in Table 1. Particularly noteworthy are the observations that with mechanical ventilation at 85 m^3/hr (50 cfm) [the upper limit recommended by ASHRAE Standard 62-73][4], CO concentrations are maintained at acceptable levels; NO_2 and HCHO concentrations, however, exceed air-quality health standards[5] at this ventilation rate. At the lower ventilation rates recommended by ASHRAE Standard 90-75[6], even higher NO_2 and HCHO concentrations result. To keep NO_2 and HCHO concentrations to levels within the established air quality limits, a kitchen ventilation rate of at least 170 m^3/hr (100 cfm) is required.

Further studies of CO and NO_2 emissions from gas appliances were conducted at an energy-efficient research house maintained by LBL in Walnut Creek, California, where we measured the air quality in the kitchen, the living room, a bedroom, and one outdoor location over a 24-hour period. Gas stove operation was based on consumption patterns determined as typical in the United States by the American Gas Association[7]. Infiltration varied between 0.33 and 0.44 air changes per hour (ach) during the course of the study. The natural gas consumption was 0.170 m^3 (6 ft^3) for both the breakfast and lunch meals and 0.425 m^3 (15 ft^3) for the dinner meal. As expected, the peak pollutant concentrations (averaged over one hour) occurred during the dinner meal. The

Table 1.

CONTAMINANT CONCENTRATIONS IN A TEST KITCHEN

Ventilation Conditions	Mechanical Ventilation Rate (m^3/hr)	Air Exchange Rate (ach)	Contaminant Concentrations[a] CO (mg/m^3)	NO$_2$ ($\mu g/m^3$)	HCHO[b] ($\mu g/m^3$)
No stove vent or hood		0.25	48	2500	460
Hood vent (with no fan) above stove		1.0	25	1500	280
Hood vent with fan at low speed	85 (50 cfm)	2.5	14	800	150
Hood vent with fan at high speed	240 (140 cfm)	7.0	4	200	40
	Typical Outdoor Concentrations During Test		1.5	50	5
	Air Quality Health Standards	Concentration	40[c]	470[d]	120[e]
		Averaging Time	1 hour	1 hour	maximum
	ASHRAE Standards for Ventilation Requirements in Kitchens	51-85 m^3/hr (30-50 cfm) (Standard 62-73) 34 m^3/hr (20 cfm) (Standard 90-75)			

a 1 hour average concentration in center of kitchen in which gas oven is operated at 180°C. (350°F.)

b Calculated from measured emission rate for gas stoves

c EPA promulgated standard (1)

d EPA recommended standard (1)

e European standard (1)

ambient air-quality standard proposed by the Environmental Protection Agency (EPA) for a one-hour exposure to NO$_2$ is expected to be 470 $\mu g/m3$ [5]. As shown in Table 2, NO$_2$ levels in both the kitchen and living room exceed this standard and, in the bedroom, NO$_2$ levels are just under this limit. The one-hour EPA standard for CO is 40 mg/m^3, and this standard was not exceeded anywhere in the house.

A recent study in England[8] has compared the incidence rates of respiratory illness in two groups of children: those living in homes in which natural gas stoves were used and those where electric stoves were used. The investigators concluded that the increased levels of respiratory illness found among children living in homes using gas stoves might be associated with the elevated levels of nitrogen dioxide emitted by these appliances. A study in progress in six cities in the United States has released its preliminary analyses which report similar conclusions[9].

Table 2.

NO_2 AND CO CONCENTRATIONS IN EEB RESEARCH HOUSE

	NO_2 ($\mu g/m^3$)	CO (mg/m^3)
Peak 1-hour average		
Kitchen	850	27.8
Living Room	750	24.1
Bedroom	440	17.8
Outside	130	0.5
24-hour average		
Kitchen	140	5.9
Living Room	140	5.9
Bedroom	85	4.7
Outside	66	0.5

Air exchange rates (air changes per hour-ach)

morning	0.43
mid-day	0.33
evening	0.34

Formaldehyde

Formaldehyde (HCHO) is an inexpensive, high-volume chemical used throughout the world in a variety of products, mainly in urea, phenolic, melamine and acetal resins. These resins are present in insulation materials, particleboard, plywood, textiles, adhesives, etc., used in large quantities by the building trades. Although particleboard and urea formaldehyde foam insulation have received the most attention, formaldehyde also emanates from combustion processes (gas cooking and heating, tobacco smoking). The pungent and characteristic odor of formaldehyde can be detected by most humans at levels below 100 $\mu g/m^3$. Several studies reported in the literature indicate that concentrations in the range of 100 to 200 $\mu g/m^3$ may be sufficient to cause swelling of the mucous membranes, depending on individual sensitivity and environmental conditions (temperature, humidity, etc.). Burning of the eyes, weeping, and irritation of the upper respiratory passages can also result from exposure to relatively low concentrations. High concentrations ($\gg$ 1000 μg/m^3) may produce coughing, constriction in the chest, and a sense of pressure in the head. There is concern that formaldehyde may have serious long-term health effects.

Several countries are moving rapidly to establish standards for formaldehyde concentrations in indoor air. In July 1978, the Netherlands established a standard of 120 μg/m^3 as the maximum permissible indoor concentration[10] and Denmark, Sweden, the United States and West Germany are considering similar action.

Indoor measurements of formaldehyde levels reported from Denmark, Sweden, West Germany and the U.S. were frequently found in excess of the recommended indoor standards of 120 μg/m^3 and, in several cases, exceeded the Threshold Limit Value (2400 μg/m^3) for workroom air.[5] In general, these studies showed that several recently constructed residential buildings and mobile homes with air exchange rates less than 0.3 ach exhibited high formaldehyde concentrations (>120 μg/m^3).

Formaldehyde and total aliphatic aldehydes (formaldehyde plus other aliphatic aldehydes) have been measured by LBL at several energy-efficient research houses at various geographic locations in the U.S. Figure 1 shows a histogram of frequency of occurrence of concentrations of formaldehyde and total aliphatic aldehydes measured at an energy-efficient house with an air exchange rate of 0.2 ach. Data taken at an energy-efficient house in Mission Viejo, California, are shown in Table 3. As shown, when the house did not contain furniture, formaldehyde levels were below 120 μg/m^3; when furniture was added, formaldehyde levels rose to almost twice the 120 μg/m^3 level. A further increase was noted when the house was occupied, very likely because of such activities as cooking with gas. When occupants opened windows to increase ventilation, the formaldehyde levels dropped substantially.

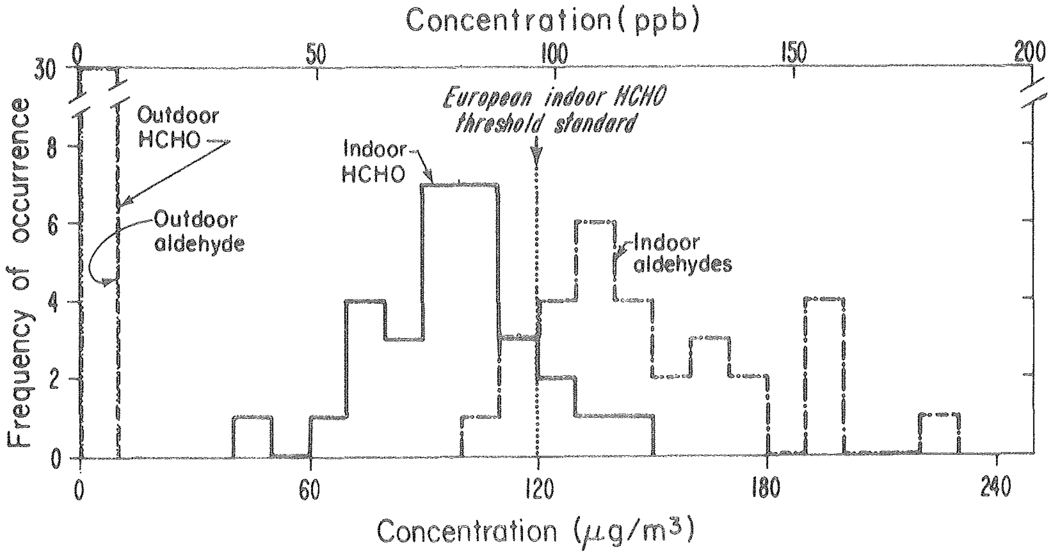

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Figure 1. Histogram of indoor and outdoor formaldehyde and total aliphatic aldehyde concentrations measured at an energy research house in Maryland during March and April 1979. The air exchange rate of the house is about 0.2 ach.

Table 3.

Indoor/Outdoor Formaldehyde And Aliphatic Aldehyde Concentrations Measured at The Med-II Residence August 1979

Condition	Number of Measurements	Sampling Time	Formaldehyde ($\mu g/m^3$)[a]	Aliphatic Aldehydes ($\mu g/m^3$)[b]
Unoccupied, without furniture	3	12	80 ± 9%	90 ± 16%
Unoccupied, with furniture	3	24	223 ± 7%	294 ± 4%
Occupied, day[c]	9	12	261 ± 10%	277 ± 15%
Occupied, night[d]	9	12	140 ± 31%	178 ± 29%

a Determined using pararosaniline method (120 $\mu g/m^3 \approx 100$ ppb). All outside concentrations $< 10\ \mu g/m^3$.

b Determined using MBTH method, expressed as equivalents of formaldehyde. All outside concentrations $< 20\ \mu g/m^3$.

c Air exchange rate ≃ 0.4 ach.

d Windows open part of time; air exchange rate significantly greater than 0.4 ach and variable.

Radon

Radon and its decay daughters are known to comprise a significant portion of natural background radiation to which the general population is exposed. Radon-222 is an inert, radioactive, naturally occurring gas which is part of the uranium-238 decay chain. Any substance that contains radium-226, the precursor of radon, is a potential emanation source. Since radium is a trace element in most rock and soil, sources of indoor radon include building materials, such as concrete or brick, and the soil under building foundations. Tap water may be an additional source if taken from wells or underground springs. Scattered observations have shown that indoor concentrations of radon and radon daughters are typically higher than outdoor concentrations, presumably because the building structure serves to confine radon entering the indoor environment from various sources. Conservation measures, particularly reduced air-exchange rates, may exacerbate this situation.

Figure 2 summarizes and compares radon concentrations in outdoor and indoor air at different geographic sites. What becomes evident from this figure is that indoor levels exceed outdoor levels in each case presented, and that houses built on phosphate-reclaimed land in Florida show radon levels above health guidelines[11].

A simple populations-at-risk model based on the "linear hypothesis" that risk is directly proportional to dose suggests an added annual risk of 50 to 110 cases of lung cancer per million based on an average concentration of 1 nCi/m^3 of radon[12]. Based on the above estimates of risk, life-time exposures to a few nCi/m^3, which might be the case with low air exchange rates (<0.3 ach), could yield increased lung cancer incidence equal to the observed rate for male non-smokers.

Since we do not yet know enough about the actual dose-response characteristics of low-level radiation exposure, we cannot say with certainty whether there is any added risk from a life-time exposure to a few nCi/m^3. However, use of a linear hypothesis model is considered prudent for radiation protection purposes until we do have a better understanding of the dose-response characteristics of radiation exposure.

LBL has conducted measurements of radon levels in energy-efficient buildings throughout the United States. For these studies, grab samples were taken with all doors and windows closed, in order to simulate worst-case conditions. Results indicate that houses with low air exchange rates (<0.3 air changes per hour) often have higher radon concentrations than conventional houses (~0.75 air changes per hour).

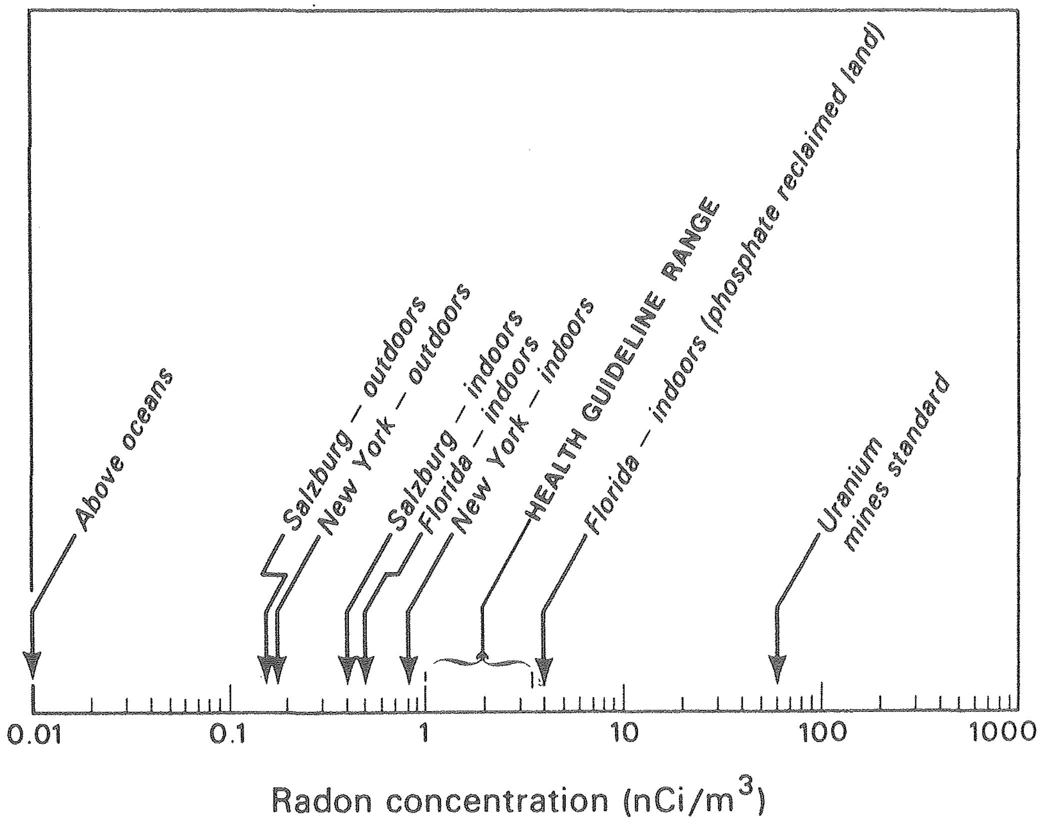

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Figure 2. Radon concentrations in air. The numbers for New York, Salzburg, and Florida are geometric means of the average for each site sampled. The value given as the uranium mines standard is calculated (asuming an equilibrium fraction of 0.5) from the annual dose limit for occupational exposures of 4 WLM. The health guidelines apply to houses built on land reclaimed from phosphate strip mining in Florida, and houses in four communities associated with uranium mining and processing in Canada.[12]

Figure 3 is a scatter plot of radon concentration vs. ventilation rate in a number of energy-efficient houses. While the data show considerable scatter, a correlation between radon concentration and air change rate is apparent. An air-exchange rate of approximately 0.5 ach is required in order to maintain radon concentrations below 4 nCi/m^3, the maximum permissible concentration allowed by present U.S. health guidelines. Integrated measurements or large numbers of grab samples need to be made under typical living conditions and various climatic conditions before we can reasonably estimate average exposures of building occupants.

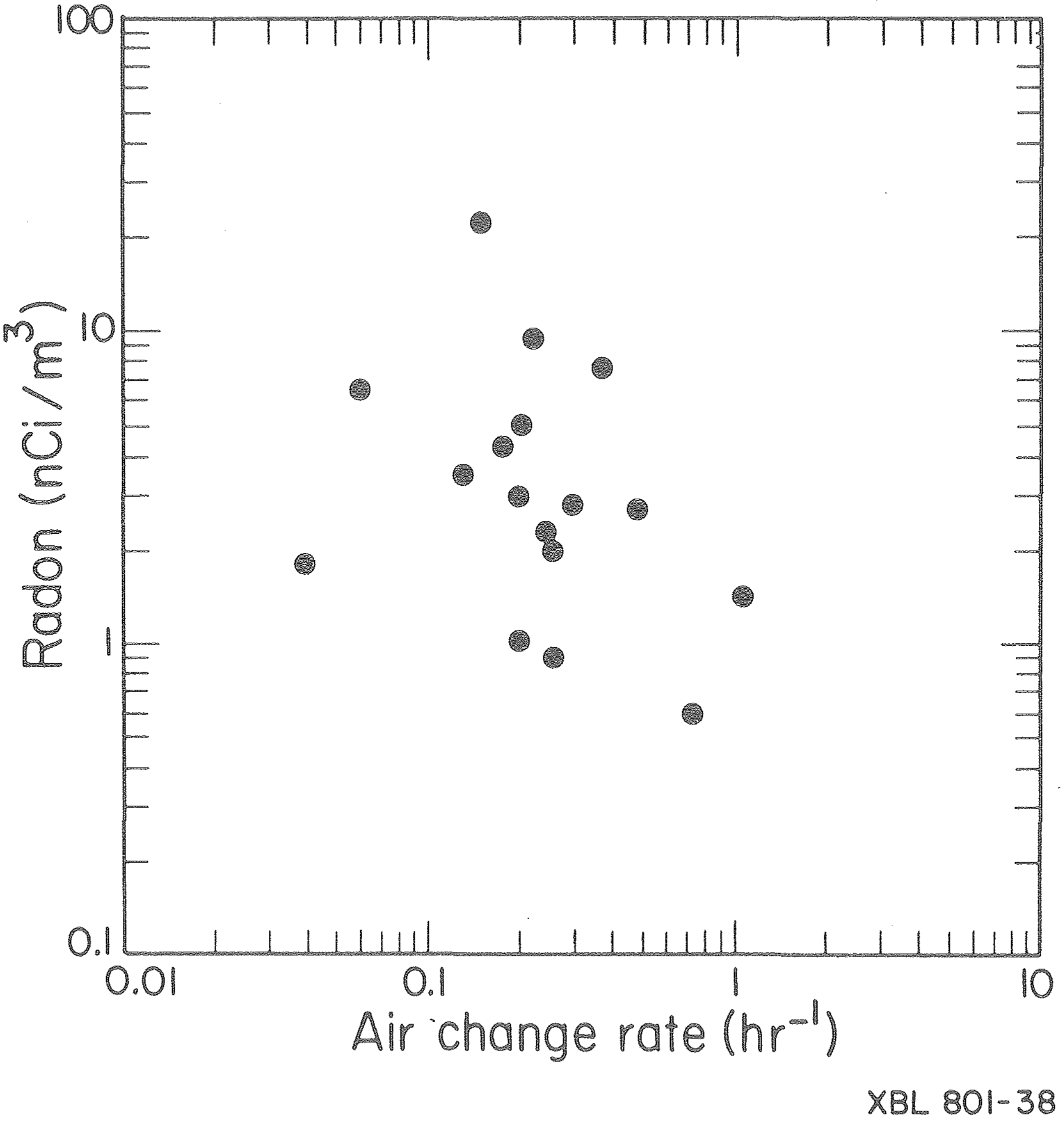

Figure 3. Radon Concentration vs. Ventilation in Energy Efficient Houses.

CONCLUSIONS

Indoor air contaminant levels are strongly affected by human activities and the manner in which materials are incorporated into buildings, as well as other aspects of building design, particularly the infiltration or ventilation rates.

Our work to date indicates that indoor air pollution may affect human health and, if this assumption is borne out by further studies, it may ultimately have a large impact on energy conservation strategies for buildings and on the need for more stringent control of air pollution from indoor sources. There are several measures that might be adopted to limit increases in indoor air pollution in both conventional and energy-efficient buildings. Options include an informed selection of building materials; coating of various building materials with sealants to reduce emissions of potentially harmful pollutants; the use of mechanical ventilation/heat exchanger systems; and the use of contaminant control devices.

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