LBL-9379
EEB-Vent 79-9
CONF-791009--1

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

ENERGY & ENVIRONMENT DIVISION

To be presented at the International Conference on Energy Use Management, Los Angeles, CA, October 22-26, 1979

MASTER

IMPACT OF ENERGY CONSERVATION IN BUILDINGS ON HEALTH

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June 1979

Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

To be presented at the International Conference on Energy Use Management, Los Angeles, October 22-26, 1979

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ABSTRACT

The levels of air contaminants inside buildings are often higher than outdoor ambient levels. Interest in conserving energy has been motivating home-owners and builders to reduce infiltration and ventilation in buildings. However, the resulting decrease of indoor/outdoor air exchange may increase the concentrations of many contaminants having indoor sources. Four indoor contaminants - carbon monoxide and nitrogen dioxide from gas stoves; formaldehyde from gas stoves, particleboard, plywood and urea-formaldehyde foam insulation; and radon from various building materials - are currently receiving considerable attention in the context of the potential health risks that are associated with reduced infiltration and ventilation rates. It is likely that some increased health risk will accompany an increase in indoor contaminant exposure; hence, it is desirable not to allow these concentrations to rise above human tolerance levels. There are several possible ways of circumventing increased health risks without compromising energy conservation considerations.

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

INTRODUCTION

Reduced infiltration and ventilation rates in buildings can lead to elevated levels of indoor generated air contaminants [1]. Chemical and biological contaminants released into indoor environments are undesirable but often unavoidable by-products of human activity, building materials and/or furnishings within enclosed spaces. Indoor contaminants include a wide spectrum of gaseous, particulate, and even radioactive pollutants. Indoor contaminants and their sources 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 (including pets), odor-masking chemicals used in several activities, and a wide assortment of chemicals released from indoor construction materials and furnishings.

When these contaminants are generated in indoor environments in excessive concentrations, they may impair the health, safety, or comfort of the occupants. Building occupants are normally protected from the accumulation of undesirable indoor air contaminants in two ways: the random introduction of outdoor air by infiltration (through cracks in the building envelope); and regulated introduction by natural ventilation (opening windows and doors) or mechanical ventilation (fan and duct systems of varying complexity).

Ventilation with outside air or recirculated air serves a variety of purposes. Among these are:

1) Removal of excessive heat and moisture generated by internal sources.

2) Establishment of a satisfactory balance between the metabolic gases (oxygen and carbon dioxide) in the occupied environment.

3) Dilution of human and nonhuman odors to levels below an acceptable olfactory threshold.

4) Dilution of contaminating toxic chemicals and viable microorganisms from indoor sources.

The United States has begun to examine its energy use because of rising concern about the availability of conventional energy resources. Because of the increased interest in energy conservation, measures are being taken to make buildings more energy-efficient. These include measures to conserve the energy used in the heating and cooling of buildings such as tightening the building envelope to reduce exfiltration and infiltration, improving insulation, and reducing ventilation. As these measures are implemented and less fresh air is introduced into buildings, the quality of the indoor air may deteriorate. Unfortunately, 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.

Ventilation standards for buildings with different functional uses have been in existence for over a half century. In general, they do not take energy conservation requirements into consideration and, since they have been established by a variety of groups, they frequently vary for the same application. A comprehensive effort is now underway at several institutions in the United States and Europe to establish a scientific basis for existing standards, to measure the actual levels of indoor air contaminants in several categories of buildings, and to provide a consistent set of recommendations for the establishment of energy-efficient ventilation standards in residential, institutional and commercial buildings.

Currently, there is incomplete information for determining the indoor air quality criteria required for establishing ventilation requirements in buildings. This information gap is due in large measure to the complex nature of indoor air pollution. In particular, the complex biological, chemical and physical mix of indoor air pollutants has been recognized only recently. Most studies of indoor air pollution to date have largely assumed that indoor pollution arises from and is directly related to outdoor sources. It is now recognized that a number of indoor air contaminants sources can be traced to the built environment itself.

The following discussion highlights four indoor-generated contaminants 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 residential buildings, as well as the added risks engendered by pursuing various strategies of reduced infiltration and ventilation are discussed.

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DISCUSSION

Gas Stove Emissions: Carbon Monoxide, Nitrogen Dioxide and Formaldehyde

Several recent field and laboratory studies have focused on combustion-generated indoor air pollution, namely air contaminants from gas stoves and heating systems in residential buildings. Field studies have shown that levels of carbon monoxide (CO) and nitrogen dioxide (NO_2) approach or exceed existing U.S. ambient outside air quality standards in some residential buildings with gas appliances [2]. Nitrogen dioxide levels in kitchens of houses with gas stoves were observed to be as high as 0.5 ppm (~950 $\mu g/m^3$) with one top burner operating for less than 30 minutes and as high as 0.8 ppm (~1500 $\mu g/m^3$) with the oven operating for 20 minutes. Concentrations of NO_2 were observed to be as high as 0.6 ppm (~1200 $\mu g/m^3$) for 8 hours in the bedroom of a house with a forced-air gas-fired heating system operating under normal conditions. These NO_2 concentrations can be compared with the short-term U.S. and foreign NO_2 ambient outside air quality standards [approximately 0.25 ppm (~470 $\mu g/m^3$) for 1 hour] [3-6].

Studies using an experimental room with a volume of 800 ft^3 (27 m^3) have characterized the emissions from a new gas stove operating in this room with air exchange rates varying from 0.25 to 10 air changes per hour (ach) [7]. These laboratory studies have shown that gas stoves generate extremely high emissions of such species as carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2),

Table I Contaminant Concentrations in a Test Kitchen

Ventilation Conditions	Mechanical Ventilation Rate (cfm)	Air Exchange Rate (ach)	Contaminant Concentrations[a] CO ($\mu g/m^3$)	NO_2 ($\mu g/m^3$)	HCHO[b] ($\mu g/m^3$)
No stove vent or hood		0.25	35	2400	400
Hood vent (with no fan) above stove		1.0	25	1600	260
Hood vent with fan at low speed	50	2.5	13	800	140
Hood vent with fan at high speed	140	7.0	3	200	35
	Typical Outdoor Concentrations During Test		1.5	50	10
	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	30-50 cfm (Standard 62-73)			
		20 cfm (Standard 90-75)			

a 1 hour average concentration in center of kitchen in which gas oven is operated at 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)

formaldehyde (HCHO), and respirable aerosols (size < 2.5 μm), and that the concentrations of these species become significant when the air exchange rate is controlled to less than 1 ach. Table I gives the one-hour average CO, NO_2 and HCHO concentrations in the experimental room. The ASHRAE ventilation requirements [8] for residential buildings are also given. Particularly noteworthy is the observation that a kitchen ventilation rate of 50 cfm (the upper limit as recommended by ASHRAE Standard 62-73) appears to maintain CO concentrations at acceptable levels, but results in NO_2 and HCHO concentrations which exceed air quality health standards [1]. Lower ventilation rates (recommended by ASHRAE Standard 90-75) result in even higher NO_2 and HCHO concentrations. A ventilation rate of at least 100 cfm is required to keep NO_2 and HCHO concentrations to levels within the limits established by air quality health standards.

A recent study in England [9] has compared respiratory illness of children living in homes in which natural gas and electric stoves were used. The investigators concluded that elevated levels of nitrogen dioxide from gas stoves might have caused the increased levels of respiratory illness found to be associated with homes using gas stoves. A study in progress in six cities in the United States has reached similar conclusions in its preliminary analysis [10].

The work to date indicates that combustion-generated indoor air pollution may affect human health in buildings, and if borne out by further work, 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 combustion sources.

Formaldehyde

Formaldehyde (HCHO) is an inexpensive, high volume chemical which is used throughout the world in a variety of products, mainly in urea, phenolic, melamine and acetal resins. These resins are used in large quantities in building materials such as insulation, particleboard, plywood, textiles, adhesives, etc.

Formaldehyde has a pungent and characteristic odor which can be detected at levels well below 0.5 ppm (~600 $\mu g/m^3$) by most humans. Formaldehyde toxicity is evidenced on contact with the skin and the mucous membranes of the eyes, nose and throat. Exposure to formaldehyde may cause burning of the eyes, weeping, and irritation of the upper respiratory passages. High concentrations (>few ppm) may produce coughing, constriction in the chest, and a sense of pressure in the head. Several studies reported in the literature indicate that swelling of the mucous membranes begins in the range of 0.05 to 0.1 ppm, depending on individual sensitivity and environmental conditions (temperature, humidity, etc.). Formaldehyde may also have serious long term health effects which are currently not well understood. Reviews of the disease effects of formaldehyde are given in a recent EPA report [11], work reported in Denmark [12], and recent studies carried out in Sweden [13,14]. European countries are moving rapidly to establish formaldehyde standards. In July 1978, the Netherlands established a standard of 0.1 ppm (120 $\mu g/m^3$) as the maximum permissible concentration [15]. Denmark, Sweden, and West Germany are all considering establishing a standard at approximately the same value (0.1 ppm).

Indoor sources of formaldehyde include combustion processes (gas cooking and heating appliances, tobacco smoking) and various building materials. Particleboard and urea-formaldehyde foam insulation have recently received the most attention, although many other building materials which contain formaldehyde through the use of phenolic- and urea-formaldehyde resins and are also potential indoor formaldehyde sources.

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In the case of formaldehyde emissions from particleboard, limited measurements in Denmark [16], Sweden [13,14,17], West Germany [18,19,20] and the U.S.A. [21] have shown that indoor concentrations often exceed the recommended ambient and indoor standards of 0.1 ppm and in several cases even exceed the Threshold Limit Value (~2 ppm) for workroom air [1]. In twenty-three Danish houses, the average formaldehyde concentration was 0.62 $\mu g/m^3$ (~0.5 ppm) and the range was 0.08-2.24 $\mu g/m^3$ (~0.07-1.9 ppm) [16]. Formaldehyde measurements in more than 200 mobile homes in the U.S. ranging from 0.03 to 2.4 ppm (~0.08-2.9 $\mu g/m^3$) have been reported in cases where occupants have complained about indoor air quality [21].

Formaldehyde and total aliphatic aldehydes (formaldehyde plus other aliphatic aldehydes) have been measured by Lawrence Berkeley Laboratory at several energy-efficient research houses at various geographic locations in the U.S. It has been found that at low ventilation rates (<0.3 ach), the indoor formaldehyde and aldehyde concentrations often exceeded the promulgated European indoor formaldehyde standard of 0.1 ppm. The outdoor concentrations during these studies were typically 0.016 ppm (20$\mu g/m^3$) or less. 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.

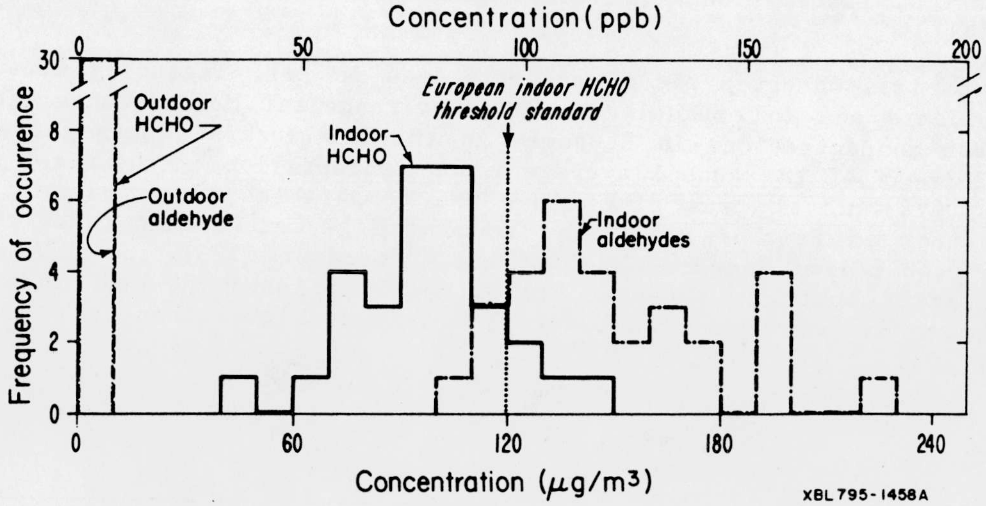

Fig. 1 Indoor/Outdoor Formaldehyde and Aldehyde Concentrations.

At a public school in Columbus, Ohio, and a large medical center in Long Beach, California, indoor and outdoor formaldehyde/aldehyde concentrations were about the same and were well below the 0.1 ppm (120$\mu g/m^3$) standard. High ventilation rates in these public buildings are the most probable reason for the similar indoor and outdoor concentrations.

Field tests and a mathematical model indicate the half life for formaldehyde found in particleboard typically used in Scandinavian home construction is about two years with a ventilation rate of 0.3 ach [17]. The formaldehyde problem cannot be solved by use of ventilation alone over a short period. However, it has been shown that the level of HCHO can be reduced to half of the original value by chemical treatment or coating with a formaldehyde absorbent paint [17].

It is evident that indoor air, in general, has higher formaldehyde and aldehyde levels than outdoor air. Results show that, in particular, residential buildings, mobile homes and office trailers have indoor formaldehyde and aldehyde concentrations that can exceed known health effect thresholds.

Radon

Radon and its decay daughters are known to contribute a significant portion of natural background radiation exposure to the population. 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 lead to elevated radon concentrations, resulting in increased radiation exposure of occupants.

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. Figure 2 illustrates the primary pathways by which radon from soil and building materials enters a building. The relative importance of these pathways depends on the specific location, design, fabrication techniques, and construction materials used in a given building.

Figure 3 summarizes observed radon concentrations in air, including measurements of radon outdoors and in houses. The DOE Environmental Measurements Laboratory measured radon concentrations in 21 homes in the New York/New Jersey area [22]. The geometric mean of the annual average radon concenration on the first floor of these homes, 0.83 nCi/m^3, was five times the comparable ambient level of 0.18 nCi/m^3. A study in Salzburg, Austria, found the geometric mean radon concenrations to be 0.42 nCi/m^3 indoors and 0.16 nCi/m^3 outdoors [23]. An EPA study of houses in Florida built on phosphate reclaimed land found the mean indoor radon concentration to be 4.0 nCi/m^3, an order of magnitude higher than in other houses in the state [24].

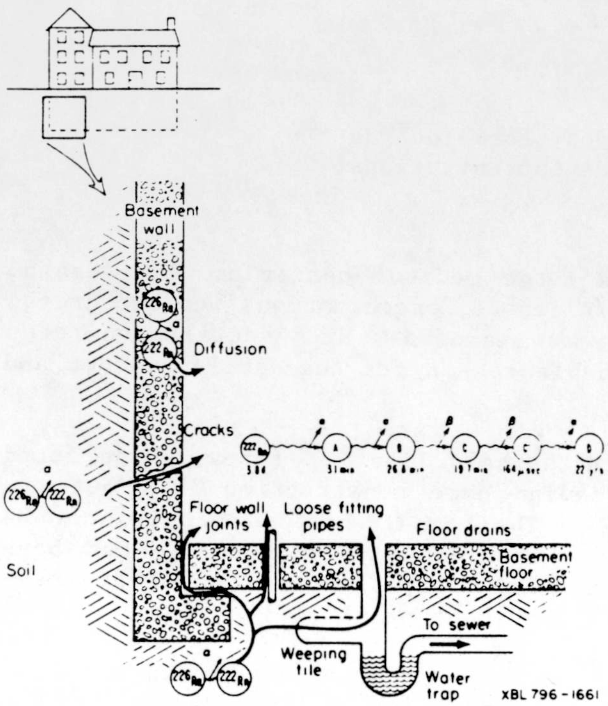

Fig. 2 Primary Pathways for Radon Entry in Buildings.

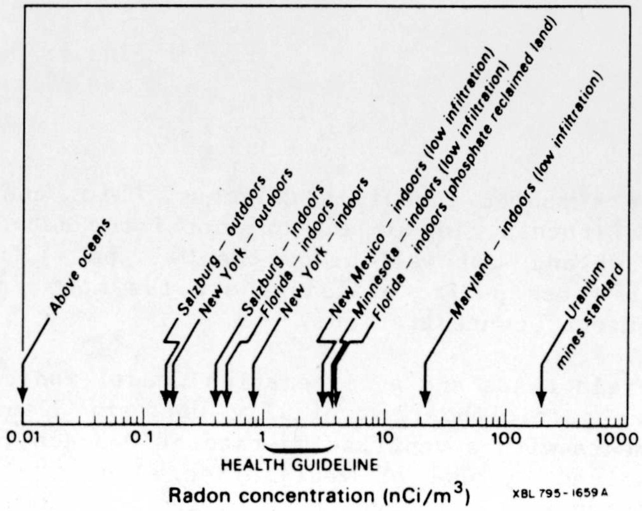

Fig. 3 Radon Concentrations in Air.

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The Lawrence Berkeley Laboratory has conducted measurements of radon levels in energy efficient buildings in Maryland, Minnesota and New Mexico. Results indicate that houses with low air exchange rates (<0.3 air changes per hour) seem to have higher radon concentrations than conventional houses (~0.75 air changes per hour). Figure 4 is a scatter plot of radon concentration vs. ventilation rate in a number of energy efficient houses. The data shows considerable scatter; however, a correlation betwen 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 given by health guidelines. The data reported here is based on grab samples taken on mild days (low wind and small indoor and outdoor temperature differences) with all doors and windows closed, resulting in a worst case estimate. These houses are expected normally to have higher ventilation rates and, therefore, lower radon concentrations. Integrated measurements of large numbers of grab samples under typical living conditions and various climatic conditions are necessary to determine average exposures of building occupants under various ventilation conditions.

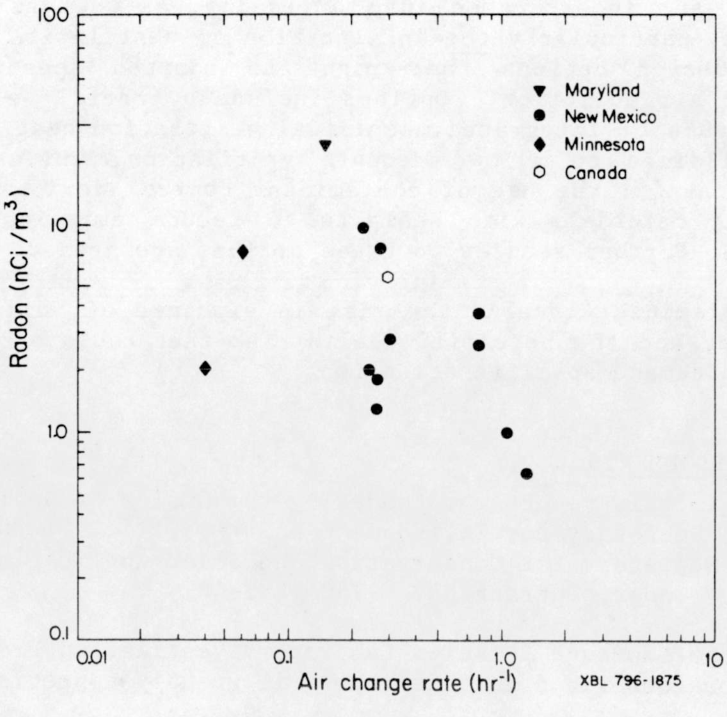

Fig. 4 Radon Concentration vs. Ventilation in Energy Efficient Houses

A simple populations-at-risk model based on a "linear hypothesis" that risk is directly proportional to dose suggests an added annual risk of 40 to 300 cases of lung cancer per million based on an average concentration of 1 nCi/m^3 of indoor radon [26]. In the United States, the 45-64 year age group is at highest risk to lung cancer. Annual incidence rates during 1969-1971 for this age group were 1200 cases per million for white males and 300 cases per million for white females [27]. Although precise quantification of lung cancer is difficult, tobacco smoking is generally thought to be causally associated with 80% or more of the male cases. Presumably, the same relationship holds for females. Based on the above estimates of risk due to exposure to 1 nCi/m^3, 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 characterisitics of radiation exposure.

CONCLUSIONS

Rising energy prices have generated a financial incentive to reduce ventilation rates and thereby reduce heating and cooling losses in buildings. Measures presently under consideration that would reduce infiltration and ventilation in buildings could significantly increase exposure to indoor contaminants and perhaps have adverse effects on occupant comfort and health.

Indoor contaminant levels are strongly affected by human activities and the manner in which materials are incorporated into a builing, as well as other aspects of the building design, particularly the infiltration or ventilation rate. There are several building design options that might be adopted specifically to limit increases in indoor air pollution. Options include a careful selection of building materials; the use of integrated mechanical ventilation/heat exchanger systems in residential buildings to allow adequate ventilation, while recovering heat losses from air exchange; the use of contaminant control devices; and the coating of various building materials with sealants to reduce emissions of potentially harmful pollutants. Further studies on these options are needed.

The increase in contaminant levels, the rise in exposure of building occupants to indoor contaminants, and the potential health risk that could occur as a result of reduced ventilation demand specific attention.

ACKNOWLEDGEMENTS

The work described in this report was funded by the Office of Health and Environmental Research, Assistant Secretary for Environment and the Office of Buildings and Community Systems, Assistant Secretary for Conservation and Solar Applications of the U.S. Department of Energy under contract No. W-7405-ENG-48.

The assistance of the Lawrence Berkeley Laboratory Ventilation Program staff in the experimental work described in this report is greatly appreciated.

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