Impact of Reduced Infiltration and Ventilation on Indoor Air Quality

Air contaminant levels inside buildings are often higher than ambient outdoor levels. Interest in conserving energy has motivated property owners and builders to reduce infiltration rates in residential buildings and to reduce ventilation rates in institutional and commercial buildings. However, the resulting decrease of indoor/outdoor air exchange will tend to increase the concentration of many indoor air pollutants. 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.

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REDUCED infiltration and ventilation rates in buildings, proposed as important energy conservation measures, can lead to elevated levels of indoor-generated air contaminants that may impair the health, safety, or comfort of occupants. Typical indoor contaminants include gaseous and particulate pollutants from indoor combustion processes (such as cooking, heating, tobacco smoking), toxic chemicals and odors from cleaning activities, odors and viable microorganisms from humans, odor-masking chemicals used in several activities, and a wide assortment of chemicals released from indoor construction materials and furnishings. Table 1 lists some of the major indoor air pollutants and their sources in residential buildings.

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The random introduction of outdoor air by infiltration (through cracks in the building envelope), or its regulated introduction by natural ventilation (opening doors and windows) or mechanical ventilation (fan and duct systems of varying complexity), is the usual way in which occupants are protected from the accumulation of undesirable indoor air contaminants. The primary engineering control for the maintenance of indoor air quality is mechanical ventilation, *i.e.*, the use of controlled flows of air to lower the levels of air contaminants by 1) dilution with fresh outside air; 2) the use of recirculation systems incorporating chemical and physical contaminant control devices; or 3) a combination system employing both dilution and recirculation.

Ventilation standards for buildings with different functional uses have been in existence for over half a century; however, because these standards have been established by a variety of groups, they frequently vary for the same application. A comprehensive effort is now underway by several laboratories in the U.S. and Europe to establish a scientific basis for ventilation requirements, to measure the actual levels of indoor air contaminants in several classes of buildings, and to provide a set of recommendations for energy efficient ventilation standards in residential, institutional and commercial buildings which are consistent with human health, safety and comfort criteria.

Most studies of indoor air pollution have assumed that indoor pollution arises from and is directly related to outdoor sources. Such studies have been concerned mainly with SO_2, O_3, CO, and total suspended particulates. They have found, in general, that the concentrations of these species in indoor air are lower than in outdoor air. Surprisingly little work has been concerned with other potentially important indoor air pollutant species, such as NO_2, organics, and the respirable fraction of the particulate matter. Furthermore, a number of air contaminant sources exist within buildings which can be traced to the built environment itself. These sources and their emissions have, until quite recently, been neglected in most indoor air pollution studies.

The following discussion highlights three indoor- generated contaminants of particular concern in residential buildings: nitrogen dioxide (NO_2), formaldehyde (HCHO), and radon (Rn).* 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.

Table 1
Indoor Air Pollution in Residential Buildings

Sources	Pollutant Types
OUTDOOR	
Ambient Air	SO_2NO, NO_2, O_3, Hydrocarbons, CO, Particulates
Motor Vehicles	CO, Pb
INDOOR	
Building Construction Materials	
Concrete, stone	Radon
Particleboard	Formaldehyde
Insulation	Formaldehyde, Fiberglass
Fire Retardant	Asbestos
Adhesives	Organics
Paint	Mercury, Organics
Building Contents	
Heating and cooking combustion appliances	CO, SO_2, NO, NO_2, Particulates
Furnishings	Organics, Odors
Water service; natural gas	Radon
Human Occupants	
Metabolic activity	CO_2, NH_3, Organics, Odors
Human Activities	
Tobacco smoke	CO, NO_2, HCN, Organics, Odors
Aerosol Spray devices	Fluorocarbons, Vinyl Chloride
Cleaning and cooking products	Hydrocarbons, Odors, NH_3
Hobbies and crafts	Organics

DISCUSSION

Gas Stove Emissions: Nitrogen Dioxide and Carbon Monoxide— Several recent field and laboratory studies have focused on 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.[1] Nitrogen dioxide levels in kitchens of houses with gas stoves were observed to be as high as 0.5 ppm with one top burner operating for less than 30 minutes and as high as 0.8 ppm with the oven operating for 20 minutes. These NO_2 concentrations can be compared with the short-term U.S. and foreign NO_2 ambient outside air quality standards of ~0.2-0.4 ppm for 1 hour.[2]

Studies have characterized the emissions from a new gas stove operating in an experimental room with air exchange rates from ¼ to 10 air changes per hour (ach).[2] These laboratory studies have shown that gas stoves generate extremely high emissions of such species as CO, NO, NO_2, and respirable aerosols (size < 2.5 um), and that the concentrations of these species become significant when the air exchange rate is controlled to less than 1 ach. Fig. 1 and 2 illustrate the levels of CO and NO_2 observed in the experimental room at ventilation rates ranging from 0.24 to 7.0 ach, with the oven of the gas stove operated at 350°F (~ 180°C) for one hour. The CO concentration exceeds the 1-hour ambient outside air quality standard only under "tight" conditions (0.24 ach); but the NO_2 concentration exceeds the recommended 1-hour standard, even with an air exchange rate as high as 2.5 ach. With a ventilation rate of 50 cfm (the upper limit of the recommended kitchen ventilation rate given in ASHRAE Standard 62-73)[3], the NO_2 concentration is approximately 0.4 ppm/hour, a value considerably higher than the promulgated standards. Lower ventilation rates (corresponding to the minimum values given in ASHRAE Standard 62-73) result in even higher NO_2 concentrations.

A recent study in England has reported that 2554 children living in homes in which natural gas was used for cooking had a greater incidence of respiratory illness than did 3204 children from homes in which electric stoves were used.[4] The investigators concluded that elevated levels of nitrogen dioxide from gas stoves might have caused the increased levels of respiratory illness.

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 odor which can be detected at levels well below 1 ppm 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 membrances begins in the range of 0.05 to 0.1 ppm, depending on individual sensitivity and environmental conditions (temperature, humidity, etc.). Reviews of the disease effects of formaldehyde are given in a recent EPA report[5] and work reported in Denmark.[6] 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. Denmark, Sweden, and West Germany are all considering establishing a standard at approximately the same value (0.1 ppm).[7]

* See article on p. 30

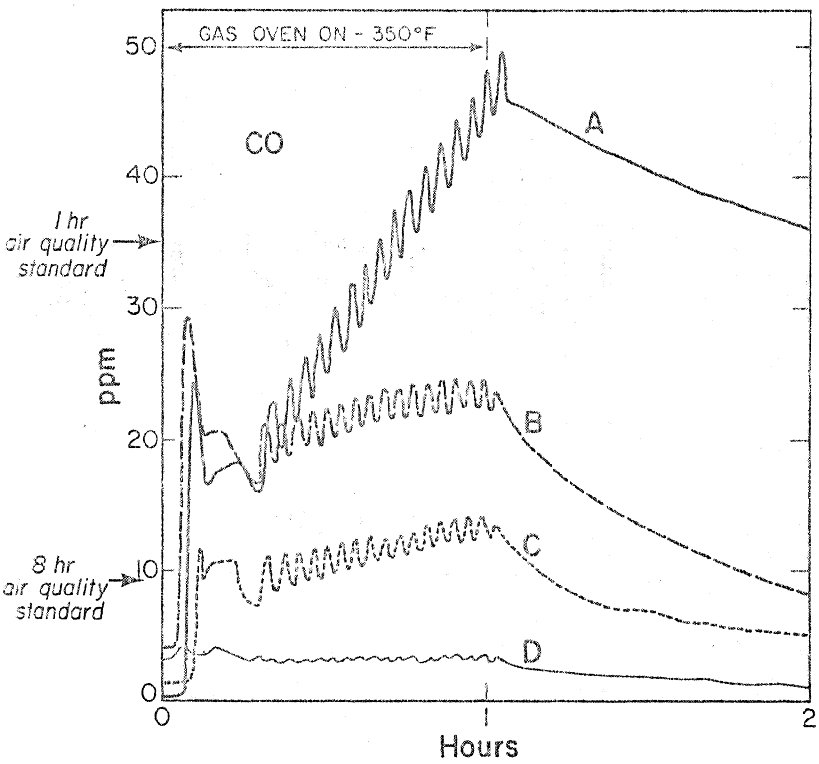

Fig. 1 Carbon monoxide concentrations in a 27m³ (950 ft³) experimental room with the gas oven operated for 1-hour at 180°C (350°F). Experiments were conducted under the following air changes per hour (ach):
A = 0.24 ach (No stove vent)
B = 1.0 ach (With hood vent above stove)
C = 2.5 ach (Stove hood with fan at 50 cfm)
D = 7.0 ach (Stove hood vent with fan at 140 cfm)

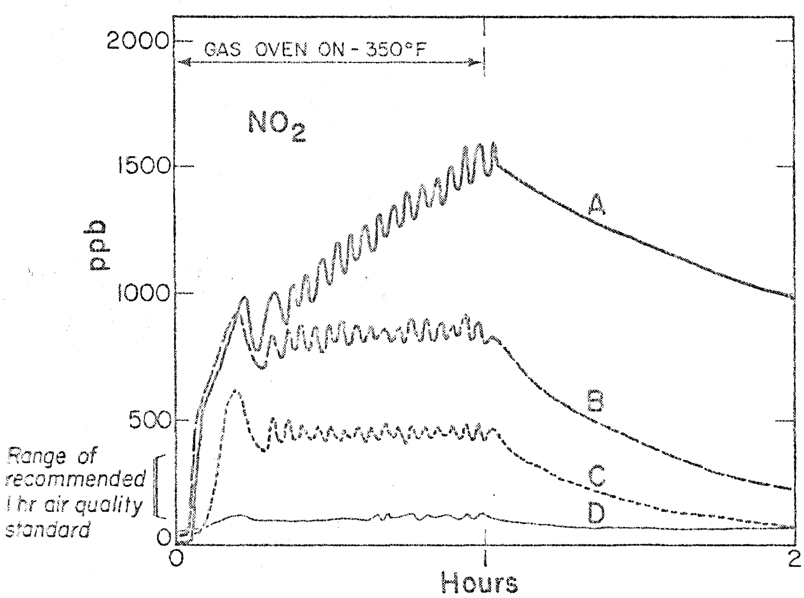

Fig. 2 Nitrogen dioxide concentrations in a 27m³ (950 ft³) experimental room with the gas oven operated for 1-hour at 180°C (350°F). Experiments were conducted under the following air changes per hour (ach):
A = 0.24 ach (No stove vent)
B = 1.0 ach (With hood vent above stove)
C = 2.5 ach (Stove hood with fan at 50 cfm)
D = 7.0 ach (Stove hood vent with fan at 140 cfm)

Particleboard is a commonly used construction material made of wood-shavings held together with a urea-formaldehyde (UF) resin, and may emit formaldehyde for a long period of time. In dwellings where it is used for furniture, partition walls, etc., the emission may reach significant levels and even exceed the Threshold Limit Value.* The emission rate varies as a function of several parameters, such as the original manufacturing process, quality control of fabrication, porosity, humidity, cutting of the board for final use, etc., as well as the infiltration and ventilation rates.

Recently, considerable concern has been raised regarding the use of UF based foam insulation materials because of the high emanation rate of formaldehyde gas. There are no well documented studies in the United States on formaldehyde emissions from UF foam; however, indoor formaldehyde concentrations exceeding 1 ppm have occasionally been reported for houses retrofit with UF foam. Detailed examination of the emission of formaldehyde from UF foam is currently underway.

In the case of formaldehyde emissions from particleboard, limited measurements, taken in residential buildings and mobile homes, in Denmark, Sweden, West Germany and the U.S. have shown that indoor concentrations often exceed the recommended ambient and indoor standards of 0.1 ppm, and, in several cases, even exceed the TLV standards for work-room air. In twenty-three Danish houses, the average formaldehyde concentration was 0.5 ppm (0.62 mg/m³) and the range was 0.07-1.9 ppm (0.08-2.24 mg/m³).[9] Formaldehyde measurements in more than 200 mobile homes in the U.S. ranging from 0.03 to 2.4 ppm have been reported in cases where occupants have complained about indoor air quality.[10]

For comparison, ambient outdoor formaldehyde measurements have been reported in a number of studies.[7]. Average formaldehyde concentrations in Los Angeles have been observed to be 0.04 ppm or lower. The peak one-hour formaldehyde concentrations in Los Angeles have been observed to be as high as 0.16 ppm while the maximum concentrations at four sites in New Jersey are reported to be in the range of from 0.014 to 0.020 ppm.

Radon— Radon-222 is an inert, radioactive, naturally occurring gas

*A Threshold Limit Value refers to an airborne concentration of a substance and represents a level under which it is believed that nearly all workers may be repeatedly exposed day after day without adverse effect.[8]

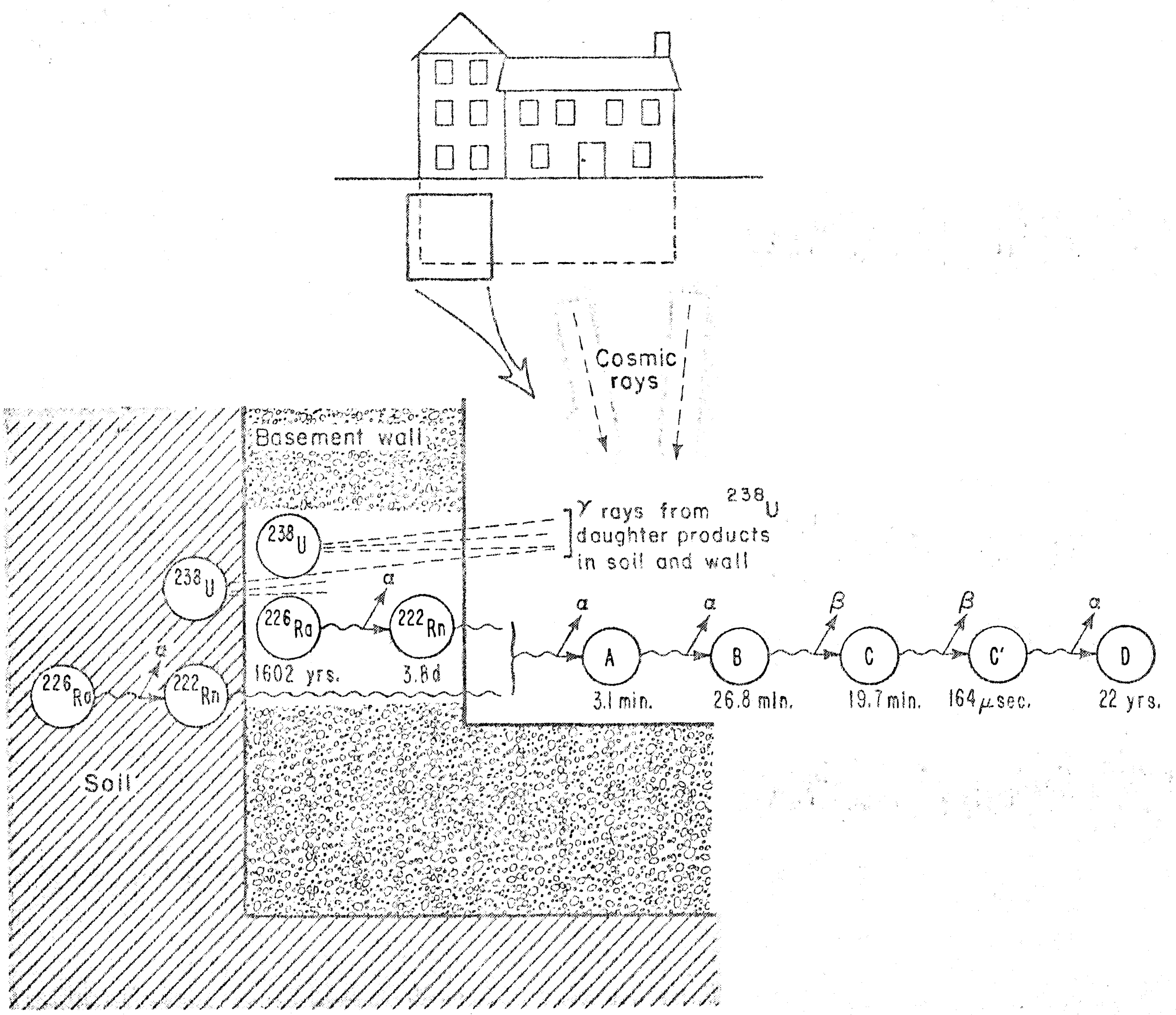

Fig. 3 Major sources of natural radiation in buildings. Radon pathways into the building include soil gas leakage through cracks in the basement floors and walls, and radon diffusion through and emanation from soil, concrete, and other building materials.

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-226 is a trace element in most rock and soil, indoor radon sources include concrete, brick, and other building materials. Radium-226 has a half life of 1602 years, so its presence in building materials results in a continuous source of radon for the life of the building. Another potentially significant source of radon in buildings is the soil beneath the foundation and tap water, especially if the water is taken from certain wells or underground springs. Fig. 3 illustrates major sources of radiation exposure in buildings.

The alpha decay of radium-226 produces a chemically inert, recoiling radon-222 atom which has a 3.8 day half-life. If the atom ends its recoil in an interstitial space of the solid source material, it may migrate to the surface and enter the air. Radon gas has four short-lived daughters which rapidly attach themselves by chemical or physical means to airborne particulates, generally less than a micron in size. These particulates, when inhaled, may be retained in the bronchi where the subsequent decays to lead-210 result in a radiation dose to the lung. The primary hazard is due to the alpha emissions of polonium-218 and polonium-214. Since alpha particles have a very short range (a few tens of microns), essentially all of the energy is deposited near the surface of the lung tissue.

Although the inert radon is not the principal health hazard in the decay chain, its concentration is a good indicator of exposure to the biologically important daughters. In the literature there are numerous examples of radon measurements showing higher indoor than outdoor concentrations. Recent measurements in the New York City area showed annual mean radon concentrations in 21 typical homes ranging from 0.2 to 3 nCi/m^3, with a geometric mean of 0.8 nCi/m^3.[11] For the same locations, outdoor concentrations were 0.1 to 0.2 nCi/m^3. Levels in Swedish homes of various construction were found to range from 1 to 12 nCi/m^3.[12] However, Swedish homes, with air exchange rates of about 0.2 to 0.8 ach[12,13], are tighter than typical U.S. homes where air exchange rates are on the order of 0.5 to 1.5 ach.[14]

The concentration of radon in indoor air depends on the emanation rate from the parent material and on the mechanisms for removal, including ventilation. Due to the fact that the vast majority of the population spends most of its time indoors, the total exposure of the general public to radon daughters will be largely determined by the elevated indoor concentrations.

A simple populations-at-risk model based on a "linear hypothesis" that risk is directly proportional to dose suggests an added annual risk of 20 to 200 cases of lung cancer per million based on an average concentration of 1 nCi/m^3 of indoor radon.[15] In the U.S., 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.[16] Although precise quantification 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 exposure to a few nCi/m^3, which might be the case with low air exchange rates (< 0.5 ach), could yield increased lung cancer incidence (~ 300 cases per million for exposure to 3 nCi/m^3) equal to the observed rate for 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 lifetime 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.

CONCLUSIONS

Because of increased energy prices, there are financial incentives to reduce air exchange rates and the resulting heat losses; but the possible increase in indoor contaminant levels requires considerable attention. Two regulatory approaches are possible for limiting exposure to indoor contaminants. One is to specify a maximum permissible level and to accept the disease incidence, if any, that may be associated with increases in contaminant levels to this limit. There is a precedent for selecting such a level in the setting of occupational exposure standards, and standards for the general public are sometimes selected by comparison with occupational standards. The other approach is to set standards based on an explicit comparison of the disease incidence that may be caused by increased indoor contaminant concentrations with the cost of preventing these increases. Such a comparison would be made considering the financial benefit to be gained from reduced energy usage, balanced with the adverse effects of increased indoor pollutant levels. A decision on this matter must be preceded by substantial work on characterizing both the sources of indoor contaminants and the impact of various building designs on indoor concentrations.

There are several design features that might be adopted specifically to limit increases in indoor contaminants:

- Mechanical ventilation could be coupled with an air-to-air heat exchanger to transfer heat (and not contaminated air) from the exhaust air to the fresh air stream in winter and vice versa in summer.

- Indoor air could be circulated through contaminant control devices (*e.g.*, electrostatic precipitators, particle filters, chemical adsorbents) substantially reducing the concentration of particulate and gaseous contaminants.

- Measures could be incorporated to seal or eliminate certain contaminants at the source. For example, radon from the soil could be reduced by crawl space ventilation. Walls or floors could be sealed with polymers. Building materials could be selected for low emanation rates.

The effectiveness and advisability of such measures depend on various circumstances, such as the type of building and the geographical location. At this time, however, insufficient information exists to provide a basis for a considered regulatory decision. The effects of elevated indoor contaminant levels are highly uncertain, and the impact of building energy conservation measures is not yet known in detail.

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