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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 ventilation in buildings may significantly increase exposure to indoor air pollution and perhaps have adverse effects on occupant health and comfort. Preliminary findings suggest that reduced ventilation may adversely affect indoor air quality unless appropriate control strategies are undertaken. The strategies used to control indoor air pollution depend on the specific pollutant or class of pollutants encountered, and differ somewhat depending on whether the application is to an existing building or a new building under design and construction. Whenever possible, the first course of action is prevention or reduction of pollutant emissions at the source. In most buildings, control measures involve a combination of prevention, removal, and suppression. Common sources of indoor air pollution in buildings, the specific pollutants emitted by each source, the potential health effects, and possible control techniques are discussed.

Keywords: air pollution, control, energy conservation, formaldehyde, indoor air quality, organics, radon, ventilation

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SUMMARY

Out of a national commitment to reduce the amount of energy consumed for heating and cooling buildings, we have been increasing insulation and tightening the building shell to enhance its thermal integrity. Such measures tend to reduce the ventilation air and thereby increase the levels of indoor pollutants. Indoor air quality is affected by a complex mix of pollutants whose sources are both outdoors and indoors. Those pollutants whose sources are indoors include carbon monoxide, nitrogen dioxide, formaldehyde, radon, and particulates. Since Americans spend 90% of their time indoors, it is essential that we assess the potential health risks of indoor air pollution, which means careful study of various issues related to indoor air quality including effective pollutant control strategies.

INTRODUCTION

All occupied buildings have various sources of indoor air pollution. Humans (and their household pets) generate carbon dioxide, moisture, odors, and microbes simply through normal living processes. Other more important sources of indoor air pollution are combustion appliances (gas stoves, unvented space heaters), building materials (used in construction, furnishings, and insulation), and soil under and around houses. These sources release carbon monoxide (CO), nitrogen dioxide (NO_2), formaldehyde (HCHO) and other organics, particulates, and radon. Table 1 summarizes the sources and types of air pollutants commonly found indoors.

Rising energy prices, among other factors, have generated an incentive to reduce ventilation rates in buildings as a means of reducing their heating and cooling costs. Preliminary research has shown that reduced ventilation can significantly increase the levels of indoor air pollutants and adversely affect occupant health and comfort unless appropriate control strategies are undertaken.

Table 1

SUMMARY OF SOURCES AND TYPES OF INDOOR AIR POLLUTANTS

SOURCES	POLLUTANT TYPES
OUTDOOR	
Stationary Sources	SO_2, CO, NO, NO_2, O_3, Hydrocarbons, Particulates
Motor Vehicles	CO, NO, NO_2, Lead, Particulates
Soil	Radon
INDOOR	
Building Construction Materials	
Concrete, Stone	Radon and Other Radioactive Elements
Particleboard	Formaldehyde
Insulation	Formaldehyde, Fiberglass
Fire Retardant	Asbestos
Adhesives	Organics
Paint	Organics, Lead, Mercury
Building Contents	
Heating and Cooking Combustion Appliances	CO, NO, NO_2, SO_2, Particulates
Copy Machines	Organics
Water Service; Natural Gas	Radon
Human Occupants	
Metabolic Activity	H_2O, CO_2, NH_3, Organics, Odors
Biological Activity	Microorganisms
Human Activities	
Tobacco Smoke	CO, NO_2, HCN, Organics, Odors Particulates
Cleaning and Cooking Products	Organics, Odors
Hobbies and Crafts	Organics, Odors

Most often, indoor air quality problems have been remedied by increasing the ventilation rate in the affected area; however, this remedy is in conflict with strategies for reducing energy consumption by lowering ventilation rates. To resolve this conflict, designers and occupants need to be informed about the sources and chemical characteristics of indoor air pollutants so that energy-efficient control strategies can be implemented for their prevention, suppression and/or removal.

The strategies used to control indoor air pollution depend on the specific pollutant or class of pollutants encountered, and differ somewhat depending on whether the application is to an existing building or to a new building under design and construction. Whenever possible, the first course of action is to prevent or reduce pollutant emissions at the source.

In this paper, we will summarize the three major classes of indoor air pollutants -- combustion emissions, organics (formaldehyde and others), and radioactive species (radon and radon daughters) -- and briefly discuss control strategies to illustrate the complexities associated with their implementation.

MAJOR INDOOR AIR POLLUTANTS

Combustion Emissions

Indoor combustion sources include tobacco smoke, gas-fired stoves, unvented gas-fired space heaters, gas-fired water heaters, and kerosene heaters. The major emissions from these sources are gaseous air pollutants (CO, NO, NO_2, and HCHO) and respirable particulates. The impact of combustion emissions in the indoor environment is summarized in a report recently published by the National Academy of Sciences (1), and the work of Lawrence Berkeley Laboratory (LBL) on emissions from combustion appliances is being summarized in this session by Traynor (2). We have found CO, NO_2, and HCHO levels often approaching or exceeding ambient air-quality standards either adopted or proposed in the U.S. and other countries, and observed levels of respirable particulates frequently 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.

Formaldehyde and Other Organics

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. that are used in large quantities by the building trades. Although particleboard and urea-formaldehyde foam insulation have received the most attention, some of the combustion processes mentioned above also release formaldehyde. 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 $\mu g/m^3$) 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 foreign countries and various states in the United States are moving rapidly to establish standards for formaldehyde concentrations in indoor air. The range of these proposed standards is 120 to 600 $\mu g/m^3$. A summary of formaldehyde measurements in various indoor environments is given in Table 2.

In the past few years, office workers throughout the country have registered numerous complaints of "bad air." These complaints come most frequently from workers occupying new office buildings with hermetically sealed windows. Although various government agencies have investigated these problems, the etiological agent(s) has frequently remained unidentified.

One of the primary contributors to poor indoor air quality in office buildings may be organic contaminants, which have numerous indoor sources: building materials, cleaning products, tobacco smoking, furnishings, common consumer products, and building occupants themselves. To date, however, there has been relatively little research on this topic. In 1980, LBL began a comprehensive DOE-sponsored research program in collaboration with the Center for Disease Control (CDC), and the National Institute of Occupational Safety and Health (NIOSH) to characterize indoor air pollution in "complaint" office buildings. Figure 1 shows comparative gas chromatograms of indoor and an outdoor air samples taken simultaneously at an office building where complaints had been registered (4). As illustrated, the indoor levels of organic pollutants were found to be considerably higher than outdoor levels. Table 3 lists those organic compounds found to be at least five times as great inside offices as outdoors, and notes, where

Table 2

SUMMARY OF FORMALDEHYDE MEASUREMENTS IN INDOOR ENVIRONMENTS

Sampling Site	Concentration[a] (ppm)[b] Range	Mean
Two mobile homes in Pittsburg, Pa.	0.1-0.8[c]	0.36
Mobile homes registering complaints in state of Washington	0-1.77	0.1-0.44
Mobile homes registering complaints in Minnesota	0-3.0	0.4
Mobile homes registering complaints in Wisconsin	0.02-4.2	0.88
Public buildings and energy-efficient homes, occupied and unoccupied	0-0.021	-----
	0-0.23[c]	-----

[a]Formaldehyde, unless otherwise indicated.

[b]1 ppm = 1200 μg/m^3.

[c]Total aliphatic aldehydes

Source: National Research Council, National Academy of Sciences.

applicable, the standards of exposure promulgated by the Occupational Safety and Health Administration (OSHA) for the workplace environment. In research now in progress, we are quantitatively determining the concentrations of these organic compounds by current state-of-the-art analytic procedures, which, although they provide only rough estimates, are indicating concentrations ranging from 1 to 100 ppb. These levels are well below existing limits established by OSHA for occupational exposure but may be excessive for the general public for whom limits are typically ten times lower.

While no single compound was present in high enough concentration to be singled out as a health hazard by existing OSHA criteria, the potential health hazard from the combined effects of the organic compounds found in these samples cannot be assessed at this time. Furthermore, the possibility cannot be overlooked that cumulative exposure to low levels of organic compounds, or synergistic health effects, may explain the symptoms reported by the occupants of these offices.

Radon and Radon Daughters

Radon and its decay daughters are known to comprise a significant portion of the 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.

ORGANIC COMPOUNDS DETECTED IN OFFICE BUILDINGS

Organic Compound	OSHA Permissible Exposure Limit (ppm)
HYDROCARBONS	
n-hexane	500
n-heptane	500
n-octane	500
n-nonane	
n-undecane	
2-methylpentane	
3-methylpentane	
2,5-dimethylheptane	
methylcyclopentane	
ethylcyclohexane	
methylcyclohexane	500
pentamethylheptane	
AROMATICS	
benzene	1
xylenes	100
toluene	200
HALOGENATED HYDROCARBONS	
trichloroethane	350
trichloroethylene	100
tetrachloroethylene	100
MISCELLANEOUS	
hexanal	
methylethylketone	200

Radon has four short-lived daughters, each with a half-life of less than 30 minutes. The four radioactive daughters of radon are not inert. Most attach themselves by chemical or physical means to airborne particulates. When inhaled, these particulates may be retained in the tracheobronchial and pulmonary regions. Subsequent decays result in a radiation dose to those areas. The primary health hazard is associated with the alpha emissions of polonium-218 and polonium-214: Since alpha particles have a very short range (a few tens of microns in tissue), essentially all of their energy is deposited near the surface of the lung tissue.

Figure 2 illustrates the major pathways of radon entry into buildings. 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 them. Conservation measures, particularly reduced air-exchange rates, may exacerbate this situation.

Figure 3 summarizes and compares radon concentrations in indoor and outdoor air at different geographic sites. What is 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 (6).

In terms of the potential health risk to building occupants, a simple populations-at-risk model based on the "linear hypothesis" that risk is directly proportional to dose suggests that exposure to an average concentration of 1 nCi/m^3 of radon would add a risk of 50 to 110 cases of lung cancer per million per year. Exposures of the entire population, even to the indoor concentrations typical of existing houses, may account for 2000-20,000 lung cancers in the United States per year. Even more serious is the risk experienced by the small percentage of homes that have much higher than typical radon concentrations. Since we do not yet know enough about the actual dose-response characteristics of low-level radiation exposure, we cannot say with certainty that there is any added risk from a lifetime exposure to a few nCi/m^3. Nevertheless, 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 and radon daughter levels in residential buildings throughout the United States. Figure 4 presents 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-exchange rate is apparent. An air-exchange rate of approximately 0.5 air changes per hour is required in order to maintain radon concentrations below 4 nCi/m^3, the maximum permissible concentration allowed by present United States health guidelines as shown in Figure 3. Integrated measurements or large numbers of grab samples need to be taken under typical living conditions and various climatic conditions before we can accurately estimate average exposures of building occupants throughout the United States.

Figure 5 shows the concentration of radon measured under five different ventilation conditions over a two-week period in a home in Maryland (7). Figure 6 illustrates the radon-daughter concentration (measured in terms of working level*) as a function of time during this measurement period. The radon daughter working level reveals the same general dependence on ventilation as was observed for radon concentration. As indicated, only when ventilation rates exceed 0.6 air changes per hour did the working level drop below the 0.02 upper limit set as an indoor guideline by the U.S. General Service Administration (8), and adopted as a standard by the Atomic Energy Control Board of Canada (9) for communities in Florida and Canada, respectively.

CONTROL STRATEGIES

Several measures can be adopted to limit increases in indoor air pollution in both conventional and energy-efficient buildings. Options include selection of low-emission building materials, coating various building materials with sealants to reduce emissions of potentially harmful pollutants, installing mechanical ventilation/heat exchanger systems, and employing special contaminant-specific control devices. Table 4 summarizes various control techniques capable of mitigating indoor air quality problems. The first strategy listed, increasing ventilation, is perhaps the most effective remedy for controlling the build-up of indoor air pollutants, and some of the more energy-efficient ways to ventilate residential buildings are given below.

Natural Ventilation

Windows

In mild weather, when heating and cooling systems are turned off, opening windows provides ventilation without wasting energy. Although an open window

*One WL (a unit established initially for application to exposure of mineworkers to radon daughters) is defined as any combination of radon daughters in one liter of air such that the decay to lead-210 will result in the ultimate emission of 1.3 X 10^5 MeV of alpha energy. This unit is insensitive to the degree of radioactive equilibrium existing among the airborne daughters and radon. If radon and its first four daughters are in radioactive equilibrium, 100 nCi/m^3 of radon implies 1 WL. In well ventilated air, where the daughters have not reached secular equilibrium, somewhat more than 100 nCi/m^3 are necessary to generate 1 WL. An equilibrium fraction of about 0.5 has been measured in both New York and Swedish homes. For our purposes, we have assumed that 200 nCi/m^3 of radon yields 1 WL.

CONTROL TECHNIQUES

DILUTION

- Natural ventilation
- Mechanical ventilation
    - Spot
    - Whole building (with heat recovery)
    - Variable ventilation based on air quality detection

MASKING

SOURCE REMOVAL

SOURCE CONTROL

- Modification of manufacturing processes for building materials
- Selection of building materials with low emanation rates
- Use of sealants and barriers
- Modification of combustion processes
- Changes in building design and construction practices

CONTAMINANT CONTROL DEVICES

- Filters
- Scrubbers

allows pollutants to diffuse throughout the house, for houses that do not have built-in exhaust fans in the bathroom or in the kitchen, opening a window is an alternate solution.

Mechanical Ventilation

Spot Ventilation

"Spot ventilation," which uses exhaust fans, is appropriate for pollution sources that are confined to a particular location (bathroom) or appliance (gas stove). Not only are exhaust fans efficient because they are used only while pollutants are being emitted (a few hours a day for a gas range hood) but also because they remove pollutants before they can migrate to the rest of the house.

Whole-house Ventilation

Ventilation can also be achieved without major energy loss by installing a mechanical ventilation system equipped with an air-to-air heat exchanger. Such devices, not yet common in U.S. residences, preheat the cold incoming air by transferring heat from the warm outgoing air. This heat exchange allows 50-80% of the energy normally lost in the exhaust air to be recovered. (This process describes its operation in winter; the same process works in reverse in the summer air-conditioning season.) Such a system can be used very effectively in houses that have been tightened since, in most cases, it brings in sufficient air to flush out indoor pollutants, and does so without sacrificing the energy-efficiency of the house. A mechanical ventilation system with an air-to-air heat exchanger can be installed in walls or windows, or as part of a central air system. Unless there is good air movement throughout the house, however, a heat exchanger may ventilate only the room in which it is installed. Two or more may be required for a large house. The estimated cost (1981) for small window units is about $300 per unit, uninstalled. For systems intended to ventilate an entire house, installation costs can vary, depending upon the amount of duct work necessary.

The preservation of indoor air quality and the continuation of weatherization programs designed to reduce national energy consumption are not incompatible. Research has already identified the major indoor air quality problems and suggested various means of preventing, mitigating or controlling them. Indoor air quality research should be regarded as an integral part of any program promoting reduced ventilation as a strategy for energy conservation in buildings.

ACKNOWLEDGEMENT

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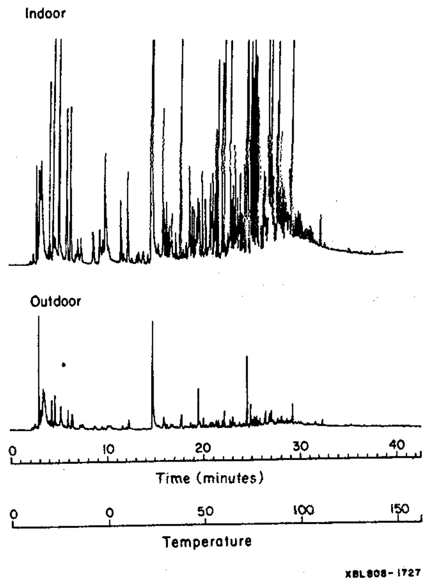

Figure 1. A comparison of gas chromatograms of indoor and outdoor air samples at an office site. Each peak represents a separate organic compound.

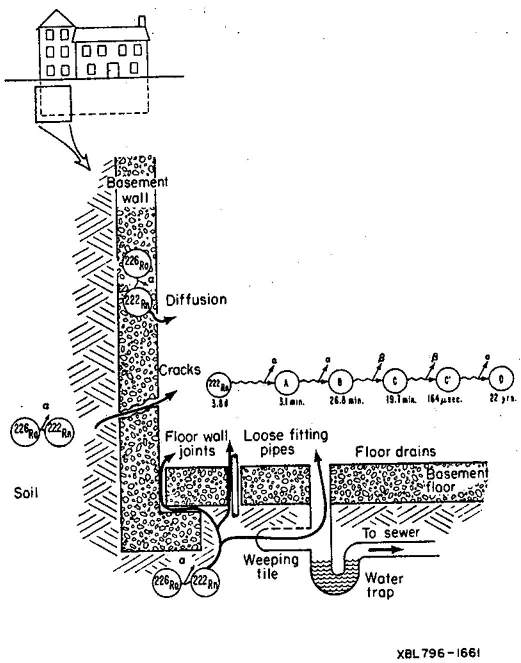

Figure 2. Primary pathways for radon entry into buildings.

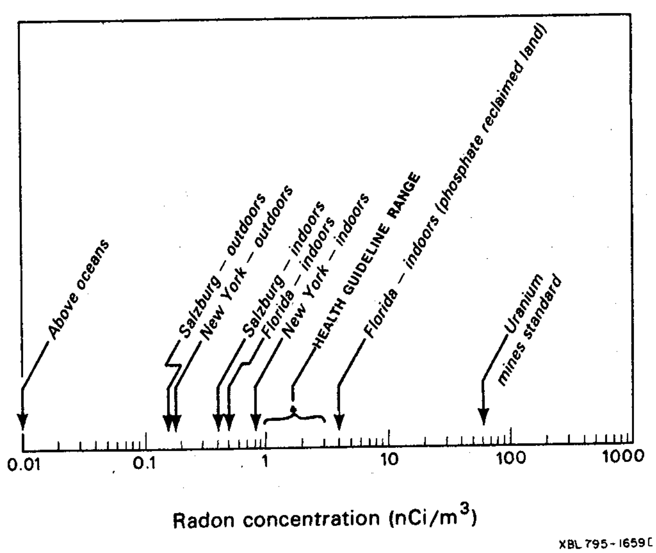

Figure 3. Radon concentrations (nCi/m3) in air. The values for New York, Salzburg, and Florida are geometric means of the average for each site sampled. The value given as the uranium mines standard is calculated (assuming an equilibrium fraction of 0.5) from the annual dose limit for occupational exposures of 4 WLM. The health guidelines were established for houses built on reclaimed land in Florida and for houses in four communities associated with uranium mining in Canada. (6)

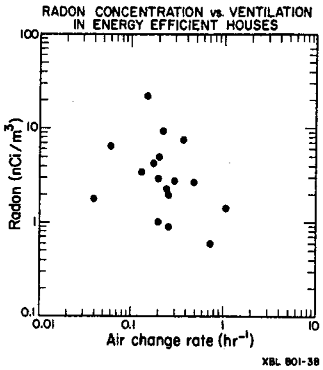

Figure 4. Scatter plot of radon concentration (nCi/m^3) vs. ventilation in energy efficient houses in the U.S.

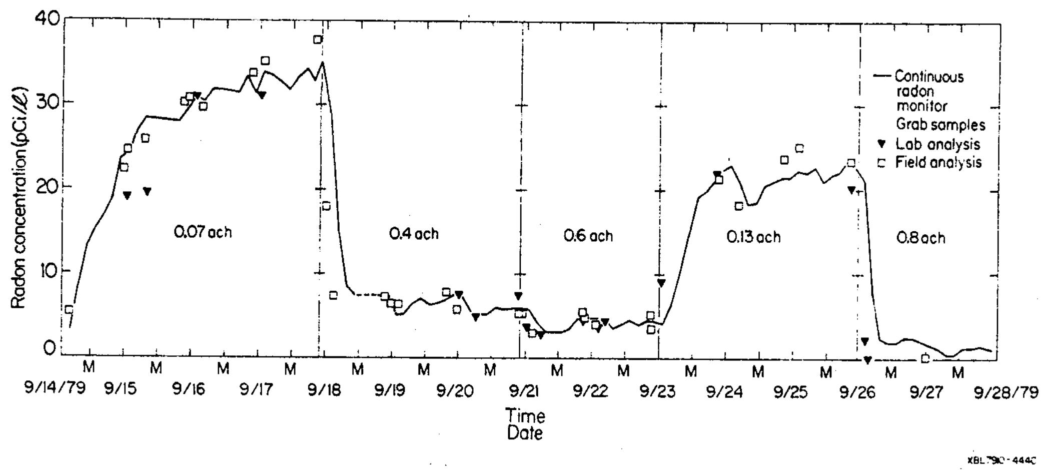

Figure 5. Indoor radon concentrations (pCi/ℓ) in an energy-efficient house under five different ventilation conditions, as measured by continuous monitoring and by grab sampling. (Note: 1 pCi/ℓ = 1 nCi/m^3.)

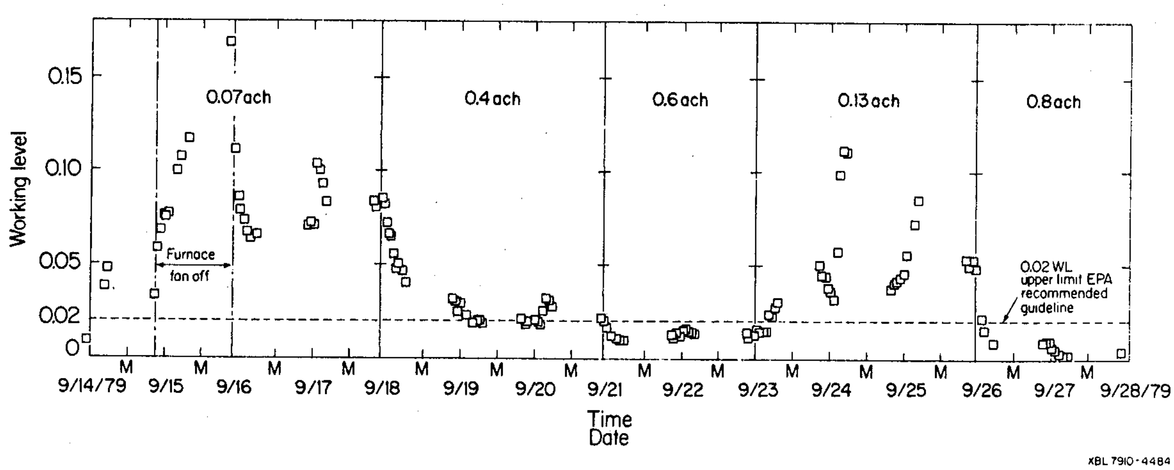

Figure 6. Variations in radon daughter concentrations (working levels) with changing ventilation rates and time.