Environment International, Vol. 8, pp. 21-36, 1982

0160-4210/82/070021-16$03.00/0

INDOOR AIR POLLUTION

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As national trends accelerate towards the reduction of ventilation and infiltration rates in buildings, coupled with an increased use of synthetic chemicals in the indoor environment, a new phenomenon has arisen: the "sick building" syndrome. Traditional approaches to environmental health developed for the outdoor air, or for the industrial occupational setting, are inadequate to deal with this problem. It is argued that a comprehensive approach to the problem of indoor air pollution is necessary to protect public health.

Introduction

The Clean Air Act provides for the establishment of National Ambient Air Quality Standards (NAAQS) in order to protect public health from the effects of air pollution. The U.S. Environmental Protection Agency in its regulations, pursuant to the Act, has defined "ambient air" as "that portion of the atmosphere, external to buildings, to which the general public has access" (U.S. EPA, 1976; 1978). Consistent with this definition, state and local governments, who have the primary responsibility for the prevention and control of air pollution, have established a network of outdoor air quality monitoring stations that are located at fixed sites.

However, a number of studies have shown that fixed monitoring stations do not accurately reflect the pollutant exposure of the population in the outdoor environment (Repace *et al.*, 1980), while for many pollutants, indoor concentrations may be far in excess of the outdoor concentrations (NAS, 1981). When these indoor concentrations are weighted by the estimated 9-to-1 ratio for the time spent indoors relative to time spent outdoors by the U.S. urban population (NAS, 1981), the importance of indoor exposures for many air pollutants may exceed that of outdoor exposures.

For example, Fig. 1 shows a 24-h total respirable particle (RSP) exposure, using a piezoelectric microbalance to take time-resolved exposures as an individual moves from microenvironment to microenvironment (Repace *et al.*, 1980). On this day, the author spent 84% of his time indoors, 9% in transit, and 7% outdoors. His total integrated RSP exposure for the 24-h period is 1428 $\mu g/hm^3$. Contributions to the total exposure break down into 82.3% from indoor microenvironments, 9.8% from in transit microenvironments, and only 7.9% from outdoor microenvironments. Such results are indicative of a general trend.

Thus, to protect public health, a prime objective for public health agencies should be to limit the total human exposure to air pollution, rather than just the fraction which is incurred in the outdoor air. In this paper we will discuss the nature of the problem of indoor air pollution, limitations in the authority of established health agencies to control the problem, research needs, and some control options.

*The views presented in this paper are those of the author.
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Background

It has been traditionally assumed that air pollution is primarily an outdoor phenomenon, and that buildings provide sanctuary from air pollutants. In fact, through ventilation and infiltration, air contaminants exterior to a building penetrate its interior to a varying extent and are persistent to a degree which depends upon ventilation/filtration system and the pollutant reactivity. For air exchange rates typical of non-energy-efficient buildings, indoor concentrations of relatively unreactive outdoor pollutants, such as CO, will lag the outdoor concentrations, but the daily average indoor and outdoor levels will be the same (Silberstein, 1979), especially in transit (Ott and Willits, 1981). For reactive outdoor

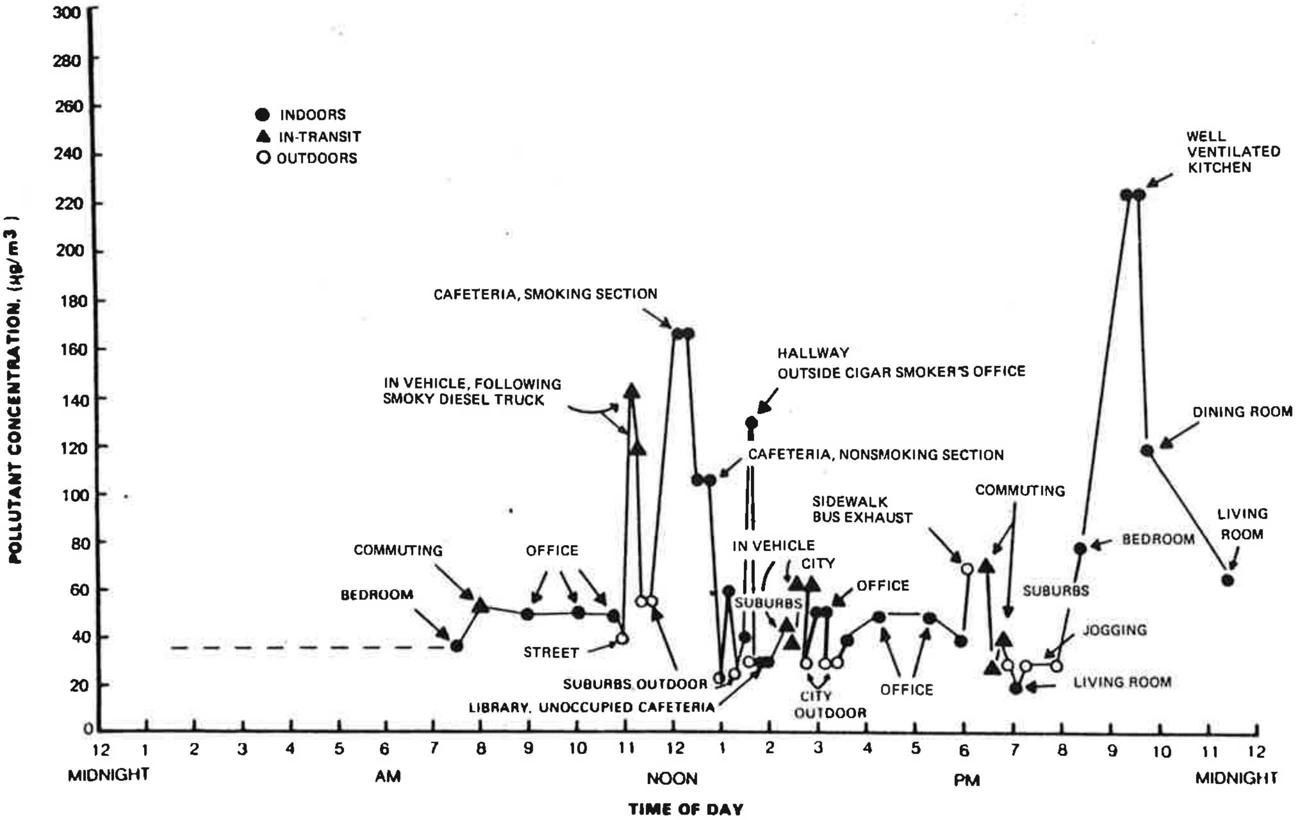

Fig. 1. 24-h indoor/outdoor RSP exposure of author, October 16, 1979. The 24-h average is 60 μg/m³ (Repace *et al.*, 1980).

pollutants, such as ozone, the indoor concentrations will lag the outdoor levels, but will average lower due to the presence of indoor sinks (Moschandreas and Morse, 1979).

However, in the presence of the persistent indoor sources, indoor concentrations of such pollutants will generally exceed the outdoor levels considerably. Moreover, there is a large class of pollutants, generated by the buildings themselves or by indoor human activities, which typically have no concentrations of physiological significance in the outdoor air. These include indoor air pollution from smoking, radioactive gases emanating from subsoil, emissions of formaldehyde from particle board, indoor pesticide use, human metabolic gases, and pathogenic organisms generated by coughing, sneezing, and flushing of toilets. Table 1 gives a partial list of indoor air pollutants in buildings by source and pollutant type.

A number of studies have indicated that indoor exposures to air pollutants can adversely affect human health and welfare (Repace and Lowrey, 1980; BNYAM, 1981; WHO, 1979; NAS, 1981). This problem is now assuming particular urgency as national energy conservation programs begin to focus on the large amounts of energy consumed by building ventilation systems in both residences and commercial buildings (Repace, 1981; Woods, 1979). Concerns about weatherization measures that can substantially reduce this outdoor air supply have arisen, because the replacement of more polluted indoor air by less polluted outdoor air constitutes the primary control measure for indoor air pollution; the slower the rate of this air exchange, the greater the level to which an indoor pollutant can rise. Such concerns prompted the U.S. Department of Energy (DOE) to call for the development of indoor air quality standards.

Indoor Pollutants of Current Concern

Radon and radon daughters

Radon gas and certain of its decay products are radioactive. Radon is emitted naturally from soil and mineral building materials. The level of radon and its decay products inside conventional buildings is often higher than the ambient level outdoor (Budnitz *et al.*, 1979), and inside poorly ventilated buildings these elements may accumulate to high levels due to the lack of diluting ventilation. It has been asserted (Budnitz *et al.*, 1979; Evans, *et al.*, 1981) that elevated radiation levels in conventional buildings and homes could increase the risk of lung cancer. The reduced ventilation and infiltration rates common to some new, airtight, energy-efficient residences could lead to a doubling of the average indoor radon levels, relative to the current building stock.

Table 1. Indoor air pollutants in buildings.[a]

Sources	Pollutant Types
Ambient air	SO_2, NO, NO_2, O_3, organics,
Motor vehicles	CO, particulates, CO, Pb,
Roofing tar	Polycyclic organics
Building construction materials	
Concrete, stone	Formaldehyde
Particle board, Plywood	Chlorinated hydrocarbons
Treated lumber	Formaldehyde, glass fibers
Insulation	Asbestos
Fire retardants	Organics
Adhesives	Mercury, organic solvents
Paint	
Building contents	
Heating and cooking combustion appliances	CO, NO, NO_2 formaldehyde, Particulates
Furnishings	Formaldehyde, other organics, mold and fungi
Well water	Radon
Natural gas	Radon
Copying machines	Ozone
Deodorants	Organics
Liquid marker blackboards	Organics
Carbonless carbon paper	PCBs
Air conditioning systems	Microbes, molds, fungi
Bathrooms, showers	Excess humidity
Flush toilets	Microbes, odors, disinfectants
"Air fresheners"	Formaldehyde, other organics
Human occupants	
Metabolic activity	CO, NH_3, odors, excess humidity
Coughing and sneezing	Microbes
Human activities	
Tobacco smoke	CO, NO_2, POM, nitrosamines Particulates, odors, irritants
Pest Removal	Pesticides
Cooking	Organics, particulates, excess humidity
Aerosol sprays	Fluorocarbons, vinyl chloride[b]
Cleaning products	NH_3, pine oil, chlorophenols
Hobbies and crafts	Organic solvents

[a]Adapted from a table originally given by Hollowell (1979).
[b]Banned by EPA in 1974 (U.S. EPA, 1975).

Evans *et al.* (1981) suggest that the radon-associated concentration in average U.S. residence is about 0.004 Working Levels (WL). The Working Level Month (WLM) is a measure of time-averaged radiation exposure from radon and radon daughters. An estimated 10%–20% of U.S. homes may exhibit levels more than twice as high; areas with anomalously high radon sources may be expected to show levels above 0.01 WL (U.S. EPA, 1979a). For a constant radon source strength, the gas concentration would increase roughly in inverse proportion to the airchange rate. Rates below 1 air change per hour (ach) are common in new housing. In Sweden, the national building code requires maximum infiltration rates of 0.6 ach and rates less than 0.2 ach are common (Anonymous, 1979; Woods, 1978). For comparison, the 1977 revisions (revision 5) of the 1973 Minimum Property Standards U.S. Department of Housing and Urban Development mandate infiltration rates for single family dwellings of less than 0.7 ach. A recent standard of the American Society of Heating, Refrigeration, and Air Conditioning Engineers (ASHRAE) suggests a rate of air change of 5 L/secRoom, or about 0.5 ach. Limited data currently exist on infiltration rates in U.S. homes. Based on a national sample of 200 homes, the U.S. Department of Energy estimates the range of infiltration rates in current housing stock is of the order of 0.75–1 ach, and between 0.4 and 0.7 ach in new housing, although some new housing is being built with exchange rates of the order of 0.1–0.2 ach (Fuller, 1981). According to Fuller (1981), a consensus seems to be developing in the U.S. building industry that an air infiltration rate of 0.5 ach can keep air pollutants below critical levels in a residence. In some homes, radon-associated lung-cancer risks can be high. USRPC summarized the available data (USRPC, 1980).

Figure 2 shows the radon concentrations in nCi/m³ versus infiltration in a sampling of 12 energy-efficient (<0.3 ach) homes in the United States, contrasted with the radon concentration in four homes whose infiltration rate is of the order of the national average (about 1 ach). Assuming a conversion factor of 1 nCi/m³ = 0.2532 WLM/yr and a risk increase of lung cancer of 1×10^{-4} lung cancer deaths per WLM (Evans *et al.*, 1981), it can be seen that each 1 nCi/m³ in radon/daughter exposure is associated with an estimated 0.25×10^{-4} increase in lung-cancer risk per year. To take an extreme case, 60 yr of residence at 75% occupancy in a home polluted at a 25 nCi/m³ radon concentration (See Fig. 2) is associated with an estimated 2 per thousand absolute lung cancer risk, assuming a 20-yr latency period. For a lifetime exposure of 12 WLM and risk factor of 10^{-4} per WLM, Evans *et al.* (1981) estimate a maximum life time risk of 0.12%. To place this in perspective, such a risk to the U.S. population of lung cancer age, about 10^8 persons over age 35, would result in a maximum of about 120,000 lung cancer deaths in 60 yr, or about 1500/yr, assuming the average person spends 75% of his or her time at home.

Tobacco smoke

One out of three adults is a cigarette smoker. The typical cigarette smoker smokes 32 cigarettes/day, liberates 65,000 μg of respirable particulate per hour into the environment, and spends more than 90% of the day indoors. Thus, tobacco-smoke contaminated air is pandemic (Repace and Lowrey, 1980). Tobacco smoke is a proven human carcinogen and respiratory toxicant which causes a 77% excess cancer mortality in smokers, as well as a twofold excess of chronic obstructive pulmonary disease mortality (U.S. Surgeon General, 1980). Evidence is now accumulating that the diseases of

Table 2. Summary of indoor air pollution issues and options.

Some Indoor Air Pollutants of Current Concern	Indoor Air Pollution Issues Facing States	Summary of Clean Indoor Air Options
Tobacco smoke	Lack of recognition of indoor air pollution health effects	Research & development
Formaldehyde	Lack of diagnostic instruments and procedures for many pollutants	Measurement instruments and procedures
Radon daughters	Lack of trained personnel	Models for pollutant growth equilibrium, and decay
Asbestos	Lack of viable control procedures	Health guidelines for maximum indoor concentrations
Unvented indoor combustion products from space heaters and gas appliances	Lack of appropriate indoor air quality standards	Epidemiological studies involving total multi-media exposure
Pesticides	Increasing frequency of sick buildings	Risk assessment
Airborne pathogens	Lack of consistency in regulation by various states creates problems for industry	Cost-effective control measures
Emissions from office copiers	Increased agitation for action by private groups	Regulatory tools for states
Carbon dioxide	Standards set by consensus groups impact industry adversely: litigation	Product standards
Cleaning, deodorizing, and disinfecting products	Legislative initiatives	Building code provisions
Solvents, glues, and paints		Ventilation and air cleaning standards
		Indoor air quality health standards

smoking may be visited upon the nonsmoker. Two recent studies of lung cancer in nonsmokers (see Repace, 1981) showed evidence that so-called passive or involuntary smoking (breathing of tobacco-smoke contaminated air by nonsmokers) more than doubles the nonsmoker's risk of lung cancer; two indoor epidemiological studies of morbidity, one of 400 adult nonsmokers who were chronically exposed to air pollution from tobacco smoke at work, the other of young children raised in households with smokers, found evidence of pulmonary impairment from passive smoking. A relationship has also been established between maternal smoking and sudden infant death syndrome (U.S. Surgeon General, 1980). These results may be placed into national perspective when it is considered that an estimated two-thirds of the children in the United States reside in households with smokers, and that nearly three-fourths of all U.S. employers allow unrestricted smoking in the workplace (Repace, 1981). Thus, for many nonsmokers, tobacco smoke exposure can be lifelong. Several studies have indicated that from one-half to three-fourths of nonsmoking adults experience symptomatic effects from ambient tobacco smoke exposure, including eye, nose, and throat irritation, headache and nausea, with much more severe effects reported in persons with cardiac or obstructive pulmonary disease. One study of 10,000 nonsmoking office workers indicated that work productivity was impaired in more than 50% of these employees as a result of co-workers' smoking (Repace, 1981). A 20% reduction in pulmonary flow has been produced in asthmatics from passive smoking (Dahms, 1981).

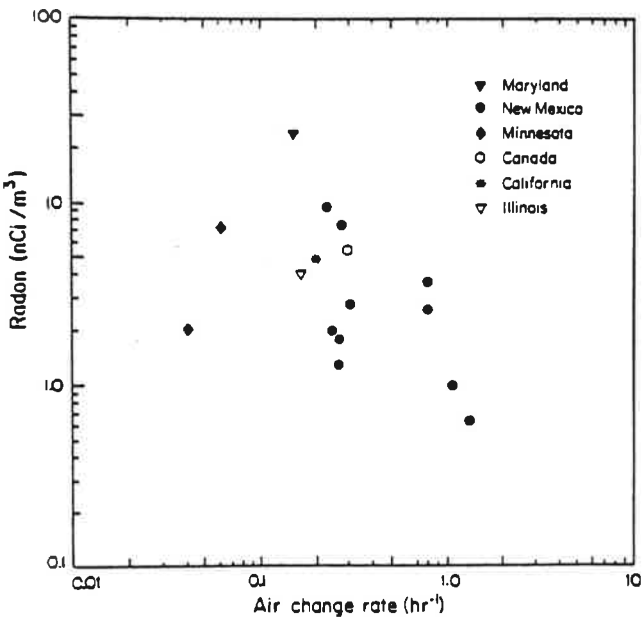

Fig. 2. Radon concentration vs ventilation in some U.S. houses (Hollowell, 1979). Under the Uranium Mill Tailings Control Act of 1978, EPA has set a maximum indoor air standard for radon decay products of 0.03 WL, with a recommended goal of 0.02 WL (roughly 3 nCi/m^3) (U.S. EPA, 1982).

Studies of the levels of respirable particles (RSP) of less than 4 μm generated by smoking under natural conditions in indoor microenvironments showed a range of 90–1140 $\mu g/m^3$, depending upon the smoker density and the effective ventilation. Levels of respirable particles in comparable indoor microenvironments in the absence of smoking ranged from 20 to 60 $\mu g/m^3$; outdoor controls, which included measurements on busy commuter highways, showed values comparable to the indoor nonsmoking figures (Repace and Lowrey, 1980, 1982). This is illustrated in Fig. 3, in which the RSP levels commonly found in smoking microenvironments are superimposed upon the U.S. National Ambient Air Quality Standards (NAAQS) for total suspended particulate matter (TSP), in order to indicate whether a given observation is "high" or "low"; actual violations of the standard are not necessarily indicated. However, repeated exposures to such levels can lead to violations of the standard (Repace and Lowrey, 1980).

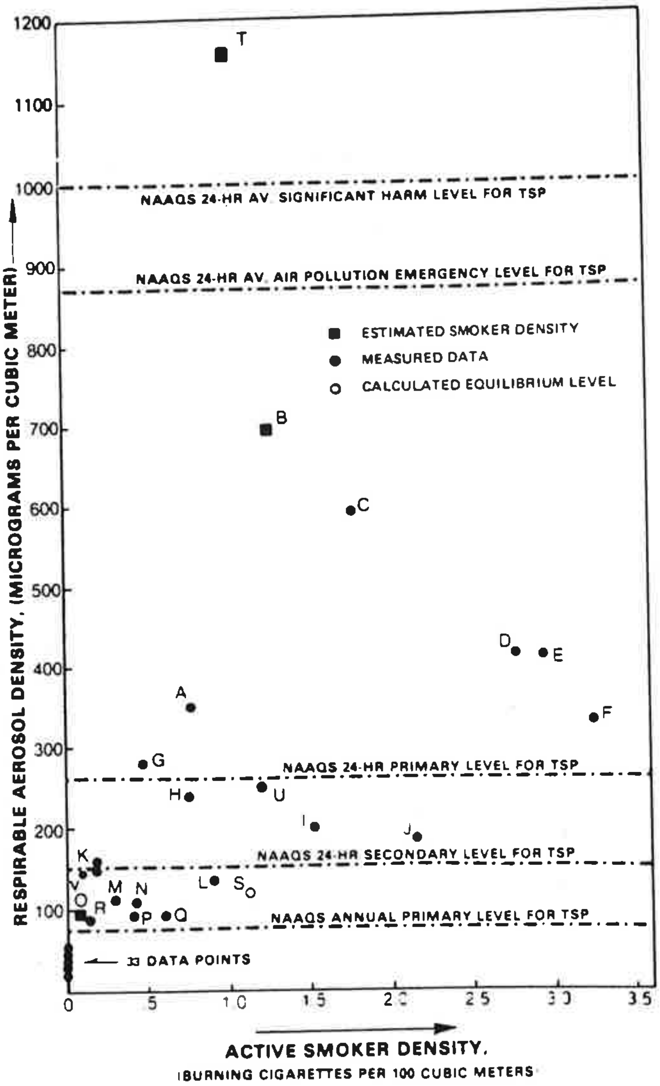

Fig. 3. Field survey of 52 microenvironments for fine-particle air pollution (Repace and Lowrey, 1980, 1982a). Areas studied included 10 restaurants, three cocktail lounges, three bingo games, two dinner-dance halls, one bowling alley, one sports arena, one hospital waiting room, and one residence. The scatter in the data is due to differences in the effective ventilation rates.

In a 1-yr study of indoor air pollution in 68 homes in six U.S. cities, Dockery and Spengler (1981) and Spengler *et al.* (1981) found that cigarette smoke was the dominant source of respirable particles, and that in tightly sealed homes, the RSP levels from smoking were more than double over the average. Nonsmokers exposed to indoor air pollution from tobacco smoke could inhale the equivalent of as much as 27 low-tar cigarettes per day; the researchers' estimates on the impact of passive smoking on nonsmokers based upon experimental and theoretical considerations support the findings of epidemiology. Figure 4 shows how the cigarette-equivalents inhaled varies as a function of the ventilation rate in an office building (Repace and Lowrey, 1980, 1982; Repace, 1981).

The indoor air pollution problems caused by smoking have generated two national constituencies: GASP (the Group Against Smokers' Pollution), a grassroots citizen's group, and ASH (Action on Smoking and Health), a legal organization. The American Lung Association has also begun to express concern. In 1979, 38 states introduced 116 bills regarding limitations of smoking in public areas. Seven were passed into law by seven states (U.S. DHHS, 1979). In 1980, of the 49 bills introduced under limitations, only one was passed into law by the state of California (U.S. DHHS, 1980). In 1979, the states passing these laws were California, Connecticut, Maryland, Montana, Nebraska, Oregon, and Rhode Island. Such laws are alternatives to nonsmokers' litigation (Repace, 1981). Many such laws require the establishment of nonsmoking sections in restaurants. Figure 5 demonstrates the efficacy of this approach. Minnesota is the only state presently to regulate smoking in the workplace as well as in restaurants, sports arenas, and other public and commercial buildings. Minnesota's law guarantees a smoke-free workplace to those nonsmokers who desire it. Enforcement of the law is reported to be working well. The U.S. Department of Health and Human Services has an internal policy that provides its own employees with a smoke-free workplace, upon request. In other federal agencies, this occurs only where there is unanimous consent of the workers. The Occupational Health and Safety Administration (OSHA) has no official policy regarding smoking. The U.S. Surgeon General, The World Health Organization, and the National Academy of Sciences have expressed concern about indoor air pollution due to tobacco smoke, and have urged greater efforts to prevent nonsmoker's exposures to tobacco combustion products (Repace, 1981; U.S. Surgeon General, 1982).

Emissions from unvented indoor combustion appliances

Another important source of indoor air pollution is from gas ranges and unvented space heating systems in

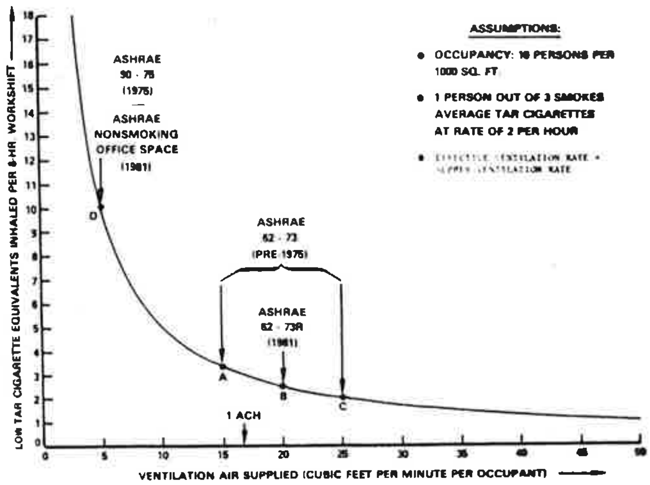

Fig. 4. The effects of ventilation on passive smoking in an office setting (Repace and Lowrey, 1982a).

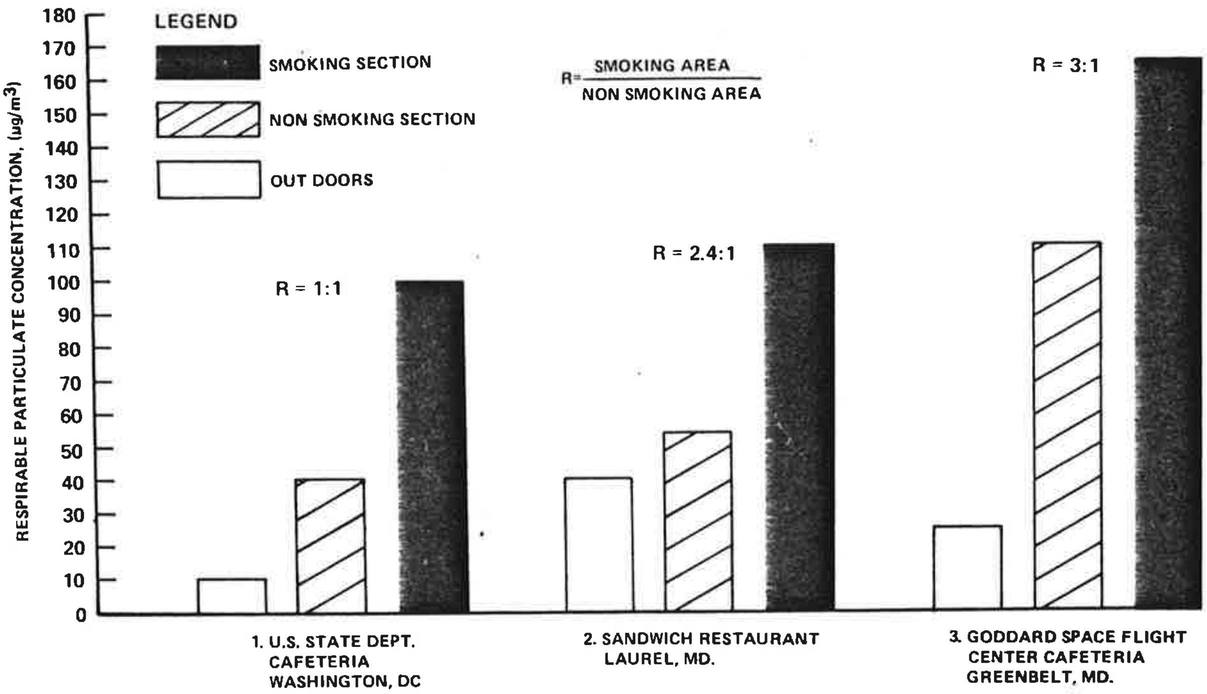

Fig. 5. Relative indoor/outdoor air pollution levels. Average sampling times were, respectively, 32, 20, and 6 min in each section for the three establishments (Repace and Lowrey, 1982a).

residential buildings. About 48% of U.S. homes use gas for cooking. There is also evidence that some urban apartment dwellers may be using unvented gas ranges for supplemental space heating. Laboratory studies have shown that gas stoves generate high emissions of such species as CO, NO_2, and also produce formaldehyde and respirable aerosol (Hollowell, 1979). Field studies have shown that levels of CO and NO_2 can exceed the levels of the short-term U.S. standards for CO, under certain conditions of ventilation in residential buildings; this is illustrated in Fig. 6, where the air change rates are given for a typical kitchen volume. The use of power ventilation reduces NO_2 levels considerably. ASHRAE now includes a 50 L/sec powered exhaust in its new indoor air standard (ASHRAE, 1981).

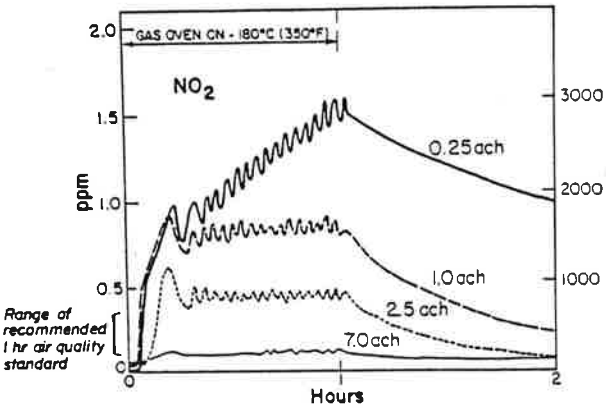

Fig. 6. Nitrogen dioxide emissions from a new gas stove in a 100-ft² experimental kitchen as a function of ventilation. Conditions: no stove vent or hood (0.25 ach); hood vent but no fan (1 ach); hood vent, fan on low (2.5 ach); hood vent, fan on high (7 ach) (Hollowell, 1979).

Retrospective indoor epidemiological studies of respiratory illness in children both in the U.S. (Speizer *et al.*, 1980) and in the United Kingdom (Melia *et al.*, 1977) have reported higher rates of respiratory illness in young children raised in homes with gas stoves as opposed to electric stoves. The U.S. study, which was corrected for socioeconomic status and parental smoking habits, also reported significantly lower levels of forced expiratory volume (1-sec) and forced vital capacity for the gas-stove-home children. It has been hypothesized that these lower levels in the rate of functioning lung growth in young children could lead to an increased chance of rapid decline in pulmonary function in adult life. Other workers have reported instances of "chemical sensitivity" in some allergy patients exposed to the fumes of natural gas combustion (Randolph and Moss, 1980).

Other evidence from the Harvard Six-City study (NAS, 1981) clearly indicates that people cooking with gas without kitchen ventilation, or with only recirculating filters, will be exposed to indoor NO_2 concentrations greater than the outdoor ambient. Residents of homes with electric stoves or gas stoves vented to the outside will have indoor exposures lower than people with unvented gas stoves. These observations indicate that actual population exposures to NO_2 may not be adequately estimated by ambient outdoor measurements, posing serious implications for previous epidemiological studies of NO_2 and morbidity (Spengler and Dockery, 1979).

Emissions from unvented kerosene heaters can cause excessive levels of NO_2 and CO_2 indoors, and the possibility of excessive SO_2 emissions must be considered as well. A survey of 150 portable kerosene heater owners disclosed that 45% of the owners provided no ventilation when using the heaters, and that 20% used them to heat the entire house (Rodale, 1981). Most manufacturers recommend the use of extra ventilation.

Aeropathogens

Epidemiological studies have established that many infectious diseases are communicated by airborne transmission (Couch, 1981). Epidemics of influenza, measles, chicken pox (varicella), and rubella affect millions of people each year. Pulmonary tuberculosis (28,000 cases in 1980), smallpox, and Legionnaire's disease are also transmitted by airborne contamination. In addition, certain respiratory viruses such as epidemic coxsackie A21 and adenovirus types 4 and 7 are transmitted primarily by an airborne route.

Viruses are submicron in diameter, typical bacteria are between 1 and 2 μm in diameter, and mold spores range from 3 to 50 μm or more in size. Thus most of these biologically active aerosols are in the respirable range. One of the most important dispersion methods of contagious disease in man is via the expulsion of germ-laden droplets in sneezing, coughing, or even talking. These droplets are usually between 1 and 100 μm in diameter, and are expelled with considerable velocities. The larger droplets rapidly settle out on nearby objects and eventually evaporate, with the infectious residue being subject to atmospheric reentrainment by room traffic. The smaller droplets evaporate in mid-air, leaving the infectious microorganisms in suspension. A closely related mechanism is indirect liberation of dried secretions on handkerchiefs or bedding. Studies in hospital wards have shown that great numbers of bacteria are dispersed during bedmaking. The effect may be equally troublesome in domestic residences. Infective aerosols may also be formed by the flushing of toilets; respirable aerosols containing high concentrations of fecal bacteria may be formed in this way. Airborne molds and fungi may also contribute to allergic disease in the population (Green and Lane, 1964).

Although little is known about the typical source strength of such pathogens, the peak concentrations and halflives of these aerosols in buildings are probably inversely proportional to the ventilation rate of the building.

As an example of the impact of a disease which is commonly transmitted in buildings, consider epidemic rubella. Although commonly thought to be a childhood disease, in 1980 nearly 47% of the 3904 cases were in age groups $\geq$ 15 yr. (In 1979, there were nearly 12,000 cases, and in 1978 more than 18,000.) 70% of the cases were young adults (CDC, 1981). This was reflected by outbreaks in secondary schools, colleges, military installations, and places of employment, particularly hospitals. Because rubella can be teratogenic, its impact is most important in young adult females, 10%–20% of whom are susceptible (CDC, 1981). One such outbreak has been described among the employees in an office building of a New Jersey-based insurance company. During the summer of 1980, 10% of the susceptible employees were stricken during a 2-week period, with absenteeism more than doubling in the workforce (CDC, 1980). Although epidemic rubella is being brought under control by immunization, other airborne diseases, particularly influenza, remain rampant. The cumulative health and economic impact has yet to be estimated. Such epidemics are probably more likely to occur in poorly ventilated buildings due to the persistence of microorganisms in such airspace.

Formaldehyde

Formaldehyde is an irritating and probably carcinogenic gas (Sun, 1981), emitted from urea-formaldehyde foam insulation (UFFI), from resins used in plywood and particle board, and from gas stoves and cigarettes. According to news reports, families have complained to state and federal health agencies about UFFI, reporting symptoms such as dizziness, rashes, nose bleeds, and nausea (Sun, 1981). Eye irritation has been reported in indoor residential situations at concentrations as low as 24 $\mu g/m^3$ or 0.02 μL/L (NAS, 1981). About 10%–20% of the population may be susceptible to formaldehyde vapors at low concentration, particularly at concentrations greater than 1.5 μL/L (NAS, 1981). Prior to its ban by the Consumer Product Safety Commission (CPSC), UFFI was banned in the States of Massachusetts and Connecticut, and also in Canada. California had imposed severe restrictions on the use of field-applied UFFI. According to news reports, there may be as many as 700 UFFI-related lawsuits currently pending, not counting a $2 billion class action filed on behalf of the 70,000 to 130,000 New York State residents who have UFFI in their homes (*New York Times*, 1982).

Mobile home residents were reported to have complained about strong concentrations of formaldehyde from wall coverings, furnishings, and carpets (Gold, 1980). One study, which involved measurements of formaldehyde emissions from particle board in residences, given typical quantities of particle board and typical infiltration rates, concluded that the use of this construction material in its present form (containing urea-formaldehyde glue) may result in higher indoor formaldehyde concentrations than permitted for continuous outdoor exposure in several European countries (Anderson *et al.*, 1975). A similar study conducted by Dally *et al.* (1981) reported that indoor residential exposure to formaldehyde may exceed levels of occupational exposure standards. Figure 7 shows relative indoor/ outdoor formaldehyde levels for an energy-efficient house (Hollowell *et al.*, 1979), 1.5 ppm or μL/L

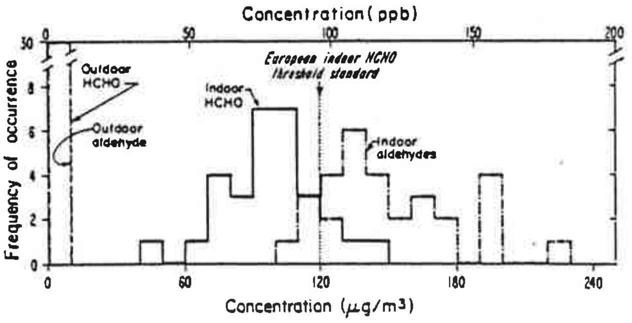

Fig. 7. Indoor/outdoor formaldehyde and aldehyde concentrations, Energy Research House, Carrol County, MD, March/April, 1979 (Hollowell, 1979).

(NAS, 1981). In Minnesota, the state chose to set a 600 μg/m³ standard. Wisconsin has also recently established a formaldehyde standard of 480 μg/m³ in mobile homes. By contrast, ASHRAE has adopted an indoor formaldehyde guideline of 120 μg/m³.

Pesticides

An estimated 84% of U.S. households use pesticides inside the house (U.S. EPA, NHPS, 1980), e.g., see Fig. 8. (The percentage of commercial buildings regularly using pesticides is not known, but may be presumed to be comparable.) Of those households, between 4 and 5% of the residents are estimated to have experienced acute toxic reactions after such use (U.S. EPA, 1980). Of households using pesticides, 17% used impregnated strips, 35% used mothballs, 90% used disinfectants, and 28% used pesticide-treated pet collars. All of these substances produce airborne concentrations of biocides. Few have been investigated for chronic toxicity. However, Dichlorvos DDVP, a constituent of some impregnated strips, is currently being investigated by EPA's Office of Pesticide Programs to determine the strength of the evidence for suspected, oncogenic, mutagenic, teratogenic, fetotoxic and neurotoxic effects (U.S. EPA, 1981).

In a study of commercial pesticide applications, treatments ranged from a low of 9% of households in EPA Region VIII to a high of 44% in Region IV. For homes treated with termiticides, the frequency of application ranged from a low of 2.5% in Region VII to a high of 55% in Region IV. In plenum-built housing or in buildings with subslab or intraslab heating and ventilation ducts, termite control chemicals have unintentionally been introduced into the living space, at times in such quantities so as to induce acute illness. Contamination of a home with pesticides or termiticides can be difficult to remove (Silberstein and Carroll, 1980). Although the extent of this problem is not known, the General Accounting Office has stated that the potential for such introduction is large, since about 40 million U.S. homes have warm air furnaces, and about 41 million are built on slabs. Chlordane, a proven animal car-

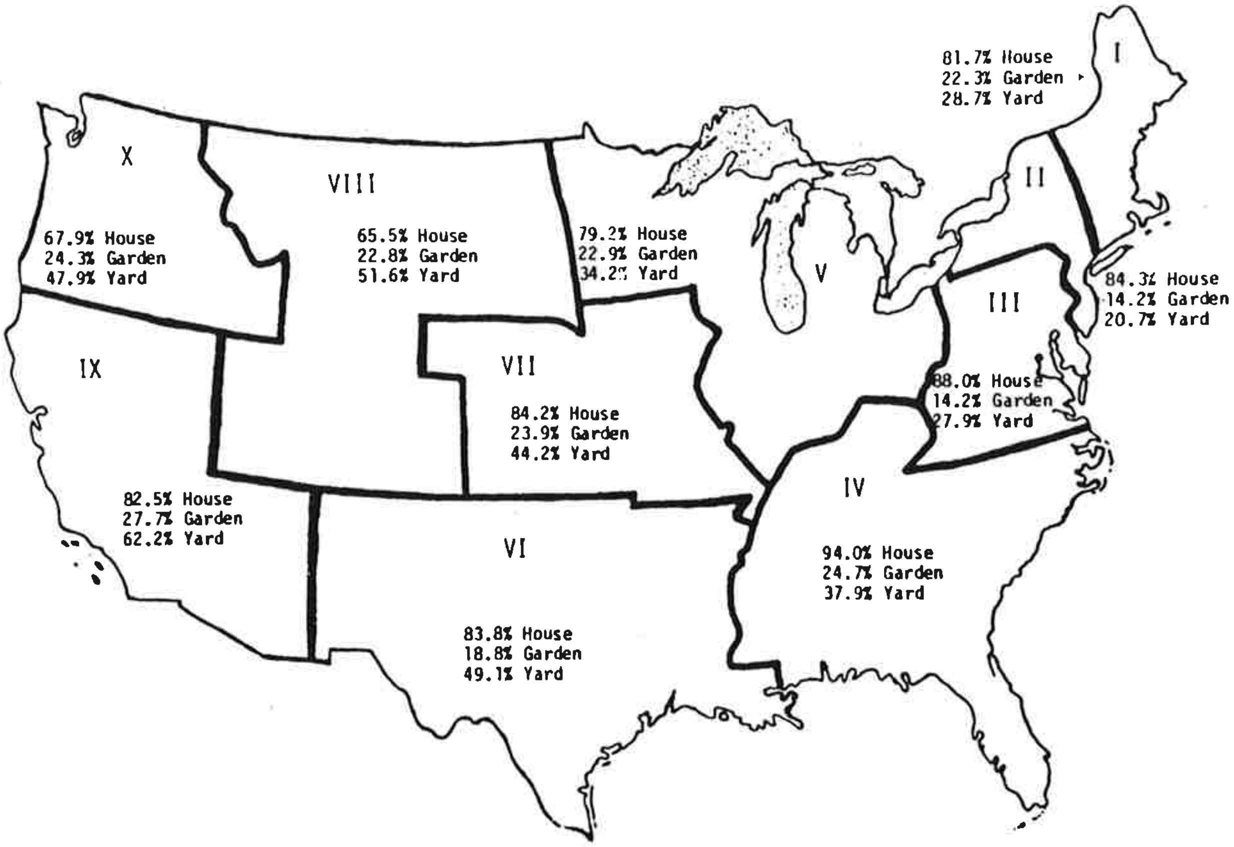

Fig. 8. Estimated percent of households using pesticides in the house, garden, or yard, divided into EPA regions (U.S. EPA, 1980).

cinogen for which EPA has cancelled virtually all above-ground uses, has been detected in the air of some termiticide-treated homes as long as 14 yr after application (Staats, 1980).

Building-related morbidity

An estimated 25% of the U.S. workforce can be found in offices (Rand, 1979). Within the past few years, the Center for Disease Control (CDC), the National Institute of Occupational Safety and Health (NIOSH), and many state health departments have been called upon with increasing frequency to investigate buildings in which a high percentage of workers report nonspecific symptoms (Kreiss, 1980). These buildings are usually office buildings, and standard industrial hygiene measurements generally fail to find a cause for the symptoms. Many of these cases are reported in modern, tight, energy-efficient office buildings, but problems are also reported in older buildings. CDC refers to such problems as "building associated epidemics," and has classified them according to probable cause: chemical, biological, allergic, "hysterical," or unknown. At times, the nonspecific symptoms persist for many months, and even years. There have been many reports from around the U.S. referring to such problems.

In addition to the evidence that buildings are not being ventilated adequately to accommodate the various sources of pollutants commonly found in buildings, studies are also showing that outside air dampers, which provide the minimal makeup air to replace that used up by human respiration, are being closed off by building owners and operators—in violation of building code provisions—in the interest of energy conservation (Repace and Lowrey, 1982; Repace, 1981; Kalika, 1970).

A random sample of the U.S. press provides anecdotal evidence of building-related morbidity. In Fort Worth, TX, the Tax Assessor's Office was forced to close down in May 1981 because "15 to 18 employees called in sick, and those who stayed on the job complained of 'burning lungs,' symptoms related to fumes that have permeated the building since it was opened in February 1981." The Assessor could not predict when the tax office would reopen (*Dallas Morning News*, 1981). In May 1978, The University of Massachusetts at Amherst was forced to shut down temporarily a three-tower, 17-story building complex after faculty and staff complained of dizziness, fatigue, nausea, and menstrual irregularities. Inconclusive studies carried out by campus authorities and OSHA prompted the faculty union to hire their own investigators, but no findings have yet been released (*New York Times*, 1980). A rash of complaints about "sinus congestion, chest pains, sore throats, headaches and general depression" began soon after the Ottawa County, MI, Human Services building opened in November 1978. The absentee rate among the 60 social services employees jumped to 64% from the normal 10% by the spring quarter of 1979, and by October 1979 it "remained high." At that time, the employees hired an attorney and submitted a petition to be moved to another building. Attempts by the county to remedy the poor air quality in the building included installing negative ion generators "to get the proper ion balance back." However, the generators had "no effect." In November 1979, the State authorities were considering ordering the building closed down. Tests of the air quality by county and State officials were inconclusive (*Muskegon Chronicle*, 1979). As of November 1981, despite the transfer from the building of several of the worst-affected employees, and the direct expenditure of more than $50,000—exclusive of investigative efforts by federal, state, and local authorities—complaints continue at the rate of several per month. The Orchard Park Elementary School in Carmel, IN, has been closed since December 1979, when 60% of the school's 52 teachers complained of headaches, nausea, and eye and nasal irritation. Nearly a year later, state health officials were still unable to identify the cause (*Indianapolis Star*, 1980).

A series of hearings by the State of California on "Buildings That Make You Sick" reported, among other problems, on the San Francisco Department of Social Services Building in which more than 50% of the workers suffered from irritation of the eyes, nose, and throat, and others reported more serious problems (*Los Angeles Times*, 1980). The NIOSH investigator complained that "even though we had conclusively demonstrated a health problem among the workers in the building, there existed no standards against which we could adequately measure their exposure." As a result, a summary of the NIOSH report issued by the building management to the employees stated that "the [NIOSH] report received . . . indicates that the quality of the air within the building appears to be acceptable according to the standards of the Public Health Service" (California State Hearing, 1980).

A pilot study of the occupational health of 960 clerical workers in Cleveland and Boston "from every industry and job category" disclosed that 70% of the workers complained that fresh air in their offices was "inadequate or nonexistent"; the study also reported that job-related stress was significantly correlated with poor indoor air quality (Gregory, 1981).

According to press reports The Office of Environmental Disease Control at the Maryland State Health Department reports one to two indoor air complaints per day, mostly related to office buildings (Minkoff, 1981). New York City's Department of Environmental Protection receives an average of 4 complaints per week concerning indoor air quality, although its activities in this area are not publicized. According to the director of its Bureau of Science and Technology, "Federal leadership is required lest we misdirect our efforts in an attempt to be responsive to growing public demand" (Ferrand and Moriates, 1981).

Schmidt and Hollowell (1980), in an investigation of air contaminants in a California office building in which the occupants complained about poor air quality, found that no contaminant exceeded individual Threshold Limit Values established by OSHA; however, many more contaminants were found indoors than outdoors, and the indoor levels were higher. In such cases (Fig. 9), the burden of exogenous chemical substances with which individuals must cope may be far higher than normal and may exceed the body's ability to detoxify.

The phenomenon of exceedance of a critical total body burden is known to be an important factor in triggering or maintaining environmentally related disease (Rea, 1979a; 1979b). Susceptible individuals among inhabitants of buildings with poor indoor air quality may experience an exceedance of this critical burden and as a result develop what has been termed "environmental maladaptation syndrome," a spectrum of noninfectious disease processes, which affect smooth muscle, mucous membranes, and collagen in the respiratory, gastrointestinal, genitourinary, and vascular systems, producing a broad variety of symptoms which defy traditional diagnostic techniques, and which may be mistaken for hypochondriasis (Rea, 1979a, 1979b).

There is therefore a need to approach indoor air quality as an ecological science. At present, however, there is little detailed knowledge of the import of the contaminant levels to which building inhabitants are exposed (Rand, 1979).

Limitations on federal authority to regulate indoor air pollution

The General Accounting Office has reviewed the responsibilities of federal agencies involved in various aspects of the problem of indoor air pollution (GAO, 1980):

a. EPA is the lead agency for air pollution, with its responsibility derived from the Clean Air Act. EPA's interpretation of this act, however, limits its responsibility to pollution occurring in the outside air.

b. OSHA is responsible for safeguarding the worker's health in the workplace. This includes setting and enforcing indoor air exposure standards for certain known pollutants. These standards are set so as to protect the majority of workers.

c. DOE, by Congressional mandate, establishes energy conservation programs for residences and new buildings. While DOE is concerned with the environmental impact that these programs have on indoor air quality, its primary interest and responsibility is energy conservation and not indoor air quality.

d. CPSC evaluates the safety and health effects of consumer products including those which may emit indoor pollutants such as formaldehyde and asbestos. CPSC can, if warranted, force a product to be withdrawn from the market, provided it is sufficiently demonstrated that the product is hazardous. CPSC can also set standards for products and has responsibility for providing information on product safety to consumers.

e. HUD establishes building standards for certain government properties and material standards for mobile home construction. HUD is therefore concerned with the impact of various pollutants, such as radon and formaldehyde, on the quality of indoor air.

GAO has concluded that there is a lack of clearly assigned responsibility which has impeded Federal actions to study indoor air pollution and to develop adequate control measures, and has recommended to the Congress that the Clean Air Act be amended to provide EPA with the authority and responsibility for the quality of air in the nonworkplace. We shall examine this recommendation.

EPA's interpretation of its mandate under the Clean Air Act derives from its definition of ambient air as "that portion of the atmosphere, external to buildings, to which the general public has access." This in turn derives from an assumption that the air internal to buildings can be no more polluted than the outdoor ambient. Thus, in principle, if the phrase "external to buildings" is deleted from the definition of ambient air, under a rule-revision process, EPA's authority could thereby be extended to encompass all of the air to which the general public has access. However, this has been viewed by some as contrary to the legislative history of the Act. Nevertheless, there are some established precedents for EPA's indirect involvement in the regulation of indoor air quality. The Clean Air Act provides EPA the authority to control or limit the manufacture and use of hazardous chemical substances such as benzene, vinyl chloride, mercury, beryllium, and asbestos, regardless of where they are used. Currently a vastly enlarged group of hazardous air pollutants is being considered for addition to this list, with carcinogens being accorded a high priority. Many of the 39 chemicals currently undergoing a Hazardous Air Pollutant Assessment may be present in high concentrations indoors.

For controlling the adverse effects of sources of hazardous pollutants, Section 112 of the Clean Air Act provides the basic EPA regulatory authority. Section 112 provides for the control of pollutants from airborne sources that may cause an increase in serious irreversible or incapacitating illness. The Act requires listing of pollutants that are considered hazardous, establishing emission limitations and in some cases, mandating work practices that provide an ample margin of safety to protect health. NESHAPS (National Emission Standards for Hazardous Pollutants) are the principal regulatory authorization for control of airborne carcinogens. In addition, under Section 122 of the Clean Air Act the Administrator is given authority to regulate radioactive pollutants, polycyclic organic matter, or other pollutants which may reasonably be anticipated to endanger public health. Under this authority, EPA has engaged in researching the problem of radon in the indoor environment.

Under the Federal Insecticide, Fungicide, and Rodenticide Act (as amended through 1978) EPA has promulgated regulations (40 CFR 162.16) which control pesticides intended for residential application, including houses, mobile homes, recreational vehicles, and other indoor areas.

With regard to certain air pollutants, particularly the ones for which ambient air quality standards have been established, EPA has viewed its authority as limited to the outdoor ambient, while for certain hazardous substances, EPA has viewed its authority as extending to the indoor environment (e.g., vinyl chloride).

The Public Health Service Act, Public Law 92-623, Title III, "General Authority Respecting Research, Evaluations, and Demonstrations in Health Statistics, Health Services, and Health Care Technology" provides that "The Secretary [of the Department of Health & Human Services] and the National Academy of Sciences shall, jointly and in cooperation with the Administrator of the Environmental Protection Agency [and other specified agencies], conduct, with funds appropriated under Section 308(i)(2) an ongoing study of the present and projected future health costs of pollution and other environmental conditions resulting from human activity (including human activity in any place in the indoor or outdoor environment, including places of employment and residence)" [Section 304(d)(1)]. The law further provides for the identification of the pollutants, the diseases caused by such pollutants, the sources of the pollutants, an assessment of the extent of the harm of the pollution, and a quantification of both the present and projected future health costs of this pollution as well as the reduction in health costs which would result from its reduction.

A persistent problem which has arisen in the investigation of many "sick buildings" is that of appropriate indoor air quality standards. A number of such standards, the Threshold Limit Values (TLVs), have been utilized by OSHA for industrial workplaces. These consensus standards are designed such that "no employee will suffer material impairment of health or functional capacity" (OSHA, 1970). However, the TLVs, unlike the outdoor air quality standards set by the U.S. Environmental Protection Agency under the Clean Air Act, are not designed to protect the general public to "within an adequate margin of safety," but rather to protect "nearly all" workers without adverse effect (ACGIH, 1978). It is explicitly recognized that because of the wide variation in individual susceptibility, a minority of workers may be affected by discomfort at levels below the TLVs, or even by aggravation of a preexisting condition or by development of an occupational illness (ACGIH, 1978). Thus, standards developed for the industrial workplace, as Coye (California, 1980), Taylor (1980), and Oslager (1980) have suggested, may not be appropriate for indoor air quality standards designed to protect the general public, and in particular the white-collar workforce which may contain many more pollution-sensitive individuals than the blue-collar workforce (Gregory, 1981).

For example, the OSHA 8-h standard for carbon monoxide is 50 μL/L, while the EPA 8-h standard is 9 μL/L. Further, the OSHA 8-h standard for "inert or nuisance dust" is 15,000 $\mu g/m^3$. Exposure at this level implies a 5000 $\mu g/m^3$ 24-hr average and a 4800 $\mu g/m^3$ annual average. By contrast, the EPA 24-h average primary standard is 260 $\mu g/m^3$ and the annual primary or health-based standard is 75 $\mu g/m^3$. Such differences in standards may account for reports in which office workers have become ill because of indoor air pollution, yet air sampling has failed to find any single compound in concentrations above the OSHA standards (Taylor, 1980; Oslager, 1980; California State Hearing, 1980; Schmidt and Hollowell, 1980). The strict application of industrial-based standards for the protection of office workers in polluted buildings may result in the exclusion

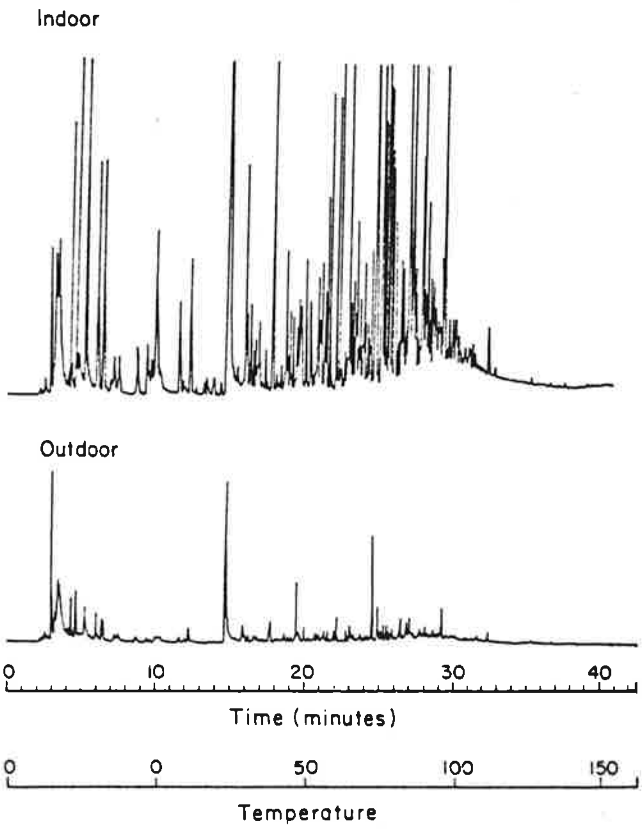

Fig. 9. Gas-chromatographic analysis comparison of indoor and outdoor air at a Lawrence Berkeley Laboratory office site. Indoor and outdoor samples were taken simultaneously (Schmidt and Hollowell, 1980).

of sensitive individuals from employment. Problems involving indoor air pollution are particularly salient in this respect (Barad, 1979; Repace, 1981). Therefore, if indoor air quality standards are promulgated, nonindustrial workplaces such as offices, public buildings, schools, hospitals, places of recreation, and residences, might best be covered by standards appropriate for the protection of sensitive groups.

Actions by Governmental Agencies and Private Groups Which Affect Indoor Air Quality

The U.S. Department of Energy (DOE) proposed two programs that will have an impact on indoor air quality through energy conservation in buildings: the Residential Energy Conservation Service program (RCS) (U.S. DOE, 1979b) and the Energy Performance Standards for New Buildings (BEPS) (U.S. DOE, 1979c). The potential for indoor air quality impacts under RCS lay mainly in retrofit caulking and weatherstripping efforts carried out by homeowners. DOE projected a 25% average reduction in infiltration rates for those homes which participated in the program. Such reductions could be expected to result in a like increase in indoor pollution equilibrium concentrations in such homes in the absence of mitigating measures. DOE, at the behest of the Congress, has proposed to expand RCS to small commercial buildings (U.S. DOE, 1980). The BEPS program, which now has been terminated, impacted both residential and commercial buildings, by setting maximum Design Energy Budgets for these structures.

Design ventilation and infiltration rates are set by ASHRAE. In 1973, these rates were codified under ASHRAE Standard 62-73, "Standards for Natural and Mechanical Ventilation," which set forth minimum ventilation rates, based on the need to limit the buildup of CO_2 in the indoor air from human metabolic processes and to control industrial air pollution in factories and recommended higher ventilation rates in certain premises, based on the necessity to control odor, mainly from tobacco smoke. These standards did not recognize that there were nonmetabolic, nonindustrial sources of indoor air pollution (ASHRAE, 1973). In 1975, ASHRAE promulgated Standard 90-75, "Energy Conservation in New Buildings" (ASHRAE, 1975). ASHRAE 90-75 eliminated the "recommended" category of ASHRAE 62-73, leaving only the minimum metabolic rates for the limitation of CO_2 (5 cfm or 2.5 L/sec of makeup air per occupant). Such low rates however, may lead to heavily polluted buildings in the presence of strong indoor sources of air contaminants (NAS, 1981; Anderson *et al.*, 1975; Repace and Lowrey, 1980).

In August 1981, ASHRAE announced a new standard, 62-1981, "Ventilation for Acceptable Indoor Air Quality" (ASHRAE, 1981). The objective of the standard is to "provide healthful and comfortable indoor environments by using materials and methods that optimize efficiency of energy utilization." Acceptable indoor air quality is defined as "air in which there are not known contaminants at harmful concentrations and with which a substantial majority (usually 80%) of the people exposed do not express dissatisfaction." ASHRAE standard 62-1981 operates to control indoor air pollution by offering alternative procedures to the design engineer: either ventilation rate tables to be used in the absence of "unusual" indoor air contaminants or an "indoor air quality standard" method. The latter method implies that the design engineer is aware of all "unusual" sources of air pollution in the proposed building, that the engineer knows the generation rates of the pollutant from all sources, and that an acceptable indoor air pollution transport model for each pollutant exists so that a maximum or an equilibrium concentration for the pollutant can be calculated and compared with an indoor air quality standard for the contaminant in the space, where such a standard exists. In the absence of a health-based indoor air quality standard appropriate for the general public, OSHA standards or "best available control technology" is recommended. However, few indoor air standards appropriate for the general public are available at the present time.

The ventilation rate tables of ASHRAE 62-1981 set minimum ventilation rates (2.5 L/sec per occupant) based on an implicit CO_2 standard of 2500 ppm (2.5 mL/L), and would apply in nonsmoking buildings; higher ventilation rates are designed to be used in buildings in which smoking is permitted, because "tobacco smoke is one of the most difficult contaminants to control at the source" (ASHRAE, 1981).

The rates set by the standard for tobacco-smoke contaminanted environments have been criticized as inadequate (Cain, 1981; Leaderer, 1981; Repace, 1981). Yet they are as much as five times higher than for equivalent indoor environments where smoking is not permitted. Tobacco smoke is also one of the most difficult contaminants to control economically by ventilation.

Approaches to the Formation of Indoor Air Pollution Policy

Issues

The basic issue is that indoor air pollution is known to produce a wide variety of health effects, but there is little explicit authority to deal with this problem. As a result, resources cannot be brought to bear the needed research and control effort. Federal, state and local health authorities are often called upon to deal with suspected cases of indoor air pollution; however, they are frequently ill-equipped to deal with problems involving diagnosis, measurement, and control of indoor pollutants. Furthermore, there is no national mechanism appropriate to control building materials, work practices, or ventilation rates to achieve good indoor air quality. Nor are there indoor air quality guidelines or standards suitable for the residential and nonindustrial work environments which typically contain members of sensitive groups. However, these health authorities are being called upon with increasing frequency to investigate "sick buildings" in which a high percentage of the occupants report the nonspecific symptoms of indoor air pollution. Traditional industrial hygiene and occupational medicine techniques often prove unsatisfactory in coping with the problem. In efforts to control indoor air pollution, some states have passed indoor air quality standards, and others have banned products. Such a sporadic approach may lead to fragmented regulation, widespread confusion, and insufficient protection for building inhabitants.

Announced federal policies

The U.S. General Accounting Office (GAO) has called for the establishment of a federal task force, led by EPA, to identify and coordinate federal and private sector research activities relating to indoor air pollution, to compile data on indoor air pollution problems which will serve as a data base for states to use when they have indoor air-pollution problems, to inform the public on how to cope with indoor air pollution, and finally to plan research and development efforts needed to deal with the indoor air pollution problem (GAO, 1980). Some initial efforts to comply with GAO's approach have been made. An Inventory of Current Indoor Air Quality-Related Research has been compiled (Meyer and Hartley, 1981) and the proceedings of a Workshop on Indoor Air Quality Research Needs (Ross and Berg, 1981) has been published by an Ad-Hoc Interagency Research Group on Indoor Air Quality. Its members included representatives from the Departments of Energy, Housing & Urban Development, Health and Humai Services, Defense, Labor, Commerce, and Interior, as well as the Consumer Product Safety Commission and the Environmental Protection Agency. Most workshop participants expressed their feeling that indoor air pollution will become a major focus of new environment-related research efforts in the 1980's.

However, a major federal role in dealing with indoor air pollution is by no means assured. In an era of declining research budgets, the lack of legislative authority to regulate indoor air quality may seriously retard the development of a national indoor air pollution research program which has been announced. A GAO inquiry has revealed that although federal money managers may agree that indoor air pollution presents a problem, they are reluctant to devote resources to such research (GAO, 1980). Indeed, the lack of legislative authority to address the problem of indoor air pollution continues to hinder EPA management, resulting in a view of indoor air pollution research as peripheral to its charter under the Clean Air Act and occurring at the expense of mandated programs.

A comprehensive approach

As recommended by the GAO, the Clean Air Act could be revised to control indoor air pollution in much the same way as outdoor air pollution is now controlled. States could be given the primary authority to regulate indoor air quality. Enforcement of regulations would be complaint-oriented. The federal government's role might include research and development of monitoring instruments and determination of standard procedures for the measurement of various pollutants in indoor air, as well as the establishment of suitable ventilation rate standards, building material standards, consumer product emission standards, work practices, training of state personnel in indoor air pollution control, and appropriate indoor air quality standards or guidelines.

The Air Pollution Control Association (APCA) has also urged (APCA, 1982) the U.S. Congress to amend the Clean Air Act to authorize the appropriation of indoor air quality research funds, to initiate an indoor air pollution health effects assessment program, and to establish a national indoor air data base and information clearinghouse.

The federal role might also involve reviewing and approving state programs for the control of indoor air quality, which would promote uniformity and consistency among the states according to the principle of equal protection under the law. An appropriate federal agency would have primary responsibility for conducting indoor air research and developing standards and guidelines for the states' use in regulating indoor air quality. How such an approach might be implemented is discussed in detail below.

Research & development needs. Federally sponsored research and development should be oriented toward determining diagnostic instruments and procedures for the precise and accurate measurement of pollutants at ambient concentrations; development of reliable models for indoor air pollution transport and indoor/outdoor air pollution relationships; establishment of health-based indoor air quality standards or guidelines; measurement of the emission rates of pollutants from typical indoor sources; performing epidemiological studies of occupants' health in both "sick" and normal buildings; development of personal monitors and computerized dataloggers for total exposure studies (Wallace and Ott, 1982); risk assessment of indoor/outdoor air pollutants; evaluation of real or putative control measures for indoor air pollution, i.e., source control ventilation, air–air heat exchangers, electrostatic precipitators, high-efficiency fabric filters, charcoal filters, negative ion generators, etc.

Indoor air pollution regulatory options. Under the Clean Air Act, the term "Ambient Air" could be defined as "that portion of the atmosphere, both internal and external to buildings, to which the general public has access." The term "general public" could be defined so as to include white-collar workers in nonindustrial settings, particularly in commercial office buildings. Regulations might cover indoor air in such places as private residences, commercial buildings, institutional buildings, and recreational facilities, as well as commercial passenger aircraft, trains, and buses. Regulatory measures would generally focus upon controlling the sources and concentrations of pollutants rather than attempting to control human behavior.

Regulatory mechanisms used to control indoor air pollution could require that some air quality standard, action level, or goal be set as a guide for the appropriate control technique. Ambient indoor air quality standards would not necessarily be set and enforced in the indoor environment in the same way as in the outdoor environment. Rather, implicit indoor air quality standards could be used as guides against which the adequacy of emissions standards or building codes would be judged. In some cases, however, explicit legal standards might be necessary, particularly pertaining to minimum ventilation rates in commercial buildings.

There are a number of alternative approaches to the setting of indoor air quality standards:

a. Criteria air pollutants: In a minor modification of the Clean Air Act, simply adopt the National Ambient Air Quality Standards as standards for the indoor environment, possibly with modifications to account for synergisms with other indoor air pollutants.

b. Hazardous air pollutants: Similarly, standards for all pollutants which are held to be hazardous under Section 112 or Section 122 of the Clean Air Act would also explicitly apply to the indoor air environment.

c. Indoor air pollutants: The act could call for the establishment of a new category of indoor air pollutants not limited to the "criteria" or hazardous air pollutant list. The maximum permissible indoor level for current "criteria" or hazardous pollutants also would not necessarily be the same as in the outdoor air to allow for potential synergisms or mitigating factors. Risk analysis could be performed to determine those worth regulating, and also the amount of control necessary.

Using the indoor ambient "action level" concept, the main thrust of new regulations in the indoor air pollutant area might thus focus on technology-based standards and emissions controls, which would be implemented through building code changes and new product standards. Listed below are three examples of how new product standards and building codes might be employed to prevent the buildup of excessive indoor air pollution.

New product standards. In order to limit indoor formaldehyde concentrations to safe levels, indoor pollutant concentrations beyond "a given" action level for formaldehyde might require the control of emissions from particle board containing urea-formaldehyde resin.

Meyer (Meyer, 1980a, 1980b) has given an instructive example: A typical one-family residence might have approximately 186 m² of particle board; a mobile home might contain as much as 743 m² corresponding to about 4.5 ton of particle board. If 0.1% of this resin is not fully cured, this could amount to 0.23 kg of free formaldehyde. The correlation between the level of formaldehyde vapor in the building and the quantity of latent formaldehyde in the particle board can be predicted, given the quality of the particle board, the total amount of board installed, and the air infiltration or ventilation rate. In Japan, a product standard issued in 1977 prescribed a maximum release of 5 mg of formaldehyde per 100 g of resin. This keeps the air concentration in a typical Japanese residence below 120 $\mu g/m^3$ (Japan, 1970, 1977). According to Sundin (1982) Swedish resin manufacturers have successfully reduced the free formaldehyde content in the resin by as much as a factor of 8.

Building code standards. For a pollutant such as radon gas, in which the source is the subsoil of the building, and the route of entry is seepage through cracks in the foundation, radon infiltration into new residential buildings could be effectively limited by building-code requirements specifying the installation of vapor barriers.

Control of indoor air quality through automatic ventilation procedures. For gas stove emissions in residences, and for carbon dioxide or tobacco smoke concentrations in large office buildings with automated centralized heating, ventilating, and air conditioning (HVAC) control systems, automatic sensors may serve to control pollutant concentrations to within acceptable limits. For example, Fig. 6 shows that the NO_2 levels exceed certain presumed short-term air quality standards at the infiltration rates currently assumed to be typical of U.S. homes with the windows closed. Thermal sensors could be required to be installed in all gas stoves (electric stoves might also be included to control particulates from cooking) to activate a ventilating fan mounted over the stove; building codes would be correspondingly modified to require ventilation fans in all new dwellings. As Fig. 6 shows, the spot ventilation rates generated by stove hood exhaust fans can be adequate to control the concentrations of NO_2 from gas stoves.

With respect to indoor air pollution in large office buildings, it is possible that a few pollutants, acting as surrogates for other, less common pollutants could be monitored by sensors mounted in central ducts located on each floor of the building. When the levels of the pollutants exceeded certain present standards, ventilation rates could be automatically increased, and larger amounts of outside makeup air could be inducted into the system. Currently, ASHRAE requires a minimum of 5 cfm per occupant in many buildings, based on limiting reports that such low rates of induction of outside air are creating indoor air pollution problems. A sensor set to limit CO_2 to, say, 500 ppm might remedy some of these.

Acknowledgements—The author would like to thank P. Stolpman for his encouragement and support in producing this work, and is indebted to H. Ross for his critical reading of the manuscript, and to A. Moghissi for his editorial suggestions.

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