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CHARACTERIZATION OF INDOOR AIR POLLUTION

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Summary

This is a review paper addressing the current state-of-the-art. Concerns that motivate studies of the indoor environment are reviewed in the introduction. The source and typical diurnal variations of the concentration of several air contaminants are discussed in the section on characterization. A dynamic model is described in the section on indoor air quality modeling. Indoor air pollution control techniques are addressed in the last section.

Introduction

Several pilot studies of the indoor air quality in residences and office buildings show that air pollutant concentrations are often higher indoors than outdoors. These studies also indicate that reduction of ventilation rates in buildings, an energy conserving measure, causes increased concentrations of pollutants that are emitted by indoor sources. Thus, energy conservation may lead to adverse health effects of the occupants. The potential problem is further enhanced because typical individuals spend up to 90% of the day indoors. Pollutants of concern include carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), particulate matter, formaldehyde (HCHO), benzo-α-pyrene (BaP), other organics, radon and radon progeny (Rn), odors, microorganisms and others.

Scientific inquiry of the character of indoor air quality and related issues is relatively recent. Research prior to the energy shortage period marks the early attempts to characterize indoor air quality in non-industrial environments [1–3, and a few others]. This early research helped identify a potential air quality problem in residences. It is essential to appreciate that the indoor air quality problem may exist before any energy conservation measures are implemented. Research between 1976 and 1979 focused on the character of indoor air quality and the relationships between energy and environment parameters. The premise is that reduction of ventilation rates may lead to increased indoor pollutant concentrations [4–9, and many others]. The current phase of research on indoor air quality is an intensified effort to assess the magnitude of the problem and to design a long-term research pro-

gram. Examples of this effort included the National Academy of Sciences publication on Indoor Pollutants [10], the National Workshop on Research Needs on Indoor Quality [11], the International Symposium on Indoor Air Quality, Health and Energy Conservation, 13–16 October 1981, Amherst, Massachusetts, and forthcoming publications on the topic by the World Health Organization (1982), the New York Academy of Medicine (1981), and others. Since individuals spend up to 90% of their time indoors, it is possible that the greatest portion of the public's exposure to pollutants occurs indoors rather than outdoors.

The motivation for studying indoor air quality is the desire to estimate real values of an individual's total exposure to air contaminants and to reduce total exposure. Total exposure is defined as an individual's exposure to a contaminant over 24 h as he or she moves through his/her daily routine in various indoor and outdoor environments: residence, vehicle, work place, outdoors, amusement centers, and so on.

This paper presents the level of knowledge of certain aspects of indoor air pollution. Sampling instruments and monitoring protocols for characterizing indoor air quality will not be addressed but indoor air quality will be characterized. The dynamic relationships between source and indoor pollutant levels will be discussed by reviewing one dynamic model. Health effects associated with indoor air pollution will not be evaluated but a brief discussion of the control technologies for indoor residential environments will be presented.

Characterization

Two classes of residential environments have been identified by the collected data base: (1) residences with major pollutant emitting sources; and (2) residences without such sources. Note that this division is pollutant dependent. There are several classes of major pollution sources, i.e., indoor pollutant emitters, see Table 1. An additional source of pollution in residences is, of course, outdoor pollution. Only two pollutants are principally generated outdoors: O_3 and SO_2. Owing to their high chemical reactivity,

TABLE 1

Pollutant sources inside residences

Source	Pollutant
Combustion	CO, NO, NO_2, HCHO, organic vapors, BαP
Building materials	Rn and Rn progeny, HCHO, asbestos, mineral and synthetic fibers
Indoor occupant activity (smoking, cleaning, hobbies)	Respirable particles, sulfates, CO_2, total suspended particles, O_3, viable organisms, odors

these pollutants absorb on indoor surfaces and the concentrations of the pollutants do not reach high levels indoors. In addition to the outdoor pollution level, the magnitude of indoor pollutant concentrations depends on three factors: (1) the indoor source strength, i.e., the pollutant emission rate; (2) the frequency of emissions from the indoor source; and (3) the ventilation rate of a residence.

Incomplete combustion

Unvented gas appliances are one of the two principal indoor emitters of CO, NO, and NO_2. Smoking is the other major source. The complex interrelationships between indoor generation, outdoor pollution levels, and meteorology are illustrated in Fig. 1. The outdoor impacts on indoor levels

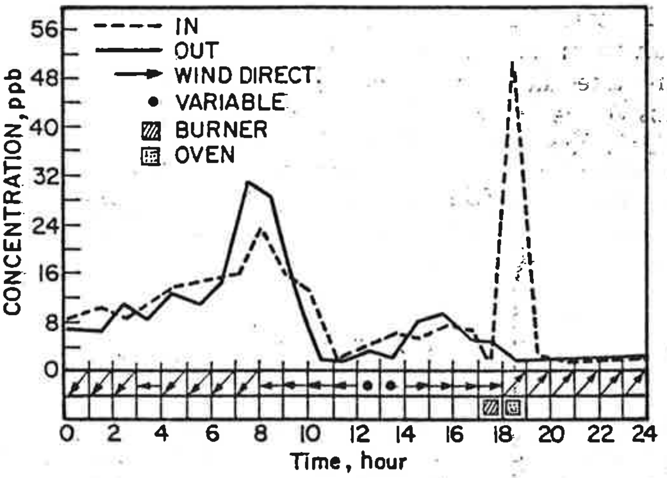

Fig. 1. Comparison of indoor—outdoor nitric oxide (NO) concentrations for a given house near a highway as a function of wind direction and range use.

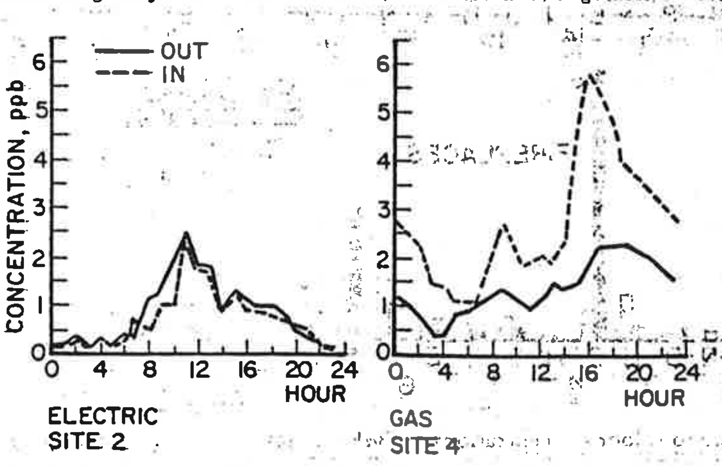

Fig. 2. Comparison of a gas and electric house of indoor—outdoor carbon monoxide concentrations.

of NO because of the wind direction from a nearby highway. At noon, the burner use has minimal impact; in the evening, the use of the range causes the NO concentration to peak. Also note that the afternoon outdoor levels are low; the traffic emissions are directed away from the test residence by the wind directions. The impact of emissions from an unvented gas appliance is illustrated in Fig. 2, which depicts two similar residences on a typical weekday, one with gas sources and the other without. Typically, the indoor concentrations of CO, NO, and NO_2 are low; however, occasionally they reach high levels that may cause adverse health effects. Reduction of ventilation rates has caused a justified concern regarding the short-term adverse health aspects from elevated indoor CO, NO, and NO_2 concentrations.

Products of incomplete combustion are also derived from woodburning, which has become a popular means of conserving energy, dollars and national resources. It is, however, a source of benzo-α-pyrene, a carcinogenic contaminant. A recent study of 20 residences [12] shows that indoor levels of BαP emitted from fireplaces and wood stoves are much higher than outdoor levels (Fig. 3). This verified a previous measurement of BαP of about 11.0 ng m^{-3} [13] versus an outdoor level of less than 2.0 ng m^{-3}.

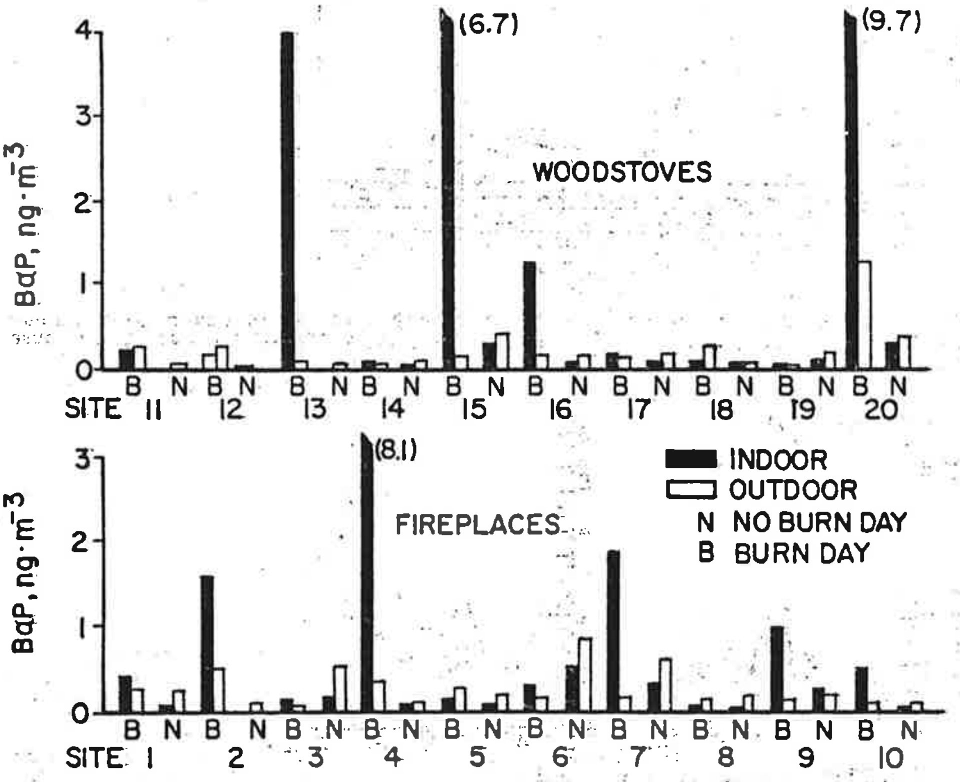

Fig. 3. Observed indoor—outdoor concentrations of BαP for houses with woodstoves or fireplaces.

Building materials

Lead and asbestos were among the first pollutants that helped focus attention on the indoor air quality of residences. Recent measurements indicate that Pb is not a widespread problem in residences as it used to be. High levels of asbestos have not been measured in residences. The problem with asbestos seems to be in large commercial buildings and in schools where it is used as fire retardant. Asbestos concentrations in schools are increased markedly when asbestos is disturbed willfully or inadvertently.

Formaldehyde is an odorous contaminant which has been recently linked with cancer. Formaldehyde is principally emitted from plywood and particle boards used as building materials. Formaldehyde levels in mobile homes have been measured at high concentrations (Fig. 4). Urea-formaldehyde foam is used for insulation of houses. Formaldehyde emissions from this foam have led to higher indoor HCHO concentrations. Massachusetts has banned the use of urea-formaldehyde foam and several other states have proposed indoor HCHO standards around the 0.2 ppm level.

Reduction of ventilation rates has helped focus attention on elevated concentrations of Rn and Rn progeny. Sources include soil under the residence,

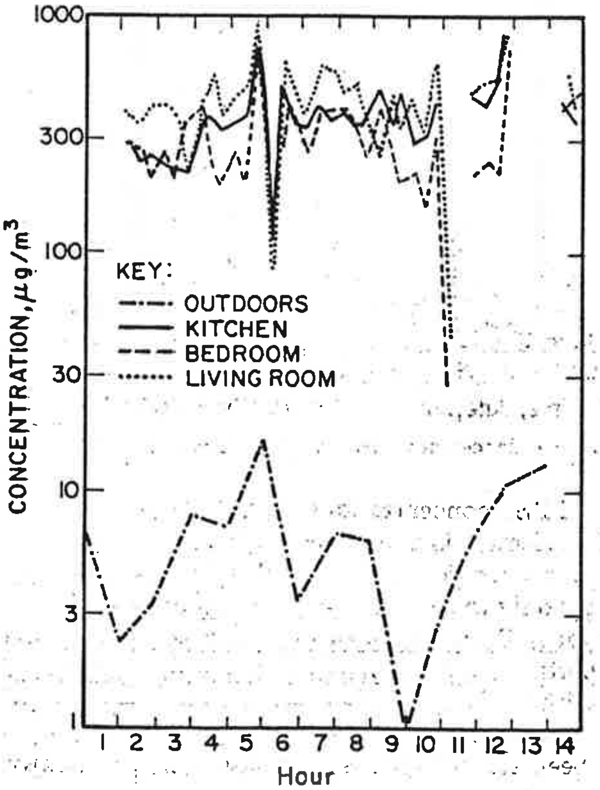

Fig. 4. Aldehydes concentrations in a mobile home in Pittsburgh, PA.

ground water and building materials. A recent study of 50 residences in a Maryland suburb of Washington, DC, shows that 55% of Rn concentrations are higher than 4.0 nCi m^{-3} which may lead to working levels above the annual guidelines [14]. This study was motivated by a previous study by the same team performed for Lawrence Berkeley Laboratories (LBL) on an experimental residence in the same location. Air-to-air heat exchangers have been shown to have a mitigating effect on Rn concentrations. These devices appear to be cost-effective in conserving energy and minimizing the adverse impact of indoor pollutant sources on indoor air quality.

Indoor occupant activity

Cooking is an indoor activity that has been associated with indoor pollution. Figure 5 illustrates a series of NO_2 peaks over a one week period [15]. All of these peaks are associated with cooking activities. Indoor activity by children has been associated with elevated total suspended particulates indoors, and it is assumed that their continuous motions causes reintrainment.

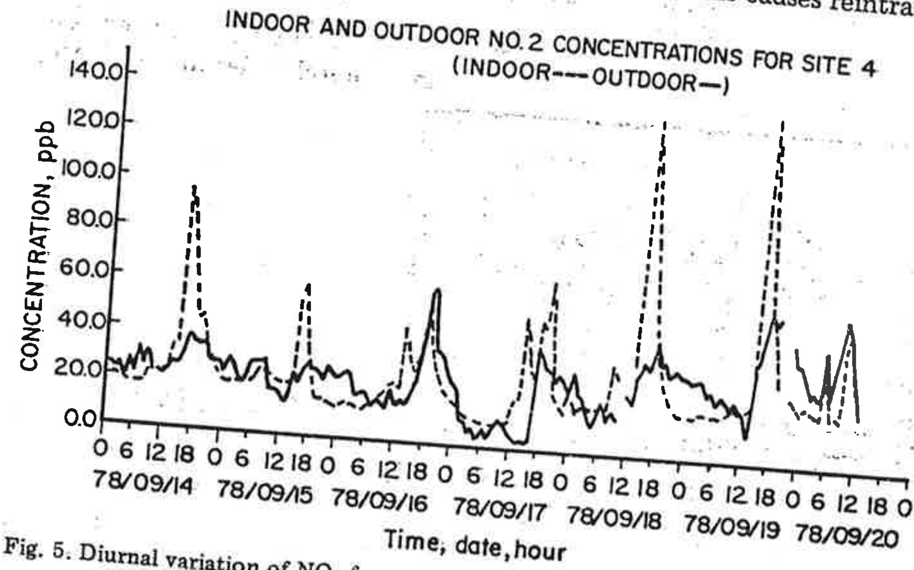

Fig. 5. Diurnal variation of NO_2 for a residence with unvented gas appliances.

Smoking is also causing elevated RSP concentrations (Fig. 6 [16]). Note that the filter devices appear to be effective in the office buildings. Smoking, of course, increases the indoor concentrations of inhalable particulates which cause adverse health effects not only to the smoker but to all others who are subjected to smoking emissions. Cleaning, such as vacuuming, has been shown to elevate airborne particulate levels indoors. Episodic release of organic vapors is associated with cleaning activities such as use of solvents, oven cleaning, furniture polishing, shaving, and similar activities [6]. Emissions from hobbies have not been studied extensively, however, it is known that they cause indoor emissions of lead and organic vapors.

Airborne contagion occurs primarily in indoor environments; the subject of viable organisms warrants further research. Indoor sources of microorganisms include the presence of humans, pets, rodents, insects, plants, fungi, humidifiers, and air conditioners. Scholars claim that up to 90% of the mortality associated with indoor environments is caused by biogenic contaminants [17].

The brief characterization presented here is representative of the state-of-the-art. The illustrations are from studies performed by the author of this article. The concentrations indicated illustrate examples from a data base of fewer than 100 residences. Statistical conclusions are not claimed, generalization for the American housing stock should not be made. All indoor studies performed are pilot studies. What is required now is a broad experimental design to characterize the indoor air quality of the American housing stock and to assess the magnitude of public exposures to indoor pollutant concentrations.

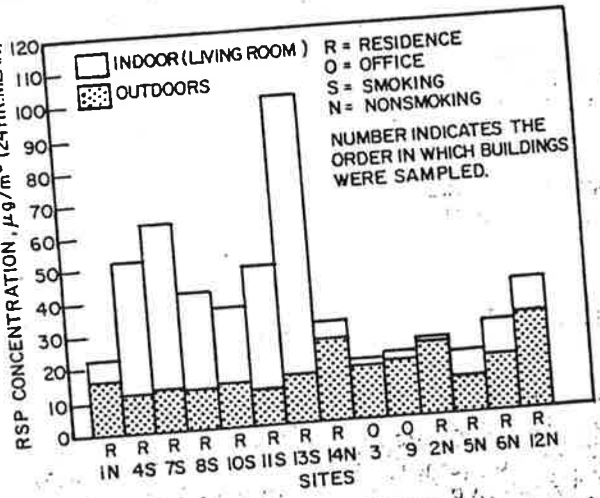

Fig. 6. Indoor and outdoor concentrations of respirable suspended particulate matter (RSP).

Indoor air quality modeling

The study of large samples of residences is a very expensive undertaking. The alternative approach is the formulation and validation of numerical models. These models can simulate a variety of conditions and can assist in estimating the indoor air quality for a large number of conditions. The GIOAP model is an example of such a model. The principle involved in the GIOAP model is that of mass balance. The basic equation of the GIOAP model is given below.

$$V\frac{dC_{in}}{dt} = V\nu C_{out} + S - V\nu C_{in} - VDC_{in} \tag{1}$$

with

$$t_0 \leqslant t \leqslant t_f$$

and

$$C_{in_0} = C_{in}(t_0)$$

where: V = volume of the residence (m^3); C_{in} = indoor pollutant concentration (mass m^{-3}); t = time of calculation (h); t_0 = initial time of calculation; t_f = final time of calculation; ν = infiltration rate (air changes per hour, ACH); C_{out} = outdoor pollutant concentration (mass m^{-3}); S = source strength (mass h^{-1}); D = sink strength (mass h^{-1}). A closed form solution of eqn. (1) is given below.

$$C(t) = \left[C_0 - m\left(\frac{\nu}{D+\nu}\right)t_0 - \left(\frac{1}{D+\nu}\right)\left(\nu b + \frac{S}{V} - \frac{m\nu}{D+\nu}\right)\right]\exp\left[-(D+\nu)(t-t_0)\right]$$
$$+ \left(\frac{1}{D+\nu}\right)\left(\nu b + \frac{S}{V} - \frac{m\nu}{D+\nu}\right) + m\left(\frac{\nu}{D+\nu}\right)t \tag{2}$$

where

$m = C_{out}(t_0) - C_{out}(t_f)$ $\qquad t_f - t_0 = 1$ h
$b = C_{out}(t_0) - mt_0$

The model relates the rate of change of the indoor pollutant concentration to the rate of introducing a pollutant indoors by ventilation ($V\nu C_{out}$) and by indoor generation (S), and the rate of removal by exfiltration ($-V\nu C_{in}$) and by chemical decay (VDC_{in}). The GIOAP model has been tested against data generated by the Moschandreas research team. It does not simulate O_3 indoor concentrations well and it has not been tested against SO_2. It predicts within 20% of the observed values 80% of the time for CO, NO, and NO_2. It does not do well on predicting episodes (high release incidents from indoor sources), but it does well characterizing the overall indoor air quality. The deficiencies of the model are associated with the present inability to quantify emission rates and modes of operations of indoor emission sources. More complex theoretical models which incorporate two components and involve mixing rates exist; however, the input values in such models are questionable and the models have not been validated. Statistical models have not been developed for indoor environments; research is warranted in that direction.

The subject of indoor pollution models is complicated and warrants a full presentation by itself. Only the surface of the topic has been addressed here. Modeling is a most powerful and inexpensive research tool that, when properly used, can assist in control assessment, cost-efficiency, exposure, and health effect studies.

Control techniques

Several techniques can be used to mitigate the elevated pollutant concentrations indoors (Table 2). Ventilation codes are written on the basis of comfort. A brief study of building ventilation codes points to two deficiencies: (1) indoor air quality is not considered in formulating these codes; and (2) there is no assurance that each code is properly implemented. The control efficiency of local ventilation warrants further research. Air-to-air heat exchangers appear to be a powerful tool for obtaining an optimum level of ventilation rate and energy efficiency [18].

TABLE 2

Control techniques

Technology	Application
Building codes	Federal, state and local authorities have promulgated building codes to protect the health and welfare of the occupants
Ventilation	Local; building wide; air-to-air heat exchangers
Sealants and barriers	Building materials
Product improvement (including removal)	Reduction of emissions rates
Control devices	Filters, adsorption bed, electrostatic precipitators
Education	Public knowledge determines path of least exposure

Sealants and barriers have been used for controlling asbestos, HCHO, and Rn. Varying degrees of success have been claimed by many. Once again independent research is required to define their efficiency. Product improvement has been tried successfully in various indoor sources. Examples include manufacturing lead-free paint, fire retardants that do not include asbestos, and others. Certain sources are totally eliminated with small economic impact, i.e., unvented gas appliances without pilot lights. Product improvement requires assurance that the substitute product is not an emitter of a new contaminant and that it does not overburden the house owner financially.

Control devices include filters (widely used for control of particulates), adsorbing charcoal beds (for controlling gas contaminants), and electrostatic precipitators. The last two devices have been used in residences only infrequently and their success in controlling pollutants is not universally accepted. These devices appear to be better suited for large buildings rather than residences. A final inexpensive but promising approach to mitigate indoor pollution is public education. By educating Americans of the potential risks, they will follow common sense and arrange their activities so that exposure to occupants will be minimal. Education is the least expensive approach of reducing indoor pollutant concentrations by using local ventilation when cooking, opening the windows when cleaning, and venting the indoor air outdoors from major sources such as gas appliances, fireplaces, work benches, and the like.

Controlling the quality of indoor air in residences and office buildings may prove to be the least expensive avenue for reducing exposure to air pollutants. Cost-efficiency studies will determine the optimum control technology that will not be too expensive, will conserve energy, and protect the integrity of indoor air quality and, consequently, public health.

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