Title
RESEARCH REVIEW: INDOOR AIR QUALITY CONTROL TECHNIQUES

Permalink
https://escholarship.org/uc/item/9bd8m4kf

Author
Fisk, W.J.

Publication Date
1986-10-01

LBL-21557 c.2

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE DIVISION

Presented at the IAQ'86: Managing Indoor Air for Health and Energy Conservation, ASHRAE, Atlanta, GA, April 20-23, 1986, and published in the Proceedings

RESEARCH REVIEW: INDOOR AIR QUALITY CONTROL TECHNIQUES

W.J. Fisk

October 1986

APPLIED SCIENCE
DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

Published in Proceedings of IAQ'86:
Managing Indoor Air for Health and
Energy Conservation, April 20 - 23,
1986, Atlanta, GA, American Society
of Heating, Refrigerating, and Air
Conditioning Engineers, Inc.

LBL-21557

RESEARCH REVIEW: INDOOR AIR QUALITY CONTROL TECHNIQUES

William J. Fisk

Indoor Environment Program
Applied Science Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

October 1986

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

ABSTRACT

Techniques for controlling the concentration of radon, formaldehyde, and combustion products in the indoor air are reviewed. The most effective techniques, which are generally based on limiting or reducing indoor pollutant source strengths, can decrease indoor pollutant concentrations by a factor of 3 to 10. Unless the initial ventilation rate is unusually low, it is difficult to reduce indoor pollutant concentrations more than approximately 50% by increasing the ventilation rate of an entire building. However, the efficiency of indoor pollutant control by ventilation can be enhanced through the use of local exhaust ventilation near concentrated sources of pollutants, by minimizing short circuiting of air from supply to exhaust when pollutant sources are dispersed and, in some situations, by promoting a displacement flow of air and pollutants toward the exhaust. Active air cleaning is also examined briefly. Filtration and electrostatic air cleaning for removal of particles from the indoor air are the most practical and effective currently available techniques of air cleaning.

INTRODUCTION

The spatial average concentration of a pollutant in the indoor air depends, at steady state, on the outdoor concentration, the indoor pollutant source strength, and the total rate of pollutant removal. Thus, indoor pollutant control measures are based on modifying either the pollutant source strength or the rate of pollutant removal.

Measured data indicate that, for most indoor pollutants of concern, the building-to-building variations in indoor pollutant source strengths are greater than the variations in pollutant removal rates (see, for example, Nero and Nazaroff 1984 and Fleming 1985). Consequently, and as shown in this paper, highly effective indoor pollutant control measures are more often based on eliminating or reducing pollutant sources than on increasing pollutant removal rates. The basic methods of reducing pollutant source strengths are exclusion or removal of sources, diversion of the pollutants emitted from sources so these pollutants do not enter the indoor air, and modification of sources to reduce the rate of pollutant emission.

The processes by which a pollutant may be removed from the indoor air are ventilation, air cleaning, deposition on surfaces, chemical reactions (on surfaces or within the air), and radioactive decay. Of these removal processes, only ventilation and air cleaning are effective and practical pollutant control measures at the present time. Ventilation and air cleaning often depend on mechanical systems and lead to increased energy demands; thus, there is generally a practical upper limit to their rate.

Source control, ventilation, and air cleaning are discussed in turn in the remainder of this paper, which emphasizes the control of radon, formaldehyde, and combustion products. The discussion is limited primarily to a description of the effectiveness of various measures in controlling indoor pollutant concentrations. Measures that have been shown to be ineffective or that were judged to be impractical in most situations are not discussed. For a more comprehensive review of this topic the reader is referred to another document (Fisk et al. 1984).

CONTROL OF POLLUTANT SOURCE STRENGTHS

Radon Source Control

Background. In the majority of U.S. buildings with high indoor radon concentrations, the primary source of radon is the pressure-driven flow of radon - laden soil gas into the building through cracks or other penetrations in the building's substructure (Nero and Nazaroff 1984). The pressure difference that drives this soil gas entry may result from wind, indoor-outdoor temperature differences, operation of mechanical ventilation systems or combustion devices that tend to depressurize the building, and possibly from changes in barometric pressure. Methods for reducing the rate of radon entry due to pressure-driven flow include elimination or sealing of specific radon entry pathways, ventilation of crawl spaces, sub-slab ventilation, basement pressurization, and ventilation of the cavities within walls constructed from hollow concrete blocks. Each of these methods is described below.

Sealing. Attempts to inhibit radon entry by sealing of cracks and other penetrations through basement floors and walls and blocking of other radon entry pathways have met with mixed success. In Elliot Lake, Ontario (DSMA 1979, 1980), and Sweden (Ericson et al. 1984) such measures have frequently reduced indoor radon concentrations by a factor of 3 to 10. On the other hand, sealing was found to be relatively ineffective for radon control in remedial studies performed in New York (Fleming 1985), Pennsylvania (Sachs and Hernandez 1984), and the state of Washington (Turk et al. 1986). A possible explanation for these contradictory results is that virtually all openings to the soil must be sealed to substantially reduce soil gas entry and that some investigators were more successful than others in obtaining a nearly leak-free substructure. The soil gas entry rate would be expected to be relatively independent of the area of leakage paths to the soil, in cases where the resistance to flow through the soil is large compared to the resistance to flow through the penetrations in the building's substructure. The resistance to soil gas flow through the soil depends on soil permeability, which varies over approximately eight orders of magnitude. However, data that relate soil gas entry rates to both soil permeability and substructure leakage area are not currently available.

Crawl Space Ventilation and Sealing of Floors. In general, soil gas and radon transport into a crawl space is not inhibited by a barrier over the surface of the soil. The same factors that lead to pressure-driven flow of soil gas through penetrations in a basement or slab on grade can cause crawl-space air to be drawn into a house through the floor above the crawl space. Sealing leakage paths through this floor is, therefore, an obvious radon control measure. This procedure is sometimes combined with increased crawl space ventilation. Quantitative information on the effectiveness of crawl space ventilation and/or sealing of floors above crawl spaces as a radon control measure is limited (see Vivyurka 1979; Nazaroff and Doyle 1985; Ericson et al. 1984). Available data from a few residences suggest that natural crawl-space ventilation and/or sealing of floors is moderately to highly effective (i.e., indoor radon concentrations may be reduced by roughly 50% or more when openings are provided in crawl space walls) and that mechanical ventilation of crawl spaces is generally highly effective in reducing radon entry from the crawl space.

Sub-slab Ventilation. Sub-slab ventilation (SSV) is generally accomplished by using one or more fans to draw soil gas from beneath a slab floor and exhaust this soil gas to outside. This procedure is also referred to as sub-slab depressurization (SSD). The fan(s) may draw from a drain tile system located beneath the slab or around the perimeter of the foundation or from one or more pipes that penetrate through the slab floor and terminate in a dry sump. SSD systems decrease the pressure within the soil beneath the slab and, therefore, decrease or reverse the normal pressure gradient that drives soil gas into buildings. In addition, a SSD system may decrease the radon concentration in the soil gas beneath the slab because it draws low-radon outdoor air from the soil surface to the region beneath the slab. SSD systems have been utilized in at least 250 buildings and in numerous geographical locations -- for example in Canada (Vivyurka 1979), Pennsylvania (Henschel and Scott 1986; Sachs and Hernandez 1984); New York (Fleming 1985); Washington State (Turk et al. 1986), and Sweden (Ericson et al. 1984). Through SSD and the sealing of large and accessible penetrations to the soil, investigators have generally been able to reduce indoor radon concentrations by 50% to more than 90% and to below typical radon concentration guidelines. However, SSD has failed to reduce indoor radon concentrations to acceptable values in a few houses, particularly those with concrete block basement walls (Henschel and Scott 1986). Theoretical considerations and available experimental data indicate that the effectiveness of SSV should be increased by the following factors: (1) drawing air from an extensive drain tile system beneath the foundation; (2) drawing air from several penetrations through the slab when a drain tile system is not present; (3) the presence of a highly permeable layer of aggregate beneath the slab; (4) a decrease in the size and number of cracks or other penetrations through the slab or basement walls; (5) increased fan flow rate and depressurization.

A variation of the usual technique of sub-slab ventilation is to reverse the direction of flow and force low-radon outdoor air beneath the slab. While this procedure of sub-slab pressurization (SSP) will increase the driving force (i.e., pressure differential) for soil gas entry into the house, it should also reduce the concentration of radon in the soil gas that enters the building to a greater degree than SSD. In the only known studies of SSP within three residences located in a region with highly permeable soil (Turk et al. 1986), a lower flow rate and lower pressure fan were required for SSP than for SSD. These results are summarized in Figure 1.

<u>Basement Pressurization</u>. Because soil gas transport into buildings is driven by a small (e.g., few pascal) pressure difference across the barrier between a building and the soil, increasing the pressure within a building or its basement by a corresponding amount should

inhibit or eliminate radon entry. Turk et al. (1986) have pressurized the basements of four houses. The process is relatively simple and inexpensive, especially in structures without ductwork for a forced-air heating or cooling system. Obvious leakage paths between the basement and the first floor were sealed and a "door closer" was installed on the door to the basement. A low-pressure fan was then utilized to draw 250 to 400 ft^3/min (120 to 190 L/s) of air from the first-floor level, force this air into the basement, and increase pressures at a point in the basement to approximately 0.004 to 0.02 inch of water (one to five pascal) greater than the pressure measured at a point within the soil at the same elevation. Indoor radon concentrations decreased by approximately 65% to 95% and to below typical radon concentration guidelines as shown in Figure 2. This simple procedure can only be utilized in buildings that have a relatively airtight basement. Opening a basement window or leaving the door to the basement in the open position would make these basement pressurization systems ineffective.

Basement pressurization, plus the associated tightening of the basement, will alter the ventilation rate of the building to a variable degree that has not been characterized. Both increases and decreases in the total building ventilation rate might be expected, depending on the situation. Similarly, sub-slab ventilation (described previously) and ventilation of the cavities within block walls (described in the following paragraph) will increase building ventilation rates to a variable degree that depends, in part, on the size and number of penetrations between the sub-slab region (or the wall cavities) and the interior of the building. As a consequence of the changes in ventilation rates, each of these techniques will modify the energy requirements for heating or cooling.

Venting the Cavities Within Concrete Block Walls. It is particularly difficult to prevent soil gas, and thus radon, entry into buildings with basement walls constructed from hollow-core concrete blocks. Soil gas may enter the cavities within the concrete blocks through cracks, imperfect mortar joints, and directly through the porous concrete from which the block is constructed, move horizontally and vertically within the wall through the interconnected network of cavities, and enter the house again through cracks, joints, and the porous block. In addition, the openings to the wall cavities at the top of the concrete block wall are another route for soil gas entry into the building. A method of inhibiting or preventing soil gas entry through such walls is to seal all major accessible openings to the network of wall cavities and to use one or more fans to draw air from this network and exhaust this air outside. Initial results from field studies of wall cavity ventilation are provided by Henschel and Scott (1986). Indoor radon concentrations were reduced by more than 90% in two houses where it was possible to seal all major openings to the network of wall cavities. In four other houses, wall cavity ventilation was highly effective only during the summer, and in one house the wall cavity ventilation system was ineffective even during the summer. To make wall cavity ventilation more widely applicable, practical methods for closing the hard-to-reach openings to the wall cavities are needed.

Formaldehyde Source Control

The predominant indoor sources of formaldehyde (HCHO) are particle board, medium-density fiberboard, hardwood plywood paneling, and urea formaldehyde foam insulation (UFFI). The emission rate of HCHO from these sources increases with their temperature and moisture content, which depend on the temperature and humidity of the surrounding air. A decrease in the surrounding HCHO concentration will also generally cause the HCHO emission rate to increase. However, HCHO emission rates generally decrease over time. Methods for controlling HCHO source strengths from pressed-wood products include complete or partial exclusion or removal of sources, changes in the composition of products and in manufacturing processes, and the application of coatings or barriers on the surfaces of source materials. Methods of mitigating indoor HCHO problems caused by the presence of UFFI are, with one exception, not described in this paper.

Source Exclusion or Removal. Complete exclusion or removal of sources is obviously effective in reducing the indoor HCHO source strength. Such a measure is difficult and expensive since urea-formaldehyde resins are utilized in many products. Partial exclusion or removal of sources will also reduce indoor HCHO concentrations; however, the HCHO emission rates from the remaining sources may increase and, to a degree, offset expected benefits of the source removal. Matthews et al. (1983) and Godish and Rouch (1984) provide some examples of the effectiveness of source removal. Matthews et al. used a mathematical model to predict the indoor HCHO concentration in a hypothetical room as various indoor sources, and combinations of sources, were removed or covered with a barrier. A reduction in indoor HCHO concentration by 65% to 80% was predicted to result from extensive source removal and application of vinyl floor covering over the particle board flooring. However, only 16% to 43% reductions in indoor HCHO concentrations were predicted for less extensive measures such as removal of the UFFI or the furniture that contained medium density fiberboard. A subset of the tabular data provided by Matthews et al. is illustrated graphically in Figure 3.

Godish and Rouch studied source removal experimentally in a house with two major HCHO sources -- particle board flooring and hardwood plywood paneling. Removal of 75% of the paneling resulted in a 49% reduction in the indoor HCHO concentration and removal of 50% of the particle board flooring caused a 29% reduction in HCHO concentration.

Product Composition and Manufacturing Processes. Many manufacturers of pressed-wood products have modified the composition of their products and manufacturing processes in order to reduce HCHO emission rates (Meyer and Hermans 1985). In addition, standard methods for measuring HCHO emission rates have been developed and some quality control procedures have been implemented. These measures can be highly effective in reducing HCHO emission rates. For example, addition of 10% more urea and 5% melamine to a particle board resin can cause a factor of 10 reduction in HCHO emission rate (Myers and Nagoada 1981). Due to reductions in the molar ratio of formaldehyde to urea in resins, the amount of unreacted formaldehyde in commercial products has fallen dramatically and lower HCHO emission rates have resulted. The large dependence of HCHO emission rate on characteristics of the urea-formaldehyde resins is illustrated in Figure 4 from a paper by Meyer and Hermans (1985). This figure shows that the HCHO emission rate from samples of seven six-week-old medium density fiberboards, each made with a different resin that was commercially available during 1983, varies by more than a factor of 23 (see Meyer et al. 1985 for further information). Figure 4 also includes some data from industry on the emission rates of HCHO from particleboard. These data indicate that industry is making progress in reducing HCHO emission rates from particle board. However, it is known that HCHO emission rates from presently available particle boards vary widely; thus, further improvement in quality control is required to ensure that products consistently emit low amounts of HCHO. The practical long-term solution to the problem of HCHO emission from pressed-wood products appears to be changes to resins and manufacturing processes and improved quality control.

Coatings and Barriers. Another procedure of HCHO source control is the application of coatings (applied as a liquid) and solid barriers on the surfaces of pressed wood products. Coatings that contain formaldehyde scavengers (materials that react chemically with HCHO) have been indicated in a few papers to be moderately to highly effective in reducing HCHO emission (Fisk et al. 1984). The effectiveness of selected solid barriers applied over particleboard flooring has been studied by Matthews et al. (1985, 1986). Vinyl floor covering reduced HCHO emission by a factor of 30 in laboratory studies; however, application of vinyl floor covering in a house with several HCHO sources reduced indoor HCHO concentrations by only 50% to 60%. Figure 3 shows one further example of the effectiveness of vinyl floor coverings -- in this example, the predicted reduction in indoor HCHO concentration is only 20%.

Combustion Product Source Control

Background. The major indoor sources of combustion products are unvented space heaters, gas ranges, tobacco smoking, and vented combustion devices from which pollutants leak into the indoor air. In addition, combustion products can be transported to indoors from parking garages, loading docks, and other areas with a high concentration of vehicular exhaust products. A variety of combustion products including carbon monoxide (CO), carbon dioxide (CO_2), particles, sulfur dioxide (SO_2), organic compounds, and oxides of nitrogen (NO_x) can enter the indoor air from these sources. Oxides of nitrogen (NO_x) include both nitrogen dioxide (NO_2) and nitric oxide (NO). NO_2 is considered to be much more significant than NO from a health standpoint; therefore, its control is generally emphasized. Source control measures are discussed on a source-by-source basis in the following paragraphs.

Unvented Space Heaters. Unvented space heaters that burn kerosene, natural gas, or propane can be a major indoor source of combustion products (Traynor et al. 1983, 1984, 1984b; Fleming 1985; Leaderer et al. 1984). The obvious and most effective source control measure is to exclude or remove these unvented heaters and use electric or vented combustion space heaters as a substitute. Other less effective control measures are possible. Burner design and state of tune (i.e., air shutter or wick adjustment) have a large impact on the rates of CO and NO_2 emission; however, the emission rate of CO_2 depends only on the rate of combustion. Recently developed unvented kerosene space heaters with a two-stage burner (i.e., both a convective and a radiant stage) emit roughly 30% to 60% as much CO and 10% to 50% as much NO_2 as single-stage heaters (Traynor 1986). One final control measure is to reduce the operating time of the heater, for example, by adding thermal insulation to the building and decreasing the demand for heat.

Gas Ranges. Gas ranges emit combustion products at a lower rate than unvented space heaters but are present in a large number of buildings. One source control option is to use an electric range. Three additional measures are the use of a range hood, substitution of an electronic ignition system for the gas pilot(s), and modification of burners.

Three investigations of the performance of residential range hoods were identified, and in each case the results were characterized in a slightly different way. Macriss and Elkins (1977) found that the increase in kitchen NO_x concentration due to operation of a gas range was only 30% smaller when a range hood with an exhaust flow rate of 200 ft^3/min (93 L/s) was operated. Traynor et al. (1982) measured a 60% to 87% decrease in the amount of CO, CO_2, and NO_x that entered the occupied space of a research house when a range hood was operated with a flow rate of 90 to 250 ft^3/min (42 to 117 L/s). Revzan (1984) injected a tracer gas 4 in (10 cm) above an operating range-top burner to simulate the emission of pollutants. A range hood with a flow rate of 130 ft^3/min (60 L/s) caused a 77% decrease in the amount of tracer within the test space after a one-hour test compared to the amount of tracer that would have been present in the test space if the indoor air were perfectly mixed during the test. Thus, one study indicates that range hoods are relatively ineffective and two studies indicate that they are highly effective. Since numerous factors, such as hood geometry and location, may affect range hood performance, these contradictory results are not unexpected.

The effectiveness of the second source control measure mentioned above -- substitution of electronic spark ignition systems for gas pilots -- has not been demonstrated by experiments, but available information suggests a reasonable degree of effectiveness. Macriss and Elkins (1977) provide data indicating that gas pilots emit roughly 150% as much NO_2 per unit of gas consumed as gas-range burners. Since the pilot(s) may consume 30% to 60% of the total gas used by the range (Meier et al. 1983; Macriss and Elkins 1976; DeWerth 1974), elimination of the pilot(s) should reduce the total NO_2 emitted from a range by 45% to 90%. However, peak NO_2 emission rates and peak NO_2 concentrations will not be as dramatically affected by this measure.

The third method of reducing pollutant emissions from gas ranges is to modify the burners. Reducing flame temperatures, such as by quenching the flame, will decrease the NO_2 emission rate; however, this process can also increase the CO emission rate. DeWerth and

Sterbik (1985) have evaluated a number of burner modifications. They indicate that the most acceptable modifications, considering CO emission rate, costs, and marketability, were the addition of inserts constructed from stainless steel wire to range-top burners and the addition of "dual rod" inserts to the oven burner. These inserts caused a 25% reduction in NO_2 emission rates and increased the emission rate of CO to a variable degree, but no more than a factor of 4.

Leakage from Vented Combustion Appliances. Many buildings contain one or more combustion appliances from which the combustion gases are vented to the outside (e.g., vented space heaters, water heaters, wood stoves, and fireplaces). These appliances can be major indoor sources of combustion products if exhaust products leak to indoors. In severe cases, sufficient carbon monoxide can accumulate indoors to cause fatalities.

Equipment problems or defects that can lead to leakage of combustion products to the indoors include cracked heat exchangers in furnaces, leaks or cracks in wood stoves, and collapsed, blocked, damaged, or disconnected chimneys or vent stacks (Russel and Robinson 1984; Moffatt 1986). The obvious solution is to repair or replace the faulty components. Periodic inspection and/or testing of combustion equipment by trained personnel or perhaps informed homeowners would help to identify such problems and reduce the incidence of both fatal accidents and nonfatal, elevated indoor concentrations of combustion products.

Another problem is the spillage of combustion products to the indoors from dilution devices (e.g., the draft hoods of gas furnaces or water heaters and the barometric dampers of oil-fired furnaces). In severe cases, a complete reversal of the direction of flow through the stack (i.e., backdrafting) can occur such that outdoor air is drawn into the building through the stack and all flue gases are vented indoors. Spillage or backdrafting will occur when the indoor air pressure at the elevation of the dilution device is lower than the pressure of the combustion gases flowing through the dilution device. Any factor that decreases the indoor air pressure or increases the pressure within the vent stack would be expected to increase the probability of spillage. Such factors include an airtight building envelope, operation of exhaust fans, and operation of combustion appliances and fireplaces that utilize significant quantities of air (see Hayden 1984; Swinton and White 1986). One energy-efficient solution to the problem of spillage and backdrafting is to utilize combustion appliances that do not require a dilution device and that force combustion gases to the outside with a pulsed-combustion process or a fan. In general these appliances are substantially more energy efficient than natural draft appliances. Other methods for reducing the probability of spillage or backdrafting include the following: assuring a positive supply of outside air for all combustion appliances including fireplaces; maintaining stacks and chimneys clear of obstructions; eliminating the use of exhaust fans, fireplaces, and other devices that exhaust large amounts of air to the outside; and developing and installing spillage detectors that shut down combustion appliances in the case of spillage (Hayden 1984; Russel and Robinson 1984; Moffatt 1986). A test procedure, for determining whether leakage of combustion products to indoors is probable in a particular building, is described by Moffatt (1986).

Tobacco Smoking. Tobacco smoking is an important indoor source of both respirable particles and a very large number of gaseous pollutants. Appropriate source control measures include complete exclusion of smoking and limiting of smoking to certain regions or rooms. Another procedure is to relocate employees so that smokers are not in close proximity to employees who object to tobacco smoke. Ideally, one should minimize the transport of smoke to nonsmoking areas. This could be accomplished by providing physical barriers between smoking and nonsmoking areas, exhaust ventilation of smoking areas, or using separate balanced ventilation systems for smoking and nonsmoking areas while maintaining a slightly higher air pressure in the nonsmoking area. Such source control measures may be inconvenient or expensive, but increased rates of ventilation for an entire building do not appear to be a practical method of controlling tobacco smoke sufficiently for many nonsmokers (Leaderer and Cain 1983).

VENTILATION

Background. In this paper the term "ventilation" refers to the replacement of indoor air with outdoor air. Ventilation can result from air leakage through the building envelope (infiltration), air flow through windows and other intentional openings (natural ventilation), and use of mechanical systems containing fans (mechanical ventilation). Ventilation is usually the largest pollutant removal process when the source of the pollutant is primarily indoors (Fisk 1985). The rate and method of ventilation is constrained primarily because of the energy required to move and condition the air but also because of the necessity to maintain thermal comfort, avoid excessive air velocities, and keep noise at acceptable levels. In the following discussion, typical ventilation rates are described, the relationship between ventilation rate and indoor pollutant concentrations is examined, and factors that enhance or degrade the efficiency of indoor pollutant control by ventilation are described.

Ventilation Rates. The three common methods of characterizing ventilation rates are: flow rate per unit volume (air changes per hour), flow rate per occupant, and flow rate per unit floor area. The ventilation rate of residential buildings in the U.S., with windows and doors closed, ranges from about 0.2 to 3.0 air changes per hour (ach) and the average residential ventilation rate has been estimated to be between 0.5 and 0.9 ach (Grimsrud et al. 1983). The current ASHRAE Standard, No. 62-1981, "Ventilation for Acceptable Indoor Air Quality" (ASHRAE 1981), specifies that residences should be designed for a minimum ventilation rate of 10 ft^3/min (5 L/s) per room and that additional ventilation capacity should be provided for intermittent use in kitchens and bathrooms.

Few measured data are available on the ventilation rates of commercial (e.g., office or institutional) buildings. Measurements by Turk et al. (1986) in 38 buildings yielded ventilation rates of 0.3 to 4.1 ach with an arithmetic average of 1.5 ach. These ventilation rates were also expressed as 9.6 to 178.6 ft^3/min (4.5 to 84 L/s) per occupant and as 0.0 to 0.7 ft^3/min per square foot of floor area. Persily and Grot (1985) report on measurements in nine office buildings, which yielded ventilation rates of approximately 0.15 to 2.0 ach. ASHRAE Standard 62-1981 specifies minimum design ventilation rates of 20 ft^3/min (10 L/s) per occupant where smoking is permitted and 5 ft^3/min (2.5 L/s) per occupant in areas without smoking for office buildings and the same or higher design ventilation rates for other types of buildings.

Ventilation Rates and Indoor Pollutant Concentrations. It is important to recognize that maintaining a typical ventilation rate, such as a rate comparable to that specified in ASHRAE Standard 62-1981, does not ensure that indoor pollutant concentrations will be acceptably low. Figure 5 presents measured data that clearly illustrate this fact for the case of indoor radon concentrations. As noted in the previous sections of this paper, pollutant source strengths vary more widely than ventilation rates; therefore, a wide range in pollutant concentrations can be expected in a group of buildings with the same ventilation rate.

Ventilation rates do impact indoor pollutant concentrations and often the relationship between these two variables is characterized using the following simple, steady-state mass-balance equation for an indoor space with perfectly mixed air:

$$C_{\iota} = (S + a\ P\ C_o)/(a + K + \lambda + R) \qquad (1)$$

where:

S = pollutant source strength per unit volume indoor air,

a = air exchange rate (i.e., air flow rate/indoor volume),

P = fraction of outdoor pollutant that penetrates the building envelope or ventilation system,

C_o = outdoor pollutant concentration,

K = pollutant removal rate by deposition on surfaces and chemical reaction per unit volume indoor air,

λ = pollutant removal rate by radioactive decay per unit volume, and

R = pollutant removal rate by air cleaning per unit volume indoor air.

Limited data are available for many of the parameters in Equation 1. The reader is referred to documents by Fleming (1985) and Fisk (1985) for data on the penetration factor (P) and the deposition or reaction constant (K). Pollutant source strengths and outdoor pollutant concentrations vary widely. In many cases, one cannot readily predict pollutant source strengths; however, measured data on source strengths are available throughout the literature on indoor air quality. Source strengths may be a function of the rate or method of ventilation (Fisk 1985). For example, HCHO source strengths increase as indoor HCHO concentrations decrease due to ventilation or other processes, and radon source strengths may increase simultaneously with the rate of infiltration or exhaust ventilation.

In this paper, Equation 1 is utilized to generate the curves within Figure 6, which serve as examples of relationships between ventilation rate and indoor pollutant concentrations. Based on an examination of Figure 6, it is clear that indoor pollutant concentrations will generally rise rapidly as ventilation rates approach a value of zero. Therefore, a small and relatively inexpensive increase in ventilation rate, for example, an increase of 0.2 ach, could lead to a large improvement in indoor air quality if the initial ventilation rate is low but have little impact on indoor air quality if the initial ventilation rate is high. Clearly, it is important and efficient to avoid extremely low ventilation rates, but it is difficult to justify any specific value for a minimum ventilation rate unless maximum pollutant source strengths and maximum allowable pollutant concentrations are also specified.

Another fact, indicated by the tabular data of Figure 6, is that the sensitivity of indoor pollutant concentration to ventilation rate is variable. The common assumption, that indoor concentrations are inversely proportional to the air exchange rate, is often substantially in error. In most cases, the indoor concentration will vary less rapidly with ventilation rate because outdoor concentrations are significant, or pollutant removal by deposition, reaction, or air cleaning are significant, or because the pollutant source strength increases with an increase in ventilation rate.

The most convincing data on the effectiveness of ventilation for controlling indoor air quality is that obtained from field studies where the ventilation rate was varied to determine the impact on indoor pollutant concentrations or to mitigate an indoor air quality problem. Relatively few studies of this type have been reported. In a field study by Offermann et al. (1982), which may provide some typical results, it was practical to increase ventilation rates by roughly 75%, and indoor radon, HCHO, NO_2, and particle concentrations generally decreased by 50% or less.

Enhancing or Degrading the Effectiveness of Ventilation. The previous discussion of ventilation rates and indoor pollutant concentrations is valid for situations when the indoor air is well mixed. Imperfect mixing can lead to substantial increases or decreases in the rate of pollutant removal by a given amount of ventilation. In fact, the efficiency of providing or removing heat can also depend substantially on the mixing and flow patterns of indoor air. The relationships between mixing, air flow patterns, pollutant removal, supply and removal of heat, and ventilation system characteristics are the basis for a field of study called "ventilation efficiency." Some of the basic concepts of ventilation efficiency are introduced in the following paragraphs; however, the mathematics and terminology associated with ventilation efficiency are omitted from this paper (see, for example; Sandberg 1981; Sandberg and Sjoberg 1983).

The largest opportunity for enhancing the efficiency of pollutant removal by ventilation occurs when pollutant sources are spatially concentrated. In such instances, exhausting air from regions with strong sources of pollutants, such as kitchens, bathrooms, and blueprint rooms, can be much more efficient than providing an equivalent amount of ventilation for the entire building. Exhaust ventilation can even be considered a method of source control -- an example is the use of range hoods as described earlier. Increasing the rate of balanced mechanical ventilation in regions with strong pollutant sources is less common than exhaust ventilation but can be relatively effective. For example, balanced mechanical ventilation of residential basements with low initial ventilation rates may frequently be an effective radon control measure based on the available data, which are summarized in Figure 7.

Even when pollutant sources are dispersed throughout a building, certain procedures may increase the rate of pollutant removal compared to that obtained with perfect mixing of the indoor air. These procedures are designed to promote the short circuiting of pollutants from their source to the exhaust airstream so that the concentration of pollutants in the air exhausted from the building is greater than the average indoor pollutant concentration. In a technique called "displacement ventilation," which is being promoted primarily in Scandinavian countries, outdoor air, with a temperature that is a few degrees below the average indoor temperature, is supplied at a low velocity near floor level and the exhaust air is withdrawn at ceiling level. To a degree, this procedure causes a displacement or piston-like pattern of flow in the upward direction, which carries along pollutants toward the exhaust. The efficiency of this process is expected to be enhanced because many pollutants, such as tobacco smoke, carbon dioxide exhaled from people, and body odors, tend to rise since their sources are at a temperature above ambient. Heat removal is also enhanced by displacement ventilation since warm air also tends to rise. The practicality of employing displacement ventilation in large U.S. buildings has not been established. Some potential problems are increased drafts and decreased cooling capacity.

The procedures described above increase the rate of pollutant removal by ventilation above that obtained with perfect mixing of the indoor air. However, it is also possible, and perhaps common, that indoor airflow patterns cause pollutant removal rates to be less than would occur with perfect mixing of the indoor air. For example, if the supplied air tends to short-circuit to the return or exhaust without capturing pollutants from a strong source, then the ventilation process will be inefficient, since the exhaust airstream will have a lower concentration of pollutants than, on average, the indoor air. Supplying and exhausting air at ceiling level, particularly when the supply air is warm and thus buoyant, is one procedure that can lead to short circuiting (Sandberg et al. 1982).

Other Considerations. Two additional factors that impact IAQ control by ventilation are mentioned only briefly. One consideration is the location of the outside air intake relative to concentrated sources of pollutants. The intake should be situated so that pollutants from general vehicular traffic, parking garages, loading docks, combustion stacks, and exhaust ducts are not readily drawn into the building.

Another obvious but important fact is that ventilation systems must be properly designed, maintained, and operated or indoor air quality may suffer. It is known that ventilation systems are sometimes shut down when they should be operating, outside air dampers may be fully closed to save energy, controls and actuators may be faulty or improperly adjusted, filters may be clogged, microbial material may grow within the ventilation system, and supply air may be distributed very nonuniformly due to improper balancing of airflows. Correction and prevention of these problems should be given high priority.

AIR CLEANING

Air cleaning is the removal of pollutants from recirculated indoor air or incoming outdoor air. It is accomplished by such processes as filtration, electrostatic precipitation, and physical and chemical sorption. These processes are described in many texts on air pollution control and also in the ASHRAE handbooks. In research conducted to date, air cleaning has rarely been demonstrated to be a practical and effective method of controlling the indoor concentrations of gaseous pollutants. The use of air-cleaning systems to remove particles from indoor air is a well-established practice but an infrequent research topic. Therefore, this paper contains only a brief discussion of air cleaning.

Removal of Particles

The impact of particle removal processes on particle concentrations in occupied buildings has rarely been measured directly. Instead, the performance of particle removal systems or devices is generally determined in laboratory tests, and calculations are employed to estimate the impact of these devices on indoor particle concentrations (see Equation 1 or ASHRAE Standard 62-1981). It is necessary to know both the flow rate through the particle removal system and the particle removal efficiency, since the removal rate is the product of these two factors. The performance of currently available particle removal systems varies widely. Many of the small inexpensive tabletop air cleaners that have become popular in recent years are almost totally ineffective (Offermann et al. 1985). Low efficiency filters, such as those typically used in residential heating systems and in some large-building HVAC systems, are designed to remove large particles and dust and remove very few of the small respirable-size particles. On the other hand, high efficiency filters and electronic air cleaners that are effective in removing respirable-size particles and that cleanse a large volume of air are readily available (Offermann et al. 1985). These high efficiency systems are infrequently used in buildings, perhaps because of installation and maintenance costs or possibly because the ventilation provided to control the indoor concentrations of gaseous pollutants is deemed adequate for particle control. The value of particle removal systems would be enhanced if data were readily available on particle removal efficiency as a function of particle size for each system or device. Considering recent advances in measuring techniques, it would not be unduly difficult to obtain such data.

Removal of Gaseous Pollutants

To remove gaseous pollutants from indoor air, one can use a solid sorbent such as an activated carbon or alumina. Often these sorbents are impregnated with some chemical that reacts with certain pollutants. These solid sorbents have a limited pollutant removal capacity; therefore, they must be periodically replaced or regenerated. Because sorbents generally remove a variety of pollutants from air, it is difficult to predict actual field performance, especially capacity or lifetime, based on the results of laboratory tests conducted with only one or a few pollutants in the test airstream. In addition to solid sorbents, various liquids including water can be employed to absorb pollutants. The low cost of water makes it an attractive medium for absorption; however, only highly water soluble pollutants (e.g., formaldehyde) are readily removed by water and it is necessary to prevent excessive humidification of the air. Numerous additional processes, such as low temperature catalysis, offer some potential, at least in theory, for the cleansing of indoor air.

Several investigations of HCHO removal processes have been completed. The studies reviewed by Fisk et al. (1984) indicate that commercially available solid sorbents are not practical for HCHO removal considering their capacity and cost. Systems (e.g., air washers) that employ liquid water as an absorption media can readily remove HCHO from air (Pederson and Fisk 1984); however, the practicality of such a HCHO removal process has not been demonstrated. No technique of removing HCHO from indoor air has been clearly demonstrated to be effective and practical.

Less information is available on the potential of air cleaning systems for several other gaseous indoor pollutants. Carbon monoxide, carbon dioxide, and radon are relatively nonreactive, and it is not practical to remove these pollutants by sorption on currently available sorbent materials. Nitrogen dioxide is more reactive and can be transformed to less toxic nitric oxide using carbonaceous materials (Girman 1986); therefore, future investigations of nitrogen dioxide removal and transformation are suggested. The potential of air-cleaning systems for removing many of the volatile organic compounds present in indoor air is not presently known.

CONCLUSIONS

Available information on indoor air quality and its control leads to the following conclusions:

1. Source control measures are generally more effective than ventilation or air cleaning. Indoor pollutant concentrations have frequently been reduced by a factor of 3 to 10 through source control. However, unless the initial ventilation rate is unusually low, it is generally impractical to reduce indoor pollutant concentrations more than approximately 50% by increasing the ventilation rate of an entire building.

2. Maintenance of a typical ventilation rate does not ensure acceptable indoor air quality unless pollutant source strengths are limited.

3. It is important and efficient to avoid extremely low ventilation rates.

4. The efficiency of ventilation can be enhanced by procedures that cause the concentration of pollutants in the exhaust airstream to exceed the average indoor pollutant concentration.

5. It is important to ensure proper operation of ventilation systems.

6. Effective methods of removing particles from indoor air are readily available; however, effective and practical techniques of removing many gaseous pollutants have not been demonstrated.

REFERENCES

ASHRAE. 1981. ANSI/ASHRAE Standard 62-1981, "Ventilation for acceptable indoor air quality." American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Atlanta, GA.

Bowen, R.P.; Shirtliffe, C.J.; and Chown, G.A. 1981. "Urea formaldehyde foam insulation: Problem identification and remedial measures for wood frame construction." Building Practice Note 23, Division of Building Research, National Research Council, Canada.

DeWerth, D.W. 1974. "Energy consumption of contemporary 1983 gas range burners and pilots under typical cooking loads." American Gas Association, Cat. No. M50155, Cleveland, OH.

DeWerth, D.W., and Sterbik, W.G. 1985. "Development of advanced residential range burners with low NO_x characteristics: Final report - phase II." Gas Research Institute Report, GRI-85/0204, Chicago, Ill.

DSMA. 1979. (Dilworth, Secord, Meagher and Associates Limited and ACRES Consulting Services Limited) "Report on investigation and implementation of remedial measures for the radiation reduction and radioactive decontamination of Elliot Lake, Ontario." Prepared for the Atomic Energy Control Board, Canada.

DSMA. 1980. (Dilworth, Secord, Meagher and Associates Limited and ACRES Consulting Services Limited) "Report on investigation and implementation of remedial measures for the radiation reduction and radioactive decontamination of Elliot Lake, Ontario." Prepared for the Atomic Energy Control Board, Canada.

Ericson, S.O.: Schmied, H.; and Clavensjo, B. 1984. "Modified technology in new constructions, and cost effective remedial action in existing structures, to prevent infiltration of soil gas carrying radon." Proceedings of the 3rd International Conference on Indoor Air Quality and Climate, August 20-24, Stockholm, Sweden. Published by the Swedish Council for Building Research.

Fisk, W.J.; Spencer, R.K.; Grimsrud, D.T.; Offermann, F.J.; Pederson, B.; and Sextro, R.G. 1984. "Indoor air quality control techniques: A critical review." Lawrence Berkeley Laboratory Report, LBL-16493, Berkeley, CA.

Fisk, W.J. 1985. "Control of indoor pollutant concentrations: Choosing a strategy." Lawrence Berkeley Laboratory Report, LBL-18875, Berkeley, CA.

Fleming, W.S., and Associates, Inc. 1985, "Indoor air quality, infiltration and ventilation in residential buildings." Prepared for the New York State Energy Research and Development Authority and Niagara Mohawk Power Corporation, NYSERDA report 85-10.

Girman, J.R. 1986. Personnel communication.

Godish, T.; and Rouch, J. 1984. "Efficacy of residential formaldehyde control measures: Source removal." Proceedings of the 3rd International Conference on Indoor Air Quality and Climate, August 20-24, Stockholm, Sweden. Published by the Swedish Council for Building Research.

Grimsrud D.T.; Sherman, M.H.; and Sonderegger, R.C. 1983. "Calculating infiltration: implications for a construction quality standard." Lawrence Berkeley Laboratory Report, LBL-9419, Berkeley, CA.

Hayden A.C.S. 1984. "Air demands of residential combustion appliances." Paper No 84-32.1, Presented at the 77th Annual Meeting of the Air Pollution Control Association, June 24-29, 1984, San Francisco, CA.

Henschel, D.B., and Scott, A.G. 1986. "The EPA program to demonstrate mitigation measures for indoor radon; Initial results." Presented at the Air Pollution Control Association's International Specialty Conference on Indoor Radon, February 24-26, 1986. Philadelphia, PA.

Leaderer, B.P., and Cain W.S. 1983. "Air quality in buildings during smoking and nonsmoking occupancy." ASHRAE Trans. 89, pp. 601-613.

Leaderer B.P.; Zagraniski, R.T.; Berwick, M.; Stolwijk, J.A.J.; and Qing - Shan, M. 1984. "Residential exposures to NO_2, SO_2, and HCHO associated with unvented kerosene space heaters, gas appliances, and sidestream tobacco smoke." Proceedings of the 3rd International Conference on Indoor Air Quality and Climate, August 20-24, Stockholm, Sweden, Published by the Swedish Council for Building Research.

Macriss, R.A., and Elkins, R.H. 1976. "Standing pilot gas consumption." ASHRAE Journal, June 1976, pp. 54-57.

Macriss, R.A., and Elkins, R.H. 1977. "Control of the level of nitrogen oxides (NO_x) in the indoor environment." Proceedings of the Fourth International Clean Air Congress, May 16-20, Tokyo, Japan, pp 510-514, CONF-770557-2.

Matthews, T.G.; Reed, T.J.; Tromberg; B.R.; Daffron, C.R.; and Hawthorne, A.R. 1983. "Formaldehyde emissions from combustion sources and solid formaldehyde resin containing products: potential impact on indoor formaldehyde concentrations and possible corrective measures." Proceedings of an Engineering Foundation Conference on Management of Atmospheres in Tightly Enclosed Spaces, October 17-21, 1983. Published by the American Society of Heating, Refrigerating, and Air Conditioning Engineers.

Matthews, T.G., et al. 1985. "Modeling and testing of formaldehyde emission characteristics of pressed wood products - Report XVIII." Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Matthews, T.G.; Dreibelbis, W.G.; Thompson, C.V.; and Hawthorne, A.R. 1986. "Preliminary evaluation of formaldehyde mitigation studies in unoccupied research homes." Presented at the Air Pollution Control Associations specialty conference on Indoor Air Quality in Cold Climates, April 29 - May 1, Ottawa, Ontario.

Meier, A.; Wright J.; and Rosenfeld, A.H. 1983. Supplying energy through greater efficiency: The potential for conservation in California's residential sector. Univ. of Calif. Press, Berkeley, CA.

Meyer, B., and Hermanns, K. 1985. "Formaldehyde release from pressed wood products." In Formaldehyde Analytical Chemistry and Toxicology, Victor Turoski, Editor. American Chemical Society, Washington, D.C.

Meyer, B.; Hermanns, K.; and Smith, D.C. 1985. "Formaldehyde release from urea-formaldehyde bonded wood products." Adhesion 17, pp. 297-308.

Moffatt, S. 1986. "Combustion ventilation hazards in housing-failure mechanisms, identification technologies, and remedial measures". Transactions of Indoor Air Quality in Cold Climates: Hazards, and Abatement Measures, April, 1985, Ottowa, Ontario. Published by the Air Pollution Control Association, Pittsburg, PA.

Myers, G.E., and Nagaoka, M. 1981. "Formaldehyde emission: methods of measurement and effects of several particleboard variables." Wood Science (3), pp. 140-150.

Nazaroff, W.W.; Boegel, M.L.; and Nero, A.V., 1981. "Measuring radon source magnitude in residential buildings." Lawrence Berkeley Laboratory Report, LBL-12484, Berkeley, CA.

Nero, A.V., and Nazaroff, W.W. 1984. "Characterizing the source of radon indoors." Radiation Protection Dosimetry 7, pp. 23-39.

Offermann, F.J.; Hollowell, C.D.; Nazaroff, W.W.; and Roseme, G.D. 1982. "Low infiltration housing in Rochester New York; A study of air-exchange rates and indoor air quality." Environment International 8, pp. 435-445.

Offermann, F.J., et al. 1985. "Control of respirable particles in indoor air with portable air cleaners." Atmospheric Environment 6 (11), pp. 1761-1771.

Pedersen, B.S., and Fisk, W.J. 1985. "An experimental study of air washing for the removal of HCHO from indoor air." Lawrence Berkeley Laboratory Report, LBL-18874, to be published in Environment International.

Persily, A.K., and Grot, R.A. 1985. "Ventilation measurements in large office buildings." ASHRAE Trans 91 (2), pp. 488-502.

Revzan K.L. 1984. "Effectiveness of local ventilation in removing simulated pollution from point sources." Proceedings of the 3rd International Conference on Indoor Air Quality and Climate, August 20-24, Stockholm, Sweden. Published by the Swedish Council for Building Research. Submitted to Environment International.

Russel, P.A., and Robinson, T.D. 1984. "Carbon Monoxide poisoning in housing: Contributing factors and remedial measures." Paper No. 84-32.8, Presented at the 77th Annual Meeting of the Air Pollution Control Association, June 24-29, 1984, San Francisco, CA.

Sachs, H.M., and Hernandez, T.L., 1984. "Residential radon control by subslab ventilation." Paper No. 84-35.4, Presented at the 77th Annual Meeting of the Air Pollution Control Association, June 24-29, San Francisco, CA.

Sandberg, M. 1981. "What is ventilation efficiency." Building and Environment 16 (2), pp. 123-135.

Sandberg, M.; Blomqvist, C.; and Sjoberg, M. 1982. "Warm air systems, part 2: Tracer gas measurements and ventilation efficiencies." Bulletin M82:23, The National Swedish Institute for Building Research, Gavle, Sweden.

Sandberg, M., and Sjoberg, M. 1983. "The use of moments for assessing air quality in ventilated rooms." Building and Environment 18 (4), pp. 181-197.

Swinton, M.C. and White, J.H. 1986. "Avoidance of chimney backdrafting in houses: Identifying the critical conditions". Transactions of Indoor Air Quality in Cold Climates: Hazards and Abatement Measures, April, 1985, Ottowa, Ontario. Published by the Air Pollution Control Association, Pittsburg, PA.

Traynor, G.W.; Apte, M.G.; Dillworth, J.F.; Hollowell, C.D.; and Sterling, E.M. 1982. "The effects of ventilation on residential air pollution due to emissions from a gas-fired range." Environment International 8 , pp. 447-452.

Traynor, G.W., et al. 1983. "Indoor air pollution due to emissions from unvented gas-fired space heaters: A controlled field study." Lawrence Berkeley Laboratory Report, LBL-15130, Berkeley, CA.

Traynor, G.W.; Apte, M.G.; Carruthers, A.R.; Dillworth, J.F.; Grimsrud, D.T.; and Thompson, W.T. 1984. "Indoor air pollution and inter-room pollutant transport due to unvented kerosene-fired space heaters." Lawrence Berkeley Laboratory Report, LBL-17600 Rev, To be published in Environment International.

Traynor, G.W.; Apte, M.G.; Carruthers, A.R.; Dillworth, J.F.; and Grimsrud, D.T. 1984b. "Pollutant emission rises from unvented infrared and convective gas-fired space heaters." Lawrence Berkeley Laboratory Report, LBL-18258, Berkeley, CA.

Traynor, G.W. 1986. Personnel communication.

Turk, B.H.; Prill, R.J.; Fisk, W.J.; Grimsrud, D.T., Moed, B.A., and Sextro, R.G. 1986. "Radon and remedial action in Spokane river valley residences." Lawrence Berkeley Laboratory Report, LBL-21399, to be presented at the 79th Annual Meeting of the Air Pollution Control Association, June 22-27, Minneapolis, MN.

Turk, B.T., et al. 1986. "Indoor air quality measurements in 38 Pacific Northwest Buildings." Lawrence Berkeley Laboratory Report, LBL-21453, Berkeley, CA, to be presented at the 79th Annual Meeting of the Air Pollution Control Association, June 22-27, Minneapolis, MN.

Vivyurka, A. 1979. "Assessment of subfloor ventilation systems." Presented at the Second Workshop on Radon and Radon Daughters, March 12-14, Ontario, Canada.

Wellford, B.W. 1986. "Mitigation of indoor radon using balanced heat recovery ventilation systems." Air exchange Inc., Hingham, Massachusetts, Presented at the Air Pollution Control Association's International Specialty conference on Indoor Radon, Feb 24-26, Philadelphia, PA.

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

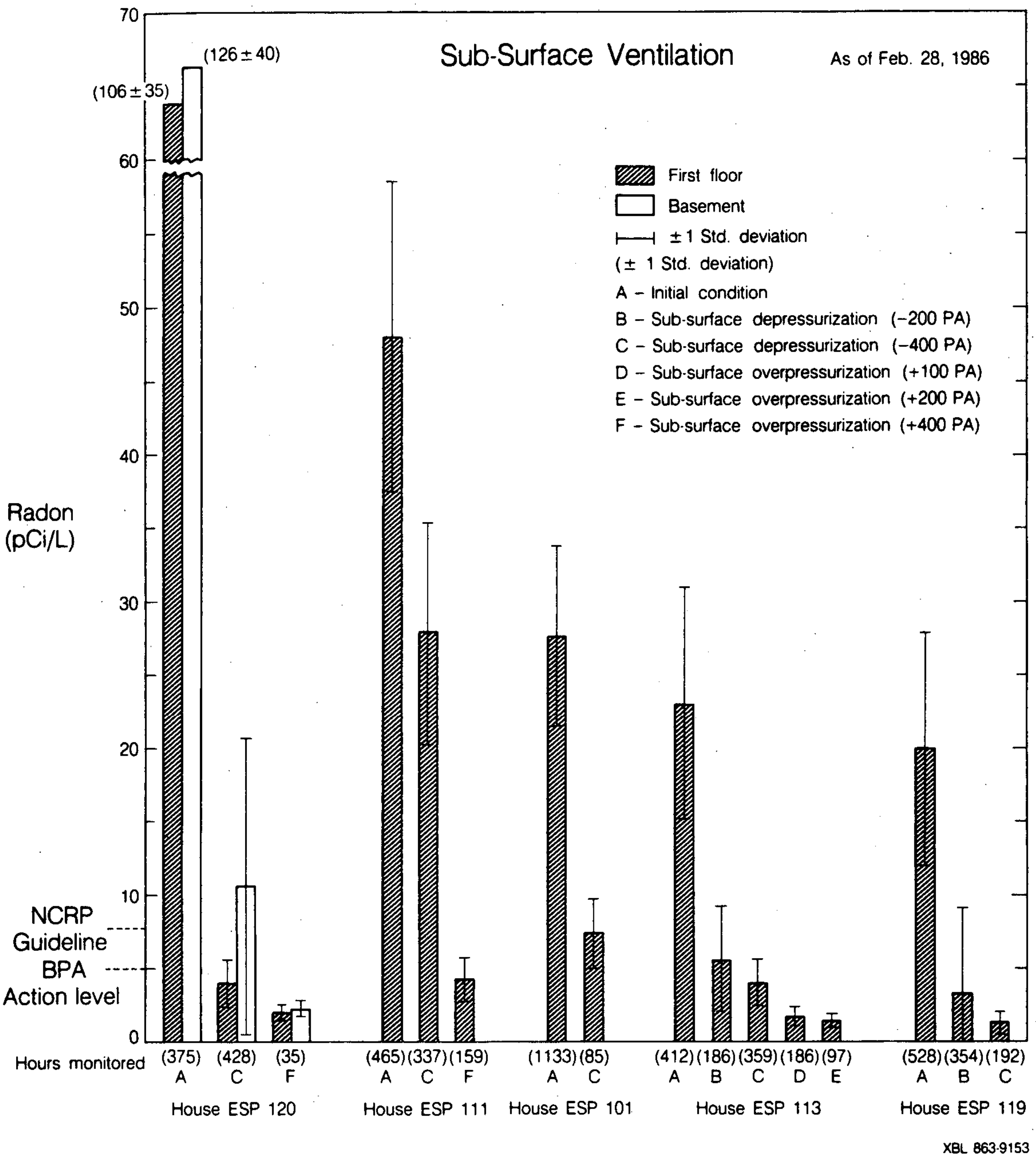


Figure 1. Impact of sub-slab ventilation on the radon concentrations in five Pacific Northwest houses. (Source: Turk et al., 1986)

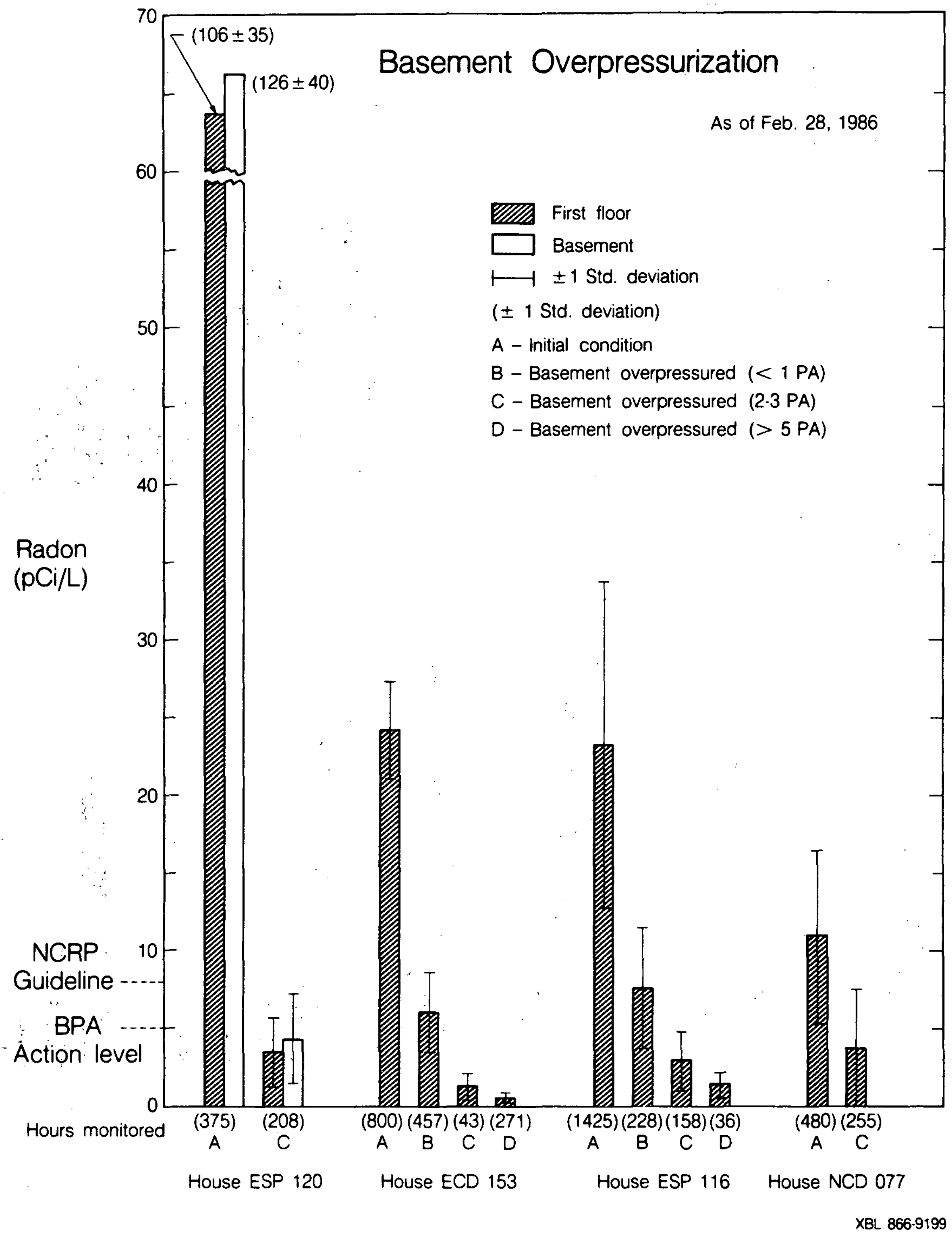
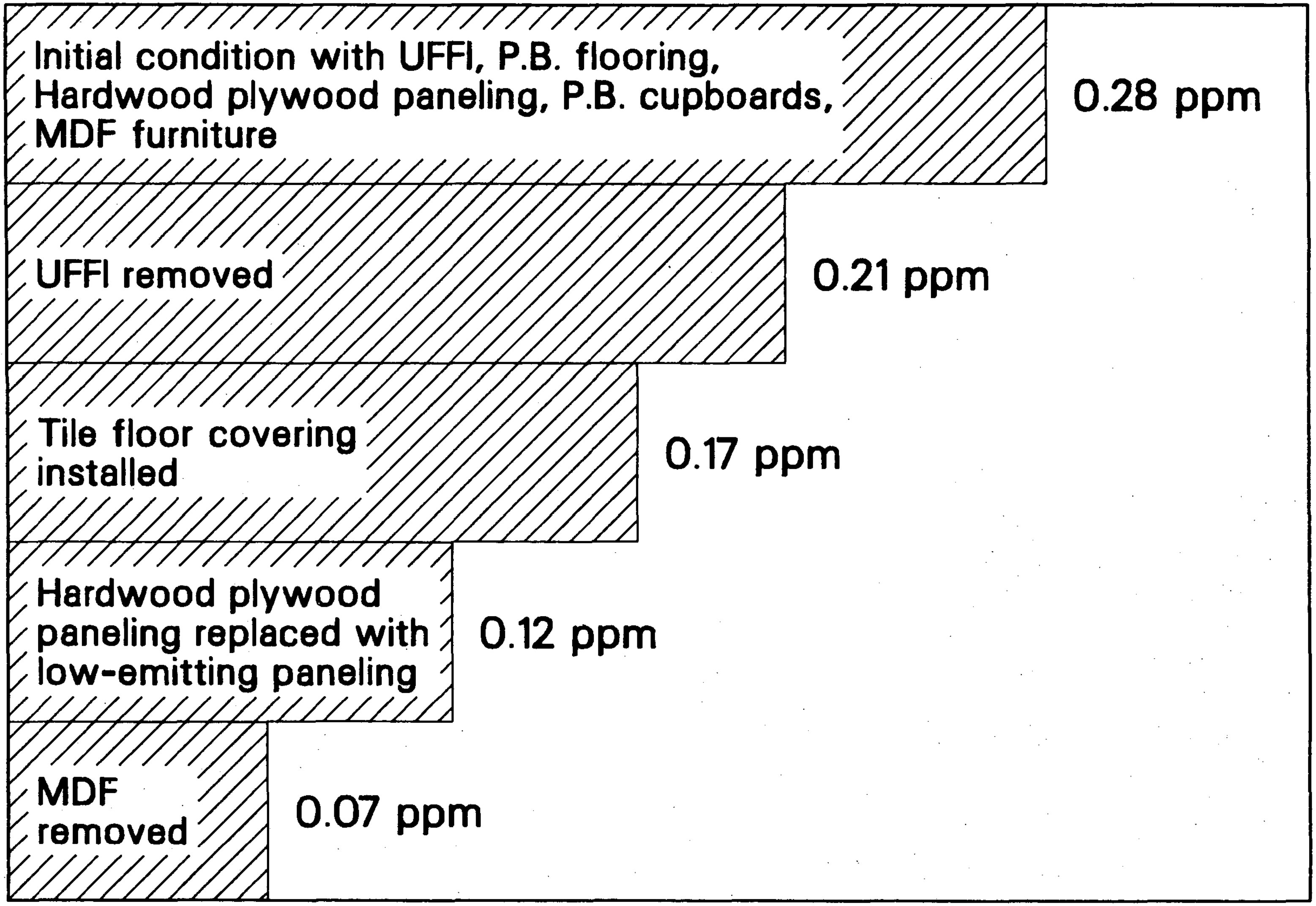
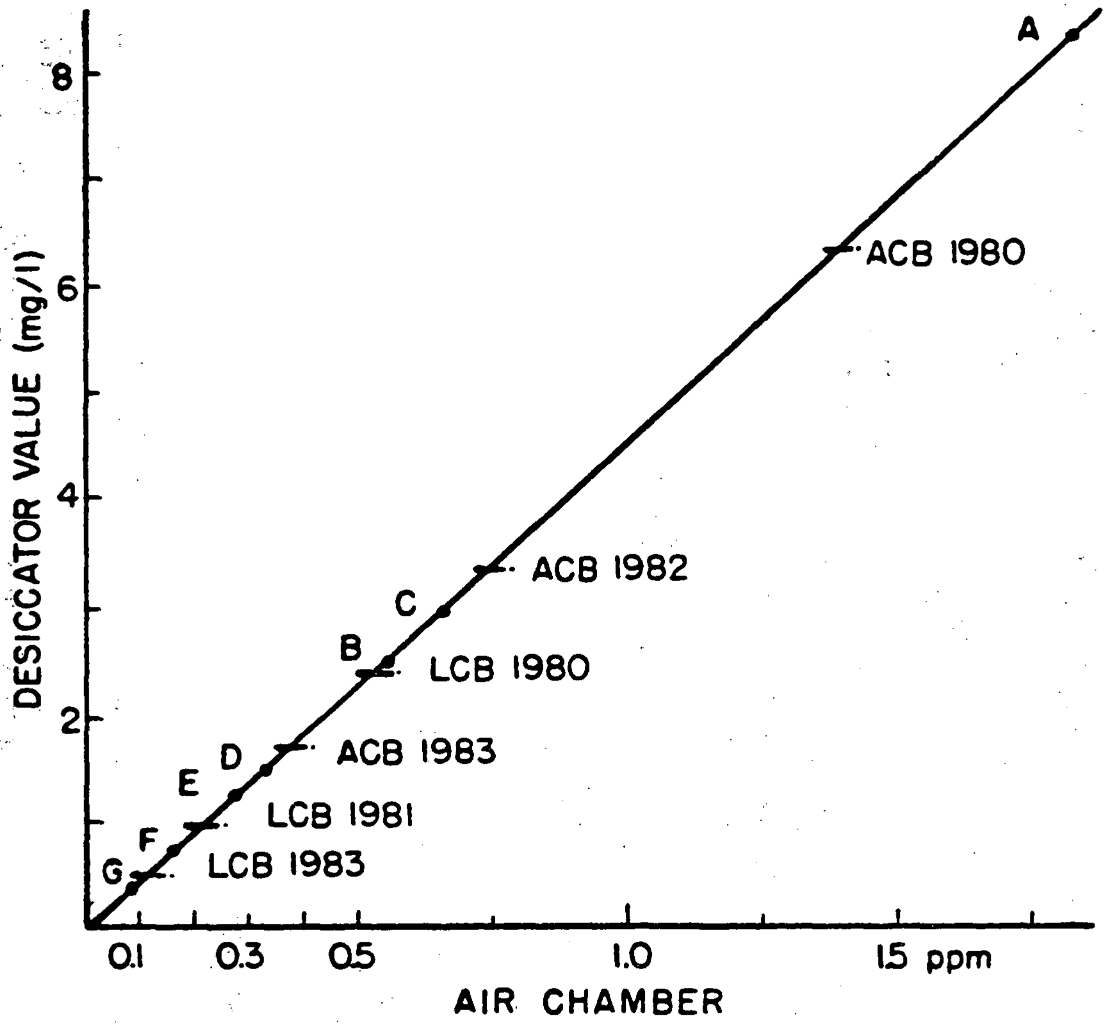


Figure 2. **Impact of basement pressurization on the radon concentrations in four Pacific Northwest houses. (Source: Turk et al., 1986**



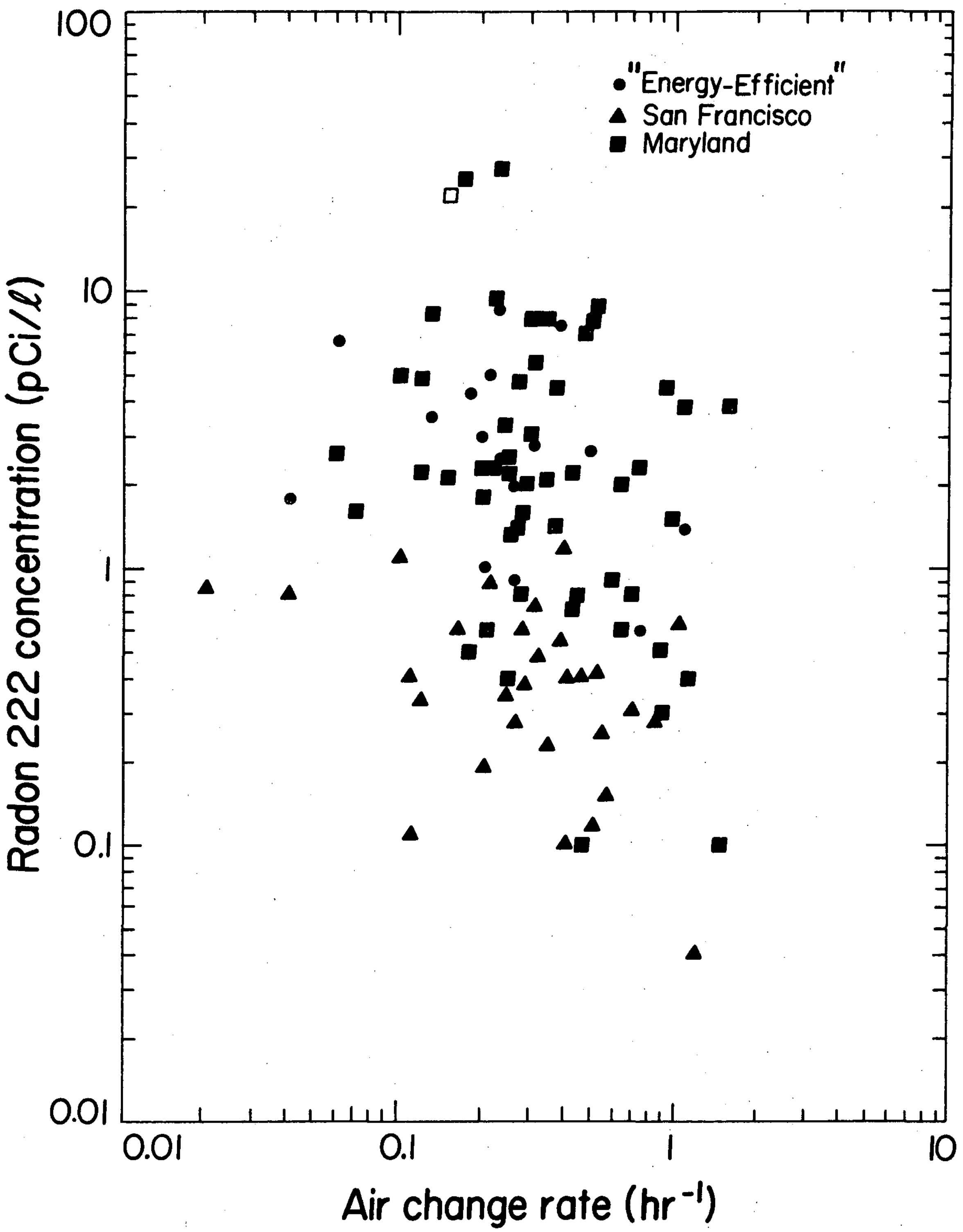
XBL 865-2035

Figure 3. Impact of sequential implementation of source control measures on the formaldehyde concentration in a hypothetical room with a multiple formaldehyde sources. (Source: Matthews et al., 1983)



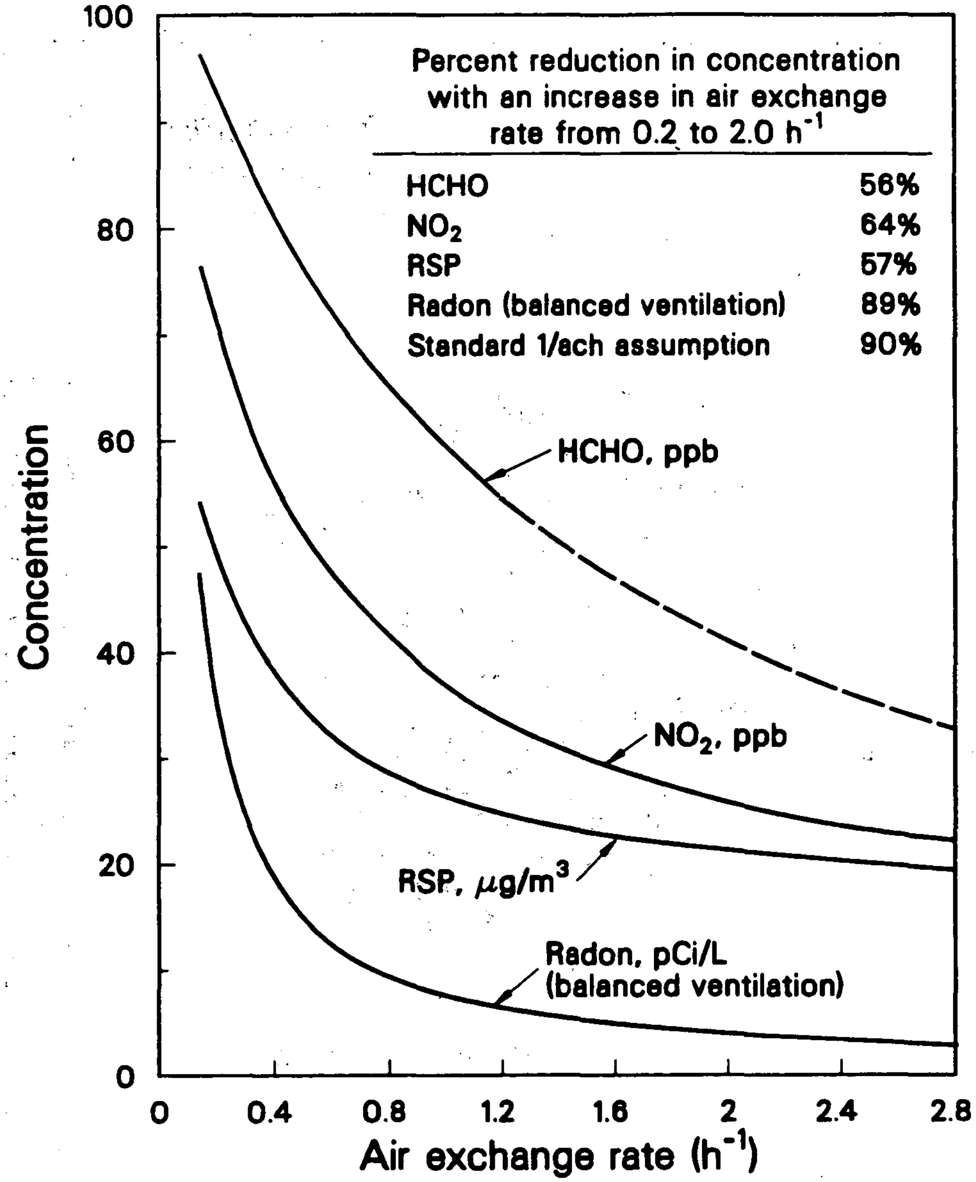
XBL 865-2036

Figure 4. Formaldehyde emission characteristics as indicated by the desiccator test and an air chamber test of seven six-week-old medium density fiberboards made with resins that were commercially available in 1983 are represented by data points A through G. Data from industry on formaldehyde emission rates for average-emitting (ACB) and low-emitting (LCB) particleboard are also included, however, it is known that the variance in HCHO emission rates from particle board is large. Reprinted with permission from Meyer, B. and Hermans, K. "Formaldehyde release from pressed wood products", in Formaldehyde Analytical Chemistry and Toxicology, Copyright 1985, American Chemical Society



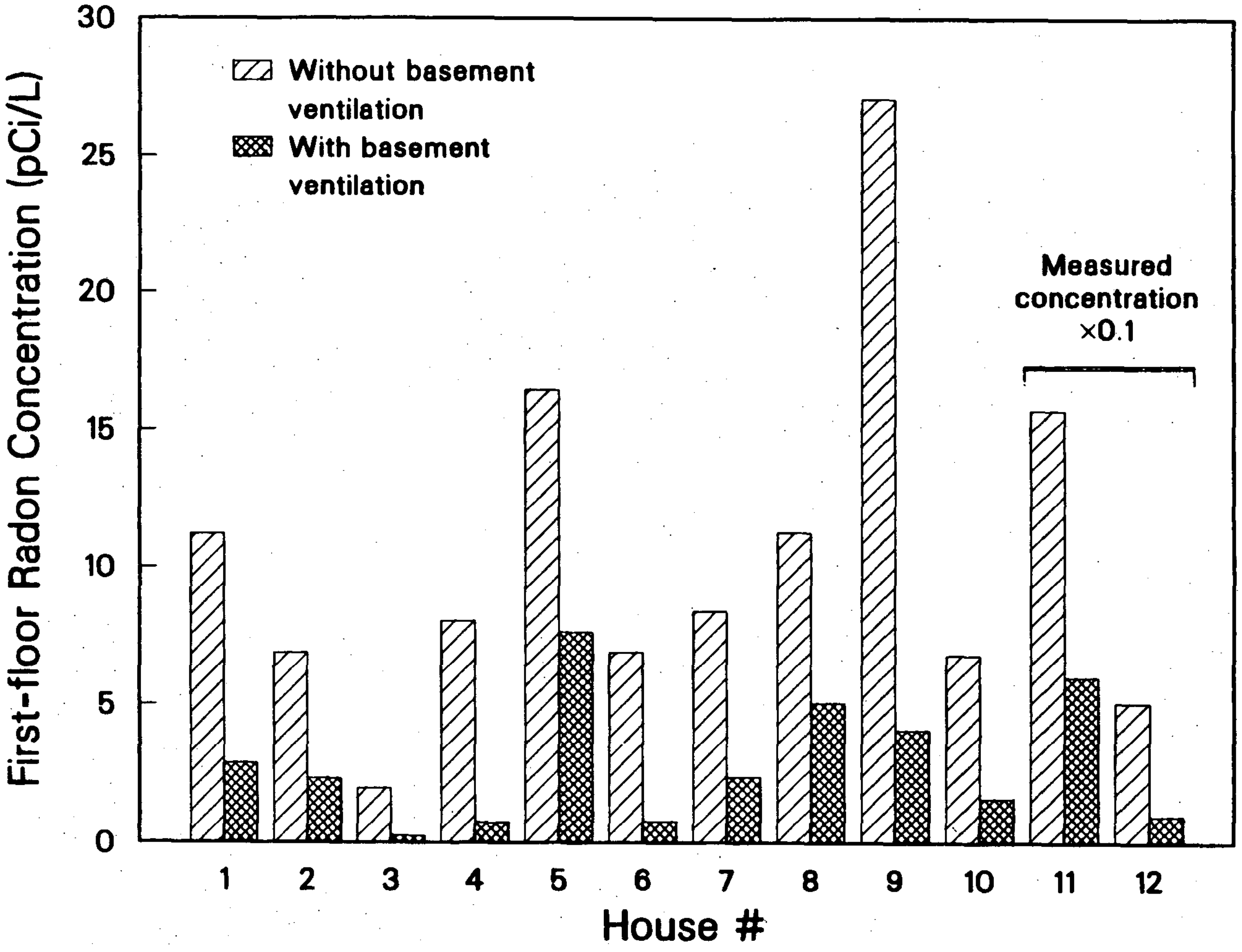
XBL 818-1115

Figure 5. Radon concentrations versus ventilation rates based on measurements in a large number of residences. (Source: Nazaroff et al., 1981)



XCG 865-7277

Figure 6. Examples of predicted relationships between pollutant concentrations and air exchange rate in residences with perfectly mixed air. The HCHO curve is based on an equation presented by Matthews et al., (1985) which fits the data obtained from measurements in a research house with one primary formaldehyde emitter. The dashed portions of the HCHO curve extend beyond the range of conditions encountered during the measurements. The remaining curves were generated using Equation 1. The NO_2 curve is based on a time weighted average source strength of 15 cc/hr*, typical of a kerosene heater, a house volume of 350 m^3, $P = 1$, $C_o = 10ppb$*, $K = 0.43\ h^{-1}$*, and $\lambda = R = O$. The RSP curve is based on a source strength of 2000 $\mu g/h$* from unknown sources and 3920 $\mu g/h$* from cigarette smoking, a house volume of 350m^3, $C_o = 15\ \mu g/m^3$*, $P = 1$, $K = 0.2\ h^{-1}$*, and $\lambda = R = O$. The radon curve is based on a relatively high source strength of 280 pCi/l-h (Nero and Nazaroff, 1984), $P = 1$, $C_o = 0.25$ pCi/l, $\lambda = 0.00758\ h^{-1}$, and $K = R = O$. The radon curve is also based on the assumption that the radon source strength and ventilation rate are independent -- available data indicates that this assumption is only valid when the ventilation is provided by a balanced (supply and exhaust) mechanical system. *See Fleming, 1985.



XCG 864-7195

Figure 7. Impact of balanced mechanical ventilation of basements, provided through a residential air-to-air heat exchanger, on the first-floor radon concentrations in twelve residences. The data from the first two houses were obtained by continuous monitoring of radon concentrations over an extended period of time by Turk et al., (1986). The data from the remaining houses are generally based on a single grab sample radon measurement by Wellford (1986) with and without basement ventilation, therefore, these data may not be representative of long-term average concentrations.

LAWRENCE BERKELEY LABORATORY
TECHNICAL INFORMATION DEPARTMENT
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720