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The Indoor Environment of Commercial Buildings: A Review
Final Report

D.T. Grimsrud, J.T. Brown,
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August 1987

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THE INDOOR ENVIRONMENT OF COMMERCIAL BUILDINGS

A REVIEW

Research Project 2285-4

Final Report, August 1987

Prepared by

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Prepared by Lawrence Berkeley Laboratory, University of California, Berkeley, CA.

ACKNOWLEDGMENTS

This work was supported by the Electric Power Research Institute under Subcontract No. RP 2034-18, and 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.

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ABSTRACT

This report reviews current information that has been gathered recently about the indoor environment in commercial buildings. Basic background information about air pollutants, their concentrations and control presented. Special attention is given to a discussion of ventilation systems since these systems provide the basic pollutant control function for the building. The contribution of pollutants, mal functioning ventilation and other causes to building complaints is a recurring theme of the treatment.

EXECUTIVE SUMMARY

The focus of research in indoor air quality until now has been on residential buildings. Residences were the initial target of most building energy conservation programs, are simpler to understand than most large commercial buildings, and are the major portion of the building stock in the United States. This report, by contrast, concentrates on commercial (office and institutional) buildings.

The report is intended for a broad audience ranging from those who have no previous background in indoor air quality to those whose indoor air quality experience has been primarily in residential applications.

A particular topic which is a recurring theme throughout the report is the sick building syndrome. This troublesome phenomenon, an attribution of the source of general feelings of irritation and malaise to the occupant's building, can cause significant economic damage to the building owners and tenants if productivity of the workforce declines. Many causes of the sick building syndrome have been identified, but considerable uncertainty about a single cause or set of causes commonly remains at the conclusion of an investigation.

Even though current research in indoor air quality issues in commercial building concentrates on sick buildings, one must be careful not to overemphasize this topic. The health outcomes associated with the sick building syndrome tend to be short-term irritation effects. Longer-term, chronic effects may also be associated with exposure to pollutants in commercial buildings. These are not addressed typically in any study focused on the sick building syndrome. Where long-term effects are understood they are discussed in this report.

This report is divided into seven chapters. Following the introductory chapter is a discussion of effects of initial design decisions on the indoor environment. A major design decision that affects the air quality in a commercial building is the choice of ventilation systems. The mechanical ventilation system, a rarity in residences but commonplace in commercial buildings, has been identified by some as a major cause of problems in the indoor environment. The effects of these systems and their influence on indoor air quality is treated in chapter three.

Pollutants present in commercial buildings are discussed in chapter four. The discussion is organized by pollutant classes arranged in order of the pervasiveness of the pollutant problem. The long pollutant chapter is followed by three shorter chapters examining human factors, investigative procedures, and general corrective procedures to be considered when problems are discovered.

The complexity of equipment and controls in commercial buildings has increased considerably in recent years. This can be traced to new hardware and software, that respond to tighter guidelines on energy use, and new building materials. The increase in complexity does not guarantee an increase in problem buildings. However, unless care is taken to address implications of the building complexity, we shall experience either more problem buildings or at least buildings that do not operate as anticipated.

Section 1
INTRODUCTION

VENTILATION AND SPACE CONDITIONING OF COMMERCIAL BUILDINGS

Ventilation and space conditioning of the occupied areas of commercial buildings helps ensure the health and comfort of the human occupants. A number of factors have contributed to the development of ventilation requirements for large buildings. The amount of fresh air required to maintain an acceptable odor level and occupant health has been the basis for setting engineering standards for ventilation with fresh or outdoor air. Thermal comfort requirements dictate the amount of heating or cooling and humidifying of this ventilation air. A recent emphasis on energy conservation actions such as eliminating openable windows and recirculating as much air as possible to avoid heating or cooling outside air has led to situations where the balance between comfort, or health, and efficiency has become precarious and occasionally tips beyond the occupant's tolerance for indoor pollution.

This paper discusses issues associated with the indoor environment in commercial and institutional buildings. It does not address situations in which occupants are exposed to high concentrations of pollutants because of special industrial processes associated with their occupation. Thus the working conditions of a painter employed in industrial spray painting is not treated while the discussion does include the exposure an office worker receives while making copies using a wet-process copier. Particular attention is given to the phenomena associated with the "sick-building syndrome" (SBS).

NEW PHENOMENA

The Sick Building Syndrome

Sick building syndrome, described briefly in papers by Stolwijk (1984) and Kreiss and Hodgson (1984), is a condition, real or imaginary, in which building occupants associate health problems with the building environment. SBS represents a current interest in indoor air quality in commercial buildings and will occupy a major place in this review as well. However, note early that SBS is only a part of the indoor environment problem in commercial buildings -- that associated with irritant effects that building occupants perceive. Other health effects, associated with mutagenic or carcinogenic activity of the pollutants found in commercial buildings, are ignored in a discussion of SBS. Ultimately we may find that the latter effects are more important than the former (McCann et al., 1987).

Scope of the Sick Building Syndrome

Sick building syndrome has been reported with increasing frequency in the past six to eight years reflecting an increasing awareness of environmental problems in general and changes in building engineering due to energy related issues. By 1983 the National Institute of Occupational Safety and Health had been called upon to investigate more than 200 complaints related to indoor air quality (Melius et al., 1984). Before 1978 only six evaluations had been made. Local and state authorities as well as private concerns also may deal with building evaluations. There is no readily available compilation of the total number of sick or complaint buildings. However, complaints do continue and frequent media attention to the more spectacular examples show that interest in the indoor environment in public places is increasing. A recent survey of 38 buildings uncovered no complaint buildings during the time of study but at least one building had been associated with previous problems and another had an acute outbreak following the study (Turk et al., 1986). It will take careful data gathering to provide statistics on the total number of buildings affected by sick building syndrome and sophisticated techniques to classify the causes. This has not yet been done.

Suspected Causes of Sick Building Syndrome

Many hypotheses have been explored in an attempt to explain SBS. These include

- indoor airborne contaminants
- inadequate ventilation
- poor thermal conditions
- airborne allergens and pathogens
- lack of air movement
- poor lighting conditions
- occupational stress
- excess noise
- outdoor airborne contaminants
- mass hysteria or psychogenic illness

The list is neither exhaustive nor exclusive. Indeed, one of the frustrations faced by those who investigate the problem is the difficulty of associating symptoms observed with unique causative agents. In addressing the issue of maintaining the indoor environment in commercial buildings, gaps in knowledge or understanding that lead to problems such as the sick building syndrome, will be identified.

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Section 2

BUILDING DESIGN AND CONDITIONING: IMPLICATIONS FOR THE INDOOR ENVIRONMENT

Indoor environmental problems may occur because building systems fail and cause the conditions in the indoor environment to deteriorate. In other situations, the problems are inherent in the building and result from inadequate information available early in the conceptual phase of the building. These errors are associated with the physical design of the building, the choice of site for the building, or the materials used in construction.

DESIGN

Elements of design which influence the indoor environment include interior layout, structural and mechanical design, and materials. Interior space design can influence the distribution of indoor pollutants or the introduction of outdoor pollutants. Open plan offices or work spaces, for example, may suffer from acoustical problems or poor ventilation. Spaces designed originally as open space are frequently subdivided by movable walls or partitions which create barriers to air movement that were not anticipated in the original design. Malmstrom and Ahlgren (1982) have shown by modeling and experiment how design placement of supply and return circulation schemes can lead to short circuiting in the air flow pattern.

The building design must also consider the access points for outside air where there is a potential problem with outdoor pollution entering the building. In urban areas where high levels of exhaust emissions can accumulate, care must be taken to prevent entry of these pollutants into the building either through the heating, ventilating, and air conditioning (HVAC) system or via infiltration. Air intakes should be located as high as feasible above the traffic zone. Parking garages which are underground in or associated with large commercial buildings can be a potential source of pollutants which may be drawn into work spaces through stairwells, elevator shafts, and entrainment into the ventilation system (Turk et al., 1986; McIntyre et al., 1984). Other exhaust reentrainment problems can result from improper placement of supply intakes relative to exhaust vents on roofs where under certain wind conditions the exhaust may contaminate the "fresh" air.

Wilson (1986) has pointed out the difficulty of making general rules for placement of ventilation system intakes and exhausts on building facades. Since wind conditions are so variable, reentrainment of exhaust is not uncommon. However, he has noted that wind tunnel studies show little mixing between airflows from the lower 1/3 of the building and upper 2/3. That rule is derived from wind-tunnel modeling. Temperature differences between indoor and outdoor air also will affect air movement. Since the exhaust air has buoyancy when discharged in cold outdoor air, Wilson's rule suggests placement of the exhaust somewhere on the upper 2/3 and the intake on the lower 1/3 of the building.

Biological agents as a source of indoor air quality difficulties may arise through problems in the design or maintenance of water handling elements of HVAC systems (Morey, 1984). Standing water, cooling towers, and humidifiers are potential habitats for amoebae, bacteria, and molds all of which may cause outbreaks of serious diseases such as hypersensitivity pneumonitis, Legionnaire's disease, or allergic reactions. Designs for control of comfort of the occupants should also encompass considerations for the possibility of indoor air pollution or stress related factors which might contribute to poor work conditions.

SITING

Siting affects the indoor environment in three major ways:

- Air flow around the structure.
- Potential outdoor sources of pollution.
- Available services.

Airflow around the structure can be a cause of concern if there are external pollution sources which might enter the building. Patterns of wind direction and speeds will influence the distribution of outdoor pollutants about the building envelope and alter the infiltration rate. The shape, size, and orientation of the building are important factors when they interact with the wind currents. Ground level pollutants can be carried onto the roof and there enter the supply system. Vortex patterns in the lee of a building may produce an area of high dust content which can infiltrate a structure via makeup air vents. Smoke or dust plumes from nearby industrial operations may also pose a problem if the prevailing wind conditions allow the plumes released from up-wind buildings to reach down-wind buildings before they are dispersed by mixing and turbulence. Nearby potential sources of pollutants are not always associated with industrial concerns; e.g., construction sites from housing tracts or new development may be large-scale dust producers. In agricultural areas plowing and harvesting are also prone to release airborne dusts and biological agents which may enter buildings downwind. Siting should account for air flow patterns, prevailing wind direction and speeds as well as any local pollutant sources. Services may contribute to indoor air quality problems through moratoria on power supplied during peak load conditions. A combination of factors leading to variability in HVAC operations may exacerbate a interior air quality problem (NAS, 1981).

MATERIALS

Materials used in constructing and furnishing a building can contribute to indoor air quality problems. Chapter IV deals in detail with sources of the volatile organic compounds which can be released into the indoor air from their use. Other possible sources of problems may arise from use or misuse of fibrous glass insulation (NAS, 1981; Holt, 1984). Use of asbestos is a problem of this sort which has come into nationwide attention in recent years (Swoszowski, 1984). Formaldehyde has not yet been found to be a serious problem in commercial buildings. It may, however, be a contributing factor in instances where new, tight buildings have caused outbreaks of sick building syndrome (Turk et al., 1986). It is released from the resins used in fiber board, and plywoods often used building interiors for shelving or paneling (Meyer and Hermanns, 1985).

Many architectural design decisions affect the occupant's perception of the indoor environment. There is not a large body of literature that helps the architect understand the implications of the decisions for the indoor environment. Initial decisions have been discussed briefly above. The next two chapters examine the effects of ventilation on the indoor environment and the major role played by various pollutant classes in causing problems in buildings.

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Section 3
VENTILATION SYSTEMS

OVERVIEW

Ventilation systems have a major influence on the indoor environment in commercial buildings. Ventilation-related problems are frequently indicated to be the most common source of complaints by occupants of commercial buildings. This chapter includes discussions of the following topics related to commercial building ventilation: 1) objectives and constraints; 2) natural ventilation; 3) mechanical ventilation systems; 4) ventilation rate characterization and measurement; 5) codes and standards; 6) measured ventilation rates; 7) ventilation effectiveness; and 8) problems.

OBJECTIVES AND CONSTRAINTS

There are two primary objectives of ventilation in buildings, maintaining thermal comfort and assuring adequate health and safety for the building's occupants. A considerable amount has been learned about conditions of thermal comfort in the past fifteen years (McIntyre, 1980). Major elements that are frequently controlled by ventilation systems in mechanically ventilated buildings are local air speeds, dry bulb temperatures, and relative humidities. Of these the dominant variable for thermal comfort considerations is the dry bulb temperature, which depends on both the air temperature and the mean radiant temperature. Fanger's classic study (1972) showed that a thermally neutral condition, i.e., a condition in which a respondent indicates that temperatures are neither too warm nor too cold, depends upon activity level, insulation value of clothing worn and the dry bulb temperature. Within certain limits, the local air speed and relative humidity perturb this condition of neutrality only slightly; however, extreme values of air speed and humidity can be a major source of discomfort.

Provision of adequate health and safety occurs primarily through the control of indoor pollutant concentrations. Ventilation interacts with indoor pollutant concentrations in many ways. By adding "clean", outdoor air to the contaminated indoor air, the indoor-generated contamination is diluted. Additional pollutant removal may occur by filtration and the ventilation process may increase deposition of contaminants on surfaces within the building. Although filtration removes only particles, sorbents are sometimes used to remove gaseous contaminants.

There are several important constraints on the ventilation process including: the need to maintain acceptable air velocities, restrictions on the amount of noise that will be tolerated by the occupants, the desire to minimize the energy required to move, condition, and distribute the air, the need to reduce building envelope heat losses, the need for smoke control in case of fires, and the always present constraint on the system cost.

NATURAL VENTILATION

Natural ventilation is the flow of air into and out of a building through leakage paths in the envelope and purposeful openings (such as windows) that is driven by wind and indoor-outdoor temperature differences. Natural ventilation is still the only method of ventilation in many smaller buildings (Turk et al., 1986; Cameron and Windell, 1981). Within naturally-ventilated buildings, the mixing of "fresh" and "indoor" air may take place naturally or be aided mechanically with fans. Many older multistory buildings with natural ventilation had central vertical ventilation shafts through which air flow was driven by thermally-induced or wind-induced pressure differences (McNall and Persily, 1984). Naturally ventilated buildings may have quite adequate ventilation rates. In a study of commercial buildings in the Pacific Northwest (Turk et al., 1986), three naturally ventilated buildings were monitored using a tracer gas technique that is described in a later section. The measured rates of entry of outside air per occupant were above those required in the ASHRAE 1981 ventilation standard for smoking areas and also above the ventilation rates measured in some mechanically ventilated buildings (Turk et al., 1986; Persily and Grot, 1985).

A major difficulty with natural ventilation systems is the lack of control of the ventilation rate. Environmental conditions (the wind speed and the indoor-outdoor temperature differences) and window openings determine the rate of natural ventilation. Therefore, precise and automated control is not possible. (Some argue that this is also true of mechanical ventilation systems.) However, operable windows increases the degree to which occupants located near windows can control their environment.

Operable windows are not universally accepted as a good design strategy for commercial buildings. Problems abound. Operable windows permit individual control at spaces near windows but core regions are not readily ventilated. Thus, the width of buildings may be constrained by the need to rely on windows for ventilation. In addition, natural ventilation alone can not provide for thermal comfort in hot (or humid) climates.

A solution may be to combine mechanical ventilation systems (see below) with operable windows. However, even this solution is not without its problems. Operable windows create problems for mechanical ventilation such as:

- the difficulty of attaining automated control of the environment since heating and cooling loads are generally more variable if windows are operable;
- the increased difficulty in producing an air-tight envelope;
- operable windows can upset the balance of flows in the mechanical system; and
- the difficulty in controlling smoke transport in case of fires if windows are open.

MECHANICAL VENTILATION SYSTEMS

Mechanical ventilation systems are used in the majority of large buildings in the United States. In this section we describe basic system configurations, methods for controlling temperature, humidity, and air flow rates, and briefly discuss the use of local exhaust ventilation.

Basic Configurations

The basic configurations and components of mechanical ventilation systems are illustrated in Figures 3-1 and 3-2. The two figures are keyed together with common symbols A-F. Central to almost all heating, ventilating and air conditioning (HVAC) systems is a supply fan which supplies air via ductwork to the conditioned space. Air flows through the conditioned spaces and is returned via a second set of ducts or through a plenum (usually located above a suspended ceiling) to be exhausted or returned to the supply fan. A return air fan may be added to aid the return and exhaust flow process and to allow some control over indoor pressures. Dampers are used to control the amount of return air which is allowed to reenter the supply system. Sets of dampers control the amount of air exhausted to the outside and the amount of fresh air allowed to mix into supply air stream. Heating and cooling coils (and sometimes humidifiers) are provided to condition the air before it is supplied to the occupied space. This basic scheme has many variations.

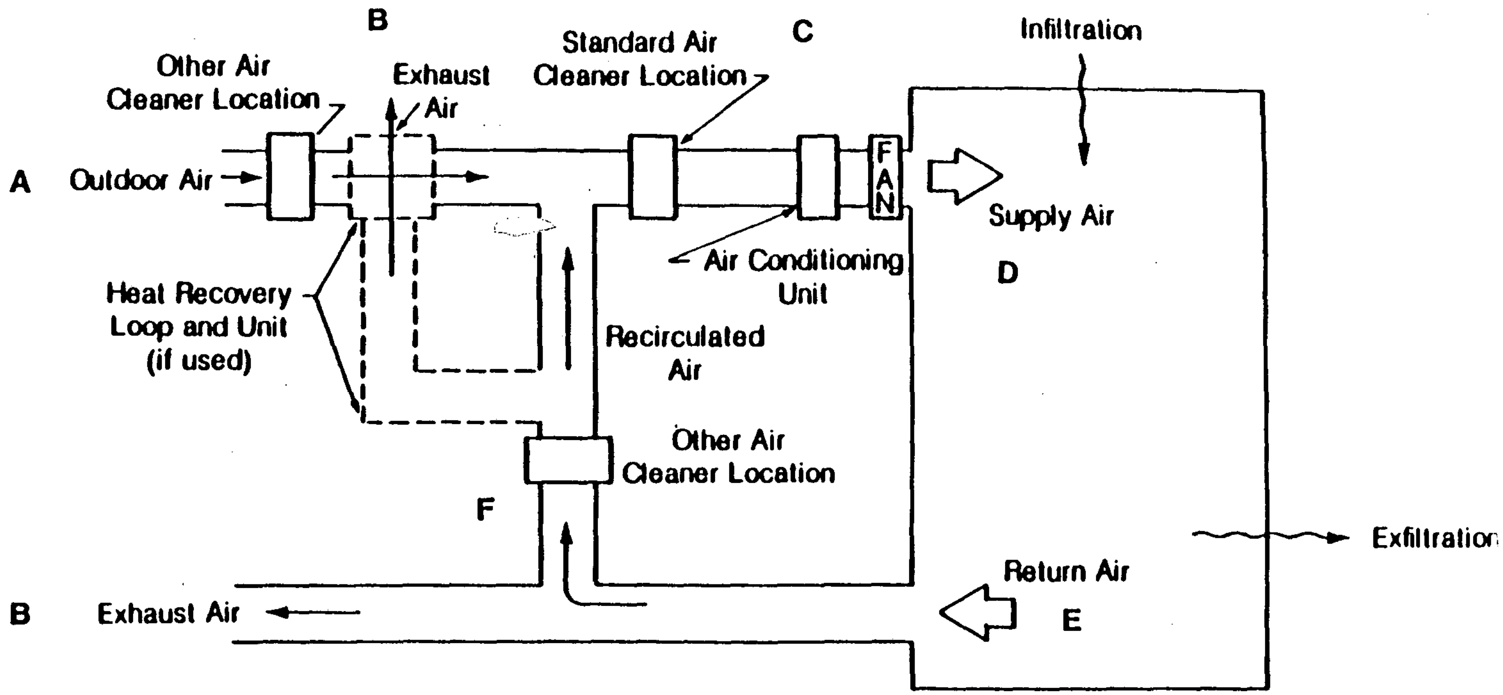

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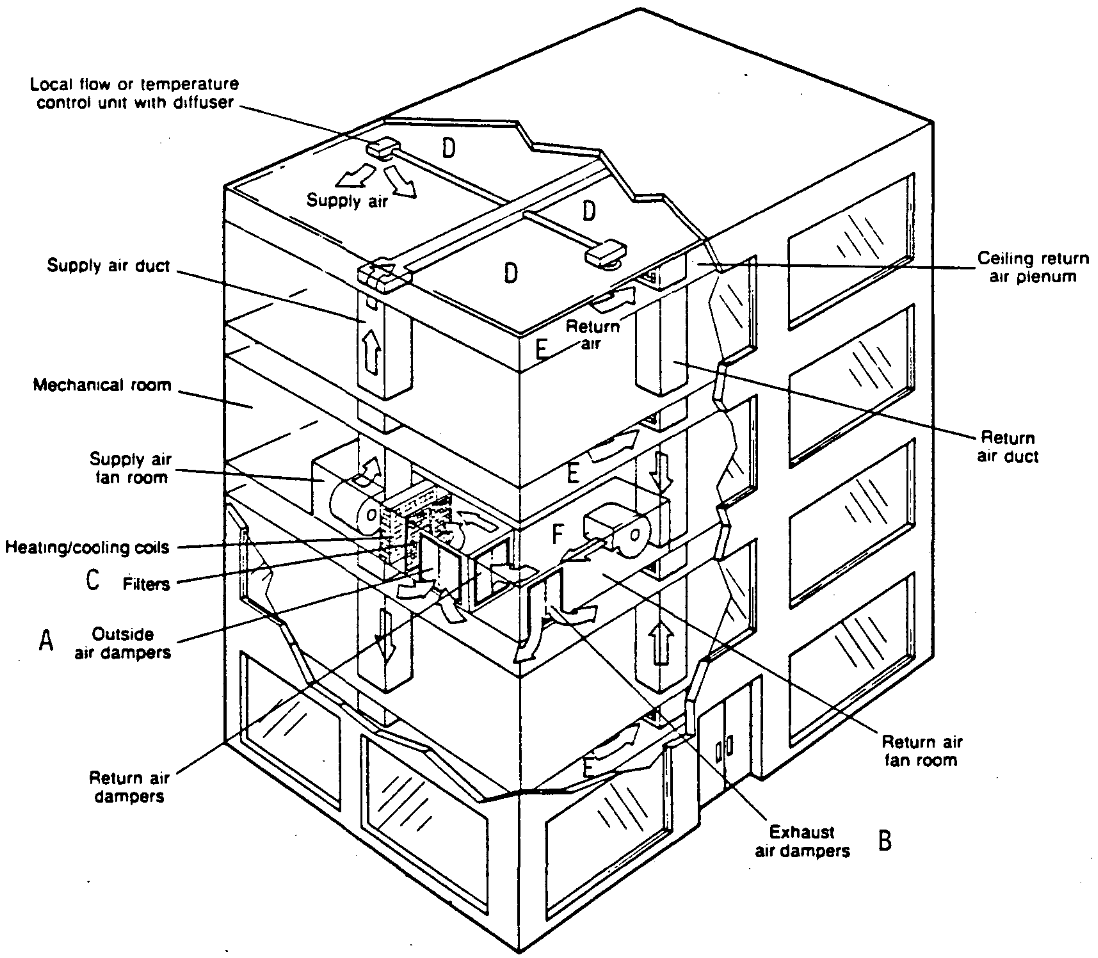
Figure 3-1. Schematic representation of a mechical ventilation system. This figure is keyed to Figure 3-2 through common symbols A-F that show equivalent features of the system.



Typical Commercial Building Air Handling System

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Figure 3-2. Pictoral representation of a typical mechanical ventilation system. This figure is keyed to Figure 3-1 through common symbols A-F that show equivalent features of the system.

Consider first the generic parts of the systems shown in Fig. 3-1 and 3-2. The supply air system contains the supply fan, the supply duct system that defines the gross distribution pattern for the supply air throughout the building, and the supply diffusers. The latter are the outlet devices attached to the supply ducts that promote mixing between the supply air and the indoor air. Since a lack of air mixing throughout the occupied space of a building (e.g., presence of stagnant regions) has often been associated with commercial building problems, it is important to note that the mixing pattern of air throughout a room is primarily a function of the air supply characteristics (diffuser type and location, supply air temperature, supply velocity) and the location of the return air grill, with the air supply characteristics usually considered the most important. The importance of air supply characteristics in determining the degree of mixing is reflected in the conventional design practices. Recirculating a portion of the return air, a common practice in U.S. buildings, will increase the mixing of the indoor air.

Supply diffusers are not always located at the ceiling. Options include a floor location near the wall so that the inlet air flows up the wall and then mixes into the room; a location high on the wall above the occupied zone so that mixing of room air with the jet of incoming air occurs before the incoming air encounters occupants; and, the most common ceiling location so that mixing of supply and indoor air occurs near the ceiling.

The supply air is conditioned to provide appropriate thermal comfort for occupants of the building. The air passes through heating and cooling coils and an optional humidifier before entering the occupied space. Since the supply jet of air entrains and mixes with room air as it enters the room, the supply air temperature and the velocity of air near the supply diffusers may be outside the thermal comfort region. In fact, it is common for supply air temperatures to be as low as 13°C (55°F). This supply air cannot be directed onto the occupants without causing thermal discomfort -- it must first mix with the warmer indoor air.

The second generic part of the system is the return air path. The air leaving the occupied space exits through a return grille found at floor level or, more commonly, in the ceiling. Some return grills are incorporated into lighting fixtures so that much of the heat generated by the lights is captured by the return air and can be rejected to outdoors or delivered along with the recirculated air as desired. The return air path to the central system may include a ceiling plenum (located above a suspended ceiling) connected to a central return duct or a dedicated return duct system. The return air path usually includes a fan to provide appropriate air flow and allow control of indoor pressures. In most systems a fraction of the return air is exhausted and the remainder is mixed with outdoor air and is recirculated to the conditioned space. Greater attention has recently been placed on the effects of return grill location on mixing of the indoor air. One concern is that supply air which exits ceiling level diffusers will largely short circuit to ceiling-level return grills under some operating conditions -- causing poor ventilation of the occupied lower regions of a room. The convenient use of unducted (ceiling-plenum) return paths is being questioned because of the associated ceiling location of return grills (Woods, 1986).

The generic system is completed with an outside air intake and dampers, the building exhaust and dampers and return air dampers to control the amount of recirculation. A source of some complaints has been inadequate separation the air exhaust and air intake locations to prevent reentrainment of exhaust air into the intake. Defining what adequate separation is presents a problem since wind can cause the exhausted air to be drawn back into an outside air intake located some distance away (Wilson, 1986). Often the intake and exhaust are in fairly close proximity, as in Figure 3-2, which increases the probability of substantial reentrainment.

Control of Temperature, Humidity, and Flow Rate

Several different methods for controlling indoor temperature, humidity, and air flow rates are used in commercial buildings. In this section we shall consider constant volume, variable air volume, and air induction systems, and also economizer cycles.

Constant volume systems supply a constant amount of air to the occupied space. This supply flow rate is not under automatic thermostatic control. Control of the thermal conditions in the space occurs by heating, cooling, and humidifying the supply air or, in a dual duct system, by mixing the necessary quantities of warm and cool air. The final supply air temperatures, and, thus, indoor temperatures, are regulated by thermostats located in the occupied space.

The designers of HVAC systems can employ a variety of design methods so that the proper amount of air flows through the various supply ducts and supply diffusers. In addition, dampers placed at various locations within the supply duct system and at diffusers are commonly used to adjust (balance) flow rates. However, adjustment of the supply air flow rate at one location can cause changes in flow rates at other points of the system. Balancing (i.e., proper adjustment of) the air flows throughout a system is known to be important and difficult.

Since the flow rate through a supply diffuser affects the nearby air temperatures, the amount of outside air delivered to the occupied space served by that diffuser, and also the degree and pattern of mixing of supply air and indoor air, careless balancing of the ventilation system can have several adverse effects. It is therefore essential that proper balancing of the air distribution system, i.e., checking to ensure design air delivery values, be completed before the building is initially occupied and at subsequent periodic intervals as the building is operated. Occasionally, the occupants may tamper with the supply diffusers and upset the balancing, in hopes of improving their own comfort or to reduce noise.

Variable air volume (VAV) systems control the temperature within a zone by varying the amount (flow rate) of air supplied to the zone rather than by varying the temperature of the supply air. Controllers called VAV boxes or VAV terminals are installed in the supply duct system and adjust the rate of air delivery out of a group of diffusers as required to control temperatures. The VAV boxes are usually controlled by a thermostat in the occupied space served by the diffusers. In some cases, the VAV controllers are integral to each supply diffuser.

Many variations of VAV systems exist ranging from the simplest that only supply cool air to a space (i.e., there are no provisions for heating) to an elaborate constant-zone-volume VAV. The latter may include fan-powered control boxes that are designed to throttle the primary supply air for conditioning purposes and add sufficient return air to maintain a constant total flow rate of supply air to the zone. Such a system may provide for greater mixing when internal heating or cooling loads are small.

Variable air volume systems have many advantages over constant volume systems. The size of heating and cooling equipment can be smaller. Since volume air flow is reduced as the load decreases, refrigeration and fan horsepower follow the actual load more closely than with a constant volume system and the reheating of air is also decreased. A true VAV system is also self-balancing. Addition of a new zone is often easier with a VAV system if reserve flow capacity exists in the central components of the system.

There are also disadvantages. Of most concern are the rate of supply of outside air when loads are low, and the mixing of supply and indoor air. The amount of air delivered through the diffuser may be reduced considerably at minimum load and the resulting rate of delivery of outside air may be inadequate. Conversely, if adequate delivery of outside air is maintained when loads are low it may be impossible to also maintain thermal comfort. Also, when supply flow rates are low due to small loads, the mixing of supply air and indoor air may be inadequate and problems such as the "short circuiting" mentioned previously are a possibility. Some VAV control units will completely close during periods of low load -- a system feature that clearly can lead to poor air quality. The control system responds properly to the increased heat loads associated with increased occupancy in a cooling load application but in the heating mode it throttles the air back when increased occupancy occurs. This is exactly opposite the behavior needed for acceptable air quality.

Air induction systems are employed with some VAV and constant volume designs to improve air mixing. For cooling applications, cool primary supply air is mixed with room air by induction or through the use of a fan. The mixed air is then delivered to the zone through the supply diffuser. The design promotes mixing of indoor air and allows increased heating or cooling capacity locally. However, it does not provide filtering of the room air induced back into the supply, nor does it add outside air to the combined air stream.

Economizer cycles are commonly used with all the systems described above. An economizer senses the outdoor air temperature and, if cool enough, opens the outside air damper and supplies up to 100% outside air to the system. This reduces the load on the cooling plant as long as the humidity of the outside air is appropriate. Since humidity and outdoor air temperature are important for this application, the best control strategy involves sensing outdoor air enthalpy which is a measure of the energy content of outside air taking both temperature and humidity into account. However, reliable humidity measurements are more difficult than reliable temperature measurements so it is more common to control the economizer cycle using only temperature measurements. Most economizer systems never completely close the outside air damper since a certain amount of outside air (i.e., minimum outside air) is required for adequate indoor air quality and to meet code requirements. The economizer system will provide the minimum amount of outside air to the building when cooling or heating loads are high and a greater amount of outside air at other times.

Buildings often have more than a single HVAC system. It is common for one air handling system to serve the perimeter zone -- the outer three to five meters of the conditioned area -- and to have another system for the interior zone. The interior zone, heated by lights and building occupants, frequently requires cooling during the entire year. This area is well-suited for a simple VAV cooling-only system. The perimeter zone, on the other hand, is subject to more variable loads since it experiences both direct solar gain and heat gain or loss through the building shell.

This use of separate HVAC systems is not limited to perimeter and interior zones. Different air handling systems may serve different floors, east and west ends of a building, etc. Each building has its own unique set of systems and resulting complexities. Older buildings that have undergone renovation may be particularly complex. The resulting mix of systems increases the complexity of the associated automatic control systems and of building operation, air balancing, and maintenance.

New Control Systems for Outside Air Flow Rate

Most ventilation systems supply a minimum amount of outside air during all periods of occupancy. New methods of controlling ventilation systems are under development. Some ventilation standards (e.g., ASHRAE 62-1981, procedure 1) are based upon occupant density since people are primary sources of carbon dioxide, tobacco smoke, and some odors. Therefore, sensors that measure numbers of occupants (often indirectly) can be used to control ventilation. The strongest correlate with occupant density is probably the indoor carbon dioxide (CO_2) concentration since the occupants are the primary indoor sources of CO_2.

Newly designed systems have been tested and are commercially available which use the concentration of CO_2 in the indoor air to control the outside air dampers directly (Sodergren, 1982; Janssen et al., 1982; Janssen et al., 1986). In this system the occupant density is sensed by measuring the CO_2 level and the ventilation rate is increased when the CO_2 level rises above a certain set value. These systems may allow significant energy savings.

The CO_2 limit (5000 ppm) set for industrial exposures by the American Conference of Governmental Industrial Hygienists is entirely too high to be useful as a set point for control systems in normal offices. Adverse occupant responses begin to occur at much lower concentrations; Japan has set a 1000 ppm maximum level in office work spaces (Ikeda et al., 1986). A study of building related illness by Rajhans (1983) shows that occupant discomfort and complaint of stale air may begin as low as 600 ppm.

Another new development in control systems, where occupant generated pollutants are the driving force behind minimum outside air requirements, is the timing function control. In this system outside air is admitted to the system at a rate that is fixed by the time of day. Thus, information on occupancy as a function of time is required.

Other occupancy sensors and control strategies are under test. Aldes, a French corporation, has begun to market a ventilation system using indoor humidity to control ventilation rate. The system, designed primarily for residential use, is a mechanical exhaust air system in which the exhaust fan and slot ventilators installed in exterior walls are each controlled by local humidity. Dampers on inlets to the exhaust fan, open to full capacity when indoor humidity rises above a preset value. The slot ventilators, which act as the outside air intakes to each room, also open wider when moisture levels in the room increase. If the moisture is generated by occupants, the ventilation rate increases in that room when occupants are present. Although descriptions of these systems have been published (Baets, 1986) the authors are unaware of published field measurements demonstrating the performance of the system.

Specific problems can also be attacked using pollutant-specific control systems. Tobacco smoke is a source of extreme concern for many building occupants. A control system based upon particle concentrations in areas designated for smoking occupancy might possibly relieve the source of much irritation for some occupants. Initial feasibility studies, (which do not include a field trial), of such a control system have been completed (Nelson and Alevantis, 1985). However, it is known that particle concentrations vary widely throughout a space with smoking (Turk et al., 1986). Thus a control system that senses the concentration of particles in the return or exhaust air would not insure that concentrations are low throughout the building.

One can conceive of other pollutants that could be used as triggers for controlling the rate of outdoor air entry into buildings. There are at least two problems with this. The first is practical, the second more fundamental. The practical consideration is that there is an absence of inexpensive, reliable sensors to perform the control function. The fundamental consideration is that the source of a pollutant should generally be controlled (when only a specific pollutant is of concern) rather than removing the pollutant from the air by dilution.

Local Exhausts

In many cases, local exhausts are more efficient in removing pollutants than general dilution. This is particularly true when a localized pollutant source such as moisture, toilets, cooking appliances, copy machines, or a region of significant tobacco smoking is present. The exhaust systems are generally complimented by a local source of make-up air although in some applications the makeup air may come from a contiguous space in the building. The high efficiency of local exhausts is due to the fact that the exhausted air can have a pollutant concentration that is much higher than the average within the building.

Energy conservation considerations have led to some questionable practices in situations where local exhausts are generally employed. In some cases codes are being waived and local exhaust air is being treated to remove odors and then recirculated back into the main supply (Cummins, 1986). Such a practice would be acceptable if it could be demonstrated that removing odors using air cleaners also removed all other harmful pollutants. However, this has not been demonstrated. Therefore, while the practice of local exhaust is an enlightened control strategy, the alternative of subsequent treatment and recirculation cannot be recommended.

VENTILATION RATE CHARACTERIZATION AND MEASUREMENT TECHNIQUES

Characterizing Ventilation Rates

Ventilation rates are indicators of the amount of outside air that is brought into a building. Minimum ventilation rates are specified in codes since a reduced rate of ventilation is associated with increased indoor concentrations of indoor-generated pollutants. Several measures are available for characterizing ventilation rates. Perhaps the most common is the flow rate (volume/time) per unit volume. The characteristic volume best suited to normalize the flow rate is the volume of the structure itself. Typically these ventilation rates are expressed as air changes per hour (ach) with units of inverse hours (h^{-1}).

Ventilation standards in commercial buildings often reflect the fact that the building occupant is a major pollutant source. For this reason ventilation rates are also expressed in units of flow rate of outside air per occupant (cfm/occ., L/s-occ., and m^3/hr-occ. are common examples).

Designers frequently normalize the flow rate of outside air and other building parameters (e.g., lighting power) by the floor area of the building. Consequently ventilation rates in the United States are sometimes expressed using the unit cfm/ft^2.

Recent interest in the mixing processes of ventilation air in the occupied zone has given rise to the concepts of local and average age of air in a space as indicators of ventilation rate, where age refers to the amount of time that has elapsed since the air entered the building. These values, similar in concept to the ages of individuals in any population and the average age of the population, are, quite obviously, measured in units of time. They are related to, but not identical with, the reciprocal of the flow rate per unit volume (ach).

Measurement of Local Flow Rates

Local flow rates are defined here as the flow rates of air through ducts, diffusers, exhaust grills, and dampers. System balancing, for example, requires measurements of local flow rates. Measurements of local flow rates are usually obtained by multipoint readings of air velocity in the duct cross section or across the diffuser/damper face. Each measured velocity is then multiplied by the associated cross sectional area and the total flow rate is the sum of all velocity-area products. Several different measurement methods are used (SMACNA, 1983; ACGIH, 1978).

In enclosed ducts, pitot tubes connected to differential pressure gauges can be used for air velocities greater than approximately 400 feet per minute, although a very sensitive pressure measurement device is required for low velocities. Although the SMACNA manual describes a "deflecting vane anemometer", the device is more of a pitot tube. The traditional "deflecting vane anemometer" is very inaccurate at low velocities. Rotating vane anemometers are used with a timing element to measure velocities at grilles, registers, or diffuser faces over a velocity range of 200 - 2000 feet per minute. A volume (i.e., flow rate) measuring device is the flow hood which is placed over a supply grill, diffuser or register and is calibrated to yield flow rate directly from an array of manifolded pitot-type sensors or from some other measurement device.

Each of the instruments described above determine velocity from the pressures that are produced on the measurement device by moving air. The hot wire anemometer, on the other hand, is based upon the cooling effect of flow over a heated wire. Hot wire anemometers are especially useful for measuring low air velocities; in addition, they are convenient and easy to use. To choose between various measurement methods, one must first have a rough idea of the velocities that will be measured. A manual, such as the SMACNA manual (SMACNA, 1983) should be consulted for guidance on the selection of a specific measurement technique and for detailed guidance on measurement and calculation procedures. Instruments should be calibrated periodically, at intervals that depend on the specific instrument utilized.

The accuracy of each technique of measuring local air flow rates depends highly on the specific equipment utilized, the method and frequency of calibration, and the skill and care of the person that makes measurements. Under ideal conditions the maximum errors could be 5 to 10% or less using any technique; however, typical measurement errors are probably much greater. One additional source of error is that some devices or techniques, such as the use of a flow hood, can change the flow rate being measured because these devices increase the resistance to air flow. Also, it should be pointed out that a large effort is required to measure all of the local flow rates in a building since there may be hundreds of ducts, diffusers, and return grills. If flow rates are changing during the measurement period, as in a VAV system, the measured data may be of limited value.

Tracer Gas Techniques

The other major technique employed to measure ventilation is through the use of tracer gas. The most common technique that has been employed in the past is a transient technique (tracer decay) in which the tracer is initially mixed as uniformly as possible in the indoor air. As outside air enters from the ventilation system or from leakage through the building shell, the concentration of tracer gas decreases (decays) with time and the measured rates of decrease in tracer gas concentration indicate ventilation rates and ages of air. If the outdoor air mixes thoroughly with indoor air, and if the outdoor air enters at a constant rate, the tracer gas concentration decreases in time exponentially. Procedures for processing the data obtained in tracer gas tests are described in various papers (Persily, 1985; Fisk et al., 1985).

The inverse of this process (i.e., a tracer build up or step up) occurs if tracer gas is injected at a constant rate into the outdoor entering the building. After tagging the outdoor air in this manner, one can monitor indoor tracer gas concentrations and tracer concentrations in the duct systems as a function of time. The tracer gas concentration increases asymptotically to reach a steady state value that is the ratio between its injection rate and the rate of entry of outside air into the space. Factors which can lead to measurement errors when employing transient tracer gas techniques are imperfect mixing of tracer and indoor air at the start of a decay, imperfect mixing of tracer and outside air in a step up, changes in ventilation rate during the test, and errors in determining tracer gas concentrations. In addition, the transient techniques generally require that expensive complex instruments are brought into the building.

In addition to these transient techniques involving the build-up or decay of tracer concentrations with time, steady-state techniques have been investigated that have both advantages and disadvantages with respect to transient techniques. The constant concentration technique uses feedback from a tracer gas analyzer to regulate the injection rate of tracer into the space. The injection rate required to hold the concentration constant is a direct measure of the amount of tracer exiting the space in the exhaust air stream. Because of difficulties with the long mixing times in some spaces, the system has a tendency toward instability. In spite of this, constant concentration systems have been developed by many research groups (Alexander et al., 1980; Collett, 1981; Kumar et al., 1979). One interesting application of the technique is in a multizone space. If the concentrations in the various zones are maintained equal, then the tracer injection rate into each zone will indicate the entry rate of outside air into that zone. Therefore, regions with unacceptably high and low ventilation rates can be identified (transient tracer techniques can also yield this information).

A second steady-state method is the constant injection technique. In this procedure a tracer gas source emits the gas into the outdoor air supply or into the occupied space at a constant rate for an extended period of time. Two separate methods are employed for analyzing the response to the tracer injection. The first requires a real-time analyzer and a continuous readout (Sherman et al., 1980). This analysis can, in principle, yield the time history of the ventilation rate in the space. In practice, this analysis is imprecise because of delays in mixing of the tracer with the indoor air.

A more common implementation of the constant injection technique involves measurement of the long-term average tracer concentration in the space. The average concentration measured is equal to the ratio of the tracer injection rate and the average of the reciprocal of the ventilation rate. If the ventilation rate is relatively constant in time, the difference between the reciprocal of the average ventilation rate and the average reciprocal of the ventilation rate is not large; the difference increases with the standard deviation of the ventilation rate.

The constant injection-average concentration technique has a convenient implementation in the form of a permeation tube source of perfluorocarbon tracer gas and diffusion tube adsorption sampler (Dietz and Cote, 1982). The source and sampler can be placed in the space for a time as short as several days and as long as a year. At the conclusion of the measurement period the sampler is sent to a laboratory for analysis. In spite of the simplicity and convenience of this system, problems remain. An inherent assumption in any constant injection rate procedure is that the tracer gas is mixed uniformly throughout the space that is tested. Since this assumption is necessary to evaluate data from constant injection procedure, the procedure is unsuitable for examining questions of distribution of outside air throughout the space (Fisk et al., 1985).

Different perfluorocarbon sources are available that can be used in different zones of a multiple-zone commercial building. The samplers, passive diffusion sorbent-type samplers, collect each of the tracers present in the space. Concentrations of individual tracers can then be determined. In principle this information can be used to determine interzonal flows for the systems and also the entry rate of outside air into each zone. Disagreement exists, however, about the accuracy of this procedure. As with any tracer gas technique, it should be used with caution and the user should be familiar with potential sources of error.

Another problem that must be addressed in using the constant injection technique in a commercial building is injection during building shutdown. The typical location for tracer sources is the supply air ductwork. The tracer is then distributed relatively uniformly throughout the building during operation. Often, however, a building's HVAC system is shut down during the unoccupied night-time hours. If the sources continue to emit tracer during this period, the concentration of tracer gas in the supply ductwork will increase and give a burst of tracer to the building when the HVAC system is restarted the following morning. Care must be taken in interpreting results from any tracer gas procedure to account for such failures of basic assumptions.

CODES AND STANDARDS

ASHRAE Standard 62

Ventilation codes and standards in the United States all have a common origin: Standard 62 of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE, 1981). This voluntary consensus standard is currently under revision. In the discussion that follows both the values for the current standard (62-1981), and the values proposed in the revision (62-1981R) are presented.

Standard 62 is actually two separate standards found together. The designer has a choice of a prescriptive procedure called the <u>Ventilation Rate Procedure</u>, i.e. supplying a specified amount of ventilation air to a space, or a performance procedure called the <u>Indoor Air Quality Procedure</u>. The latter only assumes the designer provide some method to keep specified pollutant concentrations below target levels. The procedure may be ventilation, air cleaning, pollutant source control, or a combination of these. It is important to note that these procedures are strict alternatives. The designer may choose either the ventilation rate procedure or the indoor air quality procedure to satisfy the standard.

The ventilation rate procedure was developed primarily by using CO_2 as the target pollutant of concern. Carbon dioxide concentrations (in the absence of open combustion) are a measure of occupancy and represent a surrogate for the pollutants (odors, bioeffluents, particles) associated with occupancy. The relationship between CO_2 and body odor has been demonstrated by Fanger and Berg - Munch (1983) and by Rasmussen et al., (1985). The existing 1981 ASHRAE ventilation standard uses 2500 ppm (half the occupational limit) as the maximum CO_2 concentration. In the proposed revision, this CO_2 value drops to 1000 ppm since, as noted earlier, CO_2 is considered as a surrogate for occupant-generated pollutants and complaints tend to become more frequent when CO_2 concentrations are above 1000 ppm. Because individuals are the dominant indoor sources of CO_2, the two limiting values imply a ventilation rate of 5 cfm/person (62-81) which changes to 15 cfm/person in the revision.

The existing standard uses 5 cfm/person as the basic ventilation rate in all buildings (excluding residences) in which smoking is not expected. Where smoking is permitted, the specified ventilation rates lie in the range between 20 and 35 cfm/person, depending on expected smoking frequency. Thus, two ventilation rate values are specified in the existing standard for each building type; one for buildings in which no smoking is likely, and a second for buildings in which smoking is expected. In the revision, there is only one ventilation rate prescribed -- this rate for each building type tends to be the larger of the two rates in the present version of the standard. In no case is the prescribed ventilation rate less than 15 cfm/person.

Local codes are based primarily on three model building codes, the Uniform Building Code (UBC) of the International Conference of Building Officials (ICBO), the Standard Building Code (SBC) of the Southern Building Code Congress International (SBCCI), and the Basic Building Code of Building and Code Administrators International (BOCA)(McNall, 1983). In most cases these model codes incorporate the ASHRAE standards as a routine procedure. However, ASHRAE Standard 62-1981 generated sufficient controversy so that it has not been adopted by the model codes. This led to the early revision of Standard 62 that is now concluding.

One final comment about these building codes. They all represent codes for the design of a buildings. There are not codes that mandate operation of the building as designed. California, through Cal-OSHA, is about to introduce a code that simply makes the statement, "buildings shall operate as designed under the building code that was operative at the time of construction" (Charles, 1986). While such a statement seems innocuous it actually represents a significant step forward in providing appropriate ventilation for building occupants.

MEASURED VENTILATION RATES IN COMMERCIAL BUILDINGS

There are only a few measurements available in the open literature that give tracer-gas determinations of ventilation rates in commercial buildings located within the U.S.(Persily and Grot, 1985; Turk et al., 1986).

Persily and Grot studied nine office buildings -- eight of these are federal office buildings owned by the General Services Administration. Buildings were monitored using a repeated tracer decay technique for many intervals throughout a year. The measured ventilation rates, are generally higher when indoor-outdoor temperature differences are small due to operation of economizer cycles. The annual average ventilation rates in the nine buildings ranged from 0.33 ach to 1.04 ach. The authors compared (see Table 3-1) the minimum measured ventilation rates to the rates recommended for these buildings with and without smoking in the ASHRAE ventilation standard assuming an occupant density of seven persons per 1000 ft^2. In most cases, the minimum measured ventilation rates were greater then or roughly equal to the minimum ventilation rates recommended for the building if occupants smoke. However, in two buildings, the minimum measured ventilation rates were only slightly larger than the ASHRAE recommended minimum non-smoking ventilation rate.

Table 3-1

MINIMUM VENTILATION RATES MEASURED BY PERSILY AND GROT (1985) IN NINE COMMERCIAL BUILDINGS AND ASHRAE RECOMMENDED MINIMUM VENTILATION RATES FOR THE SAME BUILDINGS CONVERTED TO AIR CHANGES PER HOUR (h^{-1}) ASSUMING AN OCCUPANT DENSITY OF 7 PERSONS PER 1000 FT^2

Building Location	Number of Stories	Occupied Floor Area (ft^2)	Primary Vent. System	Ventilation Rate (h^{-1}) Minimum Measured	ASHRAE Non-Smoking	ASHRAE Smoking
Newark, NJ	26	685000	VAV	0.55	0.16	0.63
Anchorage, AK	6	490000	VAV	0.26	0.17	0.67
Ann Arbor, MI	4	52700	VAV	0.47	0.09	0.38
Columbia, SC	16	216000	VAV	0.62	0.10	0.41
Fayetteville, AR	5	36600	CV	0.32	0.10	0.41
Huron, SD	4	69100	VAV	0.13	0.12	0.49
Norfolk, VA	8	186000	VAV	0.62	0.17	0.69
Pittsfield, MA	2	18600	CV	0.38	0.10	0.42
Springfield, MA	5	146000	VAV	0.55	0.12	0.46

Turk and colleagues measured ventilation in a group of 38 institutional and office buildings in the Pacific Northwest (see Table 3-2). Their measurements were made using a tracer gas decay procedure. The building was filled with tracer gas at night, when unoccupied, and mixed well, to the degree possible, using the central air handlers with the outside air and exhaust dampers closed. When the building achieved a "well-mixed" condition, the dampers were adjusted to a setting typical of that observed during the previous two weeks of operation during periods of occupancy. By monitoring the tracer gas concentration as a function of time, the ventilation rate was determined.

The ventilation rates measured ranged from 0.3 to 4.1 ach. The three naturally ventilated buildings that were measured had ventilation rates on the order of 0.8 to 0.9 ach, typical for older residences in the same climate zone. Based upon the occupancy attributed to the buildings by the building operators, this translated into ventilation rates per person ranging from 9 cfm/occupant to 168 cfm/occupant -- well above the rate recommended by ASHRAE for buildings where smoking is permitted.

Table 3-2

RESULTS OF MEASUREMENTS OF VENTILATION RATES IN COMMERCIAL BUILDINGS
(Turk et al., 1986)

				Ventilation Data			ASHRAE(8) Standard 62-1981	
Building No.	Seas.(9)	Volume(1) (Ft^3)	Occupancy(2)	CFM/ OCC	CFM/(3) FT^2	ACH(4) SF_6	Smok CFM/OCC	Non Smok CFM/OCC
1	W	230,000	318	9.6	0.1	0.8	--	5
2	W	158,400	421	13.8	0.4	2.2	--	5
3	W	159,970	35	95.2	0.2	1.3	20	7
4	W	206,350	35	57.0	0.1	0.6	--	5
5	W	144,100	34	118.0	0.4	1.7	20	7
6	W	5,032,000	1250	56.4	0.2	0.8	20	7
7	W	876,500	250	53.2	0.2	0.9	20	7
8	W	554,400	150	68.4	0.2	1.1	35	7
9	W	2,591,000	669	47.8	0.2	0.7	20	7
10	W	1,690,000	1286	19.3	0.2	0.9	20	7
11	W	1,454,000	400	88.2	0.3	3.6	20	7
12	W	717,200	80	40.3	0.0	0.3(7)	--	5
13	G	602,000	175	84.3	0.2	1.5	20	7
14	G	353,760	136	178.6	0.7	4.1	20	7
15	G	1,954,000	750	74.7	0.3	1.7	20	7
16	G	438,000	700	21.0	0.3	2.0	--	5
17	G	933,000	550	66.2	0.5	2.2(7)	--	5
18	G	113,100	84	12.8	0.1	0.6	20	7
19	G	215,831	65	48.1	0.2	0.9	20	7
20	S	790,000	835	28.5	0.2	1.8	--	5
21	S	413,935	150	80.9	0.3	1.8(7)	35	7
22	S	1,513,000	450	140.1	0.4	2.5(7)	20	7
23	S	165,664	25	113.8	0.2	1.0(7)	--	5
24	S	161,431	50	21.0	0.1	0.4(7)	20	7
25	S	146,442	80	53.4	0.3	1.8(7)	20	7
26	S	2,834,000	550	128.9	0.4	1.5(7)	20	7
27	S	527,000	110	22.4	0.1	0.3(7)	20	7
28	S	744,969	92	78.3	0.1	0.6(7)	35	7
29	W	828,152	678	60.7	0.6	3.0(7)	--	5
30(5)	W	933,000	659	30.0	0.2	1.3(7)	--	5
31	W	384,032	250	48.9	0.3	1.9	35	7
32	W	788,600	300	28.0	0.1	0.6(7)	20	7
33	W	523,000	600	22.7	0.3	1.6(7)	35	7
34	W	2,700,000	1200	54.8	0.3	1.5(7)	20	7
35	W	1,860,000	1200	35.1	0.2	1.4	20	7
36(6)	W	1,454,000	400	25.7	0.1	1.1(7)	20	7
37	W	1,845,000	930	75.7	0.4	2.4(7)	20	7
38	G	2,106,000	1100	60.3	0.4	1.9	20	7
39	G	2,238,000	1500	66.2	0.6	2.7	20	7
40	G	2,816,000	2500	45.2	0.6	2.4(7)	20	7
Arithmetic Mean				59.3	0.3	1.5		
Arithmetic Standard Deviation				37.81	0.16	0.87		

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(1) Volume - all space in building shell

(2) Occupancy - reported number of persons in building during normal occupied hours

(3) CFM/ft^2 - based on all building floor space and SF_6 tracer decay measurement

(4) $ACH(SF_6)$ - based on single SF_6 tracer decay measurement

(5) Repeat measurement of Building 17

(6) Repeat measurement of Building 11

(7) Building average ventilation rate includes decay rate measured in return air. Does not include that measured in supply air.

(8) From ASHRAE Standard 62-1981

(9) Season Code: G = Spring, S = Summer, W = Winter

VENTILATION EFFECTIVENESS

In theory the overall air flow pattern in a structure between supply diffusers and return grills can vary widely depending on the locations where air is supplied and removed, and the speed, direction and temperature (the temperature influences density and thus buoyancy) of the supplied air. At one end of the scale, much of the supplied air can short circuit to the return grills. In this case the return, and thus exhaust, air will generally have a lower pollutant concentration than the average within the building -- this is inefficient. In the middle of the scale, the indoor air is perfectly mixed -- this is the current design goal in most U.S. commercial buildings. At the other end of the scale, there is a displacement or piston-like flow pattern; for example between floor-mounted supply diffusers and ceiling-mounted return grills. With a displacement flow pattern, the concentration of airborne pollutants will generally increase in the direction of flow and the return and exhaust air will have a higher than average pollutant concentration -- this is efficient. The highest efficiency would occur with displacement ventilation and no recirculation of the indoor air, i.e., when the supply air is 100% outside air.

In addition to different air flow patterns caused by the methods of introducing and removing air, it is possible to have substantially different "ventilation rates" in different rooms, sections, or zones of a building because of variations in the amount of outside air supplied to these regions. The term "air distribution" is sometimes used in this context.

"Ventilation effectiveness" is the field of study involving air flow patterns and air distribution. There have also been numerous "ventilation effectiveness" indices or parameters defined which relate measured overall air flow patterns to the reference case patterns of air flow with either complete mixing or a perfect displacement flow. Other "local" ventilation effectiveness parameters relate the measured "local ventilation rate" to the ventilation rate that would occur with complete mixing or with a perfect displacement flow. Ventilation effectiveness indices are measured using tracer gas techniques.

Considerable attention is now being given to the "ventilation effectiveness" subject by researchers (Malmstrom and Ahlgren, 1982; Offermann et al., 1983; Fisk et al; 1985; Revzan, 1986; Sandberg 1981, 1984; Sandberg and Sjoberg, 1983; Skaret and Mathisen, 1982). ASHRAE is working on a standard which will specify measurement techniques for ventilation effectiveness. Novel ventilation systems are being introduced which, in theory, should provide ventilation with a higher effectiveness. For example, a system which promotes a floor-to-ceiling displacement flow, by supplying approximately $65^{o}F$ air at low velocity near the floor, removing air at the ceiling and employing no recirculation, is now used in some Scandinavian industrial and commercial buildings. In addition, an American manufacturer is promoting a system which has floor-level air supply units at work stations -- the occupants can adjust the direction and speed of air out of these units to meet individual needs. Thus, the "freshest" air can be directed toward the occupants, and the occupants also can also substantially affect their thermal comfort by manipulation of the nearby air supply units.

Laboratory-based experimental studies and simple theoretical models indicate that there is a substantial potential to improve the effectiveness of ventilation systems in commercial buildings. Undocumented reports of poor (uneven) air distribution are very common. However, further research is needed to evaluate the potential of new ventilation technologies such as those mentioned above, and to examine the ventilation effectiveness and air distribution patterns in actual occupied commercial buildings. In the few occupied commercial buildings where ventilation effectiveness has been measured (most of these buildings are located in Finland and may not be representative of U.S. buildings), the indoor air was relatively well mixed (Seppanen, 1986; Persily, 1986).

PROBLEMS

Problems with ventilation systems occur frequently and are often cited as a cause of complaints. In its investigations of complaint buildings NIOSH lists ventilation system problems as the reason for the complaint in 50% of the buildings (Melius et al., 1984). (However, to be fair it has never been clear whether the ventilation system was examined carefully enough to demonstrate this or whether the ventilation system was cited after exhausting other possible causes.)

Because there have been very few documented, comprehensive, and systematic investigations of problems in commercial buildings, it is not possible to indicate the frequency and importance of various types of problems. The following lists of problems and reasons for problems are based on the judgment of the authors.

Ventilation related problems leading to poor air quality:

- When the building is first occupied the ventilation system is not turned on. When this finally occurs, components malfunction or are improperly adjusted.

- Outside air dampers are fully closed to conserve energy or "protect" the occupants from outside pollution.
- The ventilation system is adjusted so as to provide too low a rate of outside air entry.
- There are gross imbalances in the air flows leading to poor air distribution.
- VAV flow controllers or diffusers are nearly or completely closed in a region of the building.
- The ventilation control system operates improperly.
- The ventilation system is completely lacking an outside air intake.

Ventilation-related problems leading to poor thermal comfort:

- Thermostats may be faulty or improperly adjusted.
- The ventilation system may not have sufficient capacity to maintain a thermally comfortable environment.
- Cold air may be directed onto occupants causing drafts.
- The air movement may be insufficient in some or all of the occupied space.

Many reasons can by listed for the problems that have been observed.

- Poor design of the system or of components within the system obviously should not happen but clearly does. Often the ventilation system is low on the list of priorities that the architect places on the building.
- The system may not have been commissioned and adjusted and balanced properly (multiple trades are involved in construction and coordination between trades is difficult).
- Inadequate maintenance may have occurred (e.g., filters may be plugged, coils fouled, etc.).
- Faulty sensors and actuators may be present in the system.
- The building operator may not understand the system and the subtle interactions of various parts when a portion is adjusted. An example is comfort related complaints that lead to a change in the local air supply without considering the effect in other regions of the building.
- The desire to save energy often leads to reduced entry of outdoor air.
- A building undergoing renovation is often reconfigured without appropriate changes to the ventilation system.

- The operator may have difficulty in monitoring performance, because of insufficient training, inadequate time, or poor monitoring equipment.
- Building loads may change resulting in a mechanical system that is not appropriate for the new conditions.
- A computer control system or software may be inappropriate for the building or poorly understood.
- The complexity of the system may cause inherent control problems.
- VAV units may close completely when loads are low leading to an insufficient supply of outdoor air and little air movement.
- In order to maintain an acceptable supply of outdoor air, VAV units may supply too much air for thermal comfort when loads are small.

Some of the solutions to these problems are obvious: better training, improved designs, higher quality components, more frequent maintenance, and an improved process of building commissioning. Other solutions (and possibly additional problems) may result from new designs and technologies -- for example the new ventilation technologies which may have a higher ventilation effectiveness or which allow for some degree of individual control. It is possible that operating standards for buildings coupled with improved ventilation monitoring technologies and some mechanism to improve the quality of building commissioning could help stimulate the implementation of obvious solutions to problems. If ventilation problems are shown to have significant adverse affects on productivity, incentives for better ventilation will increase. However, more detailed, and quantitative data on ventilation system problems are also required before optimal strategies for solving those problems can be developed.

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Section 4
POLLUTANTS

POLLUTANTS OF CONCERN

Pollutants, as treated here, are physical, chemical, or biological agents in an indoor environment which may singly or in combination cause an irritant or pathologic condition to exist. Some of the pollutant classes of concern that are known to be present in buildings are:

- Volatile and Semi Volatile Organic Compounds - odiferous, toxic, or carcinogenic organic compounds with indoor and outdoor sources.
- Biological Agents - particle or gas phase contaminants from colonizing microorganisms or the occupants.
- Particles - a criteria pollutant that also has numerous indoor sources.
- Criteria Pollutants - those which have regulated maximum permissible outdoor concentrations.
- Odors - gases or vapors from several sources with an especially irritating character.
- Radioactivity - radon gas and its progeny from soil, water, and building materials which may enter indoor spaces.

These pollutant classifications are not clearly defined; a pollutant may have more than one property by which it could be classified, i.e. tobacco smoke has a particulate phase and an odiferous gas phase which is composed of volatile organic compounds. The effects of these pollutants are not all the same in either their mode of action or the severity of the response to their presence. For example, radon gas is a long term carcinogen that gives no sensory clues of its presence whereas odors are an immediate source of irritation upon entering a contaminated space.

There are no non-industrial indoor air quality standards in the United States. Concentrations of certain pollutants are regulated by the National Ambient Air Quality Standards (NAAQS). These apply to outdoor air to which the general public has access. The NAAQS are given in Table 4-7 in the section on criteria pollutants, below. Other recommendations, which have been suggested by researchers, are mentioned in the relevant discussion. In the discussions of each pollutant type that follow, health effects are mentioned briefly, typical sources are identified, information on indoor concentrations in commercial buildings is reviewed, and suggestions for control are provided.

VOLATILE AND SEMI-VOLATILE ORGANIC COMPOUNDS

Introduction

Both volatile organic compounds (VOC) and semi-volatile organic compounds (SVOC) have sufficiently high vapor pressures at typical indoor and outdoor temperatures to exist as gases or vapors. As implied by their names, VOC are more volatile, while SVOC are generally associated with particles. The two classes are differentiated primarily by the collection and analytical techniques employed for the two classes of organic compounds. This will be discussed later in this section.

VOC and SVOC can be further classified on the basis of their chemical structure as was done by Miksch, Hollowell, and Schmidt (1982) for VOC. They listed three major classes of organic compounds which we list with some modification:

- aliphatic hydrocarbons, including straight-chain, branched-chain and cyclohexane derivatives,
- alkylated aromatic hydrocarbons as well as benzene,
- halogenated hydrocarbons, primarily chlorine- and fluorine-substituted.

This list is extended to include other important classes observed in indoor air:

- oxygenated hydrocarbons, including alcohols, ketones, aldehydes, organic acids and esters,
- polycyclic aromatic hydrocarbons, including substituted derivatives.

Sources of Organic Compounds

While classifying organic compounds on the basis of chemical structure can be useful in terms of analyses and, to some extent, in terms of health effects, another potentially more useful classification is based on source categories:

- building materials, including both construction materials and interior finish materials,
- furnishings -- closely related to the above category,

- building maintenance products, including waxes, cleaning products, pesticides and fungicides,
- consumer products -- closely related to cleaning products in some cases, differing primarily in packaging and use pattern, and includes expendable products in small containers which are readily available from retail outlets,
- tobacco smoking -- a consumer product of sufficient importance to warrant separate treatment,
- occupants, because of the bioeffluents produced,
- special processes - a miscellaneous category that includes sources such as those in a printing shop or a kitchen.
- outdoor air, including vehicle emissions in parking garages.

The characteristics of each source category are worth examining in some detail because of their potential importance in developing mitigation or prevention strategies. There has been surprisingly little research on source characterization of organic compounds in contrast to some other classes of indoor pollutants, e.g., for radon or combustion byproducts. As a consequence, some of what follows is based upon limited knowledge and is very general.

Building Materials and Furnishings

This is an important source category for VOC especially because of its possible contribution to the sick building syndrome. VOC emissions from products in this category are generally largest when the materials are new. (An alternate name for the sick building syndrome is the new building syndrome.) The emissions are relatively constant from day to day and appear to decrease in time periods characterized by days (for some "wet" materials such as certain adhesives) to time periods characterized by months or years (for formaldehyde emissions from pressed wood products). The VOC emitted are generally present as residual solvents; unreacted monomers or co-polymers; additives; plasticizers; and degradation products. Several studies have characterized emissions from building materials; among them are studies by Hodgson et al., (1983), Miksch, Hollowell and Schmidt (1982), Molhave (1982), and Sheldon, Thomas and Jungers (1986). The U.S. EPA has also begun an investigation of emissions from building materials (Tichenor and Mason, 1986). VOC emitted are predominantly aliphatic hydrocarbons, oxygenated hydrocarbons and alkylated aromatic hydrocarbons. Few halogenated hydrocarbon emissions have been observed from building materials. In general, building material sources (and, for the most part, furnishings as well) tend to be diffuse sources distributed over or covering large areas.

Building Maintenance Products

Much less is known about this source category. Emissions are expected to be episodic depending upon the application schedule, which may be daily (or nightly), weekly or a combination of daily and weekly (Miksch, Hollowell and Schmidt, 1982). The possibility exists that there is a gradual build-up in concentrations as residual cleaning products accumulate. Based upon product labels, one would expect emissions of oxygenated compounds (including alcohols, organic acids and esters), alkanes, aromatic compounds and halogenated compounds from these products.

Consumer Products

Again, relatively little is known about this source category despite indicators that, at least in residential settings, they are important sources (DeBortoli et al., 1985; Lebret, 1984). This category encompasses products such as cleaning/polishing products, insecticides, painting/finishing products, personal grooming products, hobbyists' products and deodorizers/disenfectants. Certain consumer products such as perfumes used in cosmetics and personal hygiene products would be expected to produce relatively constant, low level concentrations of organic compounds with some uniformity throughout an occupied building. On the other hand, the results of one study (Girman and Hodgson, 1986) suggest that other products such as aerosol sprays used, for example as pastes in "cut and paste operations", could produce large concentrations of certain VOC in an episodic manner under certain circumstances. Based upon product labels, expected emissions would be oxygenated compounds, alkanes, aromatic hydrocarbons, and halogenated compounds.

Tobacco Smoking

Tobacco smoking is a well-known source of many VOC and SVOC (NAS, 1981). Some of these compounds are listed in Table 4-1. Emissions from tobacco smoking are classified according to three categories: mainstream tobacco smoke (the fraction of tobacco smoke inhaled directly by the smoker); sidestream tobacco smoke (the fraction of tobacco smoke emitted into an air space by the smoldering cigarette, cigar or pipe); and environmental tobacco smoke (the combined fraction of sidestream smoke and the exhaled mainstream smoke from a smoker in an air space). Tobacco smoke has received extensive study in laboratory settings, but little chemical characterization has been conducted in environmental settings. Smoking is obviously an episodic source for each individual. However, when smoking is permitted in the workplace, it generally occurs with sufficient frequency that it can be treated as a continuous source. Tobacco smoking may be either distributed throughout a building or restricted to certain areas depending upon the policy associated with a building or a section of the building.

Table 4-1

ORGANIC COMPOUNDS FOUND IN CIGARETTE SMOKE.

Compound	Mainstream Smoke (mg/cigarette)	Sidestream Smoke (mg/cigarette)
SVOC		
Nicotine	0.92 0.46	1.69 1.27
Benzo[a]pyrene	3.5×10^{-5} 4.4×10^{-5}	1.35×10^{-4} 1.99×10^{-4}
Pyrene	1.3×10^{-4} 2.7×10^{-4}	3.9×10^{-4} 1.01×10^{-3}
Fluorathene	2.72×10^{-4}	1.26×10^{-3}
Benzo[a]fluorene	1.84×10^{-4}	7.51×10^{-4}
Benzo[b/c]fluorene	6.9×10^{-5}	2.51×10^{-4}
Chrysene, benz[a]anthracene	1.91×10^{-4}	1.22×10^{-3}
Benzo[b/k/j]fluoranthene	4.9×10^{-5}	2.60×10^{-4}
Benzo[e]pyrene	2.5×10^{-5}	1.35×10^{-4}
Perylene	9.0×10^{-6}	3.9×10^{-5}
Dibenz[a,j]anthracene	1.1×10^{-5}	4.1×10^{-5}
Dibenz[a,h]anthracene, indeno -[2,3-ed]pyrene	3.1×10^{-5}	1.04×10^{-4}
Benzo[ghi]perylene	3.9×10^{-5}	9.8×10^{-5}
Anthracene	2.2×10^{-5}	3.9×10^{-5}
Phenols (total)	0.228	0.603
VOC		
Hydrogen cyanide	0.24	0.16
Acrolein	0.084	0.825
Formaldehyde	----	1.44
Toluene	0.108	0.60
Acetone	0.578	1.45

From Table IV-19, NAS, 1981.

Occupants

Humans as a source of VOC have received little study. Wang (1975) reported 12 VOC, primarily oxygenated compounds (alcohols, aldehydes and ketones), produced by occupants in a college lecture room. Toluene and phenol (which is, technically, also an alcohol) were also produced in measurable quantities. The highest reported emission rates were for methanol (74 mg/person-day) and for acetone (51 mg/person-day). Overall concentrations in the room were fairly low, e.g., methanol had a peak concentration of 55 ppb. Occupants would be expected to continuously emit VOC and generally act as dispersed point sources. Table 4-2 summarizes the results of Wang's study.

Table 4-2

AVERAGE CONCENTRATIONS AND EMISSION RATES OF ORGANIC BIOEFFLUENTS IN A LECTURE CLASS (389 PEOPLE AT 9:30 A.M.)

Bioeffluent	Concentration, ppb	Emission Rate, mg/day per person
Acetone	20.6 ± 2.8	50.7 ± 27.3
Acetaldehyde	4.2 ± 2.1	6.2 ± 4.5
Acetic acid	9.9 ± 1.1	3.6 ± 3.6
Allyl alcohol	1.7 ± 1.7	19.9 ± 2.3
Amyl alcohol	7.6 ± 7.2	21.9 ± 20.8
Butyric acid	15.1 ± 7.3	44.6 ± 21.5
Diethylketone	5.7 ± 5.0	20.8 ± 11.4
Ethyl acetate	8.6 ± 2.6	25.4 ± 4.8
Ethyl alcohol	22.8 ± 10.0	44.7 ± 21.5
Methyl alcohol	54.8 ± 29.3	74.4 ± 5.0
Phenol	4.6 ± 1.9	9.5 ± 1.5
Toluene	1.8 ± 1.7	7.4 ± 4.9

[a] Data from Wang (1975).

Special Processes

Some examples of special processes are printing shop operations, office machine repair, blue print production, photographic processing, and food service operations. Few generalizations are possible about this category since emission characteristics can be as varied as the processes themselves.

Outside Air

Outside air contains many of the same compounds found in indoor air, although generally at lower concentrations. These compounds result from incomplete combustion from both stationary and mobile sources and photochemical smog as well as industrial releases. The temporal characteristics of outdoor air as a source of organic contaminants are established by the building ventilation, i.e., mechanical ventilation and/or infiltration. Because of lower concentrations, outside air is generally a minor source of organic compounds but it establishes the baseline organic concentrations to which indoor sources contribute.

Measurement techniques

Given the number and variety of the individual compounds found indoors, the methods used to determine the concentrations of VOC and SVOC can be quite varied. However, some generalizations can be made and certain methods that are appropriate for analysis of a broad spectrum of organic compounds have achieved widespread use and will be described.

While real-time spectrophotometric instruments can sometimes be used, they lack sufficient sensitivity for general use. They are employed, for the most part only for targeted VOC when the VOC source is unusually large (e.g., Girman and Hodgson, 1986). More often, the determination of organic concentrations in air is accomplished in two distinct steps: sampling; and analysis.

Sampling

Typically, methods for airborne organic compounds require that the sample also be concentrated to achieve sufficient sensitivity. In some cases, a known volume of air is bubbled through a liquid medium used as a trapping agent, e.g., sampling for formaldehyde using distilled water or a bisulfite solution in impingers. More often, for broad spectrum sampling, a solid sorbent is used, such as Tenax or charcoal for VOC and XAD or polyurethane foam (PUF) for SVOC, to concentrate the sample.

Another type of sampling, still undergoing validation, uses stainless steel canisters into which the sample is pumped under pressure. Alternatively, the canister is evacuated and the resulting vacuum is used to draw in the sample. The sample is concentrated prior to analysis by means of cryo-trapping with drying of the air stream (McClenny et al., 1984).

Yet another consideration is whether to use active or passive sampling. Active sampling requires the use of a sampling pump to draw air through a trapping agents, while passive sampling relies upon molecular diffusion to bring the compounds to a trapping agent. Several passive samplers exist for formaldehyde. Certain other VOC can be sampled with charcoal-based passive samplers that were developed for use in industrial hygiene. Some European researchers are using them successfully for targeted VOC (Seifert, 1986). The U.S. EPA is currently funding research on a Tenax-based passive sampler which shows some promise for broad spectrum VOC sampling (Countant, Lewis, and Mulik, 1986). Passive sampling can be advantageous; it is easier to do in the field and, generally, less expensive to use than active sampling. Whether passive samplers are sufficiently accurate and sensitive for broad spectrum VOC is still a subject of study.

Analysis

The first step in the analytical procedure is determined by the sampling method employed. Some sorbents, such as charcoal, PUF or XAD, must undergo a solvent extraction and, in some cases, the extraction procedure can be quite involved and elaborate. Increasingly, thermal desorption is being employed when possible (e.g., for Tenax), because of the ease and minimal handling required and because the sample is not diluted by the use of an extraction solvent. It must be noted that despite its wide utility, sorbent sampling with thermal desorption has limits. It is not appropriate for very reactive compounds and for some polar compounds. These compounds require separate, specialized sampling and analysis, often involving the formation of specific chemical derivatives.

For complex mixtures of VOC such as are found in indoor air, gas chromatography is generally used to provide the compound separation necessary for identification and quantitation. Several types of detectors are capable of providing the necessary sensitivity when used with a gas chromatograph (GC). The flame-ionization detector (GC-FID) is widely used because of its applicability for broad spectrum analysis of organic compounds and its good sensitivity. It is not a good choice for poorly combustible materials such as formaldehyde (without derivatization) and carbon tetrachloride. The electron-capture detector (GC-ECD) is most applicable for halogenated compounds, including some pesticides, and for compounds with multifunctional polar groups, in which case, it is much more sensitive than GC-FID. The sensitivity of the photo-ionization detector (GC-PID) lies between that of GC-FID and GC-ECD. It is useful for the many compounds with sufficiently low photoionization potentials, generally less than 12 eV.

While all of the above detectors are fairly commonly used, increasingly the detector of choice is a mass spectrometer (GC-MS). It provides not only sensitive detection, equivalent at least to GC-PID when operated in the selected-ion mode, but also provides tentative compound identifications even prior to the use of standards. GC-MS is also used for some SVOC. The other analytical technique generally employed for SVOC is high-performance liquid chromatography (HPLC).

Yet another technique for VOC employs a small, portable GC-PID equipped with a gas-sample loop for direct injection of the sample. While not as versatile as some of the previously described methods because of sample size limits and the lack of a temperature-controlled oven, nonetheless it can be very useful for studies of targeted VOC. It has a sensitivity of 1 to 50 ppb for many compounds.

Finally for more specialized analysis, as is required for more reactive compounds (e.g., formaldehyde), spectrophotometric methods can be used after colormetric development of the sample.

Organic Concentrations Indoors

As is evident from Figure 4-1 which shows chromatograms of air samples of equal volumes taken simultaneously inside and outside at a building where occupants registered complaints about IAQ, indoor air can differ considerably from outdoor air. In these chromatograms, for the most part, each peak corresponds to an individual compound and the height of each peak corresponds approximately to the amount of each compound. Clearly, there were more compounds present in the indoor air above the limit of detection (and this can range from about twenty compounds to several hundred) and the amount of these compounds was greater indoors than outdoors (and typically the indoor concentrations are from two to ten times greater). While the concentrations indoors are generally higher than those observed outdoors, the indoor concentrations are usually low relative to occupational health standards established for the industrial workplace.

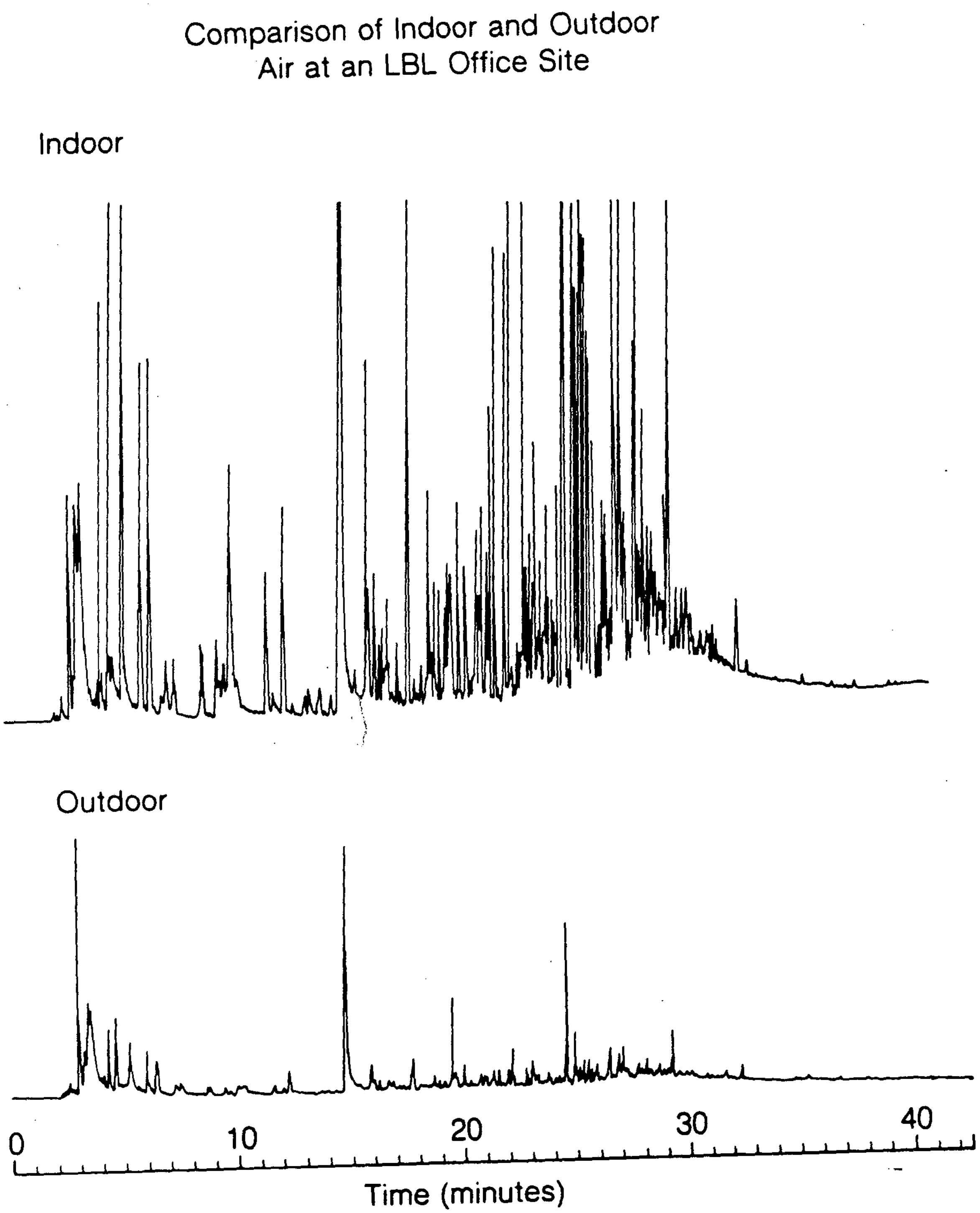

Figure 4-1. Gas chromatograms of trace organic contaminants in indoor and outdoor air at a complaint office building (Miksch, Hollowell and Schmidt, 1982).

Table 4-3

CONCENTRATION OF FIVE ORGANIC COMPOUNDS
FROM SEVERAL REPRESENTATIVE STUDIES OF INDOOR AIR QUALITY.

Compound and Building Type	Concentration (ug/m^3) Median[a]	Maximum	Reference
Acetone			
Residence	23.0	157	DeBortoli et al., 1985
Large Building	--	21.0	Johansson, 1978
Large Building	53.0	69.0	Wang, 1975
Large Building	0.49	----	Wang, 1975
Large Building, complaint	9.0	----	DeBortoli et al., 1985
Large Building, complaint	24.8	30.5	Hodgson et al., 1986
Benzene			
Residence	35.0	204.0	DeBortoli et al., 1985
Residence	9.90	150.0	Lebret et al., 1984
Residence	16.0	54.0	Wallace et al., 1984
Residence	13.0	120.0	Hartwell et al., 1984
Large Building	12.0	36.0	Pellizzari et al., 1984
Large Building	6.10	27.0	Pellizzari et al., 1984
Large Building, complaint	18.0	27.0	Turiel et al., 1983
Large Building, complaint	7.0	11.9	Hodgson et al., 1986
Benzo[a]pyrene			
Residence	0.0007	0.0034	Sexton et al., 1984
Trichloroethylene			
Residence	12.0	112	DeBortoli et al., 1985
Residence	<1.5	106	Lebret et al., 1984
Residence	2.3	12.0	Wallace et al., 1984
Residence	2.0	47.0	Hartwell et al., 1984
Large Building	0.67	1.9	Pellizzari et al., 1984
Large Building	4.9	70.0	Pellizzari et al., 1984
Large Building, complaint	8.5	10.0	Turiel et al., 1983
Large Building, complaint	3.0	----	DeBortoli et al., 1985
Large Building, complaint	----	7.2	Hodgson et al., 1986
n-Undecane			
Residence	91.0	950	DeBortoli et al., 1985
Residence	13.0	190	Lebret et al., 1984
Large Building	----	2.7	Johanssen, 1978
Residence	4.4	41.0	Monteith and Stock, 1984
Large Building	5.5	5.6	Hodgson et al., 1986

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[a] Median values are reported when possible; in some cases mean values are used.

Table 4-3 presents the results of indoor measurements of organic compounds from several representative studies. This listing is by no means comprehensive nor complete either in terms of the studies incorporated in this table or in terms of the compounds listed, since a complete list of the nearly 1000 compounds observed in indoor air is beyond the scope of this report. Rather the listing is intended to illustrate the range of compound types observed in indoor air and to illustrate the degree of consistency in the concentrations observed for individual compounds.

Indoor VOC and SVOC concentrations can be examined on the basis of some of the factors that are believed to influence concentrations significantly: building type; ventilation rate; and building age.

Building Type

There are reasons to suspect that the specific compounds observed and the frequency distributions of the concentrations measured would vary according to the type of building (e.g., office buildings versus single-family detached houses) due to differences in building materials, construction practices, ventilation systems, cleaning and consumer products and the activities of occupants. However, the data currently available are insufficient to assess these differences. The same broad spectrum of organic compounds has been observed in both types of buildings (e.g., alkanes, oxygenated hydrocarbons, halogenated hydrocarbons and aromatic hydrocarbons) and indoor air samples from both types of buildings are usually characterized by large numbers of compounds.

Ventilation Rate

Few systematic studies have been conducted in which changes in organic concentrations were related to changes in ventilation rates. Two such studies conducted in office buildings are summarized in Table 4-4. It is clear the increased ventilation, as occurred when the ventilation system was changed from supplying 15 or 16% outside air to 100% outside air, can reduce organic concentrations. In the case of the building studied by Turiel et al., (1981) it reduced concentrations of total hydrocarbons dramatically, actually to less than the 15% of the original concentrations predicted from simple steady-state considerations (11%). However, concentrations of organic compounds are not always reduced linearly with increases in ventilation. In the case of the other building studied (Hodgson, Binenboym and Girman, 1986), increasing the ventilation rate by nearly the same factor, six, reduced concentrations by only 55%. The cause of this non-linearity of concentrations with ventilation rate is not known but is probably related to ventilation efficiency and source characteristics. Further study is needed to clarify this.

Table 4-4

COMPARISONS OF THE EFFECT OF OUTSIDE AIR VENTILATION RATE ON ORGANIC CONCENTRATIONS IN TWO BUILDINGS.

% Outside Vent. Air	Compound or Compound Class	Concentration		Conc. Ratio[a]	Reference
		Indoor	Outdoor		
15%	Total hydrocarbons	1627 ug/m^3	210 ug/m^3}	0.11	Turiel et al; 1981
100%		364 ug/m^3	210 ug/m^3}		
15%	Formaldehyde	41 ppb	5 ppb}	0.44	
100%		21 ppb	5 ppb}		
15%	Total aliphatic aldehydes	90 ppb	12 ppb}	0.32	
100%		37 ppb	12 ppb}		
16%	Total quantified VOC	59.4 ppb	9.2 ppb}	0.45	Hodgson, Girman & Binenboym, 1986
100%		32.1 ppb	9.2 ppb}		

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[a] Ratio of indoor concentration minus outdoor concentration at 100% outside air to indoor concentration minus outdoor concentration at 15% outside air.

Building Age

Studies of the effect of building age on organic concentrations are, of course, using the age of the building as a surrogate for the age of building materials and changes in building practices and ventilation system design. As is the case with the effect of ventilation rate, few studies have systematically examined this effect. The exception lies with formaldehyde in residential settings, in particular for mobile homes and houses with urea-formaldehyde foam insulation (UFFI). Cohn, Ulsamer and Preuss (1984) present large data sets for both types of housing, 663 mobile homes and 1176 UFFI homes.

Despite the fact that individual houses were not followed with time, the sheer number of houses lends credibility to the half-lives obtained. (The half-life is the amount of time it takes for the concentration to decay to half of its original value.) For mobile homes, they observed a half-life of 4-5 years; and for UFFI houses, a half-life of 6 months during the first 40 weeks and then a half-life of 5-6 years. However, formaldehyde is a major component of many building materials that contain it, such as pressed-wood products and UFFI. This is not the case with most other organic compounds and this will effect their half-lives.

Table 4-5

DAYTIME CONCENTRATIONS (ug/m^3)[a] OF ORGANIC COMPOUNDS IN A NEW 3 STORY (5606m^2) OFFICE BUILDING JUST AFTER COMPLETED AND SIX MONTHS LATER.

Compounds	Outside New	Outside 6 Mo.	Secretarial Area New	Secretarial Area 6 Mo.	Office New	Office 6 Mo.
Chloroform	0.28	NC[b]	0.83	1.8	0.84	2.0
1,1,1-Trichloroethane	7.0	NC	589	100	883	94
Benzene	2.6	1.9	18	1.3	18	6.7
Carbon tetrachloride	0.87	NC	ND	1.2	ND	1.7
Trichloroethylene	0.54	NC	1.9	70	2.1	70
Tetrachloroethylene	T[c]	T	1.9	2.9	7.3	3.6
Styrene	T	1.7	6.0	8.2	8.3	8.3
o,m,p-Dichlorobenzenes	ND[d]	T	1.1	1.2	1.2	1.0
Ethylbenzene	2.8	0.3	169	8.6	140	5.9
p-Xylene	2.5	0.25	294	20	173	18
o-Xylene	1.3	0.10	129	7.7	89	7.3

From Pellizzari et al., 1984.

[a] Units are not listed in the original reference but are presumed to be ug/m^3.

[b] Not defined in original reference but presumed to mean not collected or not calculated.

[c] Present in trace amounts.

[d] Not detected.

Two studies provide some insight into the decay of VOC with building age, although data are insufficient to develop estimates of half-lives. The first study by Pellizzari et al., (1984) was conducted in a new, three-story non-complaint office building with a floor area of 5606 m^2. Measurements of organic concentrations were made when the building was new and then six months later. Table 4-5 presents a partial listing of their results. For many compounds in particular for the aromatic hydrocarbons, there was a substantial reduction in concentrations.

This is consistent with the expected source characteristics of building materials. It is also noteworthy that with the exception of 1,1,1-trichlorethane the concentrations of most halogenated compounds increased with time although not as dramatically. This is also consistent with expectations that halogenated compounds are associated with consumer and cleaning products. These data suggest that the half-lives for VOC may be on the order of months, not years as is the case for formaldehyde. This too is consistent with one of the more common manifestations of the sick building syndrome as will be discussed in the next section.

An earlier study (Berglund, Johansson and Lindvall, 1982) conducted in a preschool building also observed decays in organic concentrations over a six-month period. The concentration sum of the ten measured "indoor organic compounds" decreased from 86 to 27 ppb, and the concentration sum of the six measured compounds classified as "outdoor organic compounds" (which the authors stated "may emanate from inside the building as well") decreased from 54 to 14 ppb. These studies have obvious importance for mitigation efforts.

Health Effects of Organic Compounds

The health effects from exposure to organic compounds are varied and range from irritant effects such as unpleasant odors, mucous membrane irritation, respiratory distress and eye irritation, through general systemic effects such as fatigue, nausea and vomiting to life-threatening end points such as cancer or reproductive effects. The variety of health effects is hardly surprising given the variety of organic compounds.

It is important to note that the health effects can also be categorized as acute (short term) or chronic (long term). The health effects associated with the type of sick building syndrome believed to be caused by excessively high concentrations of organic compounds are primarily acute. This form of sick building syndrome is characterized by an often large outbreak of non-specific or systemic symptoms in a newly constructed and occupied commercial building. While in almost every case, many factors come into play including new ventilation systems which are inadequately adjusted or malfunctioning and employee dissatisfaction, the elevated level of organic compounds caused by offgassing of new building materials is also believed to be an important factor.

Two reports (Bach, Molhave and Pedersen, 1984; Molhave, Bach and Pedersen, 1984) on a Danish chamber study provide interesting insight into this factor, elevated organic concentrations. Sixty-two people, who had reported difficulty with indoor air quality but were otherwise healthy, were exposed in a double blind experiment to clean air and one of two levels of organic compounds. Twenty-two compounds, typically observed in indoor air, were used with a total organic concentration of 5 mg/m^3 or 25 mg/m^3. According to the authors, these concentrations correspond to average and maximum concentrations in new Danish houses. (The average concentration, 5 mg/m^3, is also representative of results from some complaint office buildings.) Their results are worth examining in detail.

Two mental performance tests were conducted. One test was designed to measure the subjects ability to concentrate. No significant effect was found by this test with respect to organic concentrations. The second test was designed to measure short term memory and the ability to concentrate. It is known to be a sensitive test of the memory impairment of those exposed to neurotoxins. Scores decreased significantly during exposure to the 22 organic compounds providing an objective and sensitive test. Another test to evaluate the irritation of the trigeminal nerve gave results that were not statistically correlated with the exposure.

Subjective tests were conducted in which the occupants "voted" on their perception of indoor air quality, odor intensity and other individual responses (i.e., mucous membrane irritation and eye irritation). The perception of occupants with respect to both air quality and odor intensity appeared to be linear with the square root of the total organic concentration. Mucous membrane irritation was equally high at both 5 mg/m^3 and 25 mg/m^3 and much higher than with clean air. In summary, there are now results from controlled experiments which associate some of the symptoms reported by occupants of complaint buildings with the level of organic compounds in indoor air.

However, it must be noted that the concentrations of the various organic compounds are much lower than traditional occupational health standards, many of which are based upon irritant effects. Possible reasons for the occupant complaints in sick buildings when organic concentrations are low relative to occupational health standards follow:

- Occupational health standards are too high to adequately protect all members of the general population, a percentage of which are more sensitive for a variety of reasons. (Recall that, initially, it was difficult to accept the widespread complaints of mobile-home and UFFI-house dwellers because occupational formaldehyde levels are often higher, as are the occupational standards for formaldehyde.)

- Additive effects of the organic compounds are important, particularly in conjunction with the first point. Most exposures in industrial settings are to a limited number of compounds, while in some indoor environments workers are simultaneously exposed to many compounds.

- Measurements in buildings are made too late, after the major exposures have occurred and the concentrations that provoked the responses were actually higher than those measured.

- There is a reactive compound not measured by typical broad-spectrum sampling and analytical methods which is present as a trace constituent of common solvents. Reactive compounds may produce the strongest irritant response.

- Synergism of low level compounds may be important. (However, while synergism is often offered as a possible explanation for the effect of low level organic concentrations, it is by no means the only explanation.)

- Stress in the workplace may lower peoples tolerance for low-level irritation and disagreeable odors.

While the acute effects of organic compounds indoors have received much of the publicity, it is important to recognize that many organic compounds are known or suspected carcinogens. Exposure to some compounds, e.g., benzene, is already regulated on this basis but many compounds have not been adequately tested. In addition, even for those which have been tested, considerable uncertainty exists in extending the results from animal tests to humans and in extrapolation of results to low dose, to name just two major areas of uncertainty. Consideration of the health risk associated with chronic exposure indoors to a multitude of organic compounds will undoubtedly receive more attention in the future, probably with emphasis on the effect of the many combinations that occur.

Control of VOC and SVOC Concentrations

While current knowledge about organic compounds in indoor air is rudimentary, nonetheless there is some knowledge regarding their control. The general principals are familiar to every industrial hygienist:

- Source removal/substitution
- Source modification
- Air cleaning
- Local (or spot) ventilation
- General ventilation.

Source removal is an attractive control strategy because the results are guaranteed, i.e., if a pollutant source is removed, pollutant concentrations will be reduced, although if secondary sources have been created by contamination it may take time to achieve the full benefit. As an example, if cigarette smoking is prohibited in a building, concentrations of the organic compounds associated with cigarette smoke will be reduced (but not necessarily eliminated since outdoor air remains a source of some compounds and there may be more than one indoor source of a particular compound).

One of the primary difficulties in implementing source removal is source identification. If, for example, the carpet adhesive is the cause of excessive organic concentrations considerable time and money can be expended before this is confirmed (see, for example, Breysse, 1984). Moreover, the effort and cost of the source removal can be considerable, in the present example including not only the removal of the carpet and carpet adhesive, the installation of new carpet but also the employee time lost because of the disruption. Thus, if the sources are known source removal (or substitution) is more economically implemented during construction or furnishing, i.e., selecting low-emitting materials. That this can be done is strongly, suggested by the Girman et al., (1984) study of adhesives in which ten of fifteen adhesives were not found to be significant emitters and by the Sheldon, Thomas and Jangers (1986) study which found striking differences in emissions from two latex paints.

Source modification can also be an effective strategy. An example is provided by the "bake-out" procedure. In this procedure, the temperature of a new office building is elevated and the ventilation rate is increased prior to occupancy to bake out the organic compounds and accelerate the ageing of the building materials and furnishings. The California Office of the State Architect has proposed that this be done for all new State buildings. While certainly, in principal, this should work at least to some degree, it is unknown at present just how effective this will be and little is known regarding the temperatures, time and ventilation rates required. In certain cases, sealing sources with a coating may be effective in reducing emissions.

Air cleaning by filtration will not work for VOC or SVOC in the gas phase. Certain sorbents, including charcoal-based sorbents, do adsorb organic vapors. However, their capacity is often limited which increases servicing needs and cost. In general, air cleaners with sorbent packs for organic vapors may be practical for small spaces in special circumstances but are not likely to be practical for large buildings due to limited capacity and attendant high costs.

Local ventilation is already employed in some buildings where most of the ventilation exhaust is drawn from restrooms. Special processes occurring in a building, e.g., a photography lab or restaurant would benefit from local ventilation. Segregating cigarette smokers is a crude form of establishing local ventilation. If separate ventilation exhaust (without recirculation) is furnished the degree of control should be quite good.

Finally, control of organic concentrations indoors can be accomplished by increasing the general ventilation of a space. This will certainly reduce concentrations, at least to some degree. However this is the technique of last choice for many reasons. It is expensive and moreover the effectiveness is uncertain in that as ventilation rates increase beyond a certain point, diminishing returns set in, in part, because of source characteristics and ventilation efficiency. In addition, the emissions spread throughout the space, increasing concentrations prior to removal.

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BIOLOGICAL AGENTS AS SOURCES OF INDOOR AIR POLLUTION

Introduction

Biological systems in buildings may have three types of adverse effects upon indoor air quality.

- Pathogenic organisms may cause epidemics of disease which spread through a building by air movement.
- Allergenic factors can cause definable or more generalized illnesses in susceptible members of building populations.
- Bioeffluents may contribute to the volatile organic component of building air, cause odor problems, or create "stuffy" or stale air.

Of these three categories, the first and third depend on the number of occupants and their state of health as well as physical and chemical building factors. The second category, allergenic factors, is most often associated with the state of the building and its mechanical systems. These provide an environment in which colonizing organisms, the sources of the allergy-inducing factors, can survive and multiply until they reach a level that may cause sick building syndrome.

Infectious Diseases

Pathogenic, disease-inducing, organisms, require a human reservoir of contagious individuals to initiate the spread of an epidemic in a building. A childhood disease epidemic from a single infected individual has been documented in detail in a study of a measles epidemic which was spread via the mechanical ventilation systems in a school (Riley, 1982). Outbreaks of other airborne diseases which can be spread via the ventilation systems of buildings into epidemics, such as legionellosis and tuberculosis, both bacterial in nature, or influenza and chicken pox (viral), would be treated immediately by health authorities since they require strict emergency measures for control. These types of extremely serious diseases by their very nature are less important to the general concept of "sick building syndrome" than are the respiratory illnesses commonly known as "colds" or "flu". Indoor epidemic diseases of humans are usually of the respiratory system. These disease conditions account for more lost work or school time than any other disease (Dingle, 1959).

Spread of infections via the air begins with the expulsion of aerosols from infected individuals when they sneeze, cough, or talk (Solomon and Burge, 1984). The resulting aerosol droplets carry infectious particles, bacteria, viruses, or fungi into the room air. Upon drying the resultant small particles in the 1 to 3 um size range may remain suspended and disperse by way of the normal air movement (Riley, 1982). In the course of normal mixing, the particles will become distributed throughout the ventilated volume of a building by recirculation of the air. If this is done over a period of time in which the airborne organisms remain viable, then every individual in the space served by the ventilation system can inspire the air and those who are susceptible become infected. Riley (1982) showed that as few as one infectious "quantum" per 5.17 m^3 of recirculated air was sufficient to initiate a measles epidemic. An infectious "quantum" is the number of viral units required to cause a person to develop the disease. Whether or not an individual who comes into contact with a respirable infectious agent develops disease depends upon the individual's state of health or immune status and possibly the number of agents. With the more wide-spread upper respiratory ailments, immunity is short lived and outbreaks of variants of the viral causative agents seem to occur each year. Interactions have been shown between other indoor pollutants and microorganisms in producing respiratory diseases (NAS, 1981). We can speculate that this type of interaction may, upon further study, prove to be an important contributor to outbreaks of worker illness associated with "sick building syndrome". Pathogens which may lead to outbreaks of illness usually have not been thought of as components of the "sick building syndrome". However, with more evidence, the prevalence of debilitating respiratory illness spread via recirculated air in energy efficient buildings may deserve serious consideration in maintaining whole building health.

Allergic Diseases

Allergenic factors may either be of indoor origin such as house dust or outdoor origin such as pollen. Allergic reactions in susceptible humans are extremely complex and may depend upon physical or psychological as well as biological factors (Bernstein et al., 1983). The overall contribution of airborne biological agents as sources of allergic reactions is appreciable but the contribution from the indoor environment is certainly far from being well understood (NAS, 1981). Human allergic responses to pollen and spores, fungi, actinomycetes, and arthropod fragments have been documented by Solomon and Burge (1984). Other agents such as protozoa and bacteria are also strongly suspected of causing clinically defined allergies in susceptible sets of exposed populations (NAS, 1981, Solomon and Burge, 1984). The relationship of the building environment to the spread of allergies is probably also complex. Many organisms either induce an allergic reaction directly through their presence or interact with the human subject through their effluents or byproducts (Bernstein et al., 1983).

Some of the specific allergic reactions caused by biological agents are: allergic rhinitis, asthma, hypersensitivity pneumonitis, and "Monday complaints" (NAS, 1981; Solomon and Burge, 1984). Allergic rhinitis is commonly known as "hay fever" when it occurs at some specific time usually associated with release of pollen during the reproductive season of anemophilous plants such as conifers or grasses. Bronchial asthma is caused by restriction of the airways of the bronchii and is characterized by wheezing, coughing, and difficult breathing. Hypersensitivity pneumonitis is a serious lung tissue reaction which may, if continued, lead to permanent scarring of the alveoli and incapacitation of the affected individual. "Monday complaint" is usually a flu-like series of symptoms which occur when a sensitive individual returns to a specific environment after an absence (Solomon and Burge, 1984). In each of these diseases the pattern of illness depends upon an interaction between a sensitive individual and an airborne biological agent. The size of the agent must be small enough to be inspired and therefore interact as an antigen with the subject's immune system. The complexity of the allergic reaction precludes a complete analysis of the possibilities for interaction between physical parameters of the building environment and the causative organisms as they relate to produce illness symptoms.

Bioeffluents

Bioeffluents are dealt with in part above under the heading of volatile organic compounds to which class many belong. Other "bioeffluents" can be treated reasonably as direct biological agents derived from either the human, animal or microbiological occupants of building environments. The effects of bioeffluents are threefold:

- Allergic responses to particles derived from the detritus of microorganisms. (NAS, 1981)
- Reactions to bioeffluents in the form of organic vapors which may contribute to the VOC burden of a building (Wang, 1975)
- Responses to the release of carbon dioxide and odors. (Rajhans, 1983; Turiel et al., 1983).

These are quite different aspects of the bioeffluent problem and range from potentially incapacitating, in allergic responses, to the merely uncomfortable, for example odor problems.

Allergic Responses to Bioeffluents. Allergic responses to bioeffluents have been reported to occur in response to the presence of the detrital fragments and excreta of "house dust mites" (NAS, 1981; Solomon and Burge, 1984). These small arthropods are abundant in dusts, fiber-based furniture, and floor coverings (Solomon and Burge, 1984). Their presence in air, especially in houses, has been reported in several studies (Solomon and Burge, 1984). Mites are possibly present in large buildings where both a suitable subtrate and moisture are available; however, this has not been studied explicitly.

Volatile Organic Bioeffluents. Volatile organic bioeffluents, especially alcohols and aldehydes, are released in human metabolic processes but have not been studied extensively. However, a survey by Wang (1975) did give evidence of the existence of these and other compounds in a lecture classroom. Their potential role in some human symptomatic reactions associated with "sick building syndrome" which are suspected to be related to the total VOC burden of the recirculated air in buildings are not presently known but they do contribute in some measure to the spectrum of volatile organic compounds.

Carbon Dioxide. Carbon dioxide is produced as a gaseous byproduct of human metabolism and properly is treated as a bioeffluent (Turiel and Rudy, 1980). As an atmospheric contaminant of indoor environments, CO_2 is the best known bioeffluent encountered in the building environment. Rajhan (1983) documented an outbreak of illness in a public building in which an elevated CO_2 concentration in the breathing zone is suspected to have played a conspicious part. At present occupational exposures to CO_2 are regulated and one country, Japan, has placed a 1000 ppm limit on the tolerable levels of CO_2 in office environments (Ikeda, et al., 1986). Carbon dioxide concentrations in occupied spaces have been used as a measure of the degree of outdoor air penetrating a building as ventilation or infiltration. Systems which propose to regulate the proportion of outside air used in ventilation systems based on occupant density often design their control schemes around CO_2 concentration (Berglund et al., 1982; Sodergren and Puntilla 1983; Janssen et al., 1986).

Sources of Biological Agents.

Sources of biological polluting agents in indoor building environments are:

- Outdoor air brought into the building through the ventilation system or through infiltration,
- Indoor environments which allow microorganisms to become established and thrive, and
- Indoor transients, most of which are the human occupants, as carriers of infection or sources of bioeffluents.

The second category probably has as its original source the outdoor air. An interesting study could be made of the ecology of a building as an environment to be colonized by microorganisms introduced from the outdoors into a newly completed building. One of the more active areas of terrestrial ecology has been the study of the establishment of a biota in areas which have been cleared of their complement of biological communities. A new building is certainly a new environment to be invaded and colonized. One particular instance of a case of an unknown organism which seems to be widespread in soils but which only came to prominence recently as a colonizer of building mechanical systems is Legionella, the causative bacterial species of Legionnaire's Disease. This disease seems to be contracted only through bacteria released into the air by atomization of water in building cooling systems which contain the bacteria and produce concentrated exposures to the occupants (Riley, 1982; Solomon and Burge, 1984).

In discussing sources of biological agents as a component of "sick building syndrome," we shall omit further mention of epidemics which are acute medical problems and are dependent upon active, fairly rapid transfer of infectious particles from one individual to another through the air. The remaining biological agents which may contribute to "sick building syndrome" are primarily the allergy inducing agents, both outdoor and indoor source types, and bioeffluents. These agents may be more insidious, have a longer effect, and through chronic debilitating effects of a fairly general nature, create occupant complaint conditions characteristic of sick buildings, without arousing the intervention of the medical profession. A report of a study of moldy office buildings may serve to typify the advent of conditions leading to sick building events (Morey et al., 1984). Five buildings were studied where hypersensitivity pneumonitis and other respiratory diseases were reported. These buildings seemed to have water related problems as a common denominator either in the structure, from flooding events, or in the HVAC system. Moisture is a requirement for growth and reproduction of organisms. If water is available then virtually any organic substance will serve as a substrate for the growth of some microorganism. These might not be organisms which cause illness in humans, but little is known of the range of potential transient sensitivities to high levels of airborne allergy inducing agents.

In each of the five buildings studied by Morey et al., (1984), there were outbreaks of respiratory illness which were brought to the attention of the NIOSH for evaluation. Careful studies revealed that inorganic, organic gaseous, or particulate pollutants were not in sufficiently high concentrations to cause widespread disease, in one case 100 of 350 occupants of a building. In each case microorganisms were isolated in significantly high numbers from either a portion of the building; i.e., ceiling tiles and carpets, or from the water handling portions of the cooling coils of the HVAC system. Flooding had occurred in three of the buildings and these were found to have a high fungal count in those portions of the building affected. The HVAC systems were studied and found to have organic growths, i.e., "slimes", with a high microbial content.

This study shows the method of investigation used in some "sick buildings". The types of organisms which have been implicated in human illnesses which are known to occur as a result of microbial infestation of a building are:

- Bacteria - associated with occupants or humidifying units
- Fungi - species of _Penicillium_ especially seem common indoors, _Cladosporium_ and _Alternaria_ are also common. These species will grow on many substrates if there is sufficient moisture.
- Actinomycetes - recovered from humidifier fluids and air conditioners. (Solomon and Burge, 1984; Morey et al., 1984; Bernstein et al., 1983).
- Protozoa - especially amoebae - have been implicated in human respiratory distress and found in "slimes" in HVAC cooling systems associated with outbreaks of "humidifier fever". (NAS, 1981; Sykora, 1982).

Outdoor Sources of Biological Agents. Outdoor air brought into a building will bring with it a certain amount of potentially irritating or allergy-inducing biological materials (NAS, 1981). Of particular interest here are pollens of anemophilous flowering plants and conifers which are primary source of agents which cause rhinitis and asthma. Pollens are produced during a relatively restricted portion of the year during which flowering and pollination of a specific species occurs. However, there is usually at least one or more species producing pollen for most of the year except during the winter season in more northerly latitudes. The total pollen burden of the air usually peaks in spring and early summer, but some species show a peak flowering season in late summer and fall depending upon the local conditions. Pollen entry into buildings is restricted by the building envelope and filtration system on the HVAC system. However, that pollen which does enter can induce symptoms in sensitized individuals. Some pollen may be deposited upon surfaces within the building and be reentrained in the air at a later date. An excellent review of the modes of action, as known, of allergy inducing organisms and human health responses is to be found in the relevant sections of Indoor Pollutants. (NAS, 1981)

Measurement of Indoor Levels of Biological Agents. Analysis for the existence of biological agents in air is a labor-intensive and time-consuming process. Particles which contain viable organisms that can be cultured from single cells to visible colonies are usually sampled using a six-stage, size-graded unit through which room air is drawn. The samples are then exposed to a nutrient agar which is incubated until visible colonies appear (Morey et al., 1984; Anderson, 1958). With a known air flow through the system the number of colony forming units per volume of air can be calculated. For non-viable particles light microscopy is used for identification of individual units (Solomon and Burge, 1984). In some cases direct sedimentation of airborne units onto suitable culture media is used for identification of organisms in very localized environments, such as ductwork (Bernstein et al., 1983).

Other techniques which have been used are immunoassay of bulk samples to determine if a reaction is induced in sensitized individuals but without identifying the specific organism(s) present (Solomon and Burge, 1984). Some whole organisms or parts thereof are not viable nor are they readily identifiable microscopically. These are non-enumerable at present (Solomon and Burge, 1984).

For bioeffluents and CO_2 the identification/quantification techniques are more straightforward. Bioeffluents in the volatile organic category are usually adsorbed onto a suitable sorbent material then desorbed into a gas chromatograph/mass spectrometer for analysis where their elution time and peak height relative to standards enable identification and quantification.

Carbon dioxide is usually measured using a standard non-dispersive infra-red analyser which measures the amount of infrared radiation absorbed by a gas mixture drawn from the measurement location. The instrument is tuned to infrared absorption bands in the gas of interest.

Control of Biological Agents. Control of biological agents which may be associated with "sick building syndrome" outbreaks fall into several categories:

- Source Removal - especially where a thriving colony of the offending organism is present within the building.
- Ventilation - dilution of the vapor phase of bioeffluent odor or VOC materials falls primarily under this category of control.
- Moisture Control - removal or prevention.
- Environmental (Temperature and Humidity) Control.

Source removal may include:

- Removal of affected substrates where colonies of organisms are found to be growing.
- Cleaning non-removable structural members or portions of the HVAC system.
- Proper maintenance of any portion of the HVAC system which later may provide a growth medium.
- Filtration of air where outside sources such as pollen are the cause.
- Application of biocidal agents after cleaning portions of the affected mechanical system. (Morey et al., 1984).

Ventilation by dilution of the indoor air with outdoor air reduces the impact of unpleasant or irritating odors by lowering their concentration to levels below detectability thereby rendering the environment more acceptable. With CO_2, dilution is usually quite effective with an inverse linear relationship between CO_2 concentration and the outside air ventilation rate. VOC may not follow this exact relationship in some cases where complex sources and emission rates are found indoors. However, in the case of bioeffluent odors and human emissions, ventilation should be the primary means of removal (Berglund et al., 1982). With organisms which live on organic substrates present in buildings several continual maintenance procedures are required to prevent reoccurrence of the problem (Morey et al., 1984):

- Lower the humidity content of the air where it is above 70% relative humidity. Below this level organisms do not thrive.
- Prevent water leaks into the building and avoid stagnant water in any portion of the mechanical or structural portion of the building.
- Use steam for humidification if necessary.
- Maintain an adequate filter cleaning/replacement schedule.

In pathogenic outbreaks medical advice and quarantine of the infected individuals are advised. Irradiation of the air with UV light has been shown to reduce the viral burden of the atmosphere in buildings, but this is probably not economical except in high risk facilities and where dangerous diseases are possible (Jakab and Knight, 1982).

Overall the same general techniques of control for biological pollutants as for chemical pollutants, are useful: ventilation to dilute the airborne concentration and source removal. Biological agents have some special characteristics - their ability to multiply rapidly in favorable circumstances and their ability to reenter spaces repeatedly. Constant vigilance is therefore necessary but the apparent impact upon comfort and productivity of the occupants of buildings makes this vigilance economically prudent.

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PARTICLES

Introduction.

Airborne particles are a health concern and a potential contributor to "sick building syndrome". Particles in the size range of less than 3 um in aerodynamic diameter, called respirable suspended particles (RSP), can lodge in deep lung tissues when inhaled (Task Group on Lung Dynamics, 1966). Many different chemical and biological pollutants are dispersed through the air in buildings in the form of RSP.

Particles of biological origin which occur in the RSP size range may be either pathogenic organisms such as viruses, bacteria, or fungal spores. Allergy inducing biological particles in the RSP size range include amoeba, bacteria, fungal spores, higher plant pollens, and anthropod fragments. Chemical pollutants which may cause allergic reactions or disease also occur in RSP sizes. These chemical pollutants may come from tobacco smoke, house dust, consumer products, and other indoor and outdoor sources.

Particle Classification: Size.

Airborne particles are classified in various ways. Size is one characteristic which is most frequently used in studies where human exposures are concerned. The following size breakdowns are used:

- Total suspended Particles (TSP). The particles suspended in a unit volume of air collected by a high volume sampler.
- Inhalable Suspended Particles. The fraction of TSP whose diameters fall between 3 and 15 um.
- PM_{10}. The fraction of TSP less than 10 um in diameter.
- Respirable Suspended Particles (RSP). The fraction of TSP less than 3 um in diameter.
- Fine Fraction (FF). The fraction of TSP less than 2.5 um in diameter.

The RSP and smaller fractions are of most concern relative to human health i.e. "sick building syndrome" concerns, since they are the size range most likely to remain in the deep respiratory spaces when inhaled (Task Group on Lung Dynamics, 1966). Total suspended particulate concentrations in the outdoor air are regulated by the U.S. Environmental Protection Agency National Ambient Air Quality Standards (NAAQS) with a maximum permissible exposure of 260 ug/m^3 for 24 hours. This level is allowed to be exceeded only once per year. The annual geometric mean concentration limit is 75ug/m^3. The EPA has recently added a regulation to control PM_{10} concentrations. These regulations, to go into effect 31 July 1987 will limit 24-h exposure to 150 ug/m^3 (taken as a 24-h averages) and annual exposure to 50 ug/m^3 measured as the arithmetic mean.

Particle Classification: Chemistry.
Particles can also be characterized on the basis of their chemistry or origin. These classifications are less useful in general since different sources may produce chemically similar compounds.

Particle Classification: Source.
A classification based on source in cases involved with indoor air quality is useful since the human health responses to the different particles may be quite dissimilar. This is the distinction between particles of biological origin such as viruses, bacteria, and other shed parts of organisms and particles primarily derived from tobacco smoke. A third source type is residual chemical dusts from cleaning product use (Kreiss et al., 1982). Another source which may be significant is the dust created by a mixture of outdoor material and the breakdown of building materials and furnishings due to wear. As the following classification shows there is complexity even here.

Table 4-6
SOURCES OF PARTICLES

Particle Type	Source Location	Origin
Biological:		
Pollen	Outdoors, Reentrainment	Flowering Plants
Mold Spores	Outdoors, Indoors	Soil, water, organic material

Bacteria	Outdoors, Indoors	Humans, water, soil, pets
Viruses	Indoors	Humans, pets
Chemical:		
Dusts	Indoors	Cleaning products, breakdown of building products, aerosol sprays, fiberglass fibers, cellulose fibers, asbestos fibers
Smoke	Indoors	Tobacco Smoke Cooking Emissions Combustion products from gas stoves, unvented heaters, or malfunctioning vented appliances.

Sources of Particles: Biological.

Specific sources of great interest are those that produce particles which have been implicated in direct or chronic human health effects. These include biological agents that have been discussed above. As particles, aeropathogens or aeroallergens fall largely into the RSP size ranges; however, many pollen and fungal spores are larger (Repace, 1982).

The primary pathogens of humans which are spread as aerosols are viruses, which are less than one micron in diameter, and bacteria, which are 1-2 um in diameter. The aerosols arise usually from expulsion of droplets of 1 to 100um diameter from infected humans, These droplets may then evaporate leaving the viable particles airborne (Repace, 1982). These aerosols can be uniformly dispersed by air flow throughout a ventilated space. Pathogens have a mode of action upon humans that is radically different than that associated with inert aerosols or allergens. An infective particle can spread disease if as few as one viable particle finds its way into a human host and there multiplies to induce a disease state. As few as one infectious quantum per 5.2 cubic meters of air was enough to spread a measles epidemic in a school (Riley, 1982). Allergens and chemical aerosols on the other hand, usually have a dose/response interaction where the severity of the reaction is in some way increased as challenge from the causative agent increases. Mold spores and pollen are primarily allergy-inducing agents and range from RSP diameters to greater than 100um in size. They may either enter from the outdoors, the primary source of hay fever pollen, or from the indoors in the case of fungal colonies in building or furnishing material substrates.

Source of Particles: Chemical.

Chemical dusts remaining as a residue from improperly diluted carpet shampoo have been implicated in outbreaks of sick buildings syndrome (Kreiss, et al., 1982). Two cases where the occupants reported respiratory distress have been reported where extensive carpet shampooing resulted in a residual quantity of sodium dodecyl sulfate, a detergent, remaining in the carpeting. Movement of persons across the carpet raised the fine dust to breathing height and up to 90% of the exposed occupants were seriously effected. Only steam cleaning and extraction of the carpet relieved the symptoms. General "household" dust which arises from outdoor material brought in the building on occupants footwear, material from floor covering breakdown, airborne outdoor material which infiltrates the building, and biological agents has been tested and found to induce reaction in sensitive individuals. The active portion of the dust may be the biological debris but in such a complex mixture much more analysis needs to be done to isolate the active fraction.

Asbestos Fibers.

Widespread use of asbestos in building materials such as pipe insulation, floor and ceiling tiles, and spackling compounds presents a potential health problem. Most of the asbestos in use is immobilized in strong building material, but if the material is cut or broken, asbestos fibers can be released. Occupational exposures to asbestos fibers have been linked to lung cancers in workers and in families of workers who come into contact with the fibers through contaminated clothing.

Risks to the general public from nonoccupational exposure is the topic of a recent National Academy of Sciences study (NAS, 1984). This study (whose results were modified in a note of Aroesty and Wolf (1986)) leads to the conclusion that lifetime risk to asbestos exposure (at a median concentration of 0.0004 fiber/cm^3) leads to a lung cancer risk among male smokers of 292 per million. This risk is smaller in other categories; in non-smoking women the number is 14 lung cancers per million. The risk of developing mesothelioma is 156 per million persons. As is true for all risk assessments of this type the uncertaintities in the risk estimates are large. Additional discussion of this issue can be found in articles by Zuren (1985) and Culberg (1987).

Sources of Particles: Tobacco Smoke.

Smoke from tobacco has become the chief source of interest in recent health related studies of indoor air quality (Repace and Lowery, 1980; Leaderer, et al., 1984). Tobacco smoke has both immediate irritant characteristics and possible longer term health related effects. An additional feature of tobacco smoke particulate phase material is its tendency to adsorb on surfaces and continue to release irritating odors by evaporation of volatile compounds even after smoking has ceased. Particles arising from tobacco smoke fall mainly into the RSP range as measured in chamber or controlled studies. The size distribution of tobacco smoke is log normal with median diameter measured in the submicron range. Offermann et al., (1985) give a count median diameter of 0.15 um for TSP and report that 98% of the particulate mass falls between 0.05 and 1.0 um, well within the RSP size.

Tobacco Smoke: Health Effects

Health effects of tobacco smoking on smokers have been studied extensively. While the causal associations between active cigarette smoking and cancer of the lung have been long established, the health effects of passive smoking, instances where non-smokers are exposed to either exhaled or sidestream smoke are controversial (see, e.g., Balter et al., 1986; Samet, 1985; Wells, 1986,). Exposure to smoke has been shown to cause irritation of the eyes, nose, throat, and respiratory tract (NAS, 1981; Stolwijk et al., 1984). The particulate phase seems to be the primary source of this irritation (NAS, 1981). More severe reactions to exposure have been reported. Holt and Keast (1977) observed that exposure reduced the human defense mechanism against upper airways infection. A strong causal effect between passive smoking and illnesses including reduced pulmonary function have been reported (Higgins, 1984). Repace (1982) noted that 50% to 75% of nonsmoking adults suffer symptomatic effects from exposure to ambient tobacco smoke and 50% of nonsmoking office workers reported a productivity impairment due to co-workers smoking.

Tobacco Smoke; Distributions.

Smoking is becoming an issue in public buildings and work spaces. Considerable legislation has been introduced to limit smoking to certain areas of public facilities and in offices (Turiel, 1985). It is generally assumed that approximately one third of the adults in the U.S. are smokers and that they smoke, on average, two cigarettes per hour (Leaderer et al., 1984). Measurements of TSP and RSP in commercial buildings have shown that elevated levels of particles do occur in areas where smoking is permitted (Repace and Lowery, 1980; Weber and Fischer, 1980; NAS, 1981; Repace, 1982; Turk et al., 1986). Repace and Lowery (1980) found that in areas where smoking was permitted the RSP levels ranged from 86ug/m^3 to 697ug/m^3 whereas without smoking RSP concentrations ranged from 29ug/m^3 to 55 ug/m^3. In a comparison in two restaurant studies the nonsmoking areas had 51ug/m^3 and 55ug/m^3 with measured outdoor values of 55 ug/m^3 and 40 ug/m^3 respectively (Repace and Lowery, 1980). In the same study smoking areas had 86 ug/m^3 and 110 ug/m^3 (Repace, 1982).

In a recent major study of 38 public governmental and privately owned buildings where RSP samples were taken in both smoking and non-smoking area of offices and work spaces, concentrations in smoking areas ranged from below detection levels (5ug/m^3) to 308 ug/m^3 (Turk et al., 1986). This study reported a geometric mean for all smoking areas of 44 ug/m^3. Fully 20% of the sites tested had a mean greater than 75 ug/m^3, the NAAQS (outdoor) maximum permissible annual mean for TSP. In non-smoking areas the geometric mean was reported to be 15 ug/m^3; only 1% of the sites were above the NAAQS maximum. During the tests outdoor RSP concentrations had a geometric mean of 14 ug/m^3, ranging from below detection limits (5 ug/m^3) to 68 ug/m^3. From the lognormal cumulative probability distribution it was estimated that 7% of the sites in a similarly chosen sample would have concentrations above 75 ug/m^3. From these reported values of RSP concentrations, it can be seen that smoking causes a significant elevation of the burden of particulate matter above that found in non-smoking areas. Since the particulate phase of tobacco smoke is implicated in irritant and other health effects, tobacco smoke is a widespread and detrimental component of air quality when it occurs. One feature of these studies that deserves note is the apparent localization of the distribution of tobacco smoke particles. Rather than contributing to an overall increase in the particulate loading of indoor air in a ventilation zone or whole building relative to the outdoor concentration of RSP, the particulate phase of tobacco smoke seems to become diluted or to react with surfaces and hence disappear from the recirculated air. This reactivity with surfaces in spaces has been observed in other studies such as those of Leaderer et al., (1986), and Offerman et al., (1984).

Measurement of Airborne Particles.

Many techniques are available to measure the concentrations and size distributions of particles (Lundgren et al., 1979). This discussion will summarize briefly the techniques that are used in the field to measure particle concentrations in buildings.

The most common technique used to determine mass concentration is to measure the change in weight of a filter after a measured volume of air has passed through it (Hinds, 1982). A typical RSP size filter collection method is comprised of a constant flow pump unit that draws air through a cyclone to segregate larger particles from those required for the sample. The airstream exiting the cyclone contains particles smaller than the cyclone's cutpoint which are then passed to a filter and are collected. The filter is removed after a recorded time interval and weighed. The increase in the filter's weight from the particles that have been collected divided by the known volume of air which passed through the system gives the concentration of particles in the air. Particulate matter retained on the filter can then be analyzed chemically if required.

Another technique that measures particle mass directly is the piezoelectric balance (Woods, 1979). Particles entering the piezobalance are charged by passing through a corona discharge, then impinge on a piezoelectric crystal. Particles sticking to the crystal change its mass and therefore its resonant frequency. An increase in mass of 0.005 ug changes the resonant frequency 1 Hz. The instrument is suitable for measuring masses in the range 50 to 5000 ug with an accuracy of ± 15% and a precision of ± 10%. One must be sensitive to the type of particles being measured to prevent spurious results. For example, liquid aerosols (tobacco smoke is an example) can revolatize and excape from the collecting surface.

Optical particle counters, commonly used in laboratory settings for several years (Whitby and Willeke, 1979) are now available commercially for field monitoring. These counters measure light scattered from individual particles as they pass through the point of focus of an optical imaging system. The intensity of the scattered light is a measure of the size of the particle. Therefore, these devices provide a measure of both particle number density and particle size.

<u>Control of Airborne Particles</u>.
Control of particles is best accomplished by:

- o Source removal

- Local exhaust
- Air cleaning
- Maintenance cleaning
- Ventilation for dilution

Source removal or at least isolation is probably the best method for dealing with particles from tobacco smoke. Surveys have shown that segregation of smokers to specific locations and restricting smoking to these locations reduces the overall particulate loading in nearby non-smoking zones and in the whole building to near ambient levels (Repace and Lowery, 1980; Turk et al., 1986). It can be argued that smoking of tobacco should be entirely banned from indoor public places. In lieu of that, isolation of smoking into areas removed from the general building populace seems to be useful. Local, exhaust-only ventilation in these areas should be an additional feature which serves to limit the non-smoker's exposure to tobacco smoke. The new revision of ASHRAE Standard 62 recommends an exhaust ventilation rate of 60 cfm/occupant for smoking lounges with exhaust-only ventilation. In instances of chemical dust contamination, such as carpet shampoo residues, source removal through complete cleaning was found to be effective. The same general philosophy can be applied to biological agents which have their sources indoors. This is especially true where furniture has become contaminated with microbial growth due to water exposure (Morey et al., 1984).

In situations where the building geometry or ventilation system may make the separation into smoking and nonsmoking zones ineffective, particulate air cleaners can be used to reduce the particle loading in the air. In contrast to the situation that exists for gaseous air cleaners, particle air cleaning technology is well-developed (ASHRAE, 1984; Offerman et al., 1985).

Whole-building ventilation is the basis of any general control strategy. The effectiveness of ventilation for whole-building pollutant control has been discussed extensively in two review papers by Fisk et al., (1984) and Fisk (1986).

Respirable Particle Sensitivity Analysis.

Since air from smoking areas is not always exhausted directly to the outdoors, it is returned with air from the rest of the building to the main air handling systems which partially dilutes it with outside air, filters it, and then distributes it throughout the building, including nonsmoking areas. Some smoke particles are filtered, or removed by other mechanisms (e.g. physical deposition, chemical transformation, coagulation), while many of the gas phase contaminants are unaffected. It is likely that these removal processes, along with dilution by the large building volumes, account for the comparatively low RSP concentrations in non-smoking areas even when smoking is allowed in certain areas of the building and the outdoor air is contaminated.

A relationship between smoking and RSP removal by filtering of the recirculated air has been examined by Turk et al. (1986). Their analysis quantifies the importance of filtration but shows that the RSP concentration is strongly dominated by the smoking rate of the building occupants.

More experimental work is necessary to refine and validate these conclusions. In particular, the other natural removal processes in smoking areas may be more important than assumed. Aggregation followed by deposition and plate-out, natural electrostatic precipitation, and other unidentified effects could be effective mechanisms for removing smoke particles from the air before it circulates into the remainder of the building. They could help explain the observation that RSP concentrations remain high only in the localized smoking areas.

Maintenance cleaning primarily applies to "housedust" and biological particulates. To avoid resuspension of RSP size dust particles general good housecleaning techniques, vacuuming, mopping, and dusting should suffice for most cases. For biological agents, especially those which may form colonies in the water of HVAC systems, a rigorous schedule of maintenance is required (Morey, et al., 1984). Biological agents such as colonizing fungi are nearby ubiquitous in the air in the form of viable spores. Once one or more of these spores has become associated with an appropriate substrate under conditions which permit growth new colonies can form extremely rapidly. This is much the same as the invasion of the human body by an infectious agent; only one viable particle in a susceptible location is required to start the process. Self multiplication then creates enough organic material to create a human health problem. Continued cleaning of the HVAC system may be required to keep the level of biological agents below that necessary to create an air quality problem. Chemical biocidal agents have not proven to be a long term solution to the problem of suppressing microorganisms in HVAC systems (Morey et al., 1984).

In summary, the solution to the problem of excess airborne particulates depends upon the source and type of particles. Source removal and isolation seem effective for smoking-related particles; cleaning and removal for biological agents.

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CRITERIA AIR POLLUTANTS

Standards.

The criteria air pollutants are those designated by the Environmental Protection Agency to have either long or short term exposure limits which must not be exceeded in outdoor air (CRF, 1985). Table 4-7 lists the air pollutants and the long and short term exposure limits. Note that these are standards for outdoor, not indoor, air quality.

Table 4-7
NATIONAL PRIMARY AMBIENT-AIR QUALITY STANDARDS FOR OUTDOOR AIR AS SET BY THE U.S. ENVIRONMENTAL PROTECTION AGENCY

	Long Term		Short Term	
Contaminant	Concentration ug/m^3	Averaging Time	ug/m^3	Time
Sulfur oxides, measured as sulfur dioxide	80	1 yr	365[a]	24 h
Particulate matter	75[b]	1 yr	260[a]	24 h
Carbon monoxide	--	--	10,000[a] 40,000[a]	8 h 1 h
Ozone	--	--	235[c]	1 h
Nitrogen dioxide	100	1 yr	--	--
Lead	1.5	3 mo[d]	--	--

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[a] May be exceeded only once per year.

[b] Geometric mean.

[c] Standard is attained when expected number of days per calendar year with maximal hourly average concentrations above 0.12 ppm (235 ug/m^3) is equal to or less than 1, as determined by Appendix H to subchapter C, 40 CFR 50.

[d] 3-mo period is a calendar quarter.

Carbon Monoxide.

Carbon monoxide (CO) is regulated in the environment because of its toxic effects. It replaces oxygen on the hemoglobin molecules in the blood thus reducing the oxygen carrying capacity. The EPA standard is based on the effects of CO upon persons with cardiac or peripheral vascular disease and possible effects on the oxygenation of skeletal muscles in normal persons during exercise (NAS, 1981). Carbon monoxide results from the incomplete combustion of organic substances such as fuels or tobacco. In large buildings without unvented or malfunctioning combustion appliances, the chief sources of CO are the outdoor air, attached parking garages, and smoking.

CO Concentrations.

Outdoor CO concentrations have been reported to be in the range of less than 1 to 7.9 ppm in a study of indoor and outdoor air quality within four California cities (Ott and Flachsbart, 1982). In a study of 12 large buildings in the Pacific Northwest, the 8-hr average CO concentration was above 2ppm at only three of the 12 outdoor sample locations (Turk et al., 1986). Both of the studies noted above involved comparisons of outdoor and indoor air quality in commercial buildings and the outdoor CO measurements were made at street level or near the outdoor air intake for the building.

Indoor mean CO concentrations in work places were reported, for a time-exposure study, to average 4.3 ppm on weekdays (Ziskind, et al., 1982). When the data is stratified into two groups -- smoking vs. nonsmoking work environments -- the smoking environment gave a mean of 4.7 ppm for 135 readings and nonsmoking workplaces had a mean of 3.8 ppm for 438 readings.

Indoor CO concentrations were less than 9 ppm at 204 of 210 locations based on a study by Ott and Flachsbart (1982) which included short-term measurements of CO concentration made with a personal exposure monitor in indoor public spaces including office buildings, restaurants, and other commercial settings. It was also found that the CO concentrations in these locations were relatively stable with time on any given day. Carbon monoxide concentrations were shown to be lower indoors than outdoors when doors were kept closed. Wind speed, seemed to influence indoor CO concentrations. On days with a wind speed of 10 to 15 mph, the indoor CO concentrations averaged approximately 50% of the concentration on less windy days (1.5 - 1.2 ppm vs 3.5 - 3.6 ppm). One possible explanation is that wind tends to decrease the outdoor CO concentrations in urban areas -- which in turn would lead to lower indoor CO concentrations. The exception to these relatively low indoor CO concentrations occurred, as might be expected, in parking garages where concentrations ranged from 17 ppm to 40 ppm.

A study in Salem and Portland, Oregon and Spokane and Cheney, Washington used an 8 hour integrated sampling technique to measure indoor CO in commercial and public buildings (Turk et al., 1986). In this study, the integrated samples were taken for the period when workers occupied a space and at several (1 to 7) indoor locations as well as at one outdoor location. In 126 individual indoor samples, only 36 had greater than 2 ppm of CO, the limit of detection. The highest CO concentration was 7.0 ppm. Two buildings with mean CO concentrations of 3.0 and 3.5 ppm had attached parking garages and this was suggested as the possible source of CO. In one case, where heavy smoking was reported, the sample contained 6.0 ppm of CO -- well above the outdoor concentration and the concentration at nonsmoking areas in the building. While the increased CO concentration, could not be directly attributed to the smoking, an elevated RSP concentration and no other identified CO source indicates that smoking was the most likely source.

In a specialized environment, a skating rink with gasoline-powered resurfacing equipment, up to 50 ppm of CO was reported (Spengler, et al., 1978).

Based on the available data, the indoor CO concentration exceeds the NAAQS standard of 9 ppm for 8 hour exposures only rarely in public or commercial establishments. Combustion sources such as gasoline-powered ice rink resurfacers or attached parking garages can lead to elevated indoor CO levels. The potential for CO contamination of the indoor air from parking garages loading docks, etc., is probably the most significant for most buildings (Bearg and Turner, 1986; Turk et al., 1986; Boelter and Monaco, 1987). Attached parking garages should be well ventilated, the air pressure within buildings at locations adjacent to parking garages or loading docks should be elevated to prevent the entry of combustion products. The outside air intakes of building ventilation systems should also be located well away from sources of combustion products.

Nitrogen Dioxide.

Nitrogen dioxide (NO_2) is a product of high temperature combustion. Its main health effect is respiratory irritation with a possible chronic effect of inducing lung damage leading to emphysema (NAS, 1981). Nitrogen dioxide is a widespread pollutant in urban atmospheres as a result of automobile exhaust emissions and other combustion process.

In many studies, NO_2 has been found in elevated levels in residences especially those with unvented gas, propane, or kerosene fired cooking or heating appliances. In large building studies, NO_2 has been measured rarely. As a result of a total exposure study, Quackenboss et. al. (1982) reported that indoor locations other than residences had a mean NO_2 concentration of 20.7 ug/m^3. Nitta and Maeda (1982) reported a mean office concentration of 29.3 ug/m^3 in a study in Tokyo. In a large study of commercial buildings in Washington and Oregon, with 33 buildings monitored for NO_2 at 245 sites, Turk et al., (1986) found that for all indoor sites the geometric mean concentration was 34 ug/m^3. Only two sites had values above the NAAQS standard of 100 ug/m^3. One building had a building average of 81 ug/m^3. This building has an underground parking garage and, at one measurement site, a moderately elevated CO concentration of 7 ppm. The parking garage is implicated as is the congested traffic around the building as a source of NO_2. Using the cumulative probability best fit line method it was estimated that only 3% of all sites measured in a similar sample would have concentration of NO_2 above the 100 ug/m^3 limit.

Several studies have examined smoking as a source of NO_2 in buildings (Good et al., 1982; Nitschke et al., 1985; Kim et al., 1986; Turk et al., 1986). Data indicate a small increase in average concentrations of NO_2 due to the presence of smoking. However, it is insignificant compared to the importance of outdoor air and unvented or poorly performing vented indoor combustion sources.

For 13 buildings which had measured outdoor concentrations of NO_2, the correlation coefficient between concentrations at indoor non-smoking areas and outdoor concentrations was found to be +0.92. Thus, in nonsmoking areas of commercial buildings, the indoor concentrations of NO_2 are highly dependent on the outdoor concentration.

Ventilation is a primary source of removal of gaseous pollutants except where the outdoor source dominates. In commercial buildings the outdoor air is often the dominant source of NO_2. In the case of NO_2, another removal process must be considered -- the reaction of NO_2 with indoor surfaces. Data from studies within residences indicates that the rate of NO_2 removal from indoor air by reaction may be comparable to the typical rates of pollutant removal by ventilation. (Traynor et al., 1985; Renes et al.,, 1985). Thus, ventilation is a less effective control measure for NO_2 than for many other pollutants. On the other hand, due to the process of NO_2 removal by reaction, indoor NO_2 concentrations will be lower than outdoor concentrations when there are no significant indoor NO_2 sources.

The problem of NO_2 pollution seems to be a small one in commercial buildings with the outside air as the dominant source. Restricting tobacco smoking to certain areas that are well ventilated may help to reduce indoor concentrations slightly. More importantly, one should prevent the transport of vehicular exhaust products to indoors using the same methods described earlier in the discussion of indoor CO.

Particles.

Particles, their origin and distribution are dealt with primarily in and earlier section. The present National Ambient Air Quality Standard for total suspended particles is exceeded frequently in indoor environments where tobacco smoking is permitted and more rarely in areas where it does not occur (Turk et al., 1986).

Particles in the respirable size range that do not result from smoking, such as airborne dust or biological agents, are also present in indoor air. However, no appropriate concentration standards are available. Morey et al., (1984) have suggested that a level of 1×10^3 viable microorganisms per cubic meter indicates that the indoor air is in need of improvement. Total suspended particulate standards for the outdoor air do not adequately deal with the health issues associated with particulate matter in the indoor environment. The size, chemical composition, and toxicity of particles in the indoor air may differ greatly from that of outdoor particles. In addition, particles from the various indoor sources may also differ substantially from the standpoint of the effect on human health. Particles act upon humans as irritants, odor sources, allergens, pathogens, and possibly carcinogens. It may be inappropriate to use a single standard, which limits the maximum mass of particles per unit volume, when the composition and health effects of different types of particles vary widely.

Sulfur Dioxide, Ozone, and Lead.

Three of the criteria pollutants, sulfur dioxide (SO_2), ozone (O_3), and lead (Pb) rarely have a significant effect upon air quality indoors in large, mechanically-ventilated buildings (NAS, 1981) because it is unusual to have a significant indoor source for these pollutants in large buildings. Sulfur dioxide is primarily a product of large stationary combustion sources that burn fuel containing sulfur. Sulfur dioxide contamination in commercial buildings has been reported by Melius et al. (1984). Ozone is photochemically produced from the mixture of chemicals in the outdoor air. It is a very reactive gas with a very short residence time in indoor air because of reactions with indoor surfaces. In the indoor environment, ozone may also arise from electrical equipment. Some photocopiers and electrostatic air cleaners are ozone producers. The Committee on Indoor Pollutants (NAS, 1981) indicates that indoor ozone concentrations as high as 235 ug/m^3, the one-hour exposure limit, have been measured and that typical indoor ozone concentrations are between 0 and 40 ug/m^3. Airborne lead may be produced from lead-based paint but this source is relatively limited in large buildings. Vehicular exhaust products are major sources of lead in the outdoor air (Spengler et al., 1984) and are also likely to be a significant source of lead in indoor air. However, lead is being phased out as a constituent of gasoline. Some data are available from a total exposure study on lead concentrations in residences (Tosteson, et al., 1982) which indicate that outdoor lead concentrations are generally higher than indoor concentrations. This is consistent with our expectation that the outdoor air is the primary source of indoor lead. Therefore, SO_2, O_3, and Pb do not appear to be a major concern in large buildings.

Controls.

The control of criteria pollutants relies on the same principles as other pollutant classes. A recent review is provided by Fisk (1986). 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. Indoor control measures are therefore based on modifying either the pollutant source strength or the rate of pollutant removal.

Examination of measured data leads to the following conclusions:

- Source control measures are generally more effective than pollutant removal in reducing indoor pollutant concentrations. Reductions by factors of 3 to 10 are not unusual with source control. However, unless the initial rate of ventilation is unusually low, it is generally impractical to reduce indoor pollutant concentrations by more than 50% by removal processes such as whole-building ventilation.

- The effectiveness of ventilation can be enhanced by techniques that increase the concentration of pollutants in the exhaust airstream to exceed the average indoor pollutant concentration.

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

Summary.

In summary, the indoor concentrations of SO_2, CO, NO_2, Pb and O_3 in commercial buildings are, in most cases, likely to be comparable to or lower than the outdoor concentration. Most commercial buildings do not contain significant indoor sources of these pollutants. However, in some instances, the indoor concentrations of these pollutants can be elevated. Most notably, air with high concentrations of these pollutants can be drawn into buildings from parking garages and loading docks, busy streets, and exhaust stacks that are located near the point where the HVAC system draws in outdoor air. The concentrations of RSP in commercial buildings frequency exceeds the National Ambient Air Quality Standard, in regions where smoking is permitted. Indoor particles are discussed in detail in a separate chapter. Research on criteria pollutants, other than RSP, in commercial buildings does not seem to deserve as high a priority as many of the research needs that are described elsewhere in this document.

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ODORS SOURCES AND CONTROLS

Introduction.

Odors have long been associated with "bad" or unhealthy air (NAS, 1981; McIntyre, 1980). Control of odors and this association with unhealthy conditions has been one of the primary reasons for the development, through experimental studies, of requirements for minimum amounts of fresh air to be delivered to occupants of work places. Odor detection by humans is a complex response dependent upon both the concentration of the odorant and its quality (i.e., the distinctive nature of the odor) as well as the sensitivity of the receptor. A visitor just entering a room may detect an odor whereas the occupants may not, but after some exposure to the air in the space the newcomer may acclimate and the odor becomes barely perceptible. Therefore, odor testing of a space is usually done by visitors rather than occupants (Fanger, 1986). Odors alone may not be the cause of sick building syndrome. However, they may be important indicators of an underlying problem. Alternatively, the existence of a particularly disagreeable odor in the workplace atmosphere may contribute to a feeling of illness or unease which can become a factor in a sick building event.

Odor Sources.

Sources of odors are common in indoor spaces and interact to produce a highly complex result which may not resemble any of the constituent odors if examined in isolation (NAS, 1981). The chief sources of indoor odors are:

- Outdoor air brought into the building
- Bioeffluents from human occupants and microorganisms
- Building materials and furnishings
- Consumer or maintenance products
- Cooking
- Tobacco smoke

Outdoor Sources.

Outdoor odors are often the result of industrial processes or vehicular traffic and these may dominate the indoor air odor spectrum where their outdoor concentration is high. The range of possibilities for industrial sources is very high. Odors from vehicular traffic are usually quite distinct and when detected indoors are evidence of contamination of the ventilation air by this source. Since vehicle exhaust is also a source of several criteria pollutants, i.e., CO and NO_2, exhaust odors indoors is evidence of a possible serious air pollution problem. Some outdoor odors may have a positive psychological effect upon humans and yet are considered dangerous pollutants at higher level concentrations (NAS, 1981). Ozone in particular is regarded as a deodorizer even though at higher concentrations it has a pungent odor and is regulated as a pollutant.

Indoor Sources.

Human effluents are well known sources of indoor-generated odors. These effluents may come from the exhaled breath which contains a broad spectrum of volatile organic compounds (VOC) (Wang, 1975; Wallace et al., 1985). These VOC may arise from the normal processes of metabolism or as a release of VOC taken in through normal respiration or via drinking water containing these chemicals. Most of the VOC studied in exhalation tests are suspected toxic or carcinogenic compounds where the human body exposure to the chemical was the object of the study. They may also contribute to the odor component as may other compounds not reported.

Metabolic wastes from humans are also released via the skin during perspiration; many of the odors associated with humans arise from this source. These occupant-generated odors were the basis for the original large-scale studies at Harvard that led to ventilation requirements in buildings (Yaglou et al., 1936; Cain et al., 1983). Some odors from humans arise from a complex of fatty acids and other compounds continuously released from pores of the skin.

Another source of odors of biological origin can result from colonies of microorganisms which have invaded building spaces, duct work, furnishings, or the HVAC system. Musty/moldy odors which arise from organic material after exposure to water or from stagnant water are usually due to the metabolic byproducts of fungi which have colonized these substrates. As such, they may be indicative of a potentially dangerous infestation of allergy-inducing organisms (Morey et al., 1984).

Building materials, especially when new, are the source of chemical or plastic odors (NAS, 1981; Berglund et al., 1982, Molhave 1982). In a study of solvents emitted from building materials Molhave (1982) found that of 52 compounds studied, 30 percent were considered odorous with a threshold less than the average concentration determined from a model room.

Consumer or maintenance products introduced into workspaces may, in part, be used for the suppression of an existing odor, i.e., air fresheners. These compounds may interact with existing odors to create a pleasant odor or merely mask the existing disagreeable odor (NAS, 1981). Some other maintenance products contain a built-in odor component to cover the potentially unpleasant odors which result from their manufacture. These can leave a lingering deodorant effect after their application (NAS, 1981).

Cooking odors have been ranked only after human odors and tobacco smoke odors as the most common unpleasant odors present in buildings (NAS, 1981). Cooking odors range from the pleasant, fresh-baked pastry, to the very unpleasant, "greasy, cooking odors". As a component of public buildings, they are fairly limited except in areas where restaurants or grills are in operation. Usually areas in public buildings where cooking is in progress have an exhaust-only ventilation system which restricts the odors to the immediate area. However, reentrainment of air exhausted from range hoods or uptake by the ventilation system of an adjacent building could produce a situation in which cooking odors become a source of a whole-building indoor odor complaint.

Tobacco smoke odors are a result of a wide spectrum of compounds released during the combustion of tobacco, paper, and additives (NAS, 1981; Cain et al., 1983). As many as 3,000 gaseous components of tobacco smoke have been identified (NAS, 1981). As a nuisance, it ranks first in terms of odor problems. Recent studies of the persistence of tobacco smoke odor indicate that visitors to a space perceive the odor to be stable, i.e., it decreases in time at a rate expected for a non-reactive pollutant (Clausen et al., 1985). The study also showed that removing smoke particles from the air did not reduce the odor intensity associated with tobacco smoking.

Table 4-8
TABLE OF SOME ODOROUS COMPONENTS AND SOURCES

Acrolein	Tobacco Smoke
Acetone	Tobacco Smoke, Human Breath, Building Materials, Consumer Products
Fatty Acids	Human Perspiration
o-, m-, p- Xylenes	Building Materials, Outdoor Air
*-Pinene	Building Materials, Outdoor Air
Limonene	Building Materials, Outdoor Air, Cleaning Products
n-Hexanal	Building Materials, Outdoor Air
Methylstyrene	Building Materials, Outdoor Air
Ozone	Copiers, Outdoor Sources
Methanol	Human Breath, Consumer Products, Cleaning Products
Formaldehyde	Building Materials, Air Fresheners, Tobacco Smoke

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(NAS, 1981; Berglund et al., 1982; Molhave, 1982, Hodgson et al., 1986)

Odor Measurement

Given the subjective nature of the human response to odors, methods used to describe odor quality and to quantify odor intensity are based upon human comparisons to a set of standards which have been empirically tested (Cain et al., 1983). The human reaction is apparently non-linear, not strictly additive, and very susceptible to accommodation (NAS, 1981; Cain et al., 1983). Several test methods are in use. One method uses a split air stream to divert a portion of the air to a recipient for evaluation while a gas chromatograph/flame ionization detector produces a record of the amount or odorous compound present at the same time (NAS, 1981; Duffee and Jahn, 1981; Turiel et al., 1983). This method is known as the GC/odorgram technique and is used for finding individual components of an odor spectrum. Another method usually used in conjunction with an odorgram is the forced-choice olfactometer (Dravnieks and Prokop, 1975). In this method panelists (chosen from outside the building to be tested) judge the number of dilutions, with fresh air, which are required to bring a sample of the odorous air of interest to a level when only 50% can detect the odor. A third method uses a binary dilution olfactometer based on dilution of concentrations of butanol to match the intensity of the perceived odor from the sample and the butanol dilution (Marks, 1974). A critique and evaluation of the reliability of the latter two methods is given in the report by the National Academy of Sciences (NAS, 1981). Due to the large number of possibilities of combinations and percipient interactions with odors the acceptability criteria are based upon a panel of odor judges. A common criterion is that of a panel of 20 outside judges, 80% must find the odor in a space acceptable (ASHRAE, 1981). This acceptability criterion based upon the sensations of a panel of nonaccomodated visitors may be sufficient to judge the general quality of the air but there is not a direct correlation between the odor perceived and health effects, the panel cannot be expected to make a judgment about the health effects of the air.

Another aspect of the psychological interpretation of odors is that of mood. If the perception of odors as unpleasant or associated with unhealthy conditions is true among most building occupants, then a building which has an unpleasant smell could have created a mood which contributed to an episode of sick building syndrome. Whether the actual odors in question were the cause of the episode of "sick building syndrome" could become lost if a false relationship between the odors and the outbreak were established because the odors were unpleasant and identified with unhealthy conditions (Engen, 1984).

Control Of Odors.

Treatment of a building which has an odor problem should take into account the source as well as the recorded presence of an odor. The steps to be followed to reduce excess odors in buildings are the same as those used for any indoor pollutant: source control, local ventilation, and whole building ventilation.

Source elimination is an obvious solution to the problem of tobacco smoke odor. This solution is finding wider acceptability in the United States. A compromise often reached with building occupants who use tobacco is the restriction of tobacco use to specific locations in the building. This will be most effective if the ventilation systems in the areas restricted for smoking are separated from those used for the non-smoking areas. In this case the system is operating as a type of local ventilation system. Recirculation obviously defeats the desire for separation of smoking and non-smoking areas.

Smoking imposes a major energy load on the building if the odor irritation from cigarette smoking is to be reduced to the 20% dissatisfied level for visitors. Fanger and Berg-Munch (1983) have shown a monotonic relationship between odor intensity in a space and percentage of dissatisfied visitors to that space. Cain et al., (1983) have shown that this relationship holds both for spaces in which smoking is allowed and also for those in which it is forbidden. In chamber tests in which no smoking occurred, the ventilation required to reduce body odor to acceptable levels was 7.5 l/s per occupant (16 cfm/occupant). Smoking on the part of 10% of the building occupants changes the ventilation required to achieve 80% acceptability to 27 l/s per occupant (57 cfm/occupant), an increase of 250%.

Other odors which arise from cooking should be treated by local ventilation methods to exhaust the odors to the outdoors. Consumer and maintenance products should be released into the indoor air with caution. Their associated odors are usually of a transient nature due to their a periodic application. Maintenance schedules could be arranged so that applications occur only during periods of low building occupancy and thus the major effect of their odors would be dissipated before the workforce arrived either after a weekend or in the morning.

Outdoor odors can be drawn into the building due to poor placement of the outdoor air intakes of the HVAC system. In instances of transient odor problems due to predictable vehicle traffic into garages or parking areas contiguous with the building, the HVAC could be rescheduled to 100% recirculation during those periods. Where a problem persists relocation of the HVAC intakes may be required. Altering the use pattern of vehicles might also contribute to a solution. For instance, drivers of service vehicles should not be allowed to leave them idling in parking areas during delivery or pick-up times regardless of how short these may seem.

In summary, the contribution of odors to sick building syndrome may be characterized as either direct (causing a physical response in the odor percipient) or as indicators of an underlying problem (moldy smells associated with allergy-inducing fungi). A third effect is the psychological component where odors may cause a heightened awareness of an unpleasant condition and contribute to a general perception that an environment is poorly suited to a worker's health. Odors are present everywhere indoors and their general control is best achieved by dilution to below threshold levels by fresh air.

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RADON IN COMMERCIAL OR PUBLIC BUILDINGS

Introduction.

Radon is an inert gas released to the atmosphere from the radioactive decay of radium, a member of the ^{238}U decay chain. Since its parent element ^{238}U is ubiquitous in soils derived from rock, radon is a natural component of the air outdoors. Ambient radon concentrations range from 0.1 to 0.4 pCi/L with a mean of 0.25 pCi/L. This is lower than the published means for United States residences of 1.1 pCi/L and very close to means usually encountered in larger mechanically ventilated buildings (Nero et al., 1985, Gesell, 1983, Cohen et al., 1984, Turk et al., 1986).

Health Effects.

High radon concentrations are of concern because of health effects caused by its progeny, especially ^{218}Po and ^{214}Po. These radioactive isotopes are not inert and therefore may attach to respirable airborne particles. Upon entry into the human respiratory system these particles may lodge in the bronchi or lungs and become the site of the decays of the progeny. The alpha particle energy given off by these decays is suspected to have a role in the induction of lung cancers (Nero et al., 1985). Free, unattached molecules of these isotopes may also enter the respiratory spaces and become attached to the surface cells of any portion of the bronchial tubes or alveolar sacs. This association between high radon concentrations and incidences of lung cancer was first noted in mines where extremely high radon concentrations can occur and worker exposure is consequently high (Ludewig and Lorenser, 1924).

Radon and its progeny have a term effect and the results of exposure to high concentrations may not become apparent for years. Because there is no sensory response to radon it is not associated with the acute symptoms usually associated with "sick buildings". It has become apparent, however, that radon concentrations in homes are so high that it may be the dominant residential pollutant; therefore, investigations of commercial and public buildings should be conducted in those areas where radon concentrations in residences are known to be high.

Sources

Efforts have been made to equate ventilation rates in either specific rooms or buildings, or whole buildings with the radon concentrations (Abu-Jarad, and Fremlin, 1982, Turk et al., 1986). Generally there is no clear correlation between the radon concentrations and the ventilation rate in multistory buildings. However, basement readings tend to be higher than those found on the upper floors

(Abu-Jarad and Fremlin, 1982, Turk et al., 1986). This increased likelihood of higher radon concentration in basements or the lowest floor, where construction is of the slab-on-grade or crawl space type, is apparently due to the transport of high concentrations of radon in soil gas into the spaces which have a contact with the soil.

The entry of soil gas into residences is dominated by pressure-driven flow processes in residences (Nero and Nazaroff, 1984). Studies in New York, NY; Salem, OR; Spokane and Cheney, WA; and Birmingham, UK, have shown distinctly higher radon concentrations in basements of commercial buildings (George, 1972; Abu-Jarad and Fremlin; 1982, Turk et al., 1986). In one especially interesting case a building showed a mean radon concentration of 7.4 pCi/L during the winter (minimum outside air entry) ventilation regime (minimum outside air entry) (Turk et al., 1986). This building had exposed soil and stone in the basement and used air for ventilation that was drawn from stone or concrete lined utility tunnels. In the summer the whole building average concentration dropped to 3.0 pCi/L, still well above the recorded public building mean value for the Spokane - Cheney, WA area. (1.2 pCi/L for 18 study buildings, Turk et al.,1986). Another nearby building in Cheney, WA had a building mean concentration of only 0.7 pCi/L(Turk et al., 1986).

Other sources of radon have been examined in both single family dwellings and apartment buildings (Nero et al., 1985). Outside air could possibly account for 0.1 to 0.4 pCi/L based on results published for normal air over the continental U.S. (Gesell, 1983). In areas of high background as much as 0.75 pCi/L of radon could be introduced into a building from the outdoor air (Gesell, 1983). Most mean concentrations reported in buildings occur in the range 0.15 pCi/L to 0.7 pCi/L (Table 4-9). Building materials have been implicated as a source of high radon concentrations where the component materials were discovered to be very high in ^{226}Ra. Generally, however, the masonry portion of a building has a much lower Rn emanation rate than do soils (Nero and Nazaroff, 1984). Ordinary U.S. concrete has been reported to have radon flux rates of 0.02 to 0.06 pCi m^{-2} s^{-1}. Water from public sources usually has enough residence time at the surface prior to its entry into a building to have a much reduced radon concentration and is therefore thought to contribute little to the airborne radon concentration (Nero et al., 1985). Nero et al., (1985) report that in residences served by public water supplies release of radon from water contributes approximately 3% to the average indoor concentration. In commercial/public buildings this contribution is probably much less since there are fewer processes releasing it into the air.

Flux rates of radon from soil vary depending upon the soil moisture, temperature, and physical parameters. These flux rates have been measured to range from 0.005 to 1.4 pCi m^{-2} s^{-1} (Nero and Nazaroff, 1984).

These four sources, air, water, earth and building materials are the major sources of indoor radon. Since commercial building mean airborne radon concentrations fall within the ranges given for outdoor air except for basements, where intimate contact between the walls and soil occur, the outdoor air is likely a major source. In the case where there are known large soil and rock-surfaces exposed to the air circulation system, the direct flux of radon from soil gas probably accounts for the high radon concentration (Turk et al., 1986).

Concentrations

Table 4-9 is a summary of concentration measurements in commercial and public buildings in the United States. There have not been many measurements reported. In only one case is the building mean value above 3.0 pCi/L; that a building reported by Turk et al. (1986) described above that contained an average concentration of 7.4 pCi/L.

There is no standard for indoor radon in the United States. The National Council on Radiation Protection and Measurements has recommended that remedial action is advisable if exposure to radon daughter products for an individual exceeds 2 WLM/yr (NCRP,1984). With appropriate assumptions this translates to a recommendation for remedial action in existing buildings if the radon concentration inside a building exceeds 8 pCi/L. It might be argued that this limit is too low for a commercial or public access building in which the general public spends at most 8 hours per day. On the other hand, there is strong evidence that buildings with high radon concentrations tend to be clustered geographically. Consequently, the prudent position for a standard is to assume that the building occupant may experience the same concentration in other buildings he or she occupies during the 24-hour day and therefore establish the same standard for each existing building. As Table 4-9 indicates, none of the buildings sampled to this point have had radon concentrations observed which exceed the NCRP recommendation. The EPA has issued a guideline for indoor radon in residences recommending that remedial action be considered whenever the concentration in the residence exceeds 4 pCi/L. The arguments above for the NCRP recommendation translate to this guideline as well.

TABLE OF RECORDED RADON CONCENTRATIONS IN COMMERCIAL AND PUBLIC BUILDINGS. TABLE 9.

CITY/BUILIDNG	DATE	CONCENTRATION BY FLOOR (pCi/l)																				BUILDING MEAN (pCi/l)	NUMBER (No. Bldgs Unless Noted)
		B	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	20	23		
Boston MA	1972																						
H.S.P.H (4)			0.02																				N = 1
S.O. (4)		0.06					0.09							0.11									N = 1
H.C. (4)				0.06																			N = 1
J.F.K.		0.08					0.03													0.06	0.04		N = 1
Birmingham UK	1982																						
Mason (5)				0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.2	0.3	0.3										N = 1
High(A)		3.0	0.2	0.2	0.3	0.5	0.6	1.5	-	0.8	0.8	0.4	-	0.7	-	1.1							N = 1
(B)		2.3	0.4	0.2	0.4	0.4	0.2	0.2	0.1	0.2	0.1	0.1	0.1	0.1	0.2								N = 1
(C)		-	0.5	0.2	0.1	0.1	0.5	0.8	0.2	0.3	0.2	0.1	-	0.1	-	0.2	-	0.1	0.1				N = 1
Spokane WA	1984-85	1.8	1.2	0.7	0.6	0.5	1.6	0.7	0.7	0.7	0.7	≥	-	0.3								1.2	N = 18
Portland OR	1984-85	0.7	0.8	0.6	0.4	0.1	0.5	0.4	0.4	0.4	0.4	≥	-	0.6								0.7	N = 11
Salem OR	1984-85	0.7	0.1	0.4	0.2	0.2	0.1															0.3	N = 9
Cheney WA	1985																						
Building #33			0.9	0.7	0.5																	0.7	N = 1
Building #32	Winter	8.5	9.2	5.5	7.8																	7.4	N = 6(1)
	Summer	4.6	4.9	1.3	2.8																	3.0	N = 6(1)
Raleigh NC	1968-72																					1.8-3.9	N = 1
New York NY	1972	6.0					0.3																N = 1
Las Cruces NM	1983		1.2	1.0																			N = 1
Pitsburgh PA	1982-83																						
Univ.	Summer																					0.34(3)	N = 115(2)
	Winter																					0.32(3)	N = 122(2)
	Spring																					0.45(3)	N = 79(2)
Univ.	1982																					0.60(3)	N = 40(2)
College	1982																					0.54(3)	N = 121(2)
Hospitals																						0.43(3)	N = 32(2)
Shopping Cntrs																							
"Cool"	1983																					0.33(3)	N = 100(2)
Spring	1983																					0.25(3)	N = 100(2)
Summer	1983																					0.38(3)	N = 108(2)
Oakland PA	Spring																					0.15(3)	N = 35(2)
DnTwn Pittsburg																							
Offices	Summer																					0.44(3)	N = 51(2)
Stores	Summer																					0.40(3)	N = 45(2)

(1) N = No. of measurements averaged for whole bldg.

(2) N = No. of measurements averaged for whole catagory

(3) Geometric Mean

(4) Concentrations based on reported ^{218}Po with ^{222}Rn/^{218}Po = 1.12

(5) Concentration reported mWL converted F = 0.5 0.2 pCi/l = l mWL

Measurement techniques for airborne radon gas take three common forms. A passive integrating method based on counting the number of alpha particle tracks left on a special plastic blank is commonly used where long term continuous exposure to radon is suspected. This method, the track-etch method, is possibly inappropriate in public buildings where exposure to radon is sporadic and associated with changes in ventilation rates based upon occupant demands for air conditioning (Cohen et al., 1984). In public or commercial buildings occupancy occurs usually during normal weekday working hours 0800-1700. Ventilation systems are typically operated on the basis of occupancy. During low occupancy, reduced ventilation periods, radon concentrations tend to rise. During high occupancy, ventilated periods, the outside air would lower the radon gas levels. A passive full time monitor will record elevated levels during non-occupied hours which contribute little to human exposure.

Active monitoring systems may be used intermittently such as during occupied periods, or as full-time systems to record fluctuations due to changing indoor environmental conditions. Active systems usually operate by drawing air at a known rate through a filter to remove existing radon progeny and then allowing a certain time period for radon to decay to create a known radon to progeny ratio. The subsequent decays are measured in a calibrated scintillation cell.

Grab samples are frequently used where time or economic constraints require numerous samples to be made. Cohen et al. (1984) gives an excellent discussion of the difficulties encountered in conducting a large survey for radon. Grab samples are tested by allowing radioactive equilibrium to become established between radon and its progeny after filtering, then measuring the decay activity in a calibrated scintillation cell. Periodic grab sampling has the drawback of limited sampling in time and space. Clearly the most complete method for conducting a radon sampling program would be to establish continuous monitors at several locations in a building to establish both temporal and spatial variations then using time and volume weighted averages to establish the dynamic behavior of radon concentrations throughout the building.

Control.

Among the studies conducted in large buildings only one building has been found to have a significantly elevated Rn concentration (Turk et al., 1986). Therefore no attempts have been made to develop techniques to alleviate Rn problems which might arise in large buildings. In houses, the usual remedy is to prevent the entry of soil gas into the building or to vent the soil gas to the outdoors before it enters the occupied spaces. Variations on these ventilation schemes would be the first approximation to test in dealing with radon in public buildings should the necessity arise.

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Section 5
HUMAN FACTOR CONSIDERATIONS

PHYSICAL FACTORS

Background.

Physical factors including temperature, humidity, air velocity, light, and noise are not often considered as pollutants. However, these factors influence office building environments and may be a source of complaints leading to sick buildings syndrome reports. These factors, which are pollutants in the sense that they may be the cause of a reported disorder or illness or a contributing factor which heightens the occupant's state of discomfort in the presence of chemical pollutants, are discussed in the following paragraphs.

Air Temperature, Thermal Radiation, Humidity, and Air Velocity.

Humans produce heat at a rate proportional to their consumption of oxygen and exchange heat with their surroundings by convection, radiation, and due to evaporation of body fluids. Indoor environmental parameters have a strong influence on the rate of heat exchange. Heat gain or loss by convection is a function of air temperature and velocity. Heat exchange by radiation depends on such environmental factors as the temperature of indoor surfaces and, if the subject is near a window, outdoor environmental conditions. The rate of heat loss due to evaporation of body fluids is a function of air temperature, air velocity, and humidity. Clearly, it is the combination of the environmental parameters mentioned above that influences thermal comfort. Control of air temperature, alone, does not ensure thermal comfort. Of these environmental parameters, humidity generally has the smallest impact on thermal comfort since, at normally-comfortable air temperatures, changes in relative humidity in the range of 30 to 85%, are scarcely perceptible by humans (Givoni, 1976).

An important issue is the degree to which thermal comfort is a problem in commercial buildings, leads to complaints, and contributes to the sick building syndrome. One relevant consideration is that variations between individuals make it impossible to provide a thermally uniform environment that is comfortable for all individuals. In fact, the comfort conditions specified in the International Standard on Thermal Comfort (ISO 7730) are expected to be fully acceptable to only

80% of all individuals (Fanger, 1984). Therefore, some dissatisfaction with thermal conditions should be expected in virtually all large buildings. Allowing for individual control of the thermal environment surrounding each individual might possibly eliminate this dissatisfaction.

Canadian workers were recently given the opportunity to control their local environment in a special work station designed for open plan offices (Kaplan and Mill, 1986). The work station, called FUNDI (Functional and Diagnostic research tool), contains a fan, heater, light source, and flexibility of orientation. Occupants rated the FUNDIs more positively than other types of open-plan work stations. Users benefited from their controls and used them when they perceived a need to adjust their local environment. By monitoring the use of the occupant's fans those conducting the study observed occupant dissatisfaction with temperatures above 24 C and CO_2 concentrations above 700 ppm.

Thermal discomfort is often mentioned in verbal presentations and papers as an important element of the sick building syndrome. However, data to support this assertion is largely unavailable. Some interesting data were obtained in a recent investigation of a sick building by one of the authors (JRG). In this building with 550 occupants, 366 complaints were registered during the first five months of occupancy and 127 of these complaints were about ventilation or indoor air quality. A majority (77%) of the 127 complaints were that the air was "too cold" or "windy". The second largest category (23%) of the 127 complaints was that the air was "too warm" or "stuffy". Therefore, in this particular building, thermal discomfort appears to be a major source of complaints. It was noted that a frequent response to the complaints was to adjust and/or block various supply air diffusers in order to restrict air supply. Such responses would be expected to lead to locally reduced ventilation and increased concentrations of indoor generated pollutants. Due to a complex set of factors and events, this building was evacuated three times. Indoor air quality complaints were recorded during one of these evacuations. The most severe complaints were from occupants located in regions of the building from which a disproportionate fraction of the original 127 complaints had arisen. These data suggest that prior thermal discomfort contributes to episodes of the sick building syndrome perhaps because of increased stress or awareness of problems or because thermal discomfort led to reductions in ventilation. Additional data are required before conclusions can be drawn.

Another issue regarding one of these physical parameters -- humidity -- is the degree to which low humidity causes irritation of the skin and mucous membranes or simply a feeling of dryness. McIntyre (1980) reviews this issue and concludes that there is strong evidence of irritation and feelings of dryness, induced by low humidity, only when relative humidities are below 20%. We expect that it is uncommon for the indoor relative humidity in mechanically ventilated buildings to be less than 20% (see Turk et al., 1986).

Light.

Light, as a pollutant in sick buildings, has been studied little, and the relationship between the spectral composition of light and irritation or discomfort has been studied even less. Lighting standards have been established to ensure a certain minimal illumination for work performance. Visible radiation is reported to have an effect upon comfort and a sense of well-being (NAS, 1981). Excess light or badly placed light may cause discomfort and contribute to eye strain and fatigue. These effects result from annoyance with and attempts to adjust to light intensities beyond those for which the eye is adapted. Stray light may also reduce the contrast necessary for concentration and require increased effort leading to fatigue. As eye fatigue, irritation, and dryness are frequently encountered symptoms of the sick building syndrome, lighting factors should not be ruled out as direct contributors to this condition. Overall levels of illuminance may be within the required limits but poor work or light source positioning may effectively interfere with the general illumination level and lead to stress.

It has been shown that in some cases changes in light can lead to depression in a clinical sense (Hellman, 1982). Wurtman (1975) concluded that light may have a distinct effect upon human health.

While lighting may not lead directly to the condition of sick building syndrome it may be an interacting factor either in its spectral distribution or intensity at work levels.

Noise.

Noise as a cause of complaints in the sick building syndrome has not been directly studied. There is however well documented evidence that sound can influence the human responses as to the suitability of an environment (NAS, 1981). Maximum sound intensities are regulated to prevent severe effects (EPA, 1974). Even in environments where sound levels are below those believed to have potential direct health effects, some conditions can arise where sound intensities interfere with speech and reduce productivity (NRC, 1975). As has been pointed out, any stress-inducing situation may contribute alone or in conjunction with other agents in creating an environment in which building occupants become less tolerant of further stress, and health and productivity may suffer as a result.

JOINT EFFECTS OF POLLUTANTS AND PHYSICAL FACTORS

Some pollutants of either a physical, biological, or chemical nature may act in concert with one another to produce a complaint situation when either alone would not. Several of these interactions have been documented:

- humidity - smoke irritation,
- humidity - air velocity - air temperature - thermal radiation,
- biological agents - humidity,
- formaldehyde - temperature - humidity, and
- tobacco smoke particles - volatile organic compounds.

Many more subtle interactions than these may exist and have not yet been discovered. For example, there is a growing suspicion and some testing of the potential interactions of VOC which occur at low concentrations individually and totally but which may have an effect that is greater than expected (Molhave et al., 1984). The interactions between humidity, air velocity, air temperature, and thermal radiation were discussed in a previous section, the other interactions are discussed briefly below.

Humidity is a factor that affects the severity of irritation due to tobacco smoke. Eye and nose irritation due to tobacco smoke have been shown to be most severe in warm, dry air and are reduced by an increase in humidity (NAS, 1981). The interaction of humidity and biological agents is a more direct one. Organisms are dependent upon water for establishment and growth. Excessive water vapor, usually above 70% relative humidity, is necessary for the growth of molds on indoor organic substrates. Above that level of humidity, microorganisms can thrive and multiply to the point of becoming an indoor health hazard (Morey, 1984). Moisture levels do not have to be high throughout the building for mold growth; mold can grow at locally humid or wet locations. Extreme dryness, on the other hand, may produce irritation due to parched skin and mucous membranes and may even reduce the occupant's resistance to bacterial infection (Givoni, 1976).

Tobacco smoke has both an immediate irritating effect upon the eyes and mucous membranes of most humans, and an unpleasant odor. The irritation has been shown to result from both the gaseous and particulate phase with the particulate being the dominant irritant (NAS, 1981). A secondary effect of tobacco smoke in enclosed spaces is its lingering influence on the odor of the space. This lingering odor is due to the release of volatile organic constituents from aerosol droplets that have adsorbed to surfaces. While this lingering odor is not strictly a joint effect of pollutants and/or physical parameters, it is a complex result which seems to extend the effects of the pollutant over time.

Formaldehyde is rarely found in concentrations above guidelines in public buildings. Formaldehyde concentrations depend on physical parameters which also have an effect on thermal comfort. Formaldehyde is emitted from sources at a rate which depends upon the temperature, humidity, and ventilation rate (Meyer and Hermanns, 1985).

There are probably more interactions between pollutants and between the physical environment and pollutants where the coexistence of the two or more states creates a problem which might not become apparent with only one condition.

ERGONOMIC FACTORS

Problems arising from indoor air quality deficiencies may well be increased in severity and scope by unpleasant, uncomfortable, or crowded conditions which exist in the work environment.

Fatigue which results from ill-designed office furniture has been mentioned as a stressful factor in work environments. Stress due to overcrowding, poor lighting conditions, and excess noise from co-workers or the mechanical systems of the building can create an environment which is conducive to the origin or spread of dissatisfaction. Such dissatisfaction may well be a factor in increasing the severity of an outbreak of sick building syndrome. It is generally accepted that fatigue and stress do contribute to a sense of ill health which may add to an existing air quality problem.

PSYCHOSOCIAL FACTORS

Psychosocial elements may contribute to the sick building syndrome and are often used as an explanation for complaints when no direct cause can be found. One of the severe forms of a psychosocial expression of illness is commonly called "mass hysteria", a psychogenic illness (Kreiss and Hodgson, 1984). Psychogenic illness should be diagnosed only under very specific and rigorously defined conditions. Subjective symptoms such as hyperventilation and social features such as chains of information transmission must be considered in the diagnosis. Other factors which may indicate whether an illness is psychogenic are the distributions of age or sex of those with symptoms. As Kreiss and Hodgson (1984) observe, the necessity for an air quality investigation of a building may arise from concerns generated by the occupants which are based upon information received from outside sources such as the media. Reports of illness in a similar situation may focus people's attention on the possibilities of problems from indoor pollutants. This is a psychosocial element, which may be ill founded about the existence of a real problem. However, if this element is not dealt with openly by the responsible management it could lead to complaints. Other studies have dealt with the social features of relieving employee anxiety where a real problem once existed but has been corrected (Messite and Baker, 1981).

In dealing with air quality problems in office spaces, the possibilities of stressful environments, psychosocial in origin, coupled with a real problem must be considered. At present, the effects of low pollutant levels and pollutant interactions are not well understood. The interactions between stress and low pollutant levels are completely unknown. Colligan (1981) has pointed out that stressed individuals may attribute their illness to the office environment. Selye's (1956) general adaptive syndrome -- the physical response to extended stress -- is frequently involved as a human component in the reaction to air pollution. In this syndrome, stress has a general nonspecific effect upon the body which contributes to a sense of malaise or ill health. An additional contribution to stress from the environment may lead to a situation where the individual's or group's tolerance is exceeded and thus a sick building complaint condition comes into being.

An example of the interactions between psychosocial factors and physical factors is provided in a report on an office where measured levels of pollutants were within acceptable levels and continued outbreaks of nausea, dizziness, and fainting were reported. Medical examination and environmental testing produced no evidence of disease or measurable hazard. The occupants had previously complained of a strange odor. A second outbreak was reported and measurements proved negative. Following this occurrence the workers were told that their illness was a result of a transient condition and work resumed with no further outbreaks.

Since the initial appearance of the odor was unrecorded by any monitoring equipment and the environment was considered somewhat stressful, it is probable that a combination of the two factors led to the reported illness (Colligan, 1981). Many similar situations may have led to outbreaks of building illnesses that were never fully explained.

As Melius and associates (1984) pointed out, the air quality expert is frequently not called in until a crisis situation exists. If the crisis was caused by a transient event, such as an airborne agent, the expert may arrive too late to identify the airborne agent and a suspicion of psychosocial illness may arise. Another aspect of the psychosocial dimension of the perception of unhealthy conditions in the work place is the political nature of the workers' organization. Perceptions of indifference to complaints, extreme dissatisfaction with work, and office gripes, could lead to health complaints magnified by stress that is induced by worker - management discord (Carlton-Foss, 1984).

In summary, stressful conditions in the workplace may well contribute to an air quality problem related to sick building syndrome. Many physical and personal features may contribute to the stress. In other cases, stress plus transient conditions may interact to cause an outbreak which may then appear to be entirely psychosocial since the problem pollutant may no longer be present when measurements are made. Mass hysteria or true psychogenic illness, however, should be diagnosed under very strict conditions.

It should be pointed out that social exchanges of information of potential air quality problems can help to identify and solve problems. In an industrial case, employees exposed to dibromochloropropane discovered its effect, male sterility, through just such interactions (Turiel, 1985).

PRODUCTIVITY ISSUES

Any case where sick building syndrome is serious enough to be reported has productivity implications. The productivity losses due to exposure to co-workers smoke may be wide spread. In the Repace (1981) report, 10,000 workers were interviewed and at least 50% of them reported reduced productivity due to smoke exposure. With an estimated 10% of office workers smoking at work at any one time, the potential for loss of productivity in office environments where smoking is uncontrolled is huge.

The incidence of outbreaks of building related illness in which the severity causes lost time due to evacuation of the space or building is less widespread but also contributes to work time loss. Morey et al. (1984) report on one building in which 100 occupants exposed to biological agents became ill. Eventually the entire building was evacuated permanently. The loss of productivity occurs not only through the effect on workers but due to the requirement for corrective efforts and in investigation time. In some cases, expensive replacement of HVAC components or furnishings are required, each of which is a disruptive feature in any work space and another source of reduced productivity.

As an example of the reductions in productivity from a sick building episode, one can examine the cases of respiratory distress due to carpet shampoo residues. There is the loss due to the illness of the workers, loss to study the problem, and the expense of clean-up procedures.

This situation of loss due to illness may be compounded many times in the case of the building related (spread) airborne viral infections. It has been estimated that 50% of all acute illness is due to upper respiratory infection which can be spread by mechanical ventilation in large building spaces. Respiratory illness leads all other causes in lost time from work (Dingle, 1959).

Overall, the loss of work time and declines in productivity are not the most pressing effect of sick building related diseases, -- the health of the occupants is a greater concern --, but productivity declines are concomitant effects which should be considered in dealing with the air quality problem in public or commercial spaces.

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Section 6
INVESTIGATIVE PROCEDURES FOR BUILDING PROBLEMS

Assuming that a problem exists where one or more persons are made ill by a condition relating to a building, evaluation should proceed through a series of steps designed to give an investigator as good a chance as possible to identify and correct the problem. Often the problem may come to an investigator late in a series of events which began with an initial perception of the problem, possibly without its connection to building conditions being recognized, and after local events have failed to correct it, in other words, in a crisis situation (Melius et al., 1984). A series of initial questions should be asked.

These should be related to the general symptoms associated with problem and the scope of the problem. What has happened and who is affected? This can be accomplished by either the personal interview or questionnaire technique. Here, as at all points in a problem building situation, the experience of the investigator will play an important role in the success of the analysis. A history of the complaints and a history of the building and its systems is required. A chronology of the events leading to the complaint is mandatory (Melius et al., 1984). Some features of the building and occupants which should be studied are:

- Background of design and construction
- Recent changes or renovations
- Changes in system maintenance routines
- Changes in housekeeping routines
- Changes in HVAC system operations
- Potential outdoor sources

All these questions relate to the material and operation of the building itself. An inspection should be made of the building and its ventilation system. Some problems may be noticed even at this early stage of the investigation, for example, blocked make-up air intakes or standing, contaminated water in the HVAC system. Questions related to the symptoms of the occupants should be:

- Extent of the outbreak
- Any localized areas of affected persons
- Any time-related features of the symptoms
- Sex or age distribution of the individuals
- Chronology of events
- Type of symptoms

These questions are best achieved by an experienced interviewer in a personal setting. Questionnaires may be used initially where the affected population is large or in a follow-up to determine if other conditions have been overlooked and to relate the number and distribution of the affected occupants to those not previously reporting symptoms. In questionnaires the same information should be sought as requested in the personal interview situation.

Medical reports may be sought if conditions are such that some individuals have been so severely affected that treatment by company or personal physicians has been initiated. At all steps every level of the organization(s) whose personnel are involved should be consulted. Management, unions, and employees all have an interest in the outcome of the evaluation and can provide useful information to the investigator. Building maintenance and plant engineering will have a large input into systems and routine related questions; their insights are invaluable.

The second phase, testing, should be organized on the basis of the initial analyses. Any testing must be explained to all the concerned parties in as straight-forward a way as possible. Analysis of the initial questionnaires or interviews may narrow the problem down to only a few choices of testing procedures or leave all the possibilities open. The experience and training of the evaluation experts will lead to a selection of possible tests. A set of tests for ventilation adequacy should be included. These may include measurements of concentrations of surrogate air contaminants, carbon dioxide, or actual air exchange rate measurements by tracer gas methods. Local air flow rates should also be considered. Pollutants to be tested for may be grouped into:

- Biological agents - molds, bacteria, or amoebae
- Anthropogenic sources - CO_2, bioeffluents
- Chemical sources - carpet shampoo dust, building materials.

Choices of where to test may be selected upon the basis of:

- Localized outbreaks of symptoms
- Number of Ventilation zones
- Type of ventilation system
- Observed potential pollutant sources
- Chronology of symptoms.

In cases where localized outbreaks occur, either in time or space, a control test in a supposedly unaffected portion of the exposure period or another part of the building should also be made for comparison and analysis. Sample sizes will depend upon the extent of the outbreak but should be large enough to define a problem area or time.

Reporting procedures should be complete, accurate, and available. A complete report should describe the tests that were made, how extensive they were, and the results. Accuracy of reporting is required to insure acceptability to all the involved parties. Availability means that the report is accessible physically to all the persons required and that it is written in language that can be easily understood by all who might be interested. The management should be the direct contact in reporting and they should be encouraged to release the information to the employees directly or through their channels of communication to the workers, i.e. unions or other employee groups. Health and safety personnel, if they exist, should receive the information so that conditions which led to the initial request of evaluation can be monitored in the future. Any recommended changes which result from the report should be made available to the engineering or maintenance staff who will be responsible. If medical personnel have been consulted for treatment of individuals or as evaluators they should be made aware of any conditions which have been discovered. Every case will prove to be different in its ramifications for these groups of individuals. Experience and tact will be called for and reporting procedures will vary. However, the minimum report and recommendation lists given above should be produced wherever possible.

The discussion above has been very general. As experience with building investigations grows and as new research results are reported the mysteries of associating problems and causes will decline. Draft protocols for general indoor air quality investigations have been developed by the National Institute of Occupational Safety and Health (NIOSH, 1987). The American Conference of

Government Industrial Hygienists Committee on Bioaerosols has developed a draft protocol for sampling bioaerosols in the workplace (ACGIH, 1986). Each document will change as this field develops. The references are listed to direct the reader to sources of future developments in this field.

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Section 7
CONTROL STRATEGIES

Specific strategies to control excess concentrations of pollutants have been described in the sections of this report that have discussed pollutant classes. There are common themes to these strategies; they are collected together here to emphasize this commonality. Several recent papers have discussed control techniques. These are reviewed by Fisk (1986).

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. Indoor control measures are therefore based on modifying either the pollutant source strength or the rate of pollutant removal.

When the major pollutant of concern can easily be identified a strategy that changes the pollutant source strength is usually the best choice that can be made. These can be collected into the general categories given below.

- Source removal: for example elimination of tobacco smoking in an indoor space.
- Source modification or substitution: for example, replacement of furniture having high emission rates of formaldehyde with furniture having different material composition.
- Local ventilation: the use of a range hood above a gas range.
- Air cleaning: the use of particle filters to remove pollen grains from the air.
- General cleaning and maintenance: regular inspection and maintenance of ventilation systems (sources of pollution in this example) to prevent buildup of biological materials.

Ventilation, the dominant pollutant removal mechanism in buildings, is the best general solution to pollutant problems when the pollutants of concern are not well-known. General rules about ventilation are difficult to state. An attempt to do so is provided in the ASHRAE Standard 62, a generalization of the experience of engineers and designers who are faced with the problem of designing buildings as an on-going effort. Suffice it to say that the ventilation rates specified in

Standard 62 are necessary but not sufficient to insure the indoor air quality requirements of buildings.

An examination of the field data in Fisk's review leads to the following conclusions:

- Source control measures are generally more effective than pollutant removal in reducing indoor pollutant concentrations. Reductions by factors of 3 to 10 are not unusual with source control. However, unless the initial rate of ventilation is unusually low, it is generally impractical to reduce indoor pollutant concentrations by more than 50% by removal processes such as whole-building ventilation.
- The effectiveness of ventilation can be enhanced by techniques that increase the concentration of pollutants in the exhaust airstream to exceed the average indoor pollutant concentration.
- Effective methods of removing particles from the indoor air are readily available; However, effective and practical techniques of removing many gaseous pollutants have not been demonstrated.

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