Policies & Procedures for Control of Indoor Air Quality (1987)

Pages
86

Size
8.5 x 10

ISBN
0309310377

Committee on Indoor Air Quality; Federal Construction Council; Building Research Board; Commission on Engineering and Technical Systems; National Research Council

POLICIES & PROCEDURES FOR CONTROL OF INDOOR AIR QUALITY

Committee on Indoor Air Quality
Federal Construction Council
Building Research Board
Commission on Engineering and Technical Systems
National Research Council (U.S.).

Order from
National Technical
Information Service,
Springfield, Va.
22161
Order No. PB88-110978

NATIONAL ACADEMY PRESS
Washington, D.C. 1987

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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This report was prepared as part of the technical program of the Federal Construction Council (FCC). The FCC is a continuing activity of the Building Research Board, which is a unit of the Commission on Engineering and Technical Systems of the National Research Council. The purpose of the FCC is to promote cooperation among federal construction agencies and between such agencies and other elements of the building community in addressing technical issues of mutual concern. The FCC program is supported by 13 federal agencies: the Department of the Air Force, the Department of the Army, the Department of Commerce, the Department of Energy, the Department of the Navy, the Department of State, the General Services Administration, the National Aeronautics and Space Administration, the National Endowment for the Arts, the National Science Foundation, the U.S. Postal Service, the U.S. Public Health Service, and the Veterans Administration.

Funding for the FCC program was provided through the following agreements between the indicated federal agency and the National Academy of Sciences: Department of State Contract No. 1030-621218; National Endowment for the Arts Grant No. 42-4253-0091; National Science Foundation Grant No. MSM-8600676, under master agreement 82-05615; and U.S. Postal Service grant, unnumbered.

For information regarding this document, write the Director, Building Research Board, National Research Council, 2101 Constitution Avenue, Washington, DC 20418.

Printed in the United States of America

ABSTRACT

Increasing incidents of discomfort or illness in the nonindustrial workplace that could often be traced to indoor air quality problems led to this study. Guidance is presented on how to identify and alleviate or prevent such problems. The primary focus is on existing office buildings, although the findings can be applied to other kinds of structures and to buildings being planned, constructed, or renovated. Suggestions are directed to facilities administrators, planners, designers, and managers as well as to maintenance and operating personnel and to the building occupants themselves. The various factors that affect indoor air quality are described. These include thermal conditions, odors, irritants, toxic substances, and micro-organisms. Other issues that are not technically related to air quality but that may aggravate a situation are also discussed. Procedures for diagnosing and controlling problems include consideration of the structure itself, the ventilation system requirements and performance, and the conformance with established ventilation criteria. Several case studies illustrate typical problems and their solutions.

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PREFACE

In recent years there have been increasing concerns expressed about the quality of air in the nonindustrial workplace, especially in the office environment. Because buildings owned or operated by federal agencies represent a significant percentage of the total building stock in the United States, the sponsoring agencies of the Federal Construction Council requested the Building Research Board, of the National Research Council's Commission on Engineering and Technical Systems, in cooperation with the Commission on Life Sciences, to establish a committee to provide guidance for dealing with problems related to indoor air quality in existing buildings.

This report presents the committee's findings. Its objective is to furnish suggestions on how to identify, prevent, and/or mitigate indoor air quality problems in existing public buildings. The report is primarily directed toward three sets of personnel who are responsible for the performance of existing buildings:

- Policy-makers who establish the economic, social, and political bases for owning, leasing, or occupying public buildings;

- Facilities planners and administrators who develop and administer procedures to accomplish the stated policies and missions of public agencies; and

- Maintenance and operating personnel who implement the procedures.

In addition, this report provides information to occupants of these facilities to assist them in distinguishing between human responses that may be due to the physical performance of the building and its contents and those that may be due to other influences, such as personnel interactions.

Because of the interdisciplinary nature of the subject of this report, committee members were selected who had broad experience in various aspects of building design, construction, management, and operation or who had extensive experience with indoor air quality issues from engineering and health science perspectives. As a result, it was necessary for the committee to formulate a common basis of understanding of the issues in order to achieve its objectives. One reference point was the material that resulted from the workshop on indoor air quality that was sponsored by the Building Research Board in 1985. However, because the objective of the report is to provide guidance for dealing with indoor air quality problems, an extensive bibliography was not compiled. Rather, the committee opted to digest the available literature according to the members' diverse experiences and expertise and to report consensus interpretation of the relevant material. Thus the committee members have made an important contribution to the scientific community as well as to those to whom the report is primarily directed.

In two instances, the committee asked for specific assistance in preparing the report. First, we are thankful to Philip R. Morey of Honeywell, Inc., for his contributions on the nature of biological contamination and how it can be monitored and controlled. Second, we extend our appreciation to committee members Jean-Pierre Farant and Jan Stolwijk and to liaison representative Preston E. McNall for their diligence in preparing the case studies in Chapter 4.

The committee also extends its gratitude to the BRB staff for its support: Stephen Montgomery for editing the materials we generated into a cohesive report; Gretchen Bank for her helpful coordination of the committee meetings and preparation of the minutes; Donna Allen for her secretarial support; and John Eberhard for his insights and direction.

Finally, I would like to take this opportunity to thank the committee for the professional manner in which it deliberated and reached consensus on the guidance that is presented in this report.

James E. Woods
Chairman
Committee on Indoor Air Quality

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INTRODUCTION, CONCLUSIONS, AND RECOMMENDATIONS

Although the impact of indoor air quality on occupant health and well-being is a serious concern today, the subject is not new. Evidence indicates that efforts to control indoor air quality predate recorded history, as illustrated by the judicious placement of warming fires and the presence of vent holes in the roofs of caves. When windows came into use in early Roman architecture, styles and sizes of buildings changed significantly. Gothic architecture embodied advances in structural design that allowed large areas of window to be used without affecting the stability of the wall. Renaissance architecture relied heavily on operable windows for natural ventilation. In fact, detailed prescriptive rules for window sizes were originally developed in Italy during this time. However, when these rules were imported to England in the 1600s and strictly applied to the smaller-scale buildings there, the resulting window sizes were often too small to be acceptable.

Compromises among needs for shelter, security, safety, and health have been made throughout history. From the discovery of window glazing to the middle of the twentieth century, the shapes and sizes of buildings for human occupancy were closely matched with their ability to utilize natural ventilation to dissipate internally generated thermal and contaminant loads. However, the development of twentieth-century technologies for structures and mechanical systems has permitted decisions about building shapes and sizes to be separated from the needs for natural ventilation. Thus, current concerns about indoor air quality have evolved from fulfilling the basic need for shelter to meeting complex requirements for personal, social, and economic benefits.

In a 1981 report by the National Research Council's Committee on Indoor Pollutants[4] [references cited are listed following Chapter 4], four basic reasons for increasing concern about indoor air quality were identified:

- Energy conservation efforts have tended to reduce the amount of ventilation available for diluting indoor contaminants to acceptable concentrations.

- Techniques for measuring occupant exposure to contaminants at low concentrations have improved.

- Ubiquitous sources of contaminants, including synthetic materials, exist indoors and outdoors.

- Awareness by the general public of the impact of indoor air quality on health and well-being has increased.

These and other concerns have prompted a flurry of activity by various professional organizations--e.g., promulgation of voluntary standards relating to indoor air quality by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers and the American Society for Testing and Materials. In addition, several federal agencies (Environmental Protection Agency, Department of Energy, Consumer Product Safety Commission, National Institute for Occupational Safety and Health, and others) have undertaken studies and/or issued papers or directives dealing with the subject. [For convenience, these and other organization names are abbreviated throughout this report; a list of acronyms is given following the references at the end.]

SCOPE

The focus of this report is the identification and recommendation of operational procedures that can be implemented to avoid or minimize air quality problems in existing buildings. However, this report also provides guidance on what should be done by responsible personnel if indoor air quality problems are reported, including when to obtain professional assistance. Although buildings of all types can experience indoor air quality problems, this report is limited to existing buildings that are not used for single-family residences or for industrial processes. The primary emphasis is on office buildings rather than other kinds of institutional structures such as hospitals.

Indoor air quality problems addressed in this report include those that elicit complaints of discomfort (e.g., malodors, headaches) as well as those that cause frank illness (e.g., infections). Because of the vast number of potential problems that can be caused by episodic or transient events, this report is primarily focused on disturbances that can be expected to occur continuously, or at least repeatedly (e.g., seasonally), and does not address occurrences such as accidents or spills.

APPROACH

In preparing this report, the committee has taken a three-pronged approach. Following this introductory chapter, which describes the issues addressed and presents the conclusions reached by the committee and its recommendations for action by policy-makers and administrators, Chapter 2 addresses the basis for current concern: human responses that may be expected from exposure to indoor contaminants and conditions. Chapter 3 introduces the concept of "acceptable indoor air quality," reviews methods of ventilation system characterization, and describes general methods of achieving system performance for acceptable human response. In Chapter 4, case studies that reflect specific types of air quality problems are characterized, and possible solutions are discussed.

ISSUES

In developing this report, the committee addressed the following issues:

1. What symptoms are associated with indoor air quality problems? When a significant percentage (e.g., more than 20 to 30 percent) of the occupants complain of a set of symptoms, including headaches, fatigue, nausea, eye irritation, and throat irritation, when these symptoms are alleviated by leaving the building, and when a specific cause of the symptoms is not recognizable, a problem with the quality of the indoor air should be suspected. The phenomenon has been variously termed "sick building syndrome" or "tight building syndrome," although this concept is not accepted by all authorities. Moreover, when symptoms of frank illness, including infection, fever, and clinical signs of pathology, are identified and an airborne pathway for the stressor is recognized, then a problem with the air quality can also be suspected. In this case, sometimes described as "building-related illness," the percentage of occupants affected is not a determining factor. Some investigators use two or more occupants of a building affected as a guideline.

2. When a complaint is received, how can "perceived" and "actual" air quality problems be distinguished from each other? The committee identified three categories of complaints about poor air quality: (a) perceptible physiological stressors as they relate to the building systems (e.g., odorous contaminants, heat); (b) nonperceptible physiological stressors (e.g., airborne biological contaminants); and (c) perceptible nonphysiological stressors (e.g., job-related stress).

Each of these categories was recognized as "actual," but different procedures are required to resolve the resulting air quality complaints. Perceptible physiological stressors are usually the easiest to mitigate through operational changes or physical modifications to building systems. Nonperceptible physiological stressors are more difficult to control because their existence must first be determined by appropriate tests and their abatement must be demonstrated through follow-up investigations. The third category, perceptible nonphysiological stressors, may be the most difficult to mitigate because social or psychological solutions may be required.

3. Which of the existing contaminants are of principal concern? Major sources of contaminants can exist both outdoors and indoors. Outdoor sources may be above-grade (e.g., industrial air pollution; automobile exhaust) or below-grade (e.g., soil gas such as methane; radon; pesticides). Indoor sources are the occupants themselves (e.g., bioeffluents), building materials and furnishings (e.g., volatile organics such as formaldehyde), and activities that occur within buildings (e.g., combustion such as tobacco smoking; paper processing such as photocopying).

4. Do buildings and their systems mitigate or exacerbate exposure to contaminants? As noted in the 1981 report[4] and several others since then, concentrations of contaminants indoors often exceed outdoor concentrations; however, for some contaminants, indoor concentrations are usually lower (e.g., SO_2, O_3, fungi, pollen). The dynamics of building responses to indoor contaminants are just becoming known. For example, the emission of formaldehyde within occupied spaces is apparently dependent on both thermal and humidity excursions within that space. The levels of both chemical and biological contaminants are strongly associated with the cleanliness of the heating ventilation and air conditioning system.

5. What can be done by those who set, administer, and implement policy? Most of the documentation available today about control of indoor air quality is of a scientific or technical nature and affords little or no directly usable advice for building practitioners in addressing complaints. One major objective of this report is to focus on recommendations that can be implemented without major redesign or system modifications. These recommendations are given in the form of suggested policies, management procedures, and maintenance and operational practices to provide acceptable indoor air quality in systems that are capable of appropriate responses. Recommendations are also provided for dealing with complaint situations; some of these can be resolved by in-house procedures, but others will require professional assistance, often accompanied by operational or system modifications.

6. How important are interactions between management and occupants in resolving indoor air quality complaints? Complaints about unacceptable indoor environmental conditions can be traced to stresses that may be imposed by the physical environment--some intrinsic (e.g., organismic factors) and some imposed by the situation of occupancy (e.g., functional factors). These stresses may act in some additive way to produce physiological or psychological strains. Thus, control of the physical environment may become necessary to achieve more

acceptable conditions. In many situations, complaints of poor air quality may be exacerbated when the complainant is dissatisfied with other nonenvironmental factors.

CONCLUSIONS

The committee reached the following conclusions based on its studies:

1. A high percentage of the work force spends 35 to 40 hours per week in nonmanufacturing buildings, and an even higher percentage of the federal work force is similarly located. Even small reductions in productivity caused by stresses in these environments have large consequences for total national productivity.

2. A number of factors are involved in the generation of building-related occupant complaints. Many of these can occur simultaneously. It is rare that a specific source for the complaints can be identified, and solutions can usually be implemented without such identifications.

3. Increases in occupant densities beyond the design density often produce air quality complaints.

4. Energy management strategies can lead to indoor air quality complaints if ventilation rates or operating periods of ventilation equipment are reduced.

5. Inadequate maintenance of building systems and equipment can lead to complaints by occupants.

6. If positive action is not taken to reduce the incidence of complaints about poor indoor air quality, it is likely that the frequency and intensity of complaints will continue and increase. Ongoing interactions and communication with occupants is essential if complaints are to be resolved.

7. A commitment to improved quality of maintenance and monitoring of system performance could significantly reduce occupant complaints. Much of this effort can be accomplished by staff.

8. Large buildings are served by complex control systems and equipment that are often more intricate than can be effectively maintained and adjusted by owners, managers, or operators as currently trained, especially in the face of modifications in loads or building configuration or deterioration through inadequate maintenance.

9. When measurements are needed by management to ascertain indoor air quality, or when modifications may be required to reduce complaints, professional assistance or consultation should be obtained.

RECOMMENDATIONS

The recommendations for action by administrators and policy-makers follow from the committee's conclusions and from the material presented in the balance of this report.

1. Testing and quantification should be performed to determine the effect of reduced air quality on productivity.

2. Energy management strategies that could lead to reduction in indoor air quality should be weighed against the potential reduction in productivity that could result.

3. Because of the mismatch between the complexity of current building systems and the ability of managers and operators to understand, adjust, and monitor system operation, training and education should be developed and encouraged to produce effective accountability for the proper management of building systems.

4. Federal and local government agencies should build into their capital budgets the funds required to correct indoor air quality problems and to provide adequate operations and maintenance for acceptable environmental quality.

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HEALTH AND COMFORT CONSIDERATIONS

The indoor environment is made up of many factors. The occupants of a building are the receptors of a complex array of stimuli and are directly affected by many of these factors, such as light, sound, odor, temperature, humidity, electrostatic charge, and irritants of the eyes and upper respiratory passages. The factors that express themselves in a sensory awareness are not perceived by all occupants in exactly the same way, and even for an individual occupant the perception of a given factor will vary over time. As a result it is usually not possible to identify values for these factors that will be acceptable to all occupants. Factors that are characterized by such an inability to indicate absolute acceptable values are

- Those directly affecting indoor air quality--odors, irritants, room temperature, and relative humidity; and

- Those affecting satisfaction with the overall indoor environment--lighting, noise, furniture and equipment, building vibration and motion, crowding and personal work space, and psychosocial factors.

Many other factors are of great potential importance to health, but they escape sensory detection and thus can be present without the occupants' awareness. Examples are airborne or waterborne pathogenic micro-organisms, toxic or carcinogenic substances, ionizing or nonionizing electromagnetic radiation, and radioactive substances. Occupants normally assume that their indoor working environment is free of these factors. If the presence of any of this category of factors is suspected or alleged, it produces legitimate and serious concern that is difficult to deal with, even if the anxiety has no basis in fact.

This list implicates a number of important building-related factors, such as privacy or the lack of it as perceived by the occupants, and the social environment maintained in it. If the social interactions are predominantly of a positive and encouraging nature, this will have a strong positive modifying effect on how the more directly building-related factors will be perceived. Furthermore, the proximity and ease of access to important facilities such as food services, transportation, and shopping, or the lack of one or more of these items, can have an important effect on the way a building or elements of its environment are perceived.

It is important to emphasize that a general dissatisfaction with the workplace often results in complaints focusing on indoor air quality, although they may be rooted in other factors as well.

ODORS

The human sense of smell is characterized by an extraordinary range of sensitivity, being capable of detecting and recognizing a threshold concentration as low as 0.47 part per trillion of hydrogen sulfide gas in air, for example, whereas for ammonia gas in air the threshold is as high as 48 parts per million. The mechanisms of the sense of olfaction and the chemical determinants of odor are very poorly understood. Nevertheless, odors are a common experience in everyday life and are a not-uncommon source of complaint in offices or other indoor environments to which the public is exposed. Occasionally odors are caused by a single contaminant, and on such occasions it may be easiest to identify the source and to diminish its strength. The most common odors in the indoor environment will tend to be very complex in nature, consisting of a large number of substances. Odors of this type include tobacco smoke, human body odor, and the complex odor that emanates from a variety of personal grooming products as well as from products used for the cleaning and maintenance of building surfaces. Outgassing from building materials is also common. Many people associate unpleasant odors with an unhealthy environment.

Measurement of odor intensity is only feasible by using human observers and instrumentation that allows for systematic comparison of odor intensity with the intensity of a known odorant in a known concentration. Such psychophysical methodology has demonstrated in considerable detail that all odors cause an adaptation: The perceived intensity from a constant odorant concentration decreases with time. Such adaptation causes the perceived intensity of an odor to be reduced by a factor of 2 to 3 within 6 minutes after first exposure. Several complex mixtures, such as those found in tobacco smoke, contain both odorants and irritants. A person's perception of an odor will be strongest upon first entering a space, but the perception of the odor will diminish with time. However, the irritation will in fact increase with a prolonged stay in the space.

There are pronounced differences among individuals in their abilities to detect, recognize, and tolerate odors in their environment. If these individual differences are added to the pronounced difference between visitors to a space and long-term occupants, it becomes very difficult to predict with any precision how a given group of occupants will react to a complex and time-varying exposure to odors.

Removal of odorants occurs most commonly through ventilation (i.e., dilution) with outside air. Since the production or release of odorants is often determined by the number of occupants, it is common to specify the ventilation rate, i.e., the volume of outside air to be introduced into the space, in terms of cubic feet per minute (cfm) per occupant or in liters per second per occupant. Research in this area indicates that for the control of human body odors it is necessary to provide about 6 to 9 cfm of outdoor air per occupant. If tobacco smoking is permitted and occurs in a space, it is reported that the ventilation rate required increases to levels specified as 2 to 10 times greater for 80 percent of occupants and visitors to accept the indoor air quality without complaint. This range depends on the amount and type of smoking that occurs. It appears that the odor of tobacco smoke is not substantially reduced by filtering out the smoke particles through, for example, an electrostatic air cleaner; furthermore, tobacco odor is quite stable over time, so dilution or ventilation with outside air is the most common and most effective manner in which tobacco odor can be diminished.

There is a complex reaction to a mixture of different odors, and the net result appears to be a reduction in the sensitivity to each of the component odorants, resulting in a masking. Purposeful masking by adding odorous compounds to the environment is rarely a satisfactory solution. The addition of a masking agent does not chemically alter the odorant, and therefore the dose by the odorant is not diminished.

IRRITANTS

Occupants of office buildings and other structures can experience harmful effects from exposure to irritants. Typical complaints include itching or burning eyes, watery eyes, dry nose and throat, sore throat, sneezing, coughing, tightness of the chest, and dry skin. People's sensitivities to different irritants vary significantly.

Several important sources of irritants exist in buildings. The principal sources are discussed here.

Tobacco Smoke

The smoking of cigarettes, cigars, and pipes produces environmental tobacco smoke (ETS), which is defined as the combination of sidestream smoke released directly into the air from the burning core of tobacco and mainstream smoke that is exhaled by the smoker. ETS is a mixture of gases and fine particles. It contains acrolein, phenols, formaldehyde, acetone, and many other compounds with irritant properties. Exposure to ETS can lead to irritation of the eyes, nose, throat, and respiratory tract. In sensitive individuals these effects can be quite pronounced, particularly for those with pre-existing health problems such as emphysema, bronchitis, and pneumonia.

Building Materials and Furnishings

Outgassing from such things as paints, adhesives, sealants, office furniture, carpeting, and vinyl wall coverings is the source of a variety of irritant compounds. The best known of these is formaldehyde, which can cause irritation of the eyes and upper air passages. Other compounds include aliphatic aldehydes, styrene, xylene, ethylbenzene, dichlorobenzene, and trichloroethylene, to name a few. Emission rates of these and other hydrocarbons like benzene, toluene, alcohols, and ketones are highest in new or recently renovated buildings.

Indoor contamination can result from the breakdown of man-made materials used for duct insulation and fireproofing. Exposure to mineral fibrous products can cause irritation of the eyes, nose, throat, and skin. These products tend to have an affinity for particulates and bioaerosols. If the insulation material becomes wet, water-soluble gases and vapors may accumulate and later outgas contaminants that may be odorous or deleterious.

Office Equipment, Supplies, and Cleaning Products

Ozone, an irritant of the mucous membranes and the lungs, can be produced indoors by photocopiers, laser printers, and electrostatic air cleaners and other high-voltage electrical equipment. Photocopiers, other types of copying machines, and copy papers are also potential sources of irritating hydrocarbon compounds. Organic solvents and ammonia from carpet shampooing have been associated with eye, nose, throat, and skin irritation. Buildings that are cleaned at night while the ventilation is reduced or off can accumulate high concentrations of irritants that only slowly dissipate in the morning when the ventilation is restored.

Other Irritants

HVAC system intakes located near heavy traffic, parking garages, or loading docks can result in contamination of a building space with motor vehicle exhaust. This may lead to the buildup of irritating combustion-related particles and gases, most notably the oxides of nitrogen and sulfur. Mold spores (from mold growing in the HVAC system) and pollen (brought in from outside in the make-up air) can cause allergic reactions. High humidity can result in actual health problems by encouraging the growth of mold and fungus. However, excessively low humidity (e.g., less than 20 percent) can also increase susceptibility to air quality problems by drying the eyes and mucous membranes. This can result in eye irritation (particularly for people who wear contact lenses), sinus problems, headaches, and perhaps an increased susceptibility to colds and other airborne diseases.

The occurrence of irritant symptoms cannot always be explained by measured concentrations of a single chemical substance. This has led some researchers to postulate that, since irritants and other compounds are generally present in a complex mixture, they may sometimes be acting in combination at low levels to induce symptoms. Moreover, the symptoms reported may be consistent with mild central nervous system depression, as well as mucous membrane irritation, and may partially explain the phenomenon described as sick building syndrome. There is some support for this view from experimental studies.

THE THERMAL ENVIRONMENT

People have a physiological and psychological system that is designed to keep their body temperature within very narrow ranges. The deep body temperature is normally kept at approximately 36.5 to 37.5°C (97.7 to 99.5°F). The average skin temperature under these circumstances is of the order of 33.0 to 36.5°C (91.4 to 97.7°F). To maintain these temperatures, physiological systems cause shivering and vasoconstriction in cool environments and vasodilation and sweating in warm environments. These physiological adjustments are perceived as uncomfortable, and as a result they elicit behavioral responses to counteract them. The behavioral responses include modification of the clothing insulation and modification of the physical activity by increasing it in the cold and decreasing it in environments that are perceived as too warm.

The effect of a building's thermal environment on its occupants depends on the air temperature, the radiant temperature, the air velocity, and the humidity. In addition, the individual building occupants have different rates of internal metabolic heat production, different body temperatures when entering the building, and different levels of clothing insulation. All these factors will modify the effects of the external parameters. Because of nonuniformities in the external parameters in different building locations and individual differences in metabolic rate, the occupants' surface-to-volume ratio, and clothing worn, it is impossible to satisfy the thermal preferences of more than 80 to 90 percent of the occupants under the best of circumstances (Figure 1).

Figure 2 shows the relationships between operative temperature and clothing insulation for conditions producing equal thermal comfort. Operative temperature is derived from air temperature and radiant temperature, and at air speeds of less than 0.4 m/s or 80 fpm it is approximately equal to the average of these temperatures. In most indoor spaces the air velocity will be less than 0.4 m/s, and the radiant temperature will be close to the air temperature. At normal

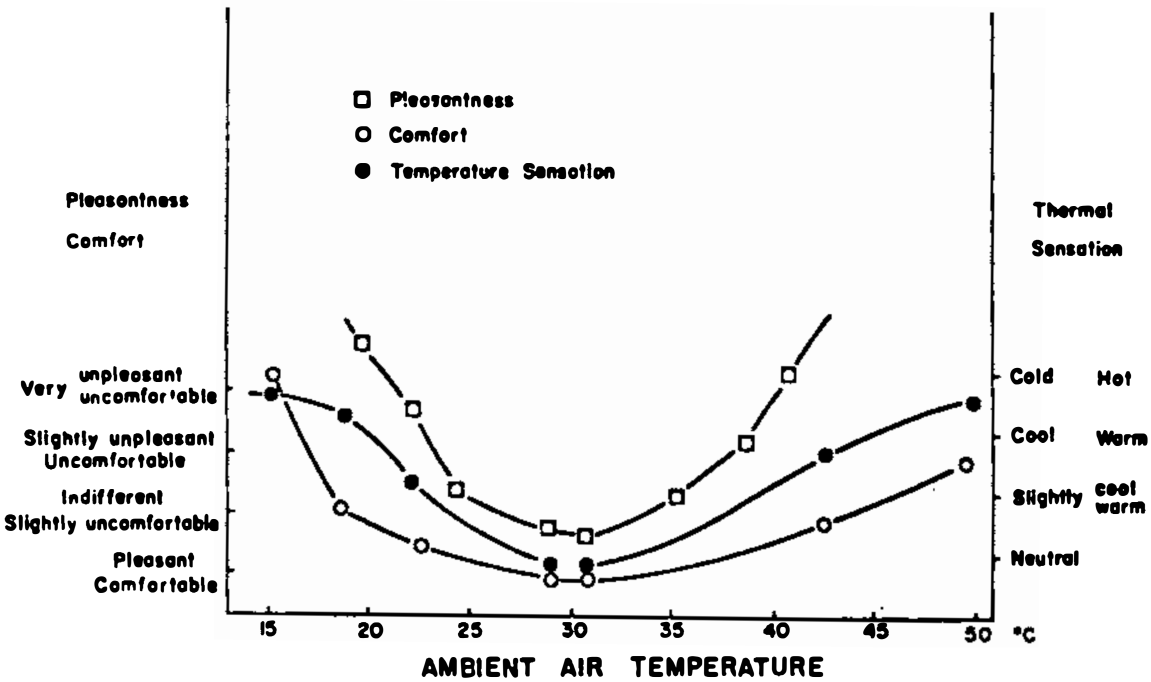

FIGURE 1. Dependence of cold discomfort and warm discomfort reports in a population exposed to a range of ambient temperatures. SOURCE: Indoor Pollutants. Committee on Indoor Pollutants, Board on Toxicology and Environmental Health Hazards, National Research Council. Washington, D.C.: National Academy Press, 1981.[4]

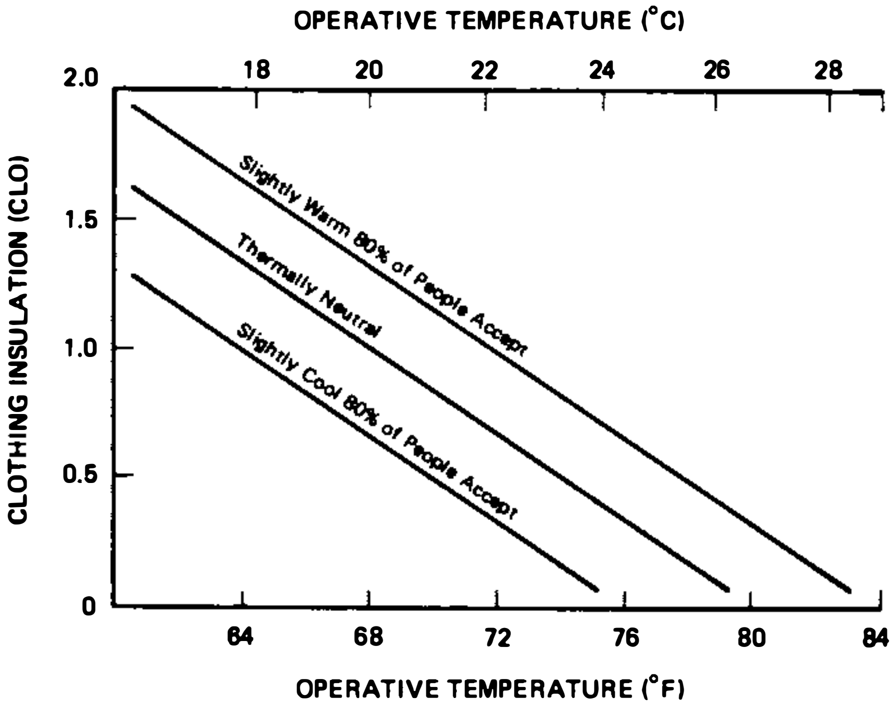

FIGURE 2. Relationship between clothing insulation and operative temperature during light, mainly sedentary, activities. The upper and lower limits indicate the levels within which 80 percent of the occupants are comfortable. SOURCE: Indoor Pollutants. Committee on Indoor Pollutants, Board on Toxicology and Environmental Health Hazards, National Research Council. Washington, D.C.: National Academy Press, 1981.[4]

indoor temperatures near the comfort range, the relative humidity will not have a strong effect on sensations of comfort or temperature. With all these provisions, Figure 2 will give useful estimates of expected thermal and comfort sensations and the range that can be achieved by adjustment of clothing insulation. The value of the clothing insulation has been defined in clo units. The normal clothing worn in the office environment in the summer will have an insulation value of 0.35 to 0.6 clo, and in the winter this will increase to 0.8 to 1.2 clo. With these clothing levels the preferred temperature during the summer will be about 75°F (25°C), and the preferred winter temperature would then be about 71°F (22°C). In many large buildings these temperatures are often reversed due to operational factors, with the lowest building temperatures occurring in the summer and the highest being encountered in the winter. This causes additional discomfort for seasonally clothed occupants.

Most of the time male occupants will be the first to object to indoor environments as too warm, and women will object to indoor environments as being too cold. In part this is because male clothing often has a higher clo value than women's clothing and in part because women's responses to cooling are more intense and occur earlier than men's responses, and men's responses to heating occur earlier and are more intense than women's responses to the same ambient temperature levels.

The usual parameter to regulate and measure is the air temperature, and in many cases this is the single most important factor. However, the radiant temperature or the air velocity can modify the effect of an otherwise acceptable air temperature to make the total thermal environment unacceptable in a given location. Examples of such unacceptable microenvironments may be found in winter near a cold window, or at any time when solar radiation affects an occupant in a space at normal air temperature. Cold air discharged from diffusers at high velocities can feel pleasant under certain circumstances but can be extremely disagreeable under other circumstances.

The conditions that most frequently cause the operative temperature to differ from the regulated air temperature arise from the presence of intense radiant fields. If direct sunlight strikes an occupant or indoor surfaces near an occupant, the radiant temperature and the operative temperature for that occupant can be considerably higher than the air temperature. In the winter large windows will have indoor surface temperatures that fall about halfway between the outdoor temperature and the indoor temperature, and under these conditions the radiant temperature near such a window can be quite low, thus lowering the operative temperature. This lowering of the operative temperature can be aggravated by a simultaneous cool downdraft near such a window, which can further reduce the operative temperature for an occupant positioned close to the window.

A significant modification of the thermal responses to a given indoor environment is determined by the immediately preceding thermal exposure history. When a person who has just experienced cold exposure elsewhere enters, there is greater acceptance of a warm environment. Similarly, when a person enters a warm indoor environment after strenuous exercise, there is likely to be a lessened acceptance.

When an indoor environment is slightly too cool or slightly too warm for a given individual, there is likely to be a cumulative change in internal body temperature as time goes on, which will ultimately result in a judgment of an unacceptable thermal environment. Such judgments are thus more likely to occur at the end of a working day than at the beginning. Furthermore, it is unlikely that reports of too cold an environment will coincide with reports of sleepiness or exhaustion, just as it is unlikely that reports of too warm an environment will coincide with reports of too high a work stress. Complaints about stuffiness (which may be confused with poor air quality) are much more frequent where high room temperatures and humidities prevail, and complaints about drafts are much more likely to occur at low room temperatures.

PRESENCE OF TOXIC SUBSTANCES

Potentially there is a very wide range of toxic substances that could find their way into offices or other public-access environments. Sporadic or episodic introduction of cleaning and maintenance products into the environment can mean a spread of constituent compounds throughout the building and its recirculating air-handling system. Installation of new carpets or painting of extensive areas is likely to bring recognition of unfamiliar odors and concern about possible toxicity. The following discussion covers contaminants that are present in many buildings to a varying degree--contaminants that have had sufficient public discussion to become known to a large number of occupants.

Asbestos

"Asbestos" is the term used for a group of silica-based minerals occurring in fibrous bundles. It covers a broad range of naturally occurring minerals that are processed to yield a manageable form for use in construction, insulation, and fire-retardation materials. In the actual processed and manufactured form used in buildings, the fibers can be very loosely bound, as in sprayed-on asbestos insulation or asbestos cloth, or they can be very tightly bound, as in asbestos-cement or in vinyl-asbestos tile flooring material. Asbestos has commonly been used for fireproofing, thermal insulation, and as part of pipes, in floor tiles and coverings, and as insulation cladding for structural members. In buildings in which asbestos was used, exposure to it is normally insignificant for most occupants except where asbestos surfaces are deteriorating or being abraded, thus releasing asbestos fibers. However, widespread publicity regarding the problem has resulted in much anxiety about exposure to asbestos.

Asbestosis is a disease in which the lungs become progressively disabled, with decreasing lung capacity (total volume) and function (flow rate of air into and out of the lungs). The overall result is that the lungs lose their ability to transfer oxygen into the bloodstream. Other nonmalignant effects of asbestos on the lungs include plaque formation on the pleura and lung surface fissures. Calcium deposits can form "sheaths" enveloping portions of the lung and impairing its function.

Most lung cancers associated with asbestos appear to be related to extended industrial workplace exposure to heavy asbestos concentrations. Two major types of cancer appear to occur in subjects with histories of chronic asbestos exposure: mesotheliomas (widespread cancers of the lining of the lungs) and bronchial carcinomas originating in the bronchi. Evidence also exists that the risk is increased when chronic exposures are influenced by cigarette smoking.

Formaldehyde

Formaldehyde and formaldehyde-based products occur widely throughout the man-made environment. Formaldehyde gas itself is pungent, readily detectable by most people at concentrations well below 1 part per million by volume; some individuals can detect it at concentrations of 0.05 ppm. When combined with other chemicals, formaldehyde will form resins that are used as glues and binders in numerous products. When reacted with urea, ureaformaldehyde is formed. The addition of excess formaldehyde speeds the reaction but then allows the excess material to diffuse slowly out into the surrounding air for an extended period. When mixed with a foaming agent, ureaformaldehyde foam insulation (UFFI) is formed. When UFFI is manufactured, there is an initial elevated release rate of formaldehyde followed by an extended period of a lower constant rate of release of the free formaldehyde that is part of the UFFI product. UFFI is seldom installed today but may exist in some buildings.

Formaldehyde resins are used as binders for interior-grade plywood, particleboard, and wallboard. Other formaldehyde resins are used to give "wet strength" to paper, tissues, and cardboards, as well as in floor coverings, carpets, and carpet backing.

Formaldehyde is generally not toxic in small quantities. It is eliminated readily from the blood if ingested, with a half-life of 1 to 2 minutes. At higher concentrations (15 ppm or more), a number of chronic effects have been noted in animal tests and human epidemiologic studies. These include asthma, impaired lung function, and chronic respiratory disease. Teratogenic (fetus-damaging) and mutagenic (chromosome-damaging) effects are not notable.

Formaldehyde causes sensitization reactions in humans exposed to low doses so that future exposure to low doses may cause symptoms that would normally occur only at higher concentrations at first exposure. This type of reaction is, however, limited to a small fraction of all individuals. Few controlled studies of humans exposed to formaldehyde over extended periods of time (more than a few days) have been carried out. Minor respiratory impairment has been reported in such studies.

Data on human cancer initiated by formaldehyde exposure are sparse and often not well controlled. The Consensus Workshop on Formaldehyde[1] found sufficient evidence to conclude that formaldehyde[1] poses a carcinogenic risk to humans. The International Agency for Research on Cancer concluded that the evidence in humans is inadequate to judge the human carcinogenicity.[3]

Radon

Radon and its immediate radioactive decay products (progeny) are ubiquitous contaminants of indoor air. They are part of a series of radioactive decays that begin with uranium and thorium, elements that are widely distributed in the earth's crust. Radon is a chemically inert gas, and as such can migrate into buildings. There are a number of possible sources of radon, including the soil, building materials, potable water, and outdoor air. With some noted exceptions, the most significant source of radon in buildings is the soil surrounding the building substructure. While transport of radon from soil can occur through diffusion and convection, the latter mechanism is generally thought to be the more important, at least for those buildings where indoor radon concentrations exceed a few picocuries per liter (abbreviated pCi/L; this is a measure of the radioactivity concentration of a sample of air or water).

In general, radon concentrations in "commercial" or office buildings are less than those found in single-family residences, partly because of the much smaller ratio of surface area in contact with the soil to building volume. Another difference is the mechanical ventilation systems more commonly found in office buildings than in residences. However, little is known about the distribution of radon concentrations in office buildings, especially those buildings with only one to three stories that may also have partial or full basements.

The health risks associated with radon exposure are caused by the radioactive decay of radon progeny. These radioactive isotopes are chemically active and can adhere to surfaces such as airborne particles, room walls, and lung tissue. The decay of progeny deposited in the lungs (specifically the alpha decay of two of the polonium isotopes) can cause lung cancer. Based on studies of lung cancer among uranium miners, estimates can be made of the lung cancer incidence among the general population resulting from exposure to radon progeny. Estimates range from 5,000 to 30,000 cases of lung cancer annually.

Tobacco Smoke

Indoor exposure of nonsmokers to tobacco smoke, termed either environmental tobacco smoke (ETS) or "passive smoking," has chronic (long-term) and acute (short-term) effects. Nonsmokers exposed to ETS are subject to similar chronic effects as smokers but at a reduced risk corresponding to their lower exposure. As noted in the earlier section on irritants, many of the contaminants in tobacco smoke are gases and vapors (e.g., carbon monoxide, nitrogen oxides, nicotine), but a significant portion of the smoke is also made up of particles of various sizes. The dynamics of particle inhalation and retention in the human respiratory system are strongly dependent on the size of the particles.

The effects of ETS can include physical irritation of mucous membranes of the eyes, nose, and throat. Because of the large variety of combustion products making up both mainstream and sidestream smoke, a great number of reactions can ensue in groups of people exposed to such passive smoking. Possible long-term health consequences include chronic heart and lung disease and respiratory cancer. Although no epidemiologic studies have specifically addressed risks to nonsmokers in the office environment, there is some evidence of an association between passive smoking and these diseases in other settings.

MICRO-ORGANISMS

Microbial contaminants in the occupied spaces of buildings may cause illnesses of two general types, namely, those that are allergic in nature and those that are infective. The extent of illnesses caused by microbial exposure in buildings is difficult to estimate because diverse types of micro-organisms or microbial products evoke human responses, exposure occurs in a variety of occupied spaces in public and commercial buildings, and human sensitivity or susceptibility to allergens and infective agents varies enormously. Despite uncertainty over the extent of health effects caused by exposure, the impact of some micro-organisms is appreciable.[4]

Allergens

Hypersensitivity pneumonitis, humidifier fever, allergic rhinitis, and allergic asthma are illnesses that are caused by exposure to airborne allergens. These illnesses are manifest among susceptible individuals because of a hypersensitivity response to inhaled particles containing viable micro-organisms, nonviable spores, or nonliving components of micro-organisms. In Europe and North America there have been numerous reports of building-associated hypersensitivity pneumonitis or humidifier fever.[6,7,8] Affected individuals usually manifest acute symptoms such as malaise, fever, shortness of breath, cough, and muscle aches, and they experience relief after they leave the building for several days or an extended period of time. These allergic respiratory diseases usually occur as a result of aerosolization of microbial allergens from HVAC-system components, such as humidifiers, air washers, and fan coil units that may be contaminated, or from other building components that have been damaged by recurrent floods or moisture. The following microbial agents are but a few of those that have been implicated in the etiology of building-associated allergic respiratory diseases:

- Acanthamoeba spp. and endotoxins present in stagnant water in some humidifiers
- Thermophilic actinomycetes (e.g., Thermoactinomyces and Micropolyspora spp.) from air washer or water spray systems
- Fungi including Penicillium and Aspergillus spp. present in fan coil units, filters, and other HVAC system components.

Micro-organisms that may cause allergic illnesses are ubiquitous in both the indoor and outdoor environments. The presence of microbial allergens in the indoor environment in sufficient amounts or types to cause hypersensitivity reactions in susceptible individuals is dependent on a number of factors, including the type of mechanical components in the HVAC system as well as the program for maintenance of mechanical systems. However, the most important factor affecting microbial contamination in the indoor environment is the presence of water. Water is required for the amplification of micro-organisms that may be present. In large buildings, the HVAC system may serve to transport micro-organisms from the locus of amplification (or contamination) to the vicinity of the sensitive occupants. With regard to assessing whether the building itself is a source of agents causing allergic respiratory illness, it is important to determine if amplification of micro-organisms or microbial materials is occurring indoors, either in the HVAC system or in the occupied space. For nonpathogenic bioaerosols (e.g., most fungi) this may be done by qualitative and quantitative comparison of indoor and outdoor microbial populations.[9]

Infectious Agents

A large number of infectious agents are potentially transmissible by the airborne route. Thus, viruses such as those causing influenza and measles can be infective in the form of droplets or droplet nuclei. One droplet containing Mycobacterium tuberculosis is all that is required to initiate an infection in a susceptible occupant. Some hospital-acquired infections occur as a result of airborne exposure; of equal or greater importance may be contact contamination. Some infectious fungi including those causing coccidioidomycosis, histoplasmosis, and crytococcosis are known to be transmissible by airborne spores or by soil particulates containing spores.

Infections of these types are very important in hospitals and other building environments with highly susceptible occupant populations. However, infective agents have only infrequently or rarely been shown to cause disease in commercial and public buildings.

One of those infrequent but nevertheless prominent examples of airborne infection caused by micro-organisms in buildings is legionellosis. For the most part, legionellosis has been associated with infiltration into the building environment of aerosols containing *Legionella pneumophila* from external sources such as a cooling tower. Some disease outbreaks have been shown to be due to transmission of this bacterium by the HVAC system. Infective micro-organisms may also be disseminated into the indoor environment through use of hot tubs (e.g., dermatitis caused by *Pseudomonas* spp.), whirlpools, and cool mist vaporizers. Control of infective organisms as well as allergens in the indoor environment is best achieved by proper attention to the reservoir or source, amplification site, and mode of transmission of the agent. Thus, control of *Legionella pneumophila* aerosol that may be entering a building from a cooling tower is usually brought about by an effective maintenance program for the tower's water basin (amplification of micro-organism controlled) or by attention to HVAC system make-up air intakes that are near the tower (transmission chain to occupant broken).

OTHER ENVIRONMENTAL FACTORS THAT AFFECT SATISFACTION WITH AIR QUALITY

Lighting

In all office environments, natural lighting must be supplemented with artificial light. Many indoor environments have essentially no natural daylighting at any time and rely completely on artificial light. Proper, desirable, and effective lighting depends on two factors: the quantity of light on the work surface or in the overall environment, and the quality of the lighting. The quantity of light refers to the strength of the light source and the distance between the light source and the work surface. The human eye is able to adjust to a wide range in light intensity, but either excessive brightness or inadequate light can cause eyestrain.

The quality of the lighting refers to the absence of glare, reflections, flicker, and contrasts and to the spectral distribution of the light. There may be more lighting problems that result from too much light causing glare and reflections than from too little light. Windows often contribute to problems with glare and reflections, especially for tasks involving video display terminals, reading, or typing. Lighting problems can cause eyestrain that can result in the same symptoms (such as tearing or headaches) as are caused by poor indoor air quality. Even where the severity of the lighting problem is not so great as to be intolerable, poor lighting can reduce the ability of people to tolerate air quality problems affecting the eyes.

Noise

The effect of noise on the perception of air quality is indirect. However, noise can affect the general perception of the quality of the indoor environment. High background levels of noise can interfere with conversations and telephone use. Intermittent noises can be distracting, resulting in interruption of ongoing work. Low noise levels or poor noise control can result in conditions where conversations are overheard, the resulting lack of privacy being interpreted as overcrowding.

Dissatisfaction with the office environment because of noise can reduce the tolerance of people for all other environmental factors, including air quality.

Furniture and Equipment

Furniture and office equipment can cause a number of physical complaints that increase sensitivity to air quality problems. The worst problem may be poorly designed and nonadjustable video terminal units that can cause muscle strain and cannot be moved to eliminate glare. The resulting headaches and eyestrain can add to the symptoms resulting from air pollution and thereby decrease people's tolerance for other environmental problems in the office.

Crowding and Personal Work Space

Air quality complaints can result from an increase in the number of people in a work area. Effects can include an increase in the source of body odors (which is why the ASHRAE ventilation standard specifies the minimum level of outdoor air per person), increased thermal loads with resulting increases in temperature, decreased flexibility in furniture arrangement and the ability to reduce glare, and general lack of privacy. Even more important may be the conclusion by workers that they are not valued as employees because the management is imposing poorer working conditions on them. The resulting general dissatisfaction with the job environment may result in complaints about any of the environmental factors.

Vibration and Motion

Low-frequency vibration can be irritating, and in extreme cases can cause numbness. Motion such as that resulting from the swaying of high-rise buildings can cause fatigue because of the necessity for constant compensatory exertions and can cause symptoms of motion sickness such as nausea and headaches. These symptoms, if mild, can be mistaken for the results of poor air quality and can increase susceptibility to air quality problems.

Psychosocial Factors

Air quality is only one of a large number of interrelated factors that affect job satisfaction. In some cases, such as major asbestos problems, the presence of disease organisms, or high levels of allergens, air quality may directly affect human health, but complaints are more likely to arise from discomfort or anxiety about health effects than from actual sickness. More common is the case where air quality is only one of a number of causes of dissatisfaction with the job environment. Whether the workers complain about air quality (rather than some other environmental factor) depends on a number of factors, including motivation and overall job satisfaction, control over working conditions, responsiveness of the management (and feared penalties for complaining), the relative importance of air quality on the list of environmental problems, and a consensus that air quality is the important problem.

Air quality problems will be more tolerated by people who have control over temperature, air flow rates, furniture placement, lighting, etc., and if there are no sensitizing problems such as glare, noise, or lack of privacy.

It is more likely that there will be complaints about air quality if they are addressed to a responsible person who cannot retaliate, such as the building management, instead of one's boss. Also, it is more likely that there will be complaints about air quality when media attention on "air quality problems" develops a consensus among a group of people on the relative importance of this issue. Air quality is more likely to become an issue when the complaints are rejected. Responding positively to complaints can increase feelings of self-worth and tolerance to minor problems.

Air quality complaints are almost always exacerbated as a result of squeezing more clerical workers (who have no control over their jobs or working conditions) into less space, a management that is not responsive to the whole range of job-related problems, and a management that directs complaints about air quality to a third party, such as the building manager, who cannot retaliate against the complainers.

THE LIMITS OF TECHNOLOGY

The most difficult air quality problems occur in buildings where, by all commonly used objective measurements, the air does not contain any contaminants that present a health risk to the workers or can account for their complaints. In these cases, factors other than air quality must be considered. The following represents a typical situation:

> A large building is occupied by several government agencies, and certain areas are devoted to clerical work. Over the past several years, the amount of work has increased, resulting in additional people being hired and being added into the clerical area by moving the desks closer together. In addition, extra file cabinets have been installed, and many of the desks now have computer terminals. Because the work continues to increase, the supervisors are experiencing pressure to improve productivity.

From the viewpoint of the clerical workers, the job conditions have become more crowded, hotter, stuffy, and stressful. The computer terminals were installed on existing desks, and there is glare on the screens and the chairs just don't feel right. The supervisors are not sympathetic because there is pressure on them to get the work out and no money in the budget to make any changes. General job dissatisfaction is increasing, and complaints increase. Since the line supervisor can't solve the problem, blame may shift to the building management. Attention is particularly likely to be focused on air quality if there is a cluster of colds or other additional stress, such as a worker who smokes or wears heavy perfume.

By general consensus, there is now an air quality problem. Objective measurements will show that certain areas are too warm and get less air movement than specified by ASHRAE standards, and they may find somewhat elevated levels of carbon dioxide and perhaps other irritants. Rebalancing the air system will reduce these local variations and may bring the ventilation up to ASHRAE requirements, but this may not render the workplace acceptable to the workers if psychological and social factors are not adequately addressed.

The problem has become useful to the workers as a social focus. It has brought the workers together with a common problem, and to the extent that their complaints are addressed, it has ameliorated their feelings of individual and collective helplessness.

The variability in occupant response places a limit on the ability to satisfy all occupants of a zone. There will always be a small fraction of workers who can validly complain if they are so motivated. For example, research indicates that conditions required to satisfy the maximum percentage of occupants will still result in 5 percent of the population not being satisfied. These people are the nucleus upon whose complaints attention can be focused. If the conditions stimulating such focusing are not addressed, no amount of adjustment of the air-handling system can cure the basic problem. However, failure to respond directly to complaints about indoor air quality will assure that the complaints will continue.[2]

3

PROCEDURES FOR DEALING WITH INDOOR AIR QUALITY PROBLEMS

Sources or causes of indoor air quality problems may be simple or complex. An outline of procedures for dealing with such problems must therefore recognize a wide range of possible tactics, only a few of which may need to be employed in a given building situation.

This chapter sets out an approach for solving indoor air quality problems in buildings. First, a means for recognizing the problem is described, broken into the two major areas of likely professional activity--architecture and HVAC engineering. This is followed by two sections concerned with problem evaluation--evaluation of system performance, and comparison with existing conditions. To assist in this evaluation, the next section covers standards and criteria that apply to the indoor air quality area. Finally, some recommendations are offered to help in determining if a problem-solving effort meets the applicable criteria.

Much of what is discussed in this chapter will sound familiar to those who work with buildings. In many instances good design practice, good construction practice, and good operation and maintenance practice are just what is needed to assure good indoor air quality. We have selected and emphasized the practices that are particularly important in the area of indoor air quality and have accompanied these with numerous recommendations, guidelines, and criteria that have been developed from recent indoor air quality research. In combination, this gives as current a level of guidance as can be offered.

ARCHITECTURAL CONSIDERATIONS

The structure, performance, and evaluation of existing buildings has been described by the Building Research Board's publication, "Building Diagnostics: A Conceptual Framework".[10]

Physically, a building is made up of a load-bearing structure, an enclosure or shell that separates the building's interior from the external environment, an interior space, and a variety of service systems. The load-bearing structure consists of the foundation, frame, load-bearing columns and walls, beams, girders, trusses, etc. The enclosure consists of the roof and exterior walls (both above and below grade) and such other features as exterior windows and doors, balconies, etc. The interior space is the usable space within the building. It is the space actually available to the building's occupants for their activities. Its configuration is determined by the interior walls, floors, and ceilings, and it contains furnishings and equipment (furniture, machinery, carpets, drapes, lighting, traffic and noise barriers) that give it definition. A portion of this space is used to house electrical wiring, ventilation ducts, plumbing, elevator shafts, and other elements of the building's service systems. These systems serve both to maintain the desired environment within the interior usable space and to provide the facilities, services, and amenities needed to support the building's activities.

There are performance characteristics associated with each of these building elements. For example,

• The exterior enclosure (outer shell) must not permit excessive passage through it of air, water, heat, or noise.

• The interior environment (temperature, humidity, air movement, air quality, illumination, noise) must be appropriate to the activities conducted within the building.

• There must be facilities and services (heating, air conditioning, electric power, communications, water, waste disposal, freight elevators) necessary for the building's activities, and the systems providing these services must function properly.

Performance characteristics in these different areas cannot be treated independently of each other for two reasons. First, they are related in a complex manner through their physical, physiological, psychological, sociological, and economic implications. Physical implications have to do with structural strength, resistance to forces, chemical interactions, etc. Physiological implications pertain to the physical health and safety of the building occupants and the need to protect basic bodily functions--seeing, hearing, breathing, feeling, moving, etc.--from such conditions as fire, building collapse, poisonous fumes, high and low temperatures, and poor light. Psychological implications have to do with supporting the building occupants' mental health through appropriate provisions for privacy, interaction, clarity, status, change, comfort, etc. Sociological (or sociocultural) considerations involve supporting the well-being of the community within which the individuals act and relating the needs of individuals to those of the group. Economic implications affect the allocation of resources in the most efficient manner to serve user needs.

Second, in trying to fulfill one set of performance requirements, side effects may arise that impinge on the fulfillment of another. A ceiling light fixture may give forth heat and noise as well as light. The ventilation rate chosen to achieve acceptable air quality may adversely affect thermal and acoustic comfort. Although a particular building component may provide adequate performance in one context, it may fail in others.

An important and valid aspect of an existing building's performance is the aesthetic expression (both externally and internally) of the functional requirements and aspirations of those who developed it. Among other things, satisfactory performance in aesthetic expression contributes to the users' sense of appropriateness or "rightness" of a building to meet performance requirements. Such appropriate aesthetic expression is as valid for an Army barracks as it is for a courthouse, although the design result may be vastly different. Aesthetics is not suggested here as a characteristic that directly bears on indoor air quality issues, but it is an important aspect of a building that may interactively relate to building elements associated with indoor air quality problems or to the building users' sense of satisfaction with the work environment.

One area of specific interest to those concerned with indoor air quality is the contaminant emission rates of various problem materials. This information is not easy to come by. Many manufacturers of pressed wood panel products, furniture, carpeting, fabrics, finishes, and adhesives have tested their products for emissions. This information is not normally provided to architects or building owners, but on large contracts it may be possible to obtain it if strong pressure is put on the vendor. The Environmental Protection Agency currently is preparing a data base on emission rates for a number of important materials. This information should be helpful in making comparative evaluations between materials for a given application. For example, various types of particleboard or plywood underlayment could be compared for formaldehyde emissions before specifications are written.

Emission rates, however, must be used with care because they are only one factor in determining potential contaminant impact on an occupied space. Numerous other factors must be considered, including area of the exposed surface as a function of room volume, any permeation barriers (i.e., covering materials such as plastic films or finishes), and ventilation rate and effectiveness.

VENTILATION SYSTEM REQUIREMENTS

For the purposes of this report, it is assumed that building systems were designed according to the standards that prevailed at the time the building was constructed. An appropriate system should supply at all times at least the minimum quantity of outside air for ventilation. For the purposes of this report, the minimum outside air quantity is defined as that required by the latest edition of ASHRAE Standard No. 62 or by local code (if the agency that owns the building chooses to follow the code, although this may not be legally required), whichever is greater. This outside ventilation air must be properly distributed so that it is not short-circuited to the air returns or air exhausts without first being delivered to the room occupants. An air diffusion performance index (ADPI) or a ventilation effectiveness rate of at least 80 percent should function as a guideline. An ADPI of at least 80 percent implies that less than 20 percent of the occupied space will have thermal draft or air stagnation.

The system should provide the proper supply air flow rate to act as a carrier and the means for distributing the outdoor air used for ventilation (Figure 3). The implications of this requirement are that the total air flow rate not only must satisfy the thermal requirements of ASHRAE Standard 55, latest edition, but also must properly distribute the outside ventilation air.

It is important that the system employ the proper means of filtering out particulate matter that is carried in both components of the air supplied to the occupied space--i.e., outside air for ventilation and

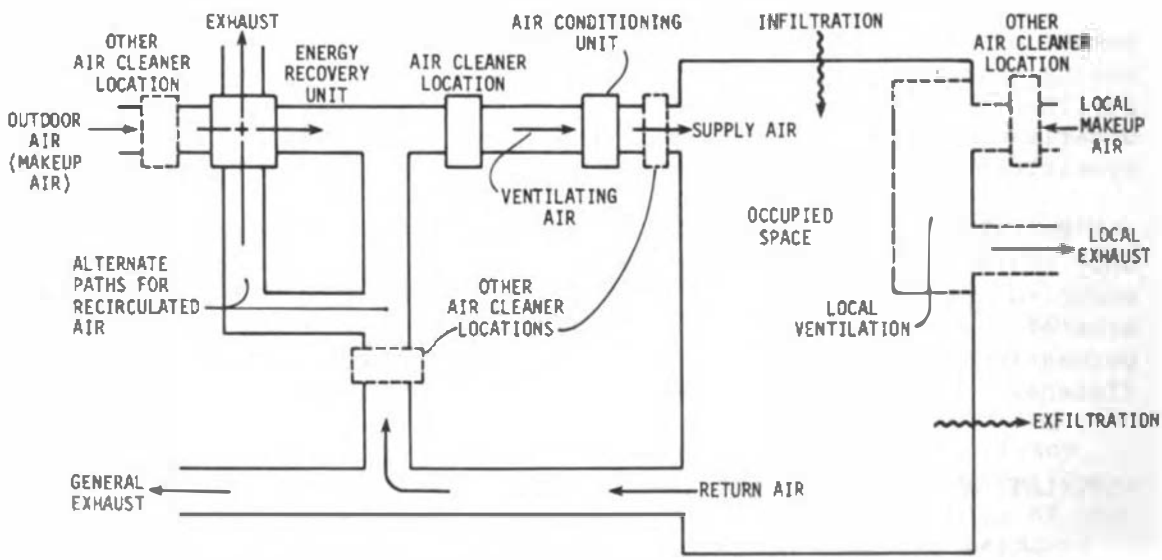

FIGURE 3. Ventilation System. SOURCE: ASHRAE Standard No. 62-1981, Ventilation for Acceptable Indoor Air Quality.

recirculated air. The system should also employ proper air cleaning, if required, of gaseous or vaporous matter that may be carried in the outside air supplied for ventilation and in the recirculated air (e.g., activated aluminum or charcoal filters).

To minimize the entry of locally produced contaminants into the occupied space, the system should provide local exhausts whenever required. These may be standard local exhausts, such as toilet exhausts and cleaning closet exhausts, or they may in fact be more specialized exhausts, such as fume hood exhausts or kitchen range hood exhausts. The ASHRAE Handbook and the ACGIH Industrial Ventilation Handbook should be used as guidelines.

It is important that the location of the system's outside intakes minimize the induction of contaminants such as automotive exhausts from street traffic, boiler exhausts from chimney discharges, fume hood exhausts from building internal processes, cooling tower discharges, and exhausts from other buildings. The ASHRAE Handbook should be used as a guideline. Similarly, particular attention should be given to the location of exhaust air discharges to prevent recirculation back into supply air intakes. This will require some explicit attention to prevailing wind directions and air flow patterns that may be created by adjoining structures.

If the system requires humidification, the humidification process should be limited to the direct injection of steam. Furthermore, particular attention must be paid to the treatment of makeup water utilized in the steam-generating process so that the steam injected carries with it no deleterious contaminants or additives. If the humidification system installed in an existing building is in fact not the type described here and it is impracticable (for economic, space, or other reasons) to change the system, the procedures called for in the following paragraph become even more important.

All systems should permit ease of maintenance and operation, and it is crucial that, once the system is installed and functioning, there be a skilled maintenance staff to operate and maintain the mechanical and electrical systems properly. Not the least of such maintenance procedures are those that assure that all water-containing vessels (condensate pans, etc.) and surfaces are kept clear of any growth and accumulation of biological and chemical contaminants. In addition, it is important that the operating staff understand the implications for indoor air quality of the procedures employed to conserve energy during the operating day (such as early-morning startup procedures, end-of-the-day shutdown procedures, and duty-cycling procedures). Building startup procedures must be such that they not only provide the proper thermal environment when the space is initially occupied but also provide the proper indoor air quality environment. The latter may be achieved by flushing the building for a sufficient length of time using the maximum amount of outside air practicably available, as limited by system design and the economics of operation. Also, indoor air quality should not be jeopardized during operating hours by excessive "off periods" for air-handling apparatus to save energy or by too early shutdown of air-handling equipment at the end of the day. ASHRAE Standard 62, latest edition, includes acceptable methods to handle these cases.

It is important that proper attention be paid to the design, installation, and operation of specialized systems that require differential pressure control between adjoining occupied spaces to prevent the migration of room-developed contaminants. Explicit examples of such installations are those commonly found in hospitals and other specialized buildings. Guidelines may be found in Health Resources and Services Administration publications.

It is also important that attention be paid to the proper mounting of machinery, the proper selection of duct sizes and pipe sizes, and the proper installation of acoustic attenuators within and around ductwork and piping so that the occupied spaces are not subject to disturbing sound and vibration. Although noise and vibration do not affect air quality as such, they nonetheless increase the frequency of complaints about the indoor environment.

EVALUATION OF SYSTEM PERFORMANCE

Three important concepts in assessing performance are suitability, reliability, and flexibility. Suitability is a measure of the degree to which a building, a building system, or a component meets user needs. Reliability is a measure of the probability that a building system or component will continue to perform as intended throughout the life of the facility, given appropriate maintenance and use. Flexibility is a measure of the foresight of the building designer in providing for changing functions and occupancies during the building's lifetime.

Suitability has three distinct aspects. The first involves the capability of the structure and interior spaces to meet the stated purpose of the building. The second involves the ability of a building's systems to remain functional under anticipated external conditions (severe winds, earthquakes, floods, adjacent excavations) and the capacity to integrate harmoniously with its surroundings (not only aesthetically but also in terms of such social factors as transportation, commerce, and crime). The third aspect involves suitability with regard to health, safety, and the public welfare, as reflected in laws and regulations.

Reliability depends primarily on the adequacy of the design, the appropriateness of the choice of materials and construction techniques, the quality with which building components are manufactured and assembled, and the diligence with which the building is maintained.

Flexibility depends largely on the foresight of the designer in anticipating trends that might require changes in the building's use or in the way in which its intended activities are carried out.

The suitability of a building's air diffusers, for example, depends on the total air flow rate they provide, their location with respect to ceilings, floors, walls, windows, furniture, and partitions, the occupant density and occupant activities at various times of day, the temperature of exterior surfaces, and the diffusers' interference with acoustic and lighting comfort. The reliability of the air diffusers depends on the quality of their components--vanes and dampers--and the maintenance effort that can be reasonably expected, including cleaning schedules, etc. The flexibility, or adaptability, of the air diffusers reflects the level of effort and resources necessary to sustain suitability when the activities carried out in the building change. New activities may require different physical arrangements of walls, partitions, and furniture, different occupant densities, or different work activities (e.g., use of video display terminals), all of which may lead to different requirements for air diffusers.

To achieve overall acceptable performance, therefore, it is necessary first to resolve conflicts and set priorities based on the use to which the building is to be put. Then choices must be made using performance evaluation techniques that consider the complex interrelationships that arise in the specification, installation, and use of different materials, components, and systems within the building.

Finally, the availability of resources (financial, technical, and material) imposes another layer of requirements, establishing limits of feasibility alongside the limits of acceptability. Decisions must be tempered by a full understanding of the need to manage resources over time, evaluating allocations for initial outlay, operating costs, maintenance costs, eventual replacement or conversion costs, and associated personnel costs. More specifically, the following procedure is recommended for assessing the architectural aspects of building performance that may bear on indoor air quality.

First, consider some key factors from the recent history of building construction practices. The project being examined may date from a period of time when certain construction practices that can affect indoor air quality were common. A project may contain building wings or levels of different age or major remodelings that were done at different times. A few characteristics to note are these:

- Asbestos--Originally introduced as pipe and boiler insulation, with major use in the 1930s, asbestos was also installed for fireproofing from 1958 to 1972, when its installation was banned. Vinyl asbestos tile was introduced after World War II and continues to be used.

• Formaldehyde--The use of formaldehyde began during World War II and continues today. It is heavily used in particleboard and plywood and was formerly used in ureaformaldehyde foam insulation. It is also used in fabrics, fiberglass insulation, and ceiling tiles.

• Plastics--With the exception of cellulose-based plastics (infrequently used in building construction), most plastics also appear no earlier than the World War II era. The increase in general use has been great, but use in buildings has lagged behind general applications. Early difficulties (1950s and 1960s) were experienced with the fire properties, particularly of suspended ceiling panels and carpets.

• Tight buildings (low infiltration rates)--Improved quality of construction, including better window gasketing and better caulking and sealing details, stems from the late 1970s.

• Low ventilation rates--Rates of ventilation as low as 5 cfm per person were allowed by ASHRAE Standard 62 in 1973.

Second, review the building's history. Obtain as much of the original (as-built) documentation on the building as possible, including drawings, specifications, shop drawings, and operation and maintenance manuals. Reconstruct the changes that have occurred up to the present time, including additions, major remodeling, and significant maintenance change-outs. A number of areas and key points should be checked:

• Room use--Are rooms properly designed for the intended function? Measures include occupant density (floor area per person); work station arrangement (graphic standards, GSA guidelines, etc.); proportions (a very subjective measure), such as low ceilings or a space that is too narrow; and tasks (are new tasks being performed in the space that differ from those planned for in the original design?).

• Adjacencies--Are walls, ceilings, and floors properly designed to give adequate separation of activities to control temperature, air movement, odors, noise, light, vibration, etc.? Are circulation paths adequately designed to provide appropriate separation of occupancies (e.g., vestibule entries to outdoors, to dusty areas such as shops, or to print rooms)?

• Fire protection--Have partitions or fire walls been added? Has exiting been changed? Have materials or ventilation systems been changed?

• Building structure--Is the structure the source of indoor air contaminants (e.g., pentachlorophenol preservative-treated wood structures)? Does the structure allow unacceptable vibration or movement (sway) or produce or allow unacceptable noise conditions (whistle, vibration, wind creak)?

• Building envelope--Have windows been sealed up or replaced, thereby reducing infiltration? (This may indicate a need for increased mechanical ventilation.) Have windows or doors been removed and replaced with solid wall material? (Again, additional ventilation may be required.) Have windows or doors been added, affecting infiltration? Have opaque walls been changed, with added insulation or recladding? Has the roof been changed, with insulation added, etc.? Are there any recently installed caulks or sealants that could be the cause of emission problems?

• Interiors--Have internal openings been made for doors, ducts, pipes, wiring, or other purposes that could contribute to indoor air quality problems? (Such openings can be the pathway for dust, dirt, and vapors from other spaces.) Have floors been altered, such as new raised floors, new underlayment with sheet flooring, or new carpeting? (Particleboard underlayment may be a source of formaldehyde emissions, and carpet adhesives can also be the source of emissions.) Have walls or partitions been added or altered with forms of construction that could introduce problem emissions? (Numerous materials should be reviewed: paneling of particleboard, plywood, plastic surface coverings, paints, adhesives, gaskets, sealants, insulation, and fabrics.) Have ceilings been altered or added? (Items of interest are ceiling tiles and insulation materials.)

• Furnishings--Have new furnishings been installed? (Aspects to consider are particleboard, fabrics, plastic surfaces, adhesives, finishes.)

Once the architectural aspects of the building performance are assessed, the next step is to address specific conditions that concern indoor air quality. To begin, there should be a review of the design drawings and specifications to verify that the performance methodology outlined earlier is met by the design. There should be a review of the shop drawings and/or the as-built drawings to verify that these drawings, in fact, comply with the design drawings.

Particular attention should be given to the zoning arrangements to ensure that control action on any given zone, although satisfactory for that particular zone, will not have detrimental effects on any other zone. This requirement is distinct from pressurization and smoke control. Also, particular attention should be given to the schematic layout and control arrangement for all variable-air-volume (VAV) systems to ensure that the performance characteristics will be maintained under low load conditions. Particular attention should be given to the population loadings in the various zones within each air supply system to avoid lack of proper ventilation in heavily populated areas and to ensure that outside air ventilation is properly distributed without using excessive energy to heat or cool sparsely populated areas.

The application of water-source heat pumps should be examined carefully. It is crucial that these be installed so that there is proper distribution of both outside ventilation air and total air and so that the environment will not be acoustically objectionable. Unless such systems are designed and installed with great care, the desired results will not be achieved.

Careful attention should be given to the application of "load-shedding" procedures when used to achieve cost savings by "peak shaving." Peak shaving is a term used to mean the reduction of utility (usually electrical) short maximum-demand load conditions when such conditions result in inordinate billing as a result of existing rate structures. The peak shaving is achieved by load shedding, a procedure by which selected pieces of equipment are arbitrarily shut off when system demand loads reach high peak conditions. It is important that load-shedding routines be set so as not to result in unsatisfactory indoor air quality or thermal discomfort.

COMPARISON WITH EXISTING CONDITIONS

Once a review of the design drawings and specifications is completed, there should be an on-site inspection of the actual conditions to verify that the installation is in fact consistent with the design, that the actual use of the space is consistent with that for which it was designed, and that proper maintenance and operating procedures are being observed and followed.

In certain circumstances, the performance of appropriate measurements may be required to confirm or elaborate on the findings of a walk-through inspection. Two types of measurements are usually made--environmental and HVAC system performance. Methods associated with the two types of measurements and selected for discussion here have been chosen on the basis of their sensitivity, specificity, accuracy, precision, reliability, simplicity, amenability to field use, widespread use, and cost. The methods selected are also nonintrusive and can be either passive or active (active methods require the use of ancillary equipment such as air pumps; passive methods do not). Emphasis is placed on the inherent difficulties to be expected during monitoring in the indoor environment and those associated with interpretation of results. It should be noted that these tests can also be quite expensive.

Thermal Factors

Thermal comfort is a function of several variables, including air temperature and velocity, humidity, radiant temperature, occupant activity level, and the insulation provided by clothing. Measurement of the quality of the indoor thermal environment is often accomplished with a thermal comfort meter--in essence, a portable, battery-powered instrument that senses environmental conditions via a transducer and yields operative temperature readings. Two parameters are preset--namely, the thermal insulation of clothes, expressed in clo units, and the activity level, expressed in met units. Both values are estimated. The meter combines all factors, and it can be read directly or recorded. The measurements provided are values of operative temperature--that is, the value of air temperature that would result in the same heat loss from a person by convection and radiation as in the actual environment if air temperature and mean radiant temperature were equal. In essence, the meter integrates the influence of air and mean radiant temperature. The stated precision for these instruments is $\pm$ 0.2°C for operative temperatures ranging from + 5°C to + 40°C. Some meters also provide other thermal comfort indices that may be useful in performing this assessment, such as the predicted mean vote (PMV) and the predicted percentage dissatisfied (PPD).

At air speeds of less than 0.4 m/s or 80 fpm and in the absence of radiant fields such as those generated by direct sunlight or cold surfaces (noninsulated windows), air temperature tends to approach operative temperature. In most indoor spaces the air velocity will be less than 0.4 m/s and the temperature will be above the operative value. The ASHRAE-ANSI Standard 55-1981 and Chapter 8 of the ASHRAE Handbook (1985) describe details of the measurements and calculations that should be made in instances of nonuniform environments and the quantitative assessment of such environments.

Since humidity can also affect the health and well-being of building occupants, it is usually measured along with operative or air temperature. Its measurement is relatively simple and is accomplished with a psychrometer or a thermohumidigraph.

Organic Contaminants

Organic compounds have many sources in the indoor environment and vary widely in physical and chemical properties, in chemical and photochemical reactivity, and in concentration. As a group they are not amenable to the use of a single universal monitoring approach.

Volatile organic compounds such as toluene and trichloroethylene can be sampled on sorbent material with an air pump. The sorbent selected will depend on the chemical and physical properties of the air contaminant samples. The substances collected are desorbed either thermally or with an appropriate solvent and are analyzed by gas chromatography or by gas chromatography-mass spectrometry. The latter method provides a positive identification of a target substance. Volatile organic compounds can also be monitored on-site with a portable gas chromatograph or photoionization detector. However, these instruments are rather sophisticated, their calibration is difficult, and they are relatively expensive.

Less volatile organic compounds such as polyaromatic hydrocarbons (PAHs) and polychlorobiphenyls (PCBs) require a different sampling approach because most of these compounds can exist as both particulates and vapor. The collection of both is usually accomplished with a glass or membrane filter followed by a sorbent. The analytical procedure is similar to that described for the volatile organic compounds.

Interpretation of the results is invariably difficult because organics are present in large numbers indoors at concentrations that rarely exceed the parts-per-billion range. Several approaches have been used. Target compounds representative of their class--e.g., toluene for aromatic hydrocarbons--or important sources such as nicotine for tobacco-smoke-related organics have been singled out for measurement. Alternatively, an estimate of the total organic fraction can be made. For several reasons, both approaches are less than satisfactory, but they can provide data that can be compared to those collected in reference spaces and outdoors.

Gases

Several gases are found in the indoor environment of modern office buildings, and the main source for some of them is outdoors. These gases include carbon monoxide, carbon dioxide, nitrogen dioxide, ozone, and radon.

Two of these gases--carbon monoxide and carbon dioxide--are amenable to simultaneous monitoring on a continuous basis with an infrared analyzer equipped with long-path optical cells. The analyzer is based on the absorption of infrared radiation at a wavelength specific for each gas. The instrument requires infrequent calibration and has the requisite sensitivity for all gases.

Alternatively, all gases, including nitrogen dioxide and ozone, can be measured individually on a continuous basis with dedicated instruments. Thus, carbon dioxide and carbon monoxide can be monitored with nondispersive infrared analyzers. Ozone and nitrogen dioxide are measured with instruments based on the principles of chemiluminescence. Carbon monoxide and nitrogen dioxide are also monitored with electrochemical analyzers. These instruments can detect the gases at concentrations of concern for indoor air quality evaluations. They are portable, rugged, and simple to use and have fast response time and few interferences. One major disadvantage is cost, which may be prohibitive.

Formaldehyde

Most systems available today to monitor formaldehyde, either actively or passively, are based on the chromotropic acid method for sampling. The active sampling procedure requires the use of glass impingers filled with an absorbing solution (1 percent sodium bisulfite) connected to an air pump. A passive sampler based on the same principle is also available and yields comparable results. The reported accuracy for these methods is ± 15 percent. However, the method does have analytical and sample preservation problems.

An alternative continuous monitoring instrument is available that is based on a modified Schiff procedure. The minimum detection limit is 10 ppb--i.e., about one-tenth of the odor recognition threshold--and it has an accuracy of 5 percent full scale. However, cost may be a problem.

Particulate Contaminants

Particulates in the indoor environment may be monitored gravimetrically or by counting. In view of the relatively small amount of particulates usually present indoors, the common gravimetric practice of collecting the dust on preweighed filters with an air pump is not advisable. Continuous monitoring instruments operating on the basis of the piezoelectric effect and giving results directly in micrograms of respirable dust per cubic meter would be more useful. However, this technique does not provide an analysis of the distribution of particle sizes.

An alternative approach is based on the collection of the particles on a membrane filter and their subsequent counting by optical or electron microscopy. The results are reported as number of particles per unit volume of air. Asbestos fibers are monitored in this fashion. This approach at best affords a crude characterization of particles into fibers and nonfibers and can further allow their characterization as to size. The collection of dust samples on filters has a distinct advantage in that it allows the chemical characterization of particles directly on the filter by X-ray diffraction spectrometry.

Instruments are available that continuously monitor particles on the basis of size and report the results as number of particles per size classification. The instruments use the principle of light scattering to achieve these measurements.

The gravimetric approach is distinctly favored when results are interpreted, since most standards available for the indoor environment are at present expressed as micrograms per unit volume of air. However, as mentioned earlier, this approach does not allow the characterization of the particulate. A combined approach would probably be desirable.

Biological Agents

At present there is no consensus as to the most appropriate manner to sample micro-organisms. Some methods favor the sampling of only so-called viable particles, the most widely used technique being the "settling plate" method, in which a dish of culture medium is set out uncovered for a certain period of time. However, this method does not collect representative samples (heavier particles are overrepresented), and it is not quantitative. A large number of cultural sampling devices are available that separate the particles as to size. However, viable sampling, even under the best conditions, can underestimate actual levels. Furthermore, only living organisms are taken into account, and for hypersensitivity conditions viability is probably not important.

An alternative approach uses particulate sampling, as described earlier for particulate matter, followed by a visual assessment. However, this approach is limited to particles such as fungal spores that are morphologically recognizable, and this is enormously restrictive.

The monitoring of biological agents has a further complication in that, even if one were to obtain reasonably accurate and representative results, there are at present no available norms on which to base an interpretation of the results. For these many reasons, the ACGIH has recently recommended that biological agents be measured in indoor air only when medical evidence indicates they are present.

Radon

Radon progeny can be sampled either actively or passively. For active sampling, a membrane filter and a battery-operated air pump are used to collect particulate matter to which the radon progeny are attached. After a certain time has elapsed (determined from Kunetz factors), the filters are counted with a radon detector, essentially an alpha scintillation counting chamber. The counts obtained are related to picocuries per liter (pCi/L), and these in turn are reported as working levels (WL); 0.037 nuclear transformations/second/liter = 1 pCi/L, and 1 WL = 100 pCi/L.

Passive sampling is accomplished with commercially available passive monitors and canisters that contain material sensitive to alpha particles emitted by radon and its progeny. These integrate exposure for days, months, and even for a whole year. The monitors are returned to the manufacturer for determining the total radioactivity to which they have been exposed. The precision of this technique is ± 10 percent for 0.02 WL per month.

Both active and passive sampling are straightforward and require no special training. The interpretation of results presents no particular difficulty.

HVAC System Performance

Heating, ventilating, and air conditioning practices that can cause building occupant stress include, but are not limited to, air contaminant migration between areas, poor air distribution, exhaust air re-entrainment, micro-organism build-up in HVAC system components, and insufficient supply of outdoor air. An environmental diagnostic approach to an indoor air problem requires qualitative and quantitative assessment of all these parameters. Such an evaluation would make use of tracer gas techniques as well as more conventional methods of verifying the performance of mechanical ventilation systems and would take into consideration meteorological factors.

Tracer gas techniques include the decay rate, equilibrium concentration, and transfer index methods. These are based on the release of a carefully selected gas into the space under investigation, either spontaneously or at a constant rate, and its measurement at the site of release and at remote sites to evaluate various facets of a ventilation system's performance. The tracer gas selected must meet stringent requirements. These include low toxicity, nonflammability, chemical stability, nonreactivity, low absorptivity by building materials and furnishings, low background concentrations, detectability at low concentrations, ease of measurement, cost, and availability. Several gases meet some or most of these requirements; one commonly used is sulfur hexafluoride. More conventional methods of performing mechanical ventilation system measurements include pressure-measuring devices such as inclined manometers, velocity meters (Pitot tubes, hot-wire anemometers), and mechanical gas flow indicators (rotating vane anemometers).

The HVAC system design drawings must first be carefully studied to determine the type and configuration of components, including the number, location, and size of outdoor air intakes and building exhausts. This should be followed by a carefully conducted on-site inspection of the HVAC system to determine its present status, including the maintenance schedule, the number, type, location, and size of floor inlets and outlets, and other pertinent information. Once familiarity with the HVAC system is gained, the relationship, if any exists, between the system and the problems at hand can be defined. Approaches to various potential HVAC system-related problems are discussed in the following paragraphs.

Contaminant and/or odor migration are the result of differences in pressure between building areas. Such pressure differentials exist in most multiarea and multistory buildings served by more than one ventilation system. In laboratories and hospitals such pressure differentials are maintained to contain contaminants in low-pressure areas.

Contaminant or odor migration can be visualized with smoke indicators. However, this technique is, at best, qualitative. A quantitative assessment of this parameter is obtained through the use of tracer gases. The tracer gas is released at a constant rate at the site suspected of having a primary source of contamination and its appearance is measured in occupied spaces where exposure is of concern. Such a procedure can yield relative exposure indices (REIs) and transfer indices that quantify contaminant migration.[16] This approach has been used to evaluate vehicle exhaust ingress into office areas from underground parking areas and the migration of gases and vapors from laboratories to adjoining offices.

Building exhaust re-entrainment is characterized by the detection of odors of contaminants in areas remote from their sources. This problem also tends to be episodic--that is, it may tend to appear and disappear on the same day or from day to day as it is affected by wind direction or transient sources such as vehicle exhaust.

A careful examination of the location of the building's inlets and exhaust outlets with respect to each other and to those of adjoining buildings would be a preliminary step in this evaluation. Thereafter, a tracer gas is released into the exhaust system at the source area at a constant rate, and its appearance in the complaint area and at the building air inlet is measured. The presence of the tracer confirms its re-entrainment. The severity of this re-entrainment can be quantified. Such an evaluation should be performed on days characterized by different wind directions. This type of problem is common in buildings that accommodate both office areas and laboratories or industrial processes.

Insufficient supply of outdoor air occurs because most HVAC systems recirculate return air. The percentage of recirculation is usually dependent on the indoor-outdoor temperature relationship. Thus, higher percentages of recirculation are observed when the temperature difference is great and lower when it is small. ASHRAE recommends in its Standard 62-1981 various outside air ventilation rates for occupied spaces. The amount of outside air should not fall below the rate recommended. Unfortunately, this is often not the case, for a variety of reasons. Although it is possible to determine the rates with conventional methods by measuring airflows of outside air intake, the HVAC system main air supply, and the air supply to the space investigated, these measurements may on occasion be difficult to perform. For instance, there may not be sufficient access to allow the measurements to be made. One alternative is to determine the thermal energy balance between recirculated air, outside air, and the supply air streams to obtain the percentage of outside air in the supply system.[16] However, this approach assumes efficient mixing of supply air in the occupied space, which is not always the case.

Another alternative is the tracer gas decay method. Thus, a homogeneous equilibrium concentration of the tracer is established in the occupant space, and its decay rate is monitored. The occupant space ventilation rate (e.g., cfm/person) is calculated from the data obtained. An interesting version of this test makes use of "in situ" carbon dioxide generated by the occupants. The test is initiated at the end of the work day when all the occupants have left the building. The ventilation rate is determined from the decay of the carbon dioxide. The test is simple and does not require sophisticated equipment.

Inadequate room air distribution may be characterized by localized complaints of stuffy air from occupants of certain parts of a floor. Adequate room air distribution should provide acceptable thermal conditions, suppression of air contaminants, and acceptable air for respiration. The effectiveness of supply air distribution to all parts of an occupant space can be evaluated in terms of the air diffusion performance index (ADPI). It is based on the ability of supply air to dissipate heat from an occupied space, but it can also serve as an index for evaluating the uniformity of thermal conditions of the air throughout a room. A minimum ADPI of 75 percent has been proposed. However, the ADPI is considered to be insufficient as an overall evaluator of room air distribution. The "within-room" ventilation efficiency index can provide such an evaluation.[16] It is expressed as a function of the percent of recirculated air and a stratification factor. Tracer gases are used in this latter determination. The tracer gas is introduced within the supply air duct to the room, and the decay in concentration is measured in the return air duct from the room. A minimum value of 80 percent has been proposed for this index.

Although the tracer gas techniques are very useful to the evaluation of the performance of a ventilation system, they have one important drawback. The methodology for conducting the tests requires further development. At present there are no standard methods for releasing the tracer gas, there are no adequate methods for collecting tracer gas samples, and the method used to measure tracer gas concentrations--gas chromatography--is somewhat sophisticated and requires trained personnel to operate. It is felt, however, that when these difficulties are overcome the technique will be indispensable to the evaluation of ventilation systems.

PERFORMANCE CRITERIA

Performance criteria, as presented in this section, provide a basis for evaluating the performance of a given building during an indoor air quality investigation. A useful listing of standards, regulations, and other technical criteria relating to indoor air quality, including a brief summary of each document's content, has been prepared by the National Institute of Building Sciences.[11] A current set of research-based guidelines that cover ventilation systems, pollutants, and human factors is also available.[12] A number of important specific criteria are described in the following paragraphs.

Temperature

ASHRAE has recommended the temperatures shown in Table 3-1 for thermal acceptability (comfort) of sedentary or slightly active persons at 50 percent relative humidity. The standard (ASHRAE 55-1981) specifies conditions in which 80 percent or more of the occupants will find the environment thermally acceptable. The standard further specifies the combination of factors necessary for thermal comfort in a built environment. It takes into consideration current seasonal clothing habits; introduces limits on the thermal nonuniformities in a workplace such as drafts, temperature variations, and radiant asymmetry that can cause local discomfort; includes temperature adjustments for activity; and allows for higher temperatures in summer if air movement is correspondingly increased.

It should be understood that occupants' satisfaction with their thermal environment is subjective and depends on many interacting variables. Design and construction of the occupant space as well as heating, cooling, ventilation, and controls will have an effect.

Humidity

The ASHRAE standard (55-1981) considers that the acceptable range of allowable dew point temperature in an indoor environment is between 32° and 60° F.

TABLE 3-1. Temperatures Recommended for Thermal Acceptability

Season	Typical Clothing	Optimal Operative Temperature[a] (°F)	(°C)	Operative Temperature for 80 percent Thermal Acceptability[b] (°F)	(°C)
Winter	Heavy slacks, long-sleeved shirt, sweater	71	21.7	68-74	20.0-23.6
Summer	Light slacks, short-sleeved shirt	75	24.4	73-78	22.8-26.1
	Minimal	80	27.2	78-84	26.0-29.0

[a]Weighted mean average air and average radiant temperatures; temperature that satisfies the greatest number of people at a given clothing and activity level.

[b]Slow air movement--i.e., 30 fpm (0.15 m/s) or less--and 50 percent relative humidity.

SOURCE: ASHRAE Standard 55-1981

Airborne Contaminants

The primary sources of performance criteria on acceptable exposure to environmental contaminants include NIOSH criteria documents; ACGIH threshold limit values; OSHA; ASHRAE indoor air quality standards; and EPA. The first three sources are usually used to assess industrial worker exposure to airborne contaminants for an 8-hour work day and 40-hour work week to ensure a working lifetime without adverse health effects. The remaining two standards, on the other hand, are applicable for the general population and refer to a 24-hour day of continuous exposure without known toxic effects. Norms available for some of the contaminants found in nonindustrial environments are given in Table 3-2.

Organic Contaminants

At present, there are few standards governing exposures to organic chemical contaminants in nonindustrial buildings. ASHRAE has recommended guidelines for continuous exposure for a relatively small number of chemical compounds and cites OSHA standard levels divided by 10 for all other substances if other information is not available. It should be realized that these are derived standards and are intended to be applicable to the nonindustrial sector. Conversely, ACGIH and OSHA have set standards for exposure to chemicals generated by industrial processes in the workplace during an 8-hour work day and 40-hour work week.

In the absence of specific standards for office area exposure to organic contaminants, the 1/10 threshold limit value (TLV) applied to the ACGIH time-weighted average (TWA) standards could be considered with certain reservations. The resulting standards are probably more rigorous than necessary; also, there is no toxicological basis for recommending the use of such standards for office buildings.

Particulate Contaminants

Indoor air particulates may have outdoor sources (e.g., automobile exhaust) or indoor sources, a major contributor in this instance being tobacco smoke. Particulates are usually categorized according to size as respirable (less than 3 μm diameter) and nonrespirable (greater than 3 μm diameter).

A typically reported range for total particulates of all sizes is 30 to 100 $\mu g/m^3$ averaged over 24 hours, with maximum readings of 2000 $\mu g/m^3$. The indoor/outdoor ratio typically varies from 0.3 to 0.4. The following standards have been established:

TABLE 3-2. Norms, Guidelines, and Standards for Indoor Air Contaminants

Contaminant	Recommended Concentration	Source	Typical Indoor Concentration
Carbon dioxide	≤ 1000 ppm 5000 ppm	ASHRAE[a] ACGIH[b]	< 1000 ppm
Carbon monoxide	9 ppm (8-hour exposure)	ASHRAE/EPA[c]	0.5-5 ppm
Chlorofluorocarbons	1000 ppm (8-hour explosure) 1/10 ACGIH standard	ACGIH[c] TLV ASHRAE	
Nitrogen dioxide	3.0 ppm (8-hour exposure) 0.05 ppm annual average	ACGIH TLV ASHRAE/EPA	0.01-0.53 ppm
Organic vapors	1/10 ACGIH TLV (8-hour exposure)	ASHRAE	< 1.0 ppm (component compound)
Particulate contaminants	≤ 260 $\mu g/m^3$ (24-hour exposure) < 75 $\mu g/m^3$ annual average	ASHRAE/EPA	< 600 $\mu g/m^3$
Fibers (asbestos)	0.2 fibers/cc	OSHA	< 0.1 fiber/cc

[a]ASHRAE Standard 62-1981R
[b]ACGIH Threshold Limit Values (TLV) and Biological Exposure Indices for 1986-1987
[c]EPA National Ambient Air Quality Standards

ACGIH	10 mg/m^3 (for nuisance dust, 8-hour TWA)
ASHRAE and EPA	260 $\mu g/m^3$ (24-hour exposure, not to exceed once per year)
	75 $\mu g/m^3$ (annual average)

Fibers

Fibers can include several types of mineral or organic fibrous material. The most important of these from a health standpoint is asbestos, and only this type of fiber is considered here. Asbestos can occur in many forms, including amosite, chrysotile, and crocidolite. It may be found indoors through its use as a construction material (insulation), although this use has been severely curtailed in recent years. The following standards have been established:

OSHA	0.2 fibers (75 μm optical)/cc (8-hour TWA for industrial exposure)
ACGIH	0.2 to 2.0 fibers (75 μm optical)/cc (8-hour TWA for industrial exposure)
ASHRAE	lowest feasible level

Allergens and Infective Agents

Baseline data have not been established for the numbers and kinds of airborne viruses, bacteria, fungi, and other microbial materials that may be present in indoor environments. Even if baseline data were present, it is unlikely that exposure standards based on dose-response relationships could be established for the following reasons: Human susceptibility to microbial agents varies enormously; one concentration (of allergen) may sensitize, and lower concentrations may then trigger adverse health responses; some microbial populations (e.g., fungi) vary qualitively and quantitively by season; and nonviable spores, endotoxins, and submicrometer-size particulate antigens should be considered in exposure standards. For indoor environments where exposure to nonpathogenic bioaerosols is of concern, the ACGIH Bioaerosols Committee recommends comparison of indoor and outdoor microbial populations and rank-order identification of predominant indoor and outdoor genera.[9] With this procedure it is possible to determine if the building itself is a reservoir or amplifier of microbial populations.

HVAC System

The principal sources of the complex criteria for HVAC system performance are the ASHRAE literature, primarily the Handbooks and the standards, which cover a number of components and subsystems. In general, the HVAC system should ensure the simultaneous control of the temperature, humidity, air velocity, and air quality (cleanliness) to provide the proper environment and to meet the applicable building codes on thermal conditions and ventilation for air quality. In addition, noise criteria are usually involved. Building codes in most areas are based on ASHRAE standards (55-1981 for thermal control, 62-1981 or its predecessor for ventilation, and 90-75 or 90A-1980 for energy use). The ASHRAE Handbook is the definitive guide, covering components, systems, equipment, and applications to enable designers to provide adequate design, installation, operation, and maintenance procedures so that HVAC systems can meet their intended functional use in an economical manner.

Achieving Compliance With Criteria

Approaches to remedying problems of indoor air quality associated with architectural elements are largely those that are used in conventional construction, remodeling, or repair. Determining the cause of the indoor air quality problem is the key to necessary actions. The methods and approaches outlined in previous sections will aid in this identification.

Achieving compliance with performance characteristics is a three-step process:

- Verify that the design is proper.

- Verify that the installation complies with the design and that the installation is subject to proper maintenance and operating procedures.

- Verify in the early stages of planning that existing building systems can in fact be adopted in the "as-is" condition or can be retrofitted within the governing economic and spatial restraints to accomplish any intended change in space use. If this is not the case, plans must change.

If there is any noncompliance, corrective action must be taken. There can be only two limiting factors that would prevent corrective action: physical space conditions and/or available capital funding. Obviously, both of these limitations must be dealt with in some satisfactory manner.

Well-documented procedures for the modification of building elements to reduce indoor air quality problems are quite limited, and experience to date is concentrated on a few pollutants. The following suggestions need to be carefully considered for appropriateness and tailored to any specific project. Guidelines related to specific pollutants are included because experience has developed in treating these materials, not because they necessarily represent large or small indoor air quality hazards in commercial buildings:

• In any new work involving highly volatile products such as paints, sprayed coatings, or adhesives, use higher building ventilation rates for a brief initial period. Rates such as 50 percent outside air 24 hours per day for a few days might be considered. Operating unoccupied buildings at elevated temperatures (100°F) has been used to speed up outgassing.[17] However, extreme care is required to assure that equipment and building components will not be damaged by this procedure.

• Consider delaying the move-in of occupants until initial evaporation and outgassing of volatiles have taken place. Periods of up to 4 weeks have been suggested. Any delay, however, is helpful, and the earliest days' delays are the most beneficial.

• For some materials that are causing problems because of formaldehyde emission, the application of permeation barriers can be quite effective. Studies have indicated [13,14] that plastic surfaces such as vinyl linoleum or polyethylene sheet work well in reducing emission rates.

• Ureaformaldehyde foam is a type of insulation for which the specific nature of installation should be carefully reviewed. Good practice suggests that well-isolated cavities are desirable so that outgassing products cannot reach interior spaces.

• Sprayed fireproofing in locations where moving air can carry off fibers into space-conditioning airstreams should be checked if problems are indicated.[7]

• In housekeeping operations, the use of carpet shampoo that was underdiluted left a very irritating powdery residue.[14] Vacuuming was insufficient to remove it, and wet extraction had to be used.

Finally, it should be understood that all of the foregoing criteria, methodology, and design, installation, and operating steps are necessary to achieve satisfactory indoor air quality. Even when all of these are complied with, however, there may be complaints of one type or another by the building occupants. Some of these complaints may be the result of building-related causes, or in fact they may be the result of causes completely extraneous to any situation resulting from building characteristics. Information regarding this subject is lacking, and it is hoped that continuing study will find solutions.

4

APPROACHES TO SOLVING TYPICAL INDOOR AIR QUALITY PROBLEMS

A general diagnostic procedure such as that described earlier is useful in planning an approach to remedy, anticipate, and/or minimize indoor air quality problems. However, it is often necessary to tailor a general procedure to a specific case. In most instances the approaches to solutions will include both operational and professional methods. Operational methods are mainly associated with modifications of existing HVAC systems to improve their performance. These include filtering outdoor, return, or mixed air, cleaning wet surfaces and coils, controlling humidity, providing local exhaust, improving air distribution, calibrating the system, installing system air cleaners, protecting makeup air intakes, and improving system maintenance. Professional methods include treatment of health effects, identification and quantification of contaminant sources, system modifications, re-evaluation of conditions, and consultation with known experts. Appendix A discusses some of the factors that are taken into account by NIOSH in the evaluation of health hazards in the workplace.

This chapter provides guidance for developing approaches to certain typical indoor air quality problems. The actual case histories on which these examples are based suffered from the same deficiences as most evaluations of remedial actions: lack of funding and lack of desire to rekindle complaints that have become quiescent. The success of these cases can only be evaluated by inference.

CASE 1. AIR DISTRIBUTION PROBLEM

Office workers on the 14th floor of a large office complex complained for several years of various ailments, including recurring headaches, general lethargy, inability to concentrate, difficulty in breathing, and eye and throat irritation. The symptoms usually manifested themselves on Monday afternoons and worsened as the week progressed. The symptoms generally disappeared whenever employees left and reappeared when they returned. Management noted a measurable drop in staff productivity and morale and a singular increase in absenteeism. This concern led to a request to investigate the problem. The investigation was conducted in the spring of the year.

Preliminary Findings

A walk-through of the 14th floor, inspection of the HVAC systems, and a study of the floor and HVAC system blueprints and design specifications gave the following information:

- Building. The 20-story building, constructed in 1972, has a brick, concrete, and glass envelope with sealed windows. No asbestos- or formaldehyde-containing materials were used in construction.

- Floor. There were 18,000 square feet of effective working area, with peripheral closed office areas (several additions since construction), semi-enclosed office areas subdivided by 5- to 6-foot textile-covered partitions extending to floor level, and a central core area housing various facilities such as board rooms, toilets, photocopy rooms, elevators, store rooms, a small kitchen and cafeteria, and computer rooms. There was a thick pile synthetic floor covering, and some walls were textile-covered. Floor-to-ceiling partitions had been added to isolate the core area from the remaining floor for security reasons in 1979; doors to the area had no grilles and were always locked.

- Facilities. The three photocopiers in the photocopy room used dry toner and were not provided with local exhaust ventilation. The three elevators serving the floor allowed access to an underground parking garage that was poorly ventilated.

- HVAC Systems. Two separate constant-air-volume systems served the floor--one for the core and one for the perimeter area. They were modified in 1979 to economize on energy. Outdoor air was filtered (filters changed quarterly) and tempered and delivered to hot/cold decks in plenum and perimeter induction units located at the windows; air distribution to the floor was via ceiling tile slots; return air intakes were located on walls in the core area. Return air from perimeter and core areas was returned via a common chase to the respective systems; both systems served the 10th through the 15th floors. The core area system was shut down at 6 p.m. and reactivated at 6 a.m., with total shutdown over weekends. The perimeter area system operated at 40 percent capacity during off hours. The percentage of recirculation of air was determined by the temperature of outdoor, mixed, and return air. Humidification was provided through live steam injection.

- Workforce. There were 142 employees, mainly concentrated in the semi-enclosed office area; they were primarily secretarial and clerical. The greatest concentration of staff was in the northeastern sector of the floor; the northern sector was the source of most complaints. Few occupants of closed offices complained except for some in the northeast sector. Most employees questioned expressed satisfaction with their jobs but unhappiness with their working environment, complaining of lack of air or stuffiness. Several employees reportedly had left during the past few years for this reason. There were no reports of frank illness.

Observations

The investigators noted a distinctive odor of stale cigarette smoke on entering the floor, a lack of air circulation, and a warm, humid sensation.

Approach

The procedures used for this investigation were those recommended by ASHRAE to measure air contaminants and to measure air distribution and supply.

• Actions	• Rationale
The 10th floor was selected as a control to match as closely as possible the working population, activities, and system characteristics of the problem area. The 10th floor had received minimal structural changes but otherwise matched the 14th floor closely.	The control floor was needed to compare the results obtained from various measurements in the problem area with those obtained in an area that had experienced few complaints.
Particulates, organic vapors, and formaldehyde were measured on the 10th and 14th floors and at the outside air intakes. A minimal number of samples were taken, mostly in the northeast sector of the floors.	The measurements were to ascertain that there was no gross source of pollutants (asbestos, fungal spores, etc.) in the building and to alleviate workers' concerns that pollutant concentrations did not exceed normal standards.
In the HVAC system, the intake air temperatures were measured hourly. Carbon dioxide was measured in the outside air and at 12 carefully chosen representative sites, beginning at 7:00 a.m. and continuing until the system was shut down in the evening. All personnel were asked to leave at 4:00 p.m., and the carbon dioxide decay was then measured every 15 minutes; carbon dioxide was also measured continuously after working hours to obtain stratification.	These measurements were to allow the investigators to characterize the HVAC system performance, including supply and distribution to occupied spaces and return. It was also necessary to know if the carbon dioxide level exceeded the ASHRAE limits of 1000 ppm.

Population counts were taken within a 15-foot radius of the measurement sites. The temperature and humidity were measured hourly with a psychrometer.

- Results

Concentrations of contaminants did not differ significantly from outdoor air; outdoor air was satisfactory.

Ventilation rates were markedly less in the northeast sector of the 14th floor, where the population density exceeded 7 persons per 1000 square feet. Temperatures were decidedly higher in the sector but were marginally in compliance with ASHRAE standards.

The carbon dioxide decay data from the return air ducts indicated that significant stratification occurred on the 14th floor, whereas ventilation rates for the 10th floor were relatively uniform and the stratification factor was nonexistent.

- Conclusions

No gross contamination was coming from outside.

The ventilation rates for outdoor air were significantly less than not recommended by ASHRAE.

The outdoor air supply did not effectively ventilate the occupied space on the 14th floor.

- Interpretation of Results

The complaints and symptoms were the result of inadequate ventilation caused by the installation in 1979 of floor-to-ceiling partitions and by overcrowding in the northeast sector.

- Recommendations

The easiest and least expensive solution would be the installation of return-air grilles in the doors to the core section or above those doors. However, because the integrity of the zone had to be maintained for security reasons, it was recommended that ducted return-air systems be installed to all perimeter offices and that grilles be installed in the doors to the perimeter offices.

CASE 2. POPULATION DENSITY PROBLEM

Occupants of the aeronautical engineering section of a well-known aircraft manufacturer complained bitterly about the quality of their working environment. The complaints concerned lack of air, stuffiness, thermal discomfort (too hot), and an inability to concentrate. Conditions had deteriorated to the point that the workers intended walking off the job if there was no amelioration.

Preliminary Findings

A walk-through of the premises was conducted in July when weather conditions were hot and humid. During this visit HVAC systems were inspected and system blueprints and design specifications were studied. The following observations were made:

- Building. The 4-story building was constructed during World War II (ca. 1942); it had cement-asbestos siding on a wood frame and a sawtooth roof; all windows were sealed since 1977 to conserve energy.

- Floor. There was a 60- by 200-foot open-concept area with a few perimeter offices, board rooms, storage room, computer room, and toilets. It had seamless floor covering, fluorescent lighting, and painted walls. Conventional desks and drafting tables were provided for workers (this description applies with minimal differences to all four floors).

- HVAC Systems. All four floors were served by four conventional HVAC systems located in a crawl space created by isolating north-wall perimeter offices from the sawtooth roof area. Access to the HVAC systems was gained via a trapdoor in the ceiling of the four perimeter offices. The HVAC systems were constant-air-volume systems modified in 1977 to conserve energy. The percentage of recirculated air depended to a great extent on outside air temperature and varied from 50 percent to 80 percent. The air supplied was filtered and cooled or heated with cooling or heating coils (cold/hot deck) that were thermostatically controlled. There had been complaints in the past that the air supplied was alternately too hot and too cold. The air was delivered to the work area via fifteen 18-inch ceiling diffusers. Twelve 6- by 12-inch louvered air return grilles were located on the south wall (1 foot below ceiling level). The HVAC system outdoor air intakes were located in the north sawtooth roof window. The air exhaust outlets were located on the north wall. The HVAC systems operated on a 24-hour basis, 7 days a week.

The floor area was steam-heated by units located along the north and south walls. The first, second, and third floors had large windows along the north and south walls. The fourth floor area had sawtooth roof windows and a few large windows along the north and south walls. Each floor also had two floor-based air-conditioning units ducted to air supply ducts.

• Workforce. All four floors were originally conceived to accommodate 80 to 90 persons per floor, and until 1978 the population of the floors did not exceed 100. However, increasing demands during the past 9 years caused the population of all four floors to increase to 130 to 150 persons per floor. A large portion of the workforce was aeronautical engineers and technicians; they worked at desks placed face-to-face, with little or no privacy. The drafting section on the second floor accommodated three times the original number of draftsmen. According to one worker, "Conditions are such that one needs to make an appointment to go to the men's room." Only a few secretaries and clerks worked in the building, and most were located in crowded quarters on the fourth floor. Although unhappy with their work environment, most expressed satisfaction and even enthusiasm for their jobs. However, several employees felt that the environment was such that it interfered with their productivity.

Observations

The investigator noted that all four floors felt stuffy; the air was stale and uncomfortably warm. Lighting was satisfactory. The number of occupants and the open-concept office area gave rise to a high noise level for this type of office. Body odors and cigarette smoke were noticeable in certain densely populated areas of the floor. Area fans did not help the situation.

Approach

On the basis of the preliminary findings, it was decided to monitor operative temperatures and carbon dioxide levels at six representative sites on all four floors.

• Actions	• Rationale
Operative temperature was monitored with thermal stands on an hourly basis during the work day.	The measurements were to determine if and when there were thermal discomfort problems.
Carbon dioxide was monitored at the outside air inlet and at six sites per floor on an hourly basis during the work day, on a 15-minute basis at the end of the work day; and on a continuous basis in the return air ducts.	These data were to determine if carbon dioxide exceeded the recommended ASHRAE level of 1000 ppm, to determine the amount of outdoor air supplied to selected work stations, and to determine if the supplied air reached occupied spaces (stratification).

Return, outside, and mixed air temperature were measured on an hourly basis.

This information was needed to determine the percentage of air recirculation.

• Results

The operative temperature exceeded the ASHRAE norm for summer conditions at most sites; some overcrowded sites were decidedly warmer (> 30°C). Most sites were markedly warmer in the afternoon. Only perimeter offices were marginally within the norms.

• Conclusions

Thermal discomfort problems were pervasive, with some areas greater than others.

Most ventilation rates were well within the acceptable range. Only very overcrowded areas had ventilation rates below the norm. The measurement of the decay of carbon dioxide concentrations in the return air ducts indicated that the air supplied to the floors effectively swept the occupied spaces.

Stratification was not a factor in the problem.

• Interpretation of Results

The air conditioners were inadequate to cope with the combination of heat, humidity, and dense population of the floors.

• Recommendations

The client faced two alternatives:
(1) to reduce the population of the four floors and relocate some people to other buildings or (2) to improve the air conditioning provided to each floor. The thermal controls on the HVAC system should also be inspected periodically to increase optimal performance.

CASE 3. ENERGY MANAGEMENT PROBLEM

Complaints by nearly 20 percent of the employees in a 450,000 square-foot multistory government-owned office building were registered with the safety manager at the facility. Typical complaints included fatigue, eye irritation, headaches, afternoon drowsiness, sore throat, and nausea. Industrial hygienists had previously investigated the complaints, taken some samples of the air quality, and concluded that concentrations of measured contaminants did not exceed OSHA limits. Because complaints persisted, a more detailed investigation was commissioned.

Preliminary Findings

A meeting in October with the safety manager and facilities manager of the building revealed that complaints had existed since initial occupancy of the new building in 1978, but the attitude of the employees had become more negative in recent months. A review of the architectural and engineering plans of the facility indicated that the building was well insulated and windows were small and not operable. Much of the floor area was designed as "open-bay" with provisions for subsequent installation of semi-enclosed partitions and other interior furnishings. Twelve primary HVAC systems were designed to serve the building from a central mechanical room located in the basement of the building. To protect the value of some of the paper documents in this facility, the amount of outdoor air provided to occupants was a fixed minimum of 15 percent, which was prefiltered with 60 percent atmospheric dust spot efficiency filters and a bed of charcoal and permanganated alumina granules for gas and vapor removal. For added protection, a sprayed-cooling coil was installed in the mixed air to absorb water-soluble contaminants and to provide humidity control. For energy efficiency, the HVAC was designed as a single-duct variable-air-volume system with terminal reheat.

Observations

During the initial walk-through of the facility in October, three environmental factors were perceived to be, at best, only marginally acceptable: The thermal conditions were notably warm and humid; a stale, musty odor permeated the facility; and the lighting was unusually harsh in some areas.

Approach

Because previous investigators had obtained measures of contaminant concentrations and found them to be within OSHA limits, it was decided to focus this investigation on the system performance and on operational and maintenance procedures.

• Actions

The actual control strategies in use were compared to the original design.

The current lighting and other thermal loads were compared to the original design.

• Rationale

Because of a government mandate to reduce energy consumption by 5 percent per year, and to reduce operational costs, a series of changes in strategies was expected to be found. The hypothesis

The management procedures for housekeeping and maintenance were compared to those of previous years.

adopted was that the pressure for demonstrating savings, the cuts in operating budget, and constraints on protecting the documents resulted in changes to system control strategies that were manifested in the frequency and intensity of employee complaints.

- Results

Many fluorescent light fixtures had been replaced with metal halide fixtures to reduce energy consumption throughout the building.

Occupancy density in many areas of the building had increased since initial occupancy.

Temperature set points were adjusted to 78°F as a policy to save energy.

Duty cycling and nighttime shutdown of primary air-handling units were implemented after initial occupancy.

- Conclusions

The metal halide lamps provided light in a narrow range of the visible spectrum around 550 nm, which can produce a sensation of nausea.

The reduction in lighting power compensated for the increased sensible loads from occupants, but latent loads in these areas increased.

Because thermostats respond only to changes in sensible loads, the variable-air-volume systems supplied less air; humidities increased because of increased latent loads; and amounts of outdoor air decreased (i.e., percentages of outdoor air remained at the fixed minimum values). Therefore, complaints of warm, humid, stale air could be expected.

Temperature, humidity, and ventilation control was further hampered during these periods.

Periods of housekeeping duties were changed to daytime hours to reduce labor costs and because of nighttime shutdown of the HVAC systems.

Employee exposure to cleaning agents increased because of temporal and spatial proximity to these sources. Complaints of odor and irritation of eyes, nose, and throat could easily result.

• Interpretation of Results

Energy-efficient operation and acceptable environmental quality were not incompatible policies. However, if both were to be achieved, the implications of each proposed procedure should have been carefully evaluated before implementation. To rectify the problems resulting from the changes in system control strategies and operational procedures, and to reduce complaints of employees, a number of different factors had to be dealt with.

• Recommendations

Install lamps that provide a broader spectrum of light. Also attempt to improve color coodination of walls and flooring to "soften" the lighting in the work areas.

Lower the set points on thermostats to 75°F to increase dissipation rates of latent heat (and corresponding moisture) and other contaminants within the occupied spaces.

Lower the chilled water temperature at the chiller, increase storage capacity for the chilled water, and charge storage during nighttime hours to improve energy efficiency. These changes may fully compensate for the energy required to satisfy the lower thermostat settings during occupancy.

Increase the percentage of outdoor air supplied to occupied spaces when sensible loads are reduced without corresponding reductions in latent loads or indoor contaminant generation rates (e.g., when housekeeping operations occur during occupancy).

CASE 4. MAINTENANCE PROBLEM

For the past few years, employee complaints of the standard symptoms associated with indoor air quality problems were filed with the safety manager of a 500,000-square-foot multistory government-leased office building. However, within the last year, several cases of acute hypersensitivity pneumonitis were diagnosed by private physicians of the employees. About that same time, some of the senior managers of the agency began to complain of the same symptoms. This investigation was authorized with some sense of urgency.

Preliminary Findings

An initial meeting with the facilities manager, the senior managers of the agency, and the safety manager was held in May. It was learned at this meeting that the lease agreement for the building was for 8 more years, that the annual charge was quite reasonable, and that the government was responsible for all maintenance and repairs on the facility. It was decided that this investigation should result in identification of the source of the problem, if possible, and recommenations should be made as to whether remedial action would be appropriate or whether the government should terminate its lease and relocate the employees. It was also learned that the building was originally designed as a condominium and was subsequently renovated to function as an office building.

A review of the architectural and engineering plans revealed that the building was originally designed in 1972 and redesigned to meet the agency requirements in 1972 and in 1973. Occupancy commenced in 1974. The building enclosure was moderately insulated and contained large, nonoperable windows. Most of the floor space was designed as "open bay" with provisions for installation of semi-enclosed partitions for office areas. Enclosed offices, however, were designed along the perimeter on several floors. Heating and cooling were provided by 2000 fan-coil units located throughout the facility. Of these, 800 were vertical units installed in interior wall cavities. Return air grilles were located only at the fan-coil units. Supply ducts distributed air within the zone. Low-efficiency, throw-away type air filters were specified to be located in the return air grilles of the interior fan-coil units; the perimeter fan-coil units were unfiltered. The plans also revealed that a drain system for the pans beneath the cooling coils of the units was not specified. Ventilation was provided by eight separate make-up air units located in two penthouses on the top floor of the building. Outdoor air was distributed to the ceiling plenums and to the interior fan-coils on each floor. Exhaust air was intended to be provided by 16 local toilet exhaust fans.

Observations

An initial walk-through of the building revealed that the occupied spaces were unusually humid and that significant soiling existed around the supply air diffusers. Discussions with occupants revealed that a musty odor and the odor of stale tobacco smoke were often bothersome. Discussions with the maintenance personnel revealed that the interior zones required cooling all year long. Inspection of several of the interior fan-coils revealed that standing water existed in the pans under the cooling coils and that obvious microbial contamination was present in the sludge in the pans. This inspection also revealed that many of the interior fan-coil units had been sealed inside wall cavities and that it was not possible to service the units without destroying the walls.

Approach

Because of the nature of the complaints (i.e., headaches, eye irritation, fatigue, drowsiness, sore throats, hypersensitivity pneumonitis), it was decided to focus this investigation on the performance of the fan-coil units and the ventilation system. The hypothesis adopted was that inaccessibility of the fan-coil units prevented reasonable service to many units installed in the building, resulting in those units becoming secondary sources of contamination in the occupied areas.

• Action	• Rationale
Airborne microbial samples were obtained in representative areas of occupancy.	Results may indicate the presence of microbials associated with hypersensivity pneumonitis.
Microbial samples were obtained from the pans of the fan-coils serving the same representative areas.	Results may indicate the presence of the same microbials found with the airborne samples.
Temperature and humidity samples were obtained in the same representative areas.	Results may indicate the conditions conducive to presence of microbial contaminants and other complaints associated with "sick building syndrome."
Tracer gas data were obtained on ventilation air exchange rates in the same representative areas.	Results may indicate if sufficient outdoor air exchange exists in these areas.

• Results

Concentrations of aspergillus and penicillium were found in samples of air in several representative areas of the facility, in samples taken from the pans in the fan-coil units, but not in the make-up air units or in the outdoor air.

• Conclusions

Aspergillus and penicillium fungi are known to cause hypersensitivity reactions in susceptible individuals. Results indicated that primary sources of these fungi were in the occupied spaces, not outdoor air. The pans of the fan-coil units probably served as secondary sources of the fungi and therefore aggravated hypersensitivity pneumonitis reactions.

Temperature and humidity conditions in the representative areas were near or slightly exceeded the upper bounds of thermal comfort defined in ASHRAE 55-1981.

These conditions can elicit some of the reported symptoms. In addition, they can enhance generation rates of the fungi in the occupied spaces.

Air exchange and ventilation rates calculated from the tracer gas data were less than recommended by ASHRAE 62-1981.

Low ventilation rates can prompt symptoms associated with sick building syndrome and prevent effective dilution of the fungi.

• Interpretation of Results

The type of HVAC control originally designed for this building provides flexible control desirable for condominium facilities but requires extensive maintenance because of the large number of fan coil units. Moreover, the loads imposed by large occupancy densities in these office facilities intensify the need to clean these units frequently. To reduce exposure of the occupants to continually increasing concentrations of chemical and biological contaminants without relocating them to other facilities, several changes would be required.

• Recommendations

Access doors must be provided in the walls concealing the interior fan-coil units so the units can be maintained.

Either drain lines must be installed on the condensate pans under the cooling coils of the fan-coil units or frequent cleaning of them must be implemented.

The low-efficiency air filters in the return air grilles of the fan-coil units should be replaced with 40 to 60 percent atmospheric dust spot efficiency filters to provide better protection of the coils from contaminant build-up and to reduce the concentration of particulates being distributed by the supply air to the occupied spaces.

The temperature and humidity in the occupied spaces should be reduced from those found to be approaching thermal discomfort as specified in ASHRAE 55-1981.

The distribution of the ventilation air from the eight primary air handling units to the occupied spaces must be improved to achieve at least the minimum ventilation rates per occupant specified in ASHRAE 62-1981.

The performance of the 16 toilet exhaust fans must be improved to be compatible with the capabilities of the revised ventilation systems.

A rigorous preventive maintenance program must be implemented to ensure that contaminant concentrations are maintained within acceptable limits for the duration of the lease.

In this case it was recognized that significant costs would be required to modify the system and to train and staff personnel to maintain the system with acceptable conditions for the next 8 years. It was also recognized that significant costs would be required to relocate the occupants. When these factors were considered, together with the loss of agency productivity that would be incurred during the time of relocation, the recommended alternative was to invest in the present location.

CASE 5. IMPROPERLY LOCATED AIR INTAKES PROBLEM

Occupants of a downtown Washington, D.C., building complained of nausea, headaches, eye and throat irritation, and difficulty in breathing. The occurrences were episodic and usually coincided with the detection of "car exhaust-like" odors in the building. Other odors detected included skunk, garbage, diesel exhaust, and sulfur dioxide.

Preliminary Findings

The affected building was inspected in late fall. HVAC system and floor blueprints and design specifications were also studied. The investigators observed the following:

- Building. The 9-story building was constructed in 1979; it had a brick and concrete exterior and sealed windows.

- Floor. All nine floors (100 by 100 feet) had a similar arrangement of perimeter office areas and open-concept core areas. Some facilities (toilets, board rooms, elevators, storage rooms) were located in the core area. Air was distributed to the floors via ceiling slots; air return inlets were located in the ceiling.

- HVAC Systems. The building was served by four variable-air-volume systems located in a penthouse on the roof; the four air intakes were located at ground level at the rear of the building. Two of the intakes were located near a parking lot, and the other two were near the loading dock. A garbage disposal unit was noted 30 feet from the intakes. It was also noted that the building's chimney was located at the rear of the building. Prevailing winds were known to blow from the front to the rear of the building. Air supplied to the floors by the HVAC systems was filtered and tempered.

- Workforce. There were 50 to 70 workers per floor, mainly secretarial or clerical. Incidents of nausea and other symptoms had been widespread throughout the building. Most workers expressed satisfaction with their jobs and considered the episodic odor occurrences an annoyance.

Approach

Pollution migration procedures were adopted for this investigation.

• Action	• Rationale
The tracer gas sulfur hexafluoride was released from a	Results may demonstrate that car or truck exhaust

cylinder at a known rate on the loading dock and at the edge of the parking lot nearest the air inlet on 3 days when different wind conditions prevailed (light, brisk, different direction), and air samples were collected on all floors during the test.

• <u>Results and Interpretation</u>

It was shown that when the wind conditions were optimal an inordinate amount of car or truck exhaust or emanations from the garbage disposal unit could enter the building via the air intakes.

can gain access to the building via its air intake.

• <u>Recommendations</u>

Relocate the air intakes.

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GLOSSARY OF ACRONYMS

ACGIH	American Conference of Governmental Industrial Hygienists
ADPI	air diffusion performance index
ANSI	American National Standards Institute
APCA	Air Pollution Control Association
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
CPSC	Consumer Product Safety Commission
DOE	U.S. Department of Energy
EPA	Environmental Protection Agency
ETS	environmental tobacco smoke
GSA	General Services Administration
HRSA	Health Resources and Services Administration, U.S. Public Health Service
HVAC	heating, ventilating, and air conditioning
IARC	International Agency for Research on Cancer
NIOSH	National Institute for Occupational Safety and Health
NRC	National Research Council
OSHA	Occupational Safety and Health Administration
PAH	polyaromatic hydrocarbon
PCB	polychlorobiphenyl
PPD	predicted percentage dissatisfied
REI	relative exposure index
TLV	threshold limit value
TWA	time-weighted average
UFFI	ureaformaldehyde foam insulation
VAV	variable air volume
WL	working level

Appendix A

COMPILATION OF NIOSH HAZARD EVALUATION FIELD STUDIES IN BUILDING-RELATED PROBLEM REPORTS

The National Institute for Occupational Safety and Health will evaluate any possible health hazards in the work environment at the request of employers, employees, or their representatives. In a number of cases in the past decade these evaluations have involved problems in nonmanufacturing workplaces, such as office buildings and schools. The reports made after such evaluations are relatively uniform in format, although in their content they respond to the particular investigation and the findings.

The Centers for Disease Control in Atlanta made available a set of 73 such reports. To demonstrate the cumulative understanding of the building-related problems, these reports were abstracted by noting in a systematic form 31 different items of information that could be expected to be present.

It is not known how representative the collection of reports is of all the buildings studied. The number of reports in the sample is probably more than 10 percent and less than 40 percent of the total universe studied. There are numerous sources of possible bias, starting with the bias in the population that seeks and gets access to the NIOSH, resources. That bias would cause oversampling of government buildings and of workplaces that are unionized. On the part of CDC and NIOSH, there might be a very understandable bias toward making available the more competently produced reports with the clearest outcomes and recommendations.

As can be seen from Table A-1, a large fraction of the studies (37 to 40 percent) yielded no items reported out of acceptable ranges and resulted in no specific or even general recommendations. One of the reasons for this high percentage of negative findings must be that investigations often follow complaints with an unavoidable delay, and a condition associated with the original complaints no longer exists.

Another reason is the use of workplace standards and workplace measurements that are geared to industrial and manufacturing workplaces. This practice leads to concluding that formaldehyde concentrations of 0.15 to 0.4 ppm are clearly acceptable, or that asbestos concentrations of 100,000 fibers per cubic meter are acceptable. These are, after all, well below the workplace standards that these teams enforce at other workplaces they investigate, although they may not be considered appropriate for an office environment.

A final reason may be that the complaints in fact are not so much based on specific complaints about the indoor air quality but relate more to the complex of all workplace conditions simultaneously and thus cannot effectively be addressed by improving only the indoor air quality.

Table A-1 also makes clear that in the great majority of buildings investigated there was either no factor or only a single factor reported out of range (86.3 percent), and in only 13.7 percent of the cases were two factors reported out of range. There was not a single instance in which more than two factors were reported to be in an abnormal range. Similarly, in 93.2 percent of the cases there was either no recommendation or only a single recommendation; in just 6.8 percent of all the cases was a recommendation made for improvement in two factors simultaneously.

The studies also clearly document the important role of ventilation in many of these instances: Lack of adequate ventilation will produce many reports of many symptoms, ascribed to any of a number of possible causes. At the same time it is also made clear that an increase in ventilation rate is the single most frequent recommendation. This again affirms that increased ventilation is universal in its ability to reduce concentrations of all contaminants simultaneously.

In fact, the similarity of the results of so many of the hazard evaluations indicates that the need for these field studies could be reduced substantially by suggesting to the building management or the employer in question that possible inadequacies in the effective ventilation rate be checked and corrected before a field evaluation team is formed and dispatched.

Table A-1 FREQUENCY OF OCCURRENCE (IN PERCENT) OF DIFFERENT CHARACTERISTICS AND REPORTS IN STUDIES OF BUILDINGS BY NIOSH TEAMS

	Complaints Justifying NIOSH Visit		NIOSH Reports		NIOSH Recommendations	
Condition	Yes	No	Yes	No	Yes	No
Temperature	8.2	91.8	11.0	89.0	4.1	95.9
Pollutants	16.4	83.6	78.1	21.9	42.5	57.5
Bioagent	8.2	91.8	8.2	91.8	5.5	94.5
Noise	1.4	98.6	2.7	97.3	1.4	98.6
Stuffy	57.5	42.5	52.1	47.9	58.9	41.1
Drafty	0	100.0	0	100.0	0	100.0

Percentage of cases with	0 items	1 item	2 items	3 items
Report items	39.7	46.6	13.7	0.0
Recommendations	37.0	56.2	6.8	0.0

Appendix B

BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS

RICHARD T. BAUM is a principal of Jaros, Baum & Bolles, an engineering firm established in New York City in 1946. He is a Fellow of the American Consulting Engineers Council (ACEC), the American Society of Mechanical Engineers (ASME), and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). He has been named to the National Academy of Engineering and is also a member of the National Society of Professional Engineers and the National Society of Energy Engineers. He received his B.A., his B.S. in mechanical engineering, and his M.S. in mechanical engineering from Columbia University.

BARRY J. DAVIS is an environmental health engineer involved with the investigation of airborne and waterborne infectious disease outbreaks at the Epidemic Investigations Branch, Center for Infectious Diseases, Centers for Disease Control. His professional experience includes work with the Mobil Oil Corporation, the U.S. Army Environmental Hygiene Agency, the U.S. Environmental Protection Agency, and the U.S. Public Health Service Commissioned Corps. He is a registered professional engineer with his B.S. in civil engineering and his M.S. in environmental health engineering from the University of Texas, Austin.

JEAN-PIERRE FARANT has been an associate professor in occupational hygiene and the Director of Environmental Laboratories at the School of Occupational Health, McGill University, since 1982. Prior to that, he was advisor in environmental toxicology for the Medical Services Branch of Health and Welfare Canada. Other posts held at that agency include the chief of laboratory services for the Medical Services Branch, industrial hygienist for the Health Protection Branch, and organic chemist for the Health Protection Branch. He holds a Ph.D. in analytical toxicology and a B.Sc. in chemistry, both from Carleton University.

JAMES T. GOLDEN has served as International Representative of the Sheet Metal Workers International Association since October 1985. In this capacity, he instituted a study of 1500 members exposed to asbestos, coordinates a national training and education program in the safe handling of asbestos, and coordinates the tracking of all federal, state, and local legislation regarding asbestos handling and victim compensation. He has been associated with the SMWIA in various capacities since 1979.

DOUGLAS A. GREENAWAY is Director of Regulatory Affairs for BOMA International (Building Owners and Managers Association), where his responsibilities are focused on BOMA's activities in the areas of model codes, state and local codes, voluntary consensus standards, federal regulatory initiatives, and building industry representatives. Previously he served as marketing director for the Washington office of Leo A. Daly Company, one of the largest architectural/engineering firms in the United States. He has also worked as a facilities management consultant and contract administrator with FACE Associates, an organization of consultants interfacing with NATO. He holds a Master of Architecture and Planning from the Catholic University of America and a B.A. in political science and sociology from Carleton University.

JOHN K. HOLTON is a Senior Associate with the architecture firm Burt Hill Kosar Rittelmann Associates. Previously he has held numerous positions with such organizations as the General Services Administration as Director of the Energy Conservation Division; with the National Bureau of Standards as the Project Leader for Solar Criteria and Standards Development; with the American Institute of Architects/National Bureau of Standards as architect in residence; and with the Mark VII Corporation of Perkins and Will as Director of Physical Planning and Design. He holds a Master of Architecture from Harvard University and a B.C.E. from Cornell University.

GEORGE T. JACOBI is currently Corporate Vice President for Technology at Johnson Controls; previously, he was the director of Building Automation Systems, also at Johnson Controls. From 1959 to 1977 he was at the IIT Research Institute, where he was assistant director of electronics research and then director of computer and management science research. Prior to that he was with the General Electric Company in several capacities. He holds the M.Sc. and B.S. degrees in electrical engineering, both from Ohio State University. He has several patents to his credit and is listed in American Men and Women of Science.

LEONARD LEVIN currently is project manager for the Air Quality Studies Program at Electric Power Research Institute. He is a certified consulting meteorologist. At the inception of this study, Dr. Levin was Senior Meteorologist with Woodward-Clyde Consultants, where he specialized in workplace and community air exposure to toxic materials, hazardous wastes, and other air pollutants. Other professional experience includes director of Physical Science Programs at Ecological Analysts, Senior Scientist with Science Applications International, a postdoctoral fellowship in fluid mechanics at Johns Hopkins University, and staff associate at the American Geophysical Union. He holds his Ph.D. from the University of Maryland in fluid dynamics and applied mathematics, his M.S. from the University of Washington in atmospheric sciences, and his B.S. from Massachusetts Institute of Technology in earth and planetary sciences.

JAN A. J. STOLWIJK is the Susan D. Bliss Professor of Epidemiology and Public Health and Chairman of the Department of Epidemiology and Public Health at the Yale University School of Medicine, a position he has held since 1982. He has been associated with the School of Medicine in various capacities since 1962 in both the Department of Epidemiology and Public Health and the Department of Physiology. He has also been associated with the John B. Pierce Foundation since 1957 as biophysicist, associate fellow, fellow, and associate director (the last from 1974 to the present). Dr. Stolwijk has served on several other National Research Council committees. He holds the B.S., M.S., and Ph.D. degrees from Wageningen University, The Netherlands.

ROBERT A. WESTIN is a Senior Chemical Engineer with Versar, Inc., a firm based in Springfield, Virginia, that specializes in toxicological diagnoses and decontamination management. He has over 20 years' engineering experience involving hazardous and toxic chemicals. During the past 8 years he has managed over $8 million dollars in contract research sponsored by the U.S. Environmental Protection Agency, state governments, and industrial firms. He is a registered professional engineer. His degrees include the B.A. in chemistry from Kalamazoo College, the B.S.E. in chemical and metallurgical engineering from the University of Michigan, and the M.B.A. in operations research and marketing from the University of Chicago.

JAMES E. WOODS is Senior Engineering Manager with the Honeywell Building Controls Division. Prior to this position, he served as Senior Staff Scientist with the Honeywell Physical Sciences Center from 1983 to 1986, where he was responsible for research and development in indoor air quality. Before joining Honeywell, Inc., he was a professor of mechanical engineering and architecture at Iowa State University. He is a registered professional engineer, with many publications in the areas of indoor air quality and energy conservation. His degrees include the B.S. in mechanical engineering from the University of New Mexico, the M.S. in physiological sciences, and the Ph.D. in mechanical engineering from Kansas State University.

CARY L. YOUNG has been Project Manager of the Health Studies Program in the Environmental Assessment Department at the Electric Power Research Institute (EPRI) since 1980, where he is responsible for a major part of the community health activities aimed at gaining a better understanding of health risks from exposure to inhalable pollutants. He is a preventive medicine physician and epidemiologist who has worked in the area of environmental and occupational health research for 12 years. Other professional experience includes a position as Senior Medical Scientist in the Center for Occupational and Environmental Safety and Health, SRI International, and a position as Medical Officer with the Centers for Disease Control, U.S. Public Health Service. He holds an A.B. from Stanford University, a M.D. from Baylor College of Medicine, and a M.P.H. from the Johns Hopkins University School of Hygiene and Public Health.