American Thoracic Society

MEDICAL SECTION OF THE AMERICAN LUNG ASSOCIATION

Achieving Healthy Indoor Air

Report of the ATS Workshop: Santa Fe, New Mexico, November 16–19, 1995

THIS WORKSHOP REPORT WAS APPROVED BY THE ATS BOARD OF DIRECTORS, MARCH 1997

OVERALL INTRODUCTION

In 1988, the American Thoracic Society and the American Lung Association convened an interdisciplinary workshop on improving indoor air quality (IAQ) and health. The workshop was prompted by the emerging literature on the health effects of air pollution, and by the need for a critical review of the evidence on control strategies directed at the adverse health consequences of indoor air pollution. The focus of the 1988 workshop was primarily on specific pollutants; also addressed were source control and building-related problems. A workshop report was published in 1990 in the *American Review of Respiratory Disease* (1). The target audience for the workshop included the many health professionals providing clinical care to patients with respiratory diseases, the American Lung Association and its constituents, and the wide range of other professionals concerned with indoor air quality.

In the ensuing years, our understanding of the adverse effects of indoor air pollution on health and comfort has broadened, supplying a stronger framework for developing and implementing control strategies. During these years, the array of professionals offering commercial services related to indoor air quality has grown steadily, as have the types of products and services advertised as improving indoor air quality (e.g., air cleaners, vacuum cleaners, radon measurement and mitigation, and air duct cleaning). Products with low emission rates of volatile compounds are available, and homes can now be designed and constructed to offer lower concentrations of pollutants than in the past.

Health problems linked to indoor air quality have persisted, however, and the scope of the health concerns has broadened. We continue to identify buildings with occupants who are affected by building-associated illnesses, and we have learned that these outbreaks may reduce productivity and perhaps result in costly litigation. The number of people who report responding adversely to environmental contaminants has increased, with many receiving the label of "multiple chemical sensitivity," for which the World Health Organization has recently suggested an alternative term: "Idiopathic Environmental Intolerance." Changing patterns of infectious disease have brought new concerns. Tuberculosis, a waning disease at the time of the last meeting, has returned, and multi-drug-resistant organisms are becoming more prevalent, particularly in inner cities. Substantial time is spent today in often-crowded microenvironments such as airplanes and day care, where there is enhanced opportunity for disease transmission.

In response to these dynamic changes since 1988, the American Lung Association and the American Thoracic Society convened a second workshop in 1995. Additional sponsoring organizations included the American Academy of Allergy, Asthma and Immunology, the American Academy of Pediatrics, the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE), the Centers for Disease Control and Prevention, the U.S. Environmental Protection Agency, and the National Association of Home Builders Research Center, Inc. Attendees represented the broad range of professional disciplines concerned with indoor air quality and health: architects, engineers, building diagnosticians, physicians, public health professionals, facilities managers, lawyers, and others. The target audience for the report was construed as broadly as in 1988.

The charges to the workshop participants reflected the changes in the problems and in the evidence base between 1988 and 1995. Solutions to problems and the technology developed to improve health and comfort through better indoor air quality received greater emphasis. After an opening session that addressed the concept of healthy indoor air, five different working groups were convened, and during the three days of the meeting they focused on: (*1*) problem-solving: design, construction, and operation of buildings; (*2*) source control; (*3*) ventilation; (*4*) air cleaning and treatment; (*5*) potentially susceptible populations. This workshop report provides summaries of the five groups' responses to these charges, and includes overarching recommendations. The report also provides a general background for readers on the conceptual basis of healthy indoor air and on institutional jurisdiction for various dimensions of indoor air quality. A brief description is included of the complex factors in the design and construction of a building that affect the air quality within the building as it is commissioned, and the diverse factors that determine air quality in a building during its use.

What Is Healthy Indoor Air?

The meeting began with a discussion of the key elements in the concept of healthy indoor air, with Richard Diamond, Thad Godish, William Cain, Ronald White, and Jonathan Samet reviewing and addressing component issues related to architectural design, the residential environment, irritation, public health, and clinical medicine, respectively.

Diamond described the multiple perspectives from which architects may approach indoor air pollution. In the traditional "one-point" perspective, architects view their work primarily for its visual impact—architecture as art—with little concern for occupant comfort and health. A more pragmatic or "two-point" perspective recognizes that architecture has aesthetic value but also needs to reflect a broader range of functional considerations such as providing for human needs,

This report gives the proceedings of the workshop. There was no attempt to achieve group consensus on all issues; consequently, the report should not be necessarily construed as reflecting the views of all participants.

allowing construction within budget, and avoiding costly litigation. The architect assumes that conventional practice will provide acceptable conditions for occupant health and comfort. A third, more comprehensive, perspective, advanced by Levin (2) and others, adds to the previous perspective a fully integrated "ecological approach," incorporating explicit concerns for a building's effects on the health of its occupants and on the environment.

Godish began by referring to the difficulty of defining "healthy air." He then discussed the characteristics of residential environments that pose unique issues: the large number of buildings and the diversity of environments, ownership status (owned or leased), diversity of construction characteristics, the limited complexity of building systems, and special exposure concerns. Godish emphasized diversity and the frequency of problems in manufactured housing. With regard to exposure, he pointed to the length of time spent at home; the diversity of the exposed population, which includes infants, children, the elderly, and persons with underlying illness; particular exposures such as radon, formaldehyde, environmental tobacco smoke, and releases from craft activities; and the limited potential for dilution through ventilation.

Cain noted that the effects of irritants may or may not be predictable. Although body odors and environmental tobacco smoke (ETS) have predictable effects, other agents may not affect everyone in a uniform way. He commented that, for irritation, the response reflects the additive contributions from the individual agents. He noted that ventilation approaches have been based largely on odor control, and he considers that since this odor-based approach has been generally successful, it should not be abandoned. He advocated for research to support a mass-balance approach and raised the problem of funding sources.

The presentations by White and Samet emphasized the broadness of the concept of health. Implied in the World Health Organization definition of health is a need for considering a wide range of responses to indoor air pollution, including irritation and symptoms. Samet noted the substantial burden of clinically diagnosed disease associated with indoor air pollution.

In the discussion prompted by these presentations, and during subsequent open discussions at the workshop, there were reminders that comfort in indoor environments reflects not only indoor air quality but the thermal environment, lighting, physical stressors, and diverse psychological and social factors.

A Conceptual Framework for Considering Indoor Air Quality and Health

Indoor air pollutants are linked to health responses through a sequence that moves from emission by the source through exposure, dose, and ultimately to the health response, as illustrated in Figure 1. This model, designed by the conference participants, simplifies a complex set of interactions but indicates the critical points at which control strategies have effects. The schema points to the central role that source control should play in any control strategy. Air cleaning and treatment can lower concentrations and thereby reduce exposures, and time-activity patterns can be modified to limit source use and exposures. Ventilation reduces pollutant concentrations through dilution. The materials selected in the design phase may determine the potential for future adverse health effects, depending on associated emission rates. As a building is used, new and unintended sources may be introduced and the original design ventilation may be either inadequate or compromised by inadequate maintenance. This model also acknowledges the range of susceptibility in the population.

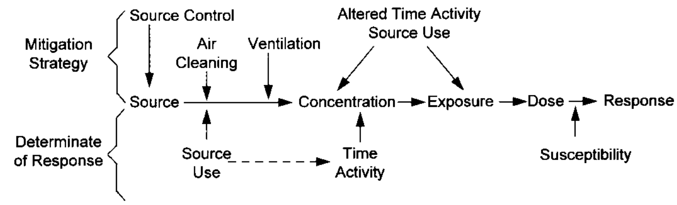

Figure 1. Sequence of health responses linked to indoor air pollution.

General Recommendations

On issues transcending the charges of the individual working groups, the workshop participants offered a series of general recommendations reflective of the interdisciplinary nature of the group.

Exposure reduction. Many products have been developed to benefit indoor air quality, including room and central air cleaners and low emission products for construction and furnishing. It is doubtful that experimental data from controlled clinical trials will become available for most of these products, and observational data, if available, may be difficult to interpret because of the multiplicity of factors determining responses to indoor environments. However, there still exists a need for recommendations concerning the purchase and use of these products. Persons seeking relief from health problems associated with indoor air quality may turn to health providers, the American Lung Association, or other organizations for guidance when considering the purchase of products promising health benefits. Even though there are no data on most specific products, the workshop participants considered that reduction of exposures could be generally recommended. Persons seeking relief from problems related to indoor air quality or attempting to minimize risk for developing problems can be counseled that using products that reduce exposure is reasonable. They need to be aware, however, that purported health benefits may not follow and they should balance costs and potential benefits.

Interdisciplinary meetings. The 1988 and 1995 workshop participants were multidisciplinary in background and reflective of the broad range of professionals concerned with indoor air quality. As at the previous meeting, the 1995 participants commented on the lack of similar meetings and of venues for multidisciplinary interactions. Participants recommended that the American Thoracic Society and the American Lung Association take the lead in conducting regular interdisciplinary workshops that promote in-depth discussion of key and timely issues.

Institutional interactions. Institutional alignments related to indoor air quality were also discussed. A specific focus of discussion was the development of ventilation standards by ASHRAE; the standard-setting process continues without formal participation from organizations concerned with clinical illnesses of individuals and with public health, although persons with health backgrounds have served on the ASHRAE committee that developed the ventilation standard and on other ASHRAE committees. The group encourages discussion of ASHRAE's unique role regarding ventilation and indoor air quality and involvement of other organizations such as the American Thoracic Society and the American Public

Health Association. The possible role of governmental agencies should also be explored.

Voluntary guidelines. There was discussion on establishing voluntary guidelines for indoor air quality practices for use in commercial buildings. The participants agreed that these guidelines already existed in the Environmental Protection Agency/NIOSH's Building Air Quality guide and that the real issue was the adoption of these good indoor air quality practices. To promote their use, the participants recommended bringing together a group similar to the Building Air Quality Alliance initiated by the EPA, which would implement a voluntary program by encouraging building owners and operators to adopt good indoor air quality practices through opportunities and incentives.

Communication. The group commented on the lack of effective strategies and processes for educating the public about indoor air quality. The American Lung Association has produced printed and video documents, but no process is in place for communicating with the public systematically and comprehensively at key times of need-to-know such as during the design or purchase of a home. The participants encourage the development of strategies for assuring consumer understanding of options and consequences as key decisions are made with regard to residences.

Needs for research. Like participants in the previous workshop, the 1995 attendees lamented the lack of information in key areas. They expressed concern about product marketing that promises health benefits without appropriate data, as absence of data handicaps those formulating recommendations on the use of such products. These large gaps in our understanding of control strategies reflect the regrettable lack of funding for research on indoor air quality. The workshop participants encouraged the American Lung Association to advocate for increased funding for indoor air research, to urge manufacturers of products related to indoor air quality to support research, and to seek a mechanism for contributing to research on indoor air quality in general.

This report is intended for professionals in a variety of fields who need to increase their understanding of how a building's indoor air quality affects its inhabitants and what can be done to eliminate or reduce potential adverse reactions to pollutants in indoor air. It is a workshop report and presents the findings of the participants. Anyone who is interested in a more in-depth treatment of the topics discussed or of other dimensions of indoor air quality should refer to the list of recently published general references at the end of the document. These references provide information on the health effects on indoor air pollution, not a topic of this report. A number of comprehensive references have been published, and the proceedings of the Triennial Indoor Air Conferences offer invaluable coverage of the subject.

Organization of This Report

The five sections of this document reflect the tasks of the meeting's five working groups. The first section provides basic information on how a building's design, construction, and operation affect the quality of its indoor air, how to prevent air quality-related problems, and how to address them when they do occur. The section that follows looks at sources of indoor air pollution and identifies strategies for minimizing or eliminating potential risks. Section three deals with ventilation as an approach to managing indoor air. It explores how a building's inhabitants are affected by the quality of its ventilation system. The fourth section discusses air cleaning and filtration and the impact of these technologies on improving indoor air quality. The fifth and final section is a brief overview of selected populations who, for various reasons, appear to be especially susceptible to the adverse effects of indoor air pollution.

PROBLEM SOLVING IN THE DESIGN, CONSTRUCTION, AND OPERATION OF BUILDINGS: THE RELATIONSHIP TO INDOOR AIR QUALITY

This section considers two aspects of indoor air quality (IAQ) as it relates to commercial and residential buildings: (*1*) how buildings are designed, constructed, and operated to achieve low concentrations of pollutants and prevent problems from occurring; and (*2*) how to mitigate problems related to indoor air in buildings when they do occur. Delivering and operating a "healthy building" is key to health and comfort. It begins with an extensive discussion of the design, construction, and operation of buildings. An understanding of the complex sequence that leads from design to building use is essential for preventing and diagnosing problems.

Current Nonresidential Design and Construction Practices: Description and Deficiencies

The quality of a building's indoor air reflects in part the processes by which it is designed and constructed. Current practices, each with advantages and disadvantages, have not consistently delivered buildings and building systems that perform as designed reliably over a building's lifetime. These performance deficiencies often lead to indoor air quality problems. What follows is a review of two common design/construction delivery practices for nonresidential buildings in use today, each with many variations.

Design/bid/build. The design/bid/build approach is by far the most common practice in most areas in the country for institutional and large commercial projects. In this approach, the owner retains an architect who takes the lead through the design phase. The architect typically hires consultants to design specific elements of the building such as structural, mechanical, electrical, and plumbing systems. Once the design is complete and documented by plans and specifications, it is let out for bid by general contractors. After award of the project, the general contractor usually subcontracts most or all of the construction to specialty subcontractors. Because the bid documents are in the form of plans and specifications, this approach is commonly referred to as the *plan & spec'* approach by contractors.

There are several variations of the *plan & spec'* approach. The general contractor may be selected before or during design on a fixed-fee basis. The contractor is then brought on to assist in developing some design details as well as to control and ultimately guarantee the budget. In another variation, a construction manager is hired by the owner to oversee both the design and construction process and to ensure that the owner receives the lowest possible price. The *plan & spec'* approach has two key elements: the designers are independent professionals (architects and consulting engineers), and all or most of the subcontractors who build the building and its systems are selected based on low bid.

Design/build. In the design/build approach, the designers work for the contractor. A design/build general contractor firm, for instance, would have its own architectural and structural engineering staff; a design/build heating, ventilation, and air conditioning (HVAC) contractor firm would have its own mechanical engineering staff. On occasion, instead of in-house designers, contractors retain local architects or consultants. The contractor may also be selected based on low bid using a performance specification as the basis of design. This approach shares many of the characteristics of the *plan & spec'* approach and there is a potential to compromise quality to save costs.

A dichotomy has developed in the building industry that can adversely affect occupational health. On the one hand, increasing litigation in the construction industry has indirectly encouraged design professionals to take less responsibility for the ultimate product of their work (the building), leaving many construction details to the contractors. On the other hand, the emergence of more sophisticated HVAC systems and control systems has made competence in design, construction, operation, and maintenance even more important. Minor deficiencies in one aspect of the building defeat excellent performance in other areas.

Attempts have been made to change these processes, but none offers a complete solution. Possibly, the most encouraging attempt has been the design/build approach in which the designer is employed directly by the contractor. This organizational approach eliminates the separation of design and construction responsibilities and should improve the design as well as reduce costs because of the close contact between designer and builder. However, this approach places the designer, who is licensed and professionally responsible, in a potentially compromising role.

The Integration of the Project Team

The need for communication among stakeholders increases as project development objectives become more sophisticated and increasingly demanding of interdisciplinary discussion. If possible, a commitment to design team integration should be made at the outset of the project. Each stakeholder then has a role and can contribute to the project development. What follows is an idealized approach showing how indoor air quality issues can be identified and addressed throughout the design and construction process.

In the **Project Planning Phase**, a commitment is made by the owner or developer to a project schedule, budget, and design team that will provide for indoor air quality requirements. The schedule should provide adequate time for airing-out of new construction materials and for commissioning building systems before occupancy. Project feasibility studies and assembly of the design team involve consultation with all relevant participants in the process. A design team should be selected on the basis of proven indoor air quality experience as well as commitment to integration of stakeholders into the design process. Budgeting fully anticipates both capital and holding cost requirements of additional time, expertise, and specialized systems or materials to address indoor air quality requirements.

In the early **Site Planning and Design Stage**, the architect and the building owner or developer define the site, parking, landscape, and future area requirements. Together with the landscape architect, they evaluate options for landscape areas to enhance the outdoor air requirements. Previous land use evaluation and testing for soil contaminants may be undertaken. The location of parking areas and vehicle access areas relative to building openings and air intakes is identified as an issue for consideration as the building mass is developed. The mechanical engineer contributes information on HVAC options and develops filter and air-cleaning options, assuring the quality of outdoor air to be used for ventilation. The site and the building need to complement each other and to be designed to work together to optimize IAQ.

During the **Overall Architectural Design Stage**, the building owner/developer, the architect, and the mechanical engineer work together to develop the most appropriate building form and preliminary window design strategies in conjunction with an overall environmental control concept covering ventilation, thermal control, lighting, and acoustics. Locations of building openings are related to vehicle access and parking areas to minimize pollutant entry.

Pollutant-generating activities located within the building are identified and separation/ventilation strategies are developed if needed. Wherever there is a potential moisture source, ventilation and dehumidification should be adequate to protect against microbial growth. Regardless, attention to dehumidification is needed throughout the building. Smoking lounge requirements and locations are determined, if necessary.

The building envelope, including roof, walls, doors, windows, and floor, is developed. Depending on ambient air quality, as identified in the previous stage, operable windows are considered by the architect, and their potential impact on the HVAC system is assessed by the mechanical engineer. The building owner/developer considers reasonable occupant use and interlock or pressure control requirements, if any. The envelope and structural materials are selected with input from the architect, the building owner/developer, the structural engineer, and the mechanical engineer.

Once the overall building and site have been selected, **Ventilation and Climate Control Strategies** are developed by the architect, the building owner/developer, the mechanical engineer, and the landscape architect. Outdoor air dilution depends on ambient air quality as affected by perimeter trees, shrubs, and landscape materials. Air intakes, exhaust locations, air cleaning, and space air distribution are developed by the mechanical engineer in conjunction with the team. Heat recovery systems and microbial development control strategies are considered at this stage. Strategies related to ventilation rates, filters, cleaning, and air distribution are selected, and a choice is made between using either ducted or plenum return air.

In the **Materials Selection and Specifications Stage**, the team explores source control options. Low-emitting materials for the envelope and the interior finishes are selected wherever possible. Materials that might support molds are reduced and design strategies are developed to ensure that moisture does not accumulate. Strategies are designed to reduce offgassing of materials in the enclosed spaces; to manage any condensation in HVAC systems; to ensure proper curing of concrete before covering; and to generally address issues of indoor air quality and make them part of the construction contract and of the operations and maintenance plan. The contractor, if available, is invited to assist in the development of the specification and selection of materials. Ideally, future building operations and maintenance staff would be involved to ensure that specification strategies are practical and will be implemented during the building operations and handover stage.

During construction, the issue of **Product Substitution** may arise. A contractor may make a request to substitute a product that carries consequences for indoor air quality performance. This can present a temptation to owners for cost-cutting because these substitution requests are made in isolation; the consequences for indoor air quality may not be fully apparent.

The **Construction Process and Initial Occupancy Stages** involve the entire team. Some decisions regarding the commissioning of the building are made at this time, but comprehensive plans and the commissioning process should begin with design. The importance of special ventilation during construction and of avoiding premature occupancy is clearly communicated to the contractor and the building owner/developer to ensure indoor air quality throughout construction and occupancy phases. The HVAC system is handed over to the building's operations and maintenance staff with a hands-on training session to ensure the building will be operated to maximize potential performance.

A recent and successful development in the management of IAQ is the **System Commissioning Process**. Commissioning is a formal process verifying that systems have been installed and are operating as designed. It involves a comprehensive review of design drawings to ensure that systems meet design intent and are readily maintainable, inspections to ensure that systems and equipment are installed per the design documents, and testing of all equipment and control systems. Several case studies have shown that a formal commissioning procedure can be highly effective (3).

The cost of building commissioning may be erroneously perceived as high and as a reason for not implementing commissioning of HVAC systems in commercial buildings. In fact, experience with commissioning to date has clearly demonstrated its financial advantage (3). Savings are realized from the reduced need for corrections of deficiencies late in the construction process and during the early occupancy period. Further savings, in some cases shown to be quite dramatic, have come from reducing energy costs in new buildings. Because the commissioning process provides complete documentation of systems and training of building operators, design intent is more likely to be executed in a fully commissioned building. A recent study in Switzerland found that symptom prevalence in occupants varied inversely with how closely building ventilation rates conformed to the original design (4). Documentation of design intent and commissioning, therefore, can be cost effective by reducing problems and their severity and by reducing lost work time from absenteeism because of building-associated illness or by contributing to optimal worker productivity.

Mitigating IAQ Problems in Commercial Buildings

The management of indoor air quality in an occupied building often starts with simple preventive measures and may include more advanced technological approaches as needed.

Housekeeping procedures. Indoor environments are continuously contaminated with dirt and dust tracked in by building occupant's footwear, from dust in the supply air, and from dust sources in the building, such as office machines and paper handling, by spillage, by residues, and from other sources. Proper housekeeping prevents build-up of dust deposits, and thus is a most important measure in controlling secondary dust sources. To date, there are very few scientific attempts to demonstrate an effect of cleaning on occurrence of Sick Building Syndrome (5).

Building entrances designed to minimize track-in of dirt may consist of grilles followed by removable, washable mats. The mats should be washed at regular intervals. If an office room is disturbed by computer cables, printer paper boxes on the floor, or other obstacles, the cleaning staff cannot carry out the cleaning job as effectively as intended in the time assigned; untidy workplaces may interfere with cleaning and thereby affect IAQ.

The building owner should take care in selecting a cleaning contractor and phrasing the final contract. Proper cleaning contributes significantly to the expenses of running a building, whereas insufficient cleaning results in an unacceptable environment. The customer should specify the degree of cleanliness to be maintained and the cleaning loads placed on rooms. The professional cleaning contractor then can design a cost-effective cleaning procedure while considering other factors such as types of room surfaces and accessibility. The contractor should specify how the proposed cleaning procedures—along with quality assurance—will be documented. Special emphasis should be put on carpets, particularly in rooms with high person/dirt loads.

Cost-effective cleaning consists of a carefully chosen combination of cleaning agents, tools, and machines applied in a specified cleaning program. The program should specify the method by which an object is cleaned and how frequently. The cleaning contractor should document procedures for selecting the least toxic cleaning agents to do the job. Cleaning personnel should be properly trained, as improper use or dosing of cleaning agents may degrade surfaces. Use of cleaning agents can be reduced by more frequent inclusion of dry mopping methods. Occupants should be informed about cleaning programs specified for each room in a building.

Computer-supported quality control procedures are available, based on subjective assessment of the quality of the cleaning (6). Assessors select a random sample of cleaning objects for inspection and count the number of "failures" such as spots, heel marks, greasy fingerprints, and visible dust deposits. The procedures can only help to assess if a given cleaning procedure has been followed, not if the quality is appropriate in relation to the indoor air quality.

A comprehensive approach to evaluating the quality of cleaning, including a method for on-site measurement by nonspecialist personnel has been proposed (6). The method is applicable to nontextile surfaces and measures the degree of surface soiling by the percentage of surface area covered by particles (*see* Table 1). Proposed guidelines for the quality of cleaning, based on what is reasonably achievable, are as follows:

1. Baseline quality. The potential dust sources can readily be controlled to this level by using appropriate cleaning methods.
2. Improved quality.
3. Indoor environment quality. Surface cleanliness can be maintained by the best currently used cleaning methods and programs. Control of secondary dust sources at this

TABLE 1

PROPOSED NORMS FOR CLEANING NONTEXTILE SURFACES

Cleaning Object	Area Covered by Dust (%)
Hard furniture surface	
Indoor environment quality	
Close to person	1
Easily accessible	1.5
Other	5
Improved quality	
Close to person	2
Easily accessible	3
Other	10
Baseline quality	
Close to person	4
Easily accessible	6
Other	15
Hard floors	
Indoor environment quality	
Walk area	3
Other	5
Improved quality*	
Walk area	7
Other	10
Improved quality*	
Walk area	12
Other	18

* Provided polish film is not sampled.
Source: Schneider *et al.*, 1994 (6).

level does not imply that sick building symptoms will not occur. The limits specify the levels not be exceeded during the period between cleanings. The cleaning contractor selects appropriate cleaning methods and frequencies.

Commercial IAQ assessments. To increase assurance that commercial buildings offer thermal, air quality, lighting, and acoustic conditions conducive to health and comfort, periodic assessments of spaces should be conducted by trained facilities staff. One readily available document that can be used by the staff for this purpose is the EPA's Building Air Quality Manual (7). Although its procedures do not require quantitative measurements or formal surveys of occupants, they can be implemented with the expectation of achieving reasonable assurance that occupant exposures are "acceptable" according to applicable guidelines (8–11). If a higher level of assurance is required, then quantitative and simultaneously obtained system performance, human response, and exposure measurements should be obtained and evaluated against a rigorous and established protocol.

Commercial system performance assessments. To carry out periodic systems assessments, ASHRAE's Guideline 1: *System Commissioning* and Guideline 4: *Operations and Maintenance Manuals* are useful (10, 11). These procedures demand extensive knowledge of building systems and may require additional training for staff or the services of a competent test and air balance (TAB) outside contractor. If system performance is deficient, a system performance assessment should be conducted using a comprehensive protocol. Air flow should be measured and compared with the original TAB report. However, if there have been modifications to the building structure, use, or occupancy, the original design TAB specification must be evaluated and modified if needed. A third party should direct and evaluate the TAB assessment or provide assurance of the competency of the selected firm.

The "healthy" building should include sensors for real-time monitoring of supply and return air flow. Cost can be reduced by placing the sensors within the fan, eliminating the need for a large expanse of straight duct to minimize turbulence and provide accurate measurements.

The transfer of HVAC building operations and preventive maintenance. In this step, information on operations and preventive maintenance is transferred from the designer and constructor of the facility to the owner and/or tenant operating the facility. The approach to the transfer varies widely. At one extreme, the owner/operator is simply handed instructions from the equipment manufacturers without any operator training. At the other, systems are formally "commissioned," including thorough system inspection and testing and careful on-site training of the operators. Detailed approaches to accomplishing this hand-off are covered in ASHRAE's Guideline 1: *System Commissioning* and Guideline 4: *Operations and Maintenance Manuals* (10, 11). At a minimum, wall displays of the HVAC system should be provided in mechanical rooms and should include a brief description of the HVAC systems that serve the facility and of the ASHRAE design standards used. Basic assumptions should be given, including the maximum number of human occupants that each HVAC system was intended to serve and the major pollutant sources in the ventilated areas. The information should also include the basic central operating sequence and the schedule for preventive maintenance.

Evaluation of current HVAC performance. Many facilities lack any routine evaluation of the ongoing performance of HVAC systems. A few states, through state OSHA regulations, do require periodic maintenance and verification of performance. One prudent approach to ensure proper performance is to conduct periodic audits of HVAC systems and to maintain records of these audits by an identified, responsible person.

If problems are found by the HVAC audit, a careful diagnostic procedure by trained professionals (i.e., mechanical engineers and HVAC control contractors) should be conducted and appropriate corrective actions taken. If the problems have come from changes in the pattern of occupancy in the area that the system serves, modifications may be needed in the design of the system.

Proactive maintenance. Proactive maintenance is far-reaching; it includes inspection for cleanliness and operations, cleaning, and filter replacement. Some procedures should be carried out seasonally and others annually. Property owners should arrange for periodic in-house or contracted maintenance service for HVAC systems.

HVAC system correction during commercial maintenance procedures. The previous section outlined typical inspection processes and the steps usually needed to determine if HVAC systems are functioning properly. Perfunctory maintenance and inspection processes, usually performed for the sake of economy, may not reveal latent indoor air quality problems, and almost always fail to assure the comfort of building occupants. The maintenance process requires diagnosis, planning, documentation, and communication with building management to assure achievement of adequate IAQ.

The qualified maintenance technician should be able to identify defects in design or installation and also to diagnose and correct items that reflect mechanical or electrical failed uses. Attempts should be made to initiate elements of "predictive" maintenance. Examples include vibration measurement of rotating devices, insulation resistance integrity of HVAC system motors (including compressors), and periodic overall airflow and water-flow measurement. Failure of HVAC systems, although sometimes instant and possibly catastrophic, is often gradual and predictable. Actual repair and remediation techniques are well documented (11) and will not be detailed here.

Preserving IAQ during building renovation. A high potential for compromising IAQ exists during building renovations, as the renovations may generate pollutants and alter ventilation. These problems may be minimized by conducting IAQ design and procedural reviews with a specific IAQ control agenda and by retaining a qualified IAQ industrial hygienist with engineering experience, or a consulting engineer with industrial hygiene and IAQ experience, to review design and implementation plans. Building personnel should be informed, and an IAQ industrial hygienist could be appointed to administer the IAQ plan. Further steps to reduce IAQ problems include renovating in off-hours, sealing off construction spaces, and ensuring that particles and gases are satisfactorily controlled. Some renovations may necessitate removing personnel from the area being renovated and the surrounding areas.

IAQ correction during renovation or remodeling operations. During renovations and remodeling operations, occupant exposures can occur; therefore a decision is needed before the process begins on whether occupancy should continue. The three critical steps in the detection and remediation process, should harmful agents be liberated, are communication, evaluation, and remediation.

1. *Communication*. The communication process begins with immediately alerting the administrator of the IAQ response plan that an incident has occurred. The report may originate with the party causing the incident or from facility

occupants. In the communication process, delay in notification should be minimized, regardless of concerns about culpability. The plan should emphasize that reports of possible incidents should be taken seriously and action should be immediate.

2. *Evaluation*. Upon notification of an IAQ incident during building renovation, it is imperative that the administrator of the IAQ response plan evaluate options rapidly and conservatively. All options, ranging from containment, vacating the area, and requests for third party assistance (i.e., local HAZMAT forces), should be considered and implemented on a timely basis.
3. *Remediation*. After communication, evaluation, termination, and containment, potentially harmful sources should be pursued vigorously and completely. Entry of particles, fumes, or vapors should be ended by use of approved direct contact measures (i.e., cleaning, vacuuming, etc.), or concentrations reduced by appropriate approved ventilation measures. All contaminants should be mitigated without transferring the problem from the area undergoing renovation to another area. Professional third-party review of these measures is encouraged to assure that complete and correct measures are undertaken.

Competent and trained staff. The healthy building has a competent and trained staff that is cognizant of the IAQ implications of HVAC maintenance. Even a well-designed building can have poor IAQ if maintained poorly. Modern HVAC equipment such as boilers, chillers, fans, and pumps, can be quite sophisticated, often incorporating sensitive electronic components. The equipment may be integrated with a variety of controls, including pneumatic, electronic, and direct digital control (DDC) devices. In larger buildings, and even in some medium-size buildings, these controls may be managed with a computerized and automated system. Thus, without extensive and continuous hands-on training, maintenance staff may be unable to operate the building properly. Appropriate hands-on training and complete operations and maintenance manuals should be provided.

Current Residential Design and Construction Practices: Description and Deficiencies

Design and delivery. Designing and building small residential buildings, especially single-family houses, contrasts markedly with the process for other types of buildings. Houses are "designed" once and built many times, in different locations, on different types of foundations, and with diverse modifications. The use of stock plans from plan books is widespread, whereas custom homes designed by an architect and incorporating systems designed by engineers are a small minority. Typically, the "design team" is a single person. The builder may also be the developer and may use employees to perform some services that would ordinarily be subcontracted. Expertise in identifying and avoiding potential IAQ problems may be lacking.

Builders of speculative housing build for an anonymous buyer whose tastes are assumed based on overall perceptions about buyers and experience with previous buyers. There are always exceptions, but few home builders see upgrading IAQ as a significant marketing opportunity, nor do they see failure to incorporate IAQ upgrades as leading to buyer complaints or call-backs. As a result, IAQ upgrades are likely to be incorporated voluntarily in new homes only where their incremental cost is very small, the measures are prescriptive in nature and understandable to the nonspecialist, and/or the changes are beneficial and marketable for reasons aside from their impact on IAQ.

Design and delivery of combustion equipment. The design/delivery phase can have significant influence on the exposures to combustion emissions in residential structures. All combustion devices should be ventilated effectively, and major combustion devices such as furnaces should be isolated from the interior space. In designing venting systems, one should consider the interactions of all the devices acting on the house airflow system. Vented appliances are designed to have combustion emissions released to the outdoors when operated normally. Back-drafting may bring combustion products into the house because of a malfunctioning venting condition.

Radon control. New homes built in areas with high radon potential should be designed and constructed to facilitate remediation if elevated radon levels are found after occupancy. Radon-resistant construction features include a permeable layer underneath the basement floor slab or slab-on-grade; a polyethylene membrane above the subslab layer prior to pouring the floor slab; a vent stack extending from below the floor to above the roof, and electrical wiring to facilitate installation and activation of a fan to depressurize the layer below the slab. A set of prescriptive requirements for radon control along these lines has been added to the *1995 Council of American Building Officials (CABO) One and Two Family Dwelling Code*, so this type of construction should become more common (12).

Surface drainage. It is standard practice to slope the ground away from foundation walls to provide positive drainage of surface water and discharge from downspouts. However, as this soil must be placed after the foundation wall is poured or erected, proper compaction of the fill is critical if the final grade is to be maintained. If the fill is not fully compacted, it will settle around the foundation wall and eliminate positive drainage away from the home. In that event, the likelihood of a damp basement or crawl space, or even of major leaks at the basement floor level, is greatly increased, facilitating growth of microorganisms and subsequent IAQ and other problems.

Multifamily buildings. Multifamily buildings represent nearly a quarter of new housing construction stock and 18% of the new residential construction since 1990 (13) in the United States. As building types, they fall between other residential and commercial construction. The population in this housing stock has a higher proportion than single family housing of renters, lower income, and minority group members, but not—as popularly perceived—elderly residents. The two main issues relating to indoor air quality and the design and construction of apartment buildings are the provision of mechanical ventilation systems and the lack of attention to details to prevent moisture penetration.

Ventilation systems are typically required in large apartment buildings to exhaust air from kitchens and bathrooms. Outdoor air is typically supplied through the corridors, where it enters the apartments through the gap under the door. However, because of noise complaints from the tenants on the top floors, the roof exhaust fans are often shut down.

New apartments are often required by code to have direct supply and exhaust at each apartment. There is no evidence from the field on the efficacy of these systems. Because of the conflicts over reducing energy costs and the provision of ventilation air, ventilation systems in multifamily buildings are often run intermittently, if at all. Apartment building managers and owners may not perceive ventilation as critical, and it may be given low priority in the maintenance and operation of the building, unless tenant complaints—usually regarding cooking smells from other apartments—are frequent. Unlike single-family housing where infiltration and natural ventilation have been used to provide adequate air entry, the patterns of air flow in multifamily buildings are quite complex; depending on the height of the unit and the wind direction, some apartments may not receive any natural infiltration.

Moisture inspection and repair. Moisture is a major problem in multifamily buildings, because of the configuration of units. Balconies are prime locations for rain penetration, and flat roofs may be ineffective in preventing water entry. Coupled with the frequent lack of maintenance, moisture entry in apartments can lead to water-damaged materials. Another source of moisture in apartments is the use of unvented gas stoves and ranges for space heating. In large multifamily buildings, tenants are often billed directly for their electric space heat, but the gas stove is typically metered centrally and the tenants are not billed for their individual consumption. The tenant realizes the economic benefit of using the "free" gas heat, but the unvented stoves produce a great deal of moisture—in addition to the combustion gases—that frequently results in condensation on walls and other surfaces.

Entry mechanisms. (*1*) External leakage. There are two entry paths through which moisture can enter the residential environment. The first is leakage through the building shell, either through the roof, walls, windows, doors, or other building structures and components. The second is through paths below grade slabs and walls. (*2*) Internal leakage. Another cause of water presence within the home is internal leakage or overflow (i.e., pipes, basins, tubs, appliances) or condensation of internal moisture on cold surfaces. Moisture condenses at a temperature known as *dew point.* Expressed in units of temperature (degrees), the dew point varies with the temperature and the relative humidity within a space. For example, if a home environment is kept at 75° F and 50% relative humidity, any surface lower in temperature than 55° F will cause condensation to occur. Thus, cold window surfaces can promote condensation with subsequent water damage and mold growth at window sashes within and on the surface of adjacent walls. This problem is most likely with single-pane windows or thermally unbroken window frames in cold climates. Installation of furnaces directly onto concrete floors may also promote mold growth as dew-point condensation occurs during the summer. Leaving a small gap between furnace and floor can solve this problem. The manufacturer's installation instructions should be consulted for more information.

Preventive maintenance and inspection checklist. The workshop participants' recommendations for homeowners' checklists for periodic inspection and repair as required, to prevent leakage and sources of condensed moisture within the home are shown in Tables 2 and 3.

Moisture control in the home. Remediation is generally a two-step process undertaken once the presence of water has been detected. The first and obvious step is to prevent further damage by correcting structural defects, repairing leaks, correcting drainage, and managing internal sources.

The second step involves repairing the damage. Mechanical deterioration, spalling, rot, component separation, and delamination generally require the conventional correction techniques of removal, patching, and/or replacement. Hidden surfaces should be fully exposed to examine moisture entry or deposition sites for signs of mold or bacterial growth. These contaminants are usually readily identifiable by color, texture, or odor, and, once identified, they need to be removed.

Inspection and maintenance of residential HVAC systems. HVAC systems that are poorly operated or maintained can cause significant indoor air quality problems by not providing proper environmental conditions of temperature or humidity, or by contaminating living areas through malfunction. Most HVAC systems in homes are not designed to clean air by removing particles—other than very large particles—and gases. A list of tasks designed to prevent operating and maintenance problems is given in Table 4.

HVAC remediation in the home. This section deals with remedial procedures to be employed once signs of HVAC malfunction are detected.

Remediation is again effected in two steps. First is the determination of a design or installation deficiency, or a maintenance problem such as improper heating system flue sizing,

TABLE 2

EXTERNAL LEAKAGE

Yearly	Seasonally
• Inspect chimney for cracks or damage	• Inspect all roof gutters for pitch and drainage
• Inspect all roof flashings for integrity and soundness	• Inspect all leaders for conducting water away from the building
• Inspect attic spaces from below for sites of leakage,either after rainstorms or during snow melts	• Inspect attics for adequate ventilation to outdoors to avoid condensation
• Inspect roof surface for missing or damaged shingles or roofing	
• Inspect soffits for adequate seal at roof and wall surfaces	
• Inspect pitch of all exterior grade surfaces so that water leads away from the building	
• Inspect all glazing and window and door frames for adequate sealing and caulking	
• Inspect all building walls and above-grade foundation walls for cracks and spalling if concrete	

TABLE 3

INTERNAL MOISTURE

Yearly	Seasonally
• Inspect all crawl spaces for signs of liquid moisture. Examine the insulation and wood framing for mold and mildew discoloration	• Check all basement wall and floor surfaces for signs of leakage or mold growth. If there is a strong mold odor there is a problem, and the source of the problem must be eliminated
• Check for proper venting of all supplementary home heating and water heating appliances	• Limit home humidifier settings (if used) to the lowest possible setting during dry winter conditions
• Check all exposed pipes for signs of present or past leakage (mineral deposits)	• Utilize dehumidifiers for all below-grade surfaces suspected of containing recurrent moisture
• Inspect, when possible, exposed pipes leading upward to concealed wall spaces	• Check the pitch of air conditioning condensate lines and drainage at exit point of building
• Check for proper venting to outdoors of bathroom fans and clothes dryers	
• Examine "Floating Floor" trenches for signs of mold or moisture	
• Look for signs of moisture on floors of attic spaces	
• Look for water stains at window sash, on exposed walls, and ceilings	

TABLE 4
PREVENTIVE MAINTENANCE CHECKLIST FOR HOMEOWNERS

Yearly	Seasonally
• If possible, install inspection door in supply and return ductwork mains for visual duct inspection. Ducts can be checked from registers with a mirror and a flashlight • Consider installation of carbon monoxide detector(s) in the home • Inspect all supply and return registers for correct operation and cleanliness • Check all heating and hot water flues for pitch and integrity • Check all refrigerant lines for proper insulation to prevent water condensation	• If suspect, have local utility check furnaces, heaters, or appliances for gas leaks or improper conditions • Inspect the outside of the house during heavy rain to observe the performance of gutters and drainage • Vacuum all heat exchange surfaces, filters, racks, and blowers at filter changes • Examine air conditioning drain pans for pitch, absence of organic material, and proper condensed water flow • Inspect and clean humidifiers on biweekly basis during humidification season • Replace heating/cooling filters at least seasonally

installation, or slope. Common deficiencies also include improper pitch of the air conditioning condensate pan with inadequate drainage and inadequate disposal of collected air conditioning condensate (e.g., piping condensate to the space under a basement or crawl space floor slab). Improper filter size installation permits bypass of dust particles and their reintroduction into the house. Once a deficiency is identified, then the second step—repairing the damage—should take place.

HVAC maintenance issues. Low airflow, odors, and discomfort can result from blocked filters or obstructed or closed air ducts. Humidifiers require frequent cleaning during the humidification season, and can themselves be significant sources of microorganisms. In combustion appliances, fuel-air ratios can be incorrect, resulting in incomplete combustion, and leading to a release of carbon monoxide or carbon particles. In older systems, heat exchange surfaces may deteriorate or become punctured, liberating products of combustion into the space. A preseason service contractor or utility checkup of a heating system should identify many of these defects.

Control of residential renovation processes. To assure that occupants will not be adversely affected by renovations generating dust, particulates, or vapors, the space under construction should be physically isolated from the rest of the residence, and air from the isolated space should be exhausted. The supply and return ducts of the heating and air conditioning system that serve this area should be sealed with 6-ml polyethylene sheeting and the ducts kept clean during construction. If the existing HVAC system will be reconnected to the renovated or remodeled space, the capacity of the system must be adequate to provide the required/desired thermal and air quality control throughout the residence (14, 15).

Other IAQ Problem-Solving Issues

Emission tests. To eventually establish emission guidelines, architects, purchasing agents, and general consumers will require both accurate emissions testing and an understanding of the health effects of emissions. Emissions from a great variety of materials have been measured using controlled chamber tests. American Society for Testing and Materials (ASTM) Standards for chamber testing have been established and emission rates are usually reported as "steady state" in mass (microgram or milligram) per square meter per hour. These studies have been conducted at national and private facilities in North America and Europe. Results depend on the test condition's temperature, humidity, and volume flow rate. Emission rates are shown to depend on material preparation, preconditioning, and age. For example, emissions from paints vary with drying rates, number of layers, and composition.

We know substantially less about the emission rates of materials under conditions of actual use. Only recently has a standardized method for *in situ* testing of emission become available (16, 17). Although "as used" conditions are more relevant from the point of view of the occupant, tests of this type will not provide a readily useful way to discriminate among components. Standardized laboratory testing, along with modeling and health evaluation, does provide an objective evaluation scheme to compare among products.

Product labeling. Modern building materials and products may have complex chemical formulations and release volatile organic compounds (VOCs). There is a substantial body of literature and general experience that associate elevated mixtures of VOCs with symptoms (18). Products are often used on a daily basis in homes and offices, and population exposures are ubiquitous. Aging of materials and/or reactions with gases (i.e., ozone) may continue the release of VOCs or aldehydes. Emission rates and composition vary among specific products and sometimes among batch productions.

In the long-term, it may be cost effective to reduce emissions from building materials and equipment. Reduction is accomplished by product/component reformulation and process/production controls. Removal or reduction of these and other sources avoids total reliance on ventilation to achieve a safe indoor air quality. Broader societal gains potentially include conservation of petroleum chemical stocks, reduction of photochemical compounds, and conserving of energy.

A study of the olfactory properties can also be helpful in understanding the sensory emission of building materials (19). Recently, Jensen and coworkers (20) compared the perceived (relative) odor intensities with chemical emission data from 13 linoleum products. Multivariate analysis of the data revealed that two principal factors could explain 68% of the odor intensity variation. The factors were aliphatic C_6-C_8 acids and C_5, C_7, and C_{10} unsaturated aldehydes, respectively. The GC/sniffing analysis of emissions and the above approach appear to be a powerful combination to identify odorous VOCs.

The Danish indoor climate labeling system. Denmark uses a labeling system that rates VOC emission from building materials according to impact on comfort and health (21). The system unifies chemical emission testing over time (months) (including a standard room and mathematical modeling of the emission profile, when necessary), and health evaluation. The Danish system focuses on comfort and includes odor annoyance and mucous membrane irritation, with plans to add other material characteristics (e.g., fiber release). Two design criteria were set: the labeling system shall be easily comprehensible, and, at the same time, operational and dynamic. The parameter used for labeling is the time value $t(C_{mi})$ required for emissions to decay to a point at which room concentrations would be below the indoor relevant values, C_{mi} of VOC_i, presently based on either odor detection thresholds or mucous membrane irritation thresholds. The time value, $t(C_m)$, is a measure of the duration during which new building material may increase exposure, as well as the probability of indoor air quality problems. Odor thresholds are used because they generally are at least one order of magnitude lower than mucous membrane irritation thresholds. The system may also be used for single VOCs when a specific health end point has been reported. In addition, the system has a built-in safety procedure for sensory testing over time, thus providing sensory emission profiles (intensity and acceptability) by the use of a special chamber and a panel of judges (22). The evaluation should be performed at approximately the same time as the chemically determined time value. Several building products have now been labeled by this process.

The Canadian experience. To help builders, architects, and sensitive persons who are intending to build and renovate, the Canada Mortgage and Housing Corporation has compiled a reference guide on building materials (23). Product listings for residential construction materials were gathered that contain information on health effects from two sources: existing or published health information and experiential information based on the experiences of perceived environmentally hypersensitive persons on exposure to these materials.

It should be noted that incentives to protect the environment such as recycling materials may not be compatible with efforts to improve indoor air quality. The incorporation of recycled materials can introduce new pollutants into the indoor environment, e.g., recycling rubber tires. Although the landfill burden is reduced, using them in such products as carpet underpads results in an increase of emissions from rubber inside buildings. The applications of recycled materials must be carefully selected. Recycled cellulose—primarily newsprint—is used in chemically treated slurry for insulation in residential construction. In hot and humid climates, this can provide a microbial growth site, as the composite is closed in with gypsum prior to complete dryout. There is also potential outgassing from the chemical fire retardants used in the slurry to meet fire code restrictions

Strategies to encourage product labeling. For labeling to be useful to decision-makers, including consumers, architects, interior designers, engineers, and building owners, it must be relevant to design-condition parameters and also must identify the classes of contaminants of concern. For target products to reduce VOCs, labeling should probably be kept to a very simple pass/fail standard. Behind this label, additional standardized, independently tested information should be available to those charged with special construction of low-emissions buildings for sensitive populations or for specific climate conditions. Information on the VOC emission rate should show a simple quantitative analysis tool that relates square feet of installation to cubic loads. Any quantitative standard relating to the performance calculation method should recognize the inherent difficulties in assessing total surface areas of all materials specified for buildings and the relatively limited practical application of this method for most types of construction. If the quantitative analysis standard is simplified, it is more likely to be used in ventilation load calculation.

Supply-type strategies for reducing VOC emissions from building materials can complement demand-type strategies such as product labeling. One approach is to provide an incentive to reformulate or modify products by, for example, revising the current system for reporting and regulating emissions at the point of manufacture so that downstream emissions are also considered, thereby regulating total emissions instead. Under this approach, manufacturers who could demonstrate reduced emissions at the point of end-use could take credit for emissions reductions in their Toxic Release Inventory filings and pollution prevention strategies. This could shift the emissions from locations where effective ventilation is problematic to locations where exhaust systems designed to eliminate large amounts of emissions are present, and reduce the overall burden of dealing with released chemicals while effecting greater reductions of population exposures. A variation of this approach would be to foster development of voluntary industry standards for VOC release on a product-by-product basis. Although this approach has some appeal and follows the current cooperative trends, results to date have been mixed. Substantial improvements in woodstove performance have been made. However, labeling for carpets lack specificity and sensitivity and consequently has limited usefulness for architects and consumers.

Recommendations

The problems in indoor air quality resulting from the common practices of building design, construction, commissioning, and maintenance/operation are not likely to improve without involvement of other stakeholders. A potentially important player in the solution of indoor air quality problems is the insurance industry. Not only is the insurance industry a major holder of commercial building investment property but its business encompasses workers' compensation and tort liability coverages. To date, workers' compensation claims for building-related illness are limited by physicians' inability to identify building-related etiologies for asthma and hypersensitivity pneumonitis in individual patients; lack of familiarity of infectious disease physicians of the workers' compensation coverage for *Legionella* pneumonia among employees; and infrequent claims of financially significant, permanent impairment for sick-building syndrome. Nevertheless, the financial incentives for insurance companies may increase as a function of public and medical professional recognition and the shift from workers' compensation to third party liability claims against manufacturers, building owners, and ventilation contractors.

In a climate of litigation, another opportunity for intervention/prevention regarding indoor air quality is during lease negotiation, which could include specifying building performance for indoor air quality. In the short run, marketing of indoor air quality performance may provide a competitive advantage for building owners and a health/productivity advantage for tenants/buyers seeking commercial or residential property. In commercial property transfers, financial interests could include indoor air quality inspections both for system design and postdesign performance. Such inspection is routine for termite infestation in some parts of the country, for asbestos in some older commercial properties, and for radon in residential property in some locations. Thus, extension of due diligence with respect to broader indoor air quality concerns is perhaps feasible in order to increase incentives to address indoor air quality by building owners.

Several professional organizations show substantial activity regarding indoor air quality because of membership involvement in problem-solving or prevention. The leading group in impact is ASHRAE, as its standards become the basis of building codes in many localities. However, the process by which standards evolve is driven by consensus among various interested parties, and public health is not necessarily the driving principal. Other professional groups with substantial educational or standard setting activities include the Building Owners and Managers Association (BOMA), International Facility Management Association (IFMA), American Institute of Architects (AIA), American Industrial Hygiene Association (AIHA), and the American Conference of Governmental Industrial Hygienists (ACGIH). The ACGIH Bioaerosols Committee does not believe that quantitative standards with respect to bioaerosols are feasible given current measurement methods for most bioaerosols and the dearth of exposure-response relationship information.

Several trade associations may develop or have developed an interest in indoor air quality because such concerns are critical to their business and protection from liability. These include the North American Insulation Manufacturers Association, the Air-Conditioning and Refrigeration Institute, the North American Duct Cleaners Association, the National Air Filtration Association, the National Association of Home Builders, and the Association of Home Appliance Manufacturers. These trade associations should have a substantial interest in needed research on etiologies of indoor air quality complaints, along with their resolution, and prevention. Certainly, individual companies have occasionally taken aggressive roles in IAQ investigation teams because of attribution of IAQ problems to their products.

Employee representatives have taken a role in motivating attention to indoor air quality for specific groups of employees. Examples include service, teacher, and government employee unions. With the absence of accountability for indoor air quality, the role of an educated public in motivating change is important. Approaches are needed for informing the public, possibly beginning with school curricula.

Finally, government at federal, state, and local levels is an important stakeholder regarding indoor air quality. Government buildings account for a significant number of office buildings in the United States, and government workers are among the major groups affected by poor indoor air quality. Aside from productivity concerns in an era of government downsizing, the government has substantial agency commitment pertinent to indoor air quality regulation, investigation, and research. The obvious federal agencies include the General Services Administration (GSA), the Occupational Safety and Health Administration (OSHA), the National Institute for Safety and Health (NIOSH), the Centers for Disease Control and Prevention (CDC), the Department of Defense (DOD), the Department of Housing and Urban Development (HUD) and the Department of Energy (DOE). State and local governments also have the burden of governmental employee complaints and the responsibility for public health investigation of complaints from nongovernmental workers, including the substantial source of problems in schools. There is perhaps room for an educational partnership between government agencies and trade associations that can lead to favorable changes for indoor air quality. In this regard, NIOSH and CDC—with respect to communicable disease in hospitals, schools, and other community facilities—may be able to take leading roles as nonregulatory agencies.

SOURCE CONTROL

Source control is essential to achieving healthy indoor air quality. The methods used for source control vary according to the pollutants and range from complex and costly solutions (e.g., earth removal in the case of severe radium contamination) to relatively simple remedies (e.g., not smoking in the home). This section includes recommendations for the general population and some recommendations for special populations. Appendix A provides a list of recommendations for reducing the number of particles in the indoor environment to minimize the negative health effects of indoor air pollution. As possible, statements in this section are referenced to the literature, but some recommendations are based on professional judgment, absent published data. The pollutant sources addressed include moisture, building materials and products that emit VOCs, pesticides, household products, and other point sources and particulates. Specific sources well-covered elsewhere in the literature and in the previous workshop such as environmental tobacco smoke, radon, asbestos and lead paint, did not receive extensive consideration by this working group (24, 25). For radon, asbestos, and lead paint, the Environmental Protection Agency offers guidance (26–29).

Moisture

Moisture underlies some of the most common indoor air quality problems. For example, high relative humidity allows house dust mite infestation to occur, and water damage and water reservoirs facilitate proliferation of microbes. Water incursion can also lead to structural degradation of building and ventilation system components, which can result in further indoor air quality problems.

Associations between moisture problems and health effects. Moisture-related health problems are diverse, including allergic diseases, infection, and complaints of musty odors. The allergic diseases affected by moisture include allergic rhinitis and asthma, with house dust mites and building-associated fungi as possible moisture-related triggers for those diseases. Hypersensitivity pneumonitis, a less commonly recognized immunologic lung disease, has occurred in endemic form in buildings with contaminated spray water humidification, water-damaged materials, and visible bacterial or mold growth. Apart from physician diagnoses of asthma and hypersensitivity pneumonitis, epidemiologic studies document that indicators of residential dampness are associated with respiratory symptoms in children (30).

Contaminated reservoirs from which water is entrained into indoor air can produce bacterial infection, with *Legionella* pneumonia as the prototype. Legionellosis has been attributed to diverse sources, including cooling towers, hot water heaters, shower heads, and whirlpools. Pontiac fever, a febrile syndrome, is also associated with exposure to aerosolized *Legionella* bacteria. Immunocompromised persons are at risk for fungal infection from saprophytic fungi in indoor air (31).

Sources of moisture. The primary source of moisture-related problems is usually in the building envelope—in the walls, roof, and foundation of the structure. A major area of concern is the failure of the water-proof roof membrane. Leaks typically occur at the junction of the roof and the wall parapet. Any opening in the exterior envelope (e.g., vents, flashings, skylights, doors, windows) is a potential site for the entry of moisture. As mentioned previously, balconies and overhangs are also well-documented areas of moisture entry. Deterioration and ultimate failure of sealing materials such as grout, caulking, and other sealants can lead to moisture entry. The location and the installation of the vapor barrier in the building envelope are critical in preventing future moisture damage, particularly moisture condensation in the walls. Subgrade leakage from rain, irrigation, and ground water all speak to the need for careful design and construction of basement walls and foundation drainage.

In addition to moisture introduced from outside the building, there are also numerous indoor sources of moisture, including unvented combustion equipment, as well as activities such as showering and cooking. Good design should provide ventilation for areas where indoor moisture levels can be high. People, pets, and plants are sources of indoor moisture, as are indoor pools, spas, and fountains.

HVAC equipment is a frequent source of moisture problems because of inadequate disposal of condensate from condensation on pipes and ducts and from cooling coil condensate drainage and carry-over. Standing water in humidifiers, evaporative coolers, cooling towers, condensers, and air washers may become a source of contamination. Water damage, whether caused by flooding from broken pipes or natural flooding, may also lead to moisture damage of materials.

Moisture mitigation strategies. Drying affected areas and materials is a first step in tackling moisture-damaged areas. Identifying the sources of recurrent moisture can help determine strategies for remediation, whereas repairing the damaged area may not address the underlying reasons for the moisture. In the case of moisture damage, all water-damaged porous materials such as carpets, insulation, acoustic materials, and ceiling tiles, should be removed and replaced.

Inadequate dehumidification capacity of HVAC systems may lead to moisture problems as well. HVAC equipment should be designed and installed so that reservoirs of stagnant water can drain as intended; for example, drain pans and sump pumps should be sloped to drain. A critical design requirement is that all systems have easy accessibility to allow for routine inspection and maintenance; individual interior components of systems must be easily accessible as well.

Building Materials

Building materials that are potential sources of indoor pollutants include particleboard, adhesives, glues, sealants, wall coverings, paints, stains and varnishes, cabinets, tile grout, plasters and cements, furniture, draperies, carpeting, and plastic laminates. The principal pollutants from these materials are volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs). Emissions from building materials are typically maximal at the time of installation and retrofitting, and outgassing decays over a period of weeks or months. Thus, building materials are more likely to be sources of problems during initial occupancy.

Associations of exposure to VOCs with health effects. VOCs are ubiquitous in indoor air, although they are also found outdoors. They can be characterized by their indoor/outdoor concentration ratios. For typical indoor-related VOCs, the ratio is larger than 1. Concentrations of indoor VOCs may be characterized by substantial variation both in time and in space, depending on the source dynamics and the building attributes. Indoor concentrations are typically below Threshold Limit Values (TLV) levels and airway irritation thresholds, but often above odor thresholds.

Links between VOC concentrations and complaints about indoor air quality and symptoms have been postulated. However, the etiology of complaints and symptoms is likely complex and multifactorial, and characterizing the contributions of VOCs may be difficult. Effects of VOCs might follow directly from inhalation of gases, but VOCs may also have effects by binding to particles. Particles, in particular, floor dust, can act as carriers of VOCs and SVOCs. Exposures to VOCs and SVOCs might thus occur through deposition of particles on the skin, as well as by inhaling the compounds themselves.

Mechanistic hypotheses have been advanced that ascribe a role to VOCs in causing symptoms in building occupants. Thus, responses have been proposed as consequent to: (*1*) total exposure to VOCs—additivity of individual VOCs is proposed so that a mixture might have adverse consequences even though individual VOCs are present at concentrations well below TLV values; (*2*) specific irritants, e.g., formaldehyde or acrolein, underlie the effect; (*3*) VOCs in combination with other pollutants (particles) or other elements of the work environment combine to produce adverse effects; (*4*) physicochemical properties of the VOCs such as acidity, basicity, or effects on surface tension of the eyes tear film are responsible; (*5*) odors trigger symptoms; (*6*) reactive species formed by chemical reactions in indoor air are responsible.

Furthermore, in most indoor environments, pollutants other than VOCs are present, such as ozone, nitrogen oxides, and particles with VOCs adsorbed on their surfaces. In addition, other factors affecting responses to air pollutants such as thermal climate and psychosocial dynamics of the workplace should be considered in a holistic manner (18).

The VOCs emitted from building materials may originate from different types of pollutant sources. Primary pollutant sources emit free (nonbound) VOCs. The primary VOC pollutants are generally of low molecular weight. Chemically or physically bound VOCs may also be relevant to health. Hydrolytic decomposition may also result in release of VOCs, as may oxidative degradation and reemission of adsorbed VOCs.

Specific Building Materials

Carpets. The benefits of carpets include acoustic control, soft surface, protection against trauma, thermal insulation, durability, attractiveness, and resilience. However, carpets can be reservoirs for allergens and growth environments for house dust mites and molds. To date, these concerns about carpets have related to their uses in homes, offices, and schools, and particularly to their being sources of biologic particulate antigens. Carpet underlays may also be VOC emitters, and the adhesives used for commercial installations to subsurface have a potential to release VOCs. There is also concern that carpet cleaning can be a source for indoor pollutants, as can fumigation of carpets.

The issues below relate primarily to special populations (32).

1. *Reservoir for allergens.* House dust mites are unavoidable in climates of high and moderate humidity. The carpet is not the primary means of exposure but provides a reservoir for infestation of bedding in homes and for the generation of airborne particulates with vacuuming and human activity. For animal dander from household pets, carpeting is the major reservoir from which particulate antigen can be generated by human activity. Approximately 30% of American homes have one or more cats and 40% have one or more dogs, with more than 60% having one or both types of animal (33).
2. *Growth environment for house dust mites and molds.* Dirt accumulates over time, rendering the carpet a favorable medium for the growth of molds. Carpets in basements, bathrooms, and other areas prone to moisture are likely sources of molds. Carpets laid on concrete slab-on-grade are also subject to trapping of moisture below the carpet, which is a potential source of microbial contamination.
3. *Cleaning and fumigation*. Carpet steam injection cleaning is less likely to leave large amounts of residual moisture than carpet shampooing, but it may leave carpets damp, contributing to mite and mold growth. Both methods may leave residual chemicals, so products should be carefully selected. Waterless processes are chemically based, and more information on the potential health effects of these products is needed. Vacuuming can contribute to the load of respirable particles in the air. This loading can be avoided by using equipment that is directly exhausted outside (i.e., central vacuum systems), with a HEPA filter or a double electrostatic bag.
4. *Chemical emissions.* Numerous VOCs, including 4-PC (4-phenyl cyclohexene), toluene, and styrene, have been identified as released from carpets. These emissions originate from the latex backing and the numerous chemical treatments applied to the carpet fibers such as those for soil and stain repellency, antistatic, and pest resistance. Chemical emissions are higher when the carpet is newly installed,

and then diminish with time: it may be prudent, therefore, to increase ventilation at the time of installation. As carpets age, the reservoir effects in No. 1 above predominate.

5. *Odors.* Carpets act as efficient sinks for odors generated from human activities such as cigarette smoking and cooking. Solvent emissions from painting and other maintenance activities can be adsorbed by the carpet fibers and reemitted.
6. *Carpet underpads and adhesives.* Carpet underpad materials also contribute VOCs. The underpad also serves as a reservoir for dirt from the top or moisture from below when laid on concrete. Underpads deteriorate in time, turning brittle and becoming sources of particulates. The underpad selected should be stable and have minimal emissions. Commercial installations typically use adhesives. Mechanical installations using tacks or fasteners on soft subfloor surfaces or Velcro-type tapes on concrete or hard surfaces are preferable. Water-based adhesives have fewer emissions than solvent-based adhesives.

Wall vinyls. These materials are VOC emitters, as may be the adhesives used to mount them. If a durable wall surface is needed and a latex-based paint is not acceptable, a water-based commercial grade coating should be used instead of vinyl wall covering.

Paints, stains, and varnishes. Interior water-based paints can substitute for oil-based paints as their VOC emissions tend to be lower, although emission decay may be much slower. In cases where water-based paints are not appropriate, special durable, washable paints have been developed for the market. There are numerous labeling and manufacturer's information sheets available for guiding the consumer. In some instances, odorless stains and varnishes are available. Stored paints in enclosed spaces such as garages may affect indoor air quality and should be recycled rather than stored or disposed of improperly.

Drywall. Drywall is a fairly inert substrate and an acceptable finish material from the IAQ perspective. Installation and finishing generates particles. When drywall is being taped and sanded in occupied buildings, all ventilation ducts should be sealed, as should openings to occupied areas.

Ceiling tiles. Suspended ceiling tile systems may form the underside of the return airflow in an institutional or commercial building. The top surface of the ceiling tile is typically covered with one coating of sealant to offset the potential for fine particulate dusting. Sample tiles should be examined carefully to assure that the sealant coat is effective. Where the return air plenum has an exposed steel structure sprayed with fire retardant materials, care should be taken to ensure that the spray-on material has enough cementitious content to maintain proper binding and prevent contamination of the return air plenum. Fully ducted return air systems using sheet metal ducts are preferable to using ceiling cavities as the air plenum.

Cabinets and other uses of particleboard. Cabinets made of particleboard or medium-density fiber board (MDF) manufactured from urea-formaldehyde resin can be sources of formaldehyde and other organic compounds. Emissions are of less concern if solid hardwood is used, but higher costs are involved. If particleboard or MDF are used, all surfaces and edges should be laminated to encapsulate the emissions. Alternatively, several coatings of a low-odor acrylic sealant can be used. Composite wood in substrate applications such as flooring system reinforcement is a potential source of formaldehyde and other VOCs; carpet over pressed wood subfloor will still allow the emissions to pass through. Other subfloors such as construction-grade plywood, manufactured with phenol-formaldehyde resin, have lower formaldehyde emissions than does particleboard or MDF, and should be selected.

Adhesives, glues, and sealants. These can be sources of aliphatic hydrocarbons, aromatic hydrocarbons, chlorinated hydrocarbons, ketones, and esters. Exposures should be minimized by vacating the premises and increasing ventilation during and after application. Use of these products may be reduced by mechanical connections and cementitious grout compounds. Alternatively, low emissions products are available and consumers should use manufacturers' product information in making their selections.

Plastic laminates. Plastic laminates are typically used in the finishing of counter tops, cabinetry, elevator cab interiors, door surfaces, and washroom partitions. Laminates are unlikely sources of emissions; they can, as stated previously, seal the emissions from the substrate (usually particleboard or MDF). Emissions, however, will escape from unlaminated surfaces—the undersides, backs, edges, and holes for adjustable shelving. All surfaces should be laminated or sealed, or alternates for application should be considered. Solid wood products could be used for cabinetry and doors, whereas metal partitions are recommended for washrooms, mirrored glass and fabric installations for elevators, and ceramic tile, stainless steel, or natural stone for counter tops.

Furniture. Furniture made of composite wood can be a source of formaldehyde and other emissions. Upholstered furniture can also be a source of formaldehyde emissions. The emissions can come from the fabric covering, chemical finish on the fabric, the foam upholstery, or composite wood base. It can also support mite growth and be a reservoir for mite and animal dander allergens. For persons prone to or having allergic diseases or asthma, it may be prudent to consider limiting the amount of upholstered furniture in their home.

Pesticides Used In or Around the Home

All pesticides—whether herbicides, insecticides, or fungicides, depending on their target—are intended to control pests. The active ingredients are semivolatile, whereas inert ingredients and carrier solvents may have varying volatility and content. The inert ingredients may themselves be as or more toxic than the active ingredients. Of the many pesticides that are in use today, we know the acute and chronic health effects of only a small fraction.

Herbicides applied on lawns and termidicides applied around foundations can enter the house in soil gas, in the same manner that radon enters the house. These chemicals therefore potentially can contaminate indoor air of homes. The termidicides used have been the persistent organochlorine insecticides such as chlordane, and contamination of some houses has been demonstrated (34). Direct application indoors exposes the occupants to the volatile ingredients and residues. Exposure may occur through inhalation of particles on which these semivolatiles are adsorbed.

Homeowners may want to explore methods of controlling pests without the use of pesticides. Some pests, notably silverfish and carpenter ants, are bioindicators of moisture in the house. The first line of control of these insects is to control moisture. Cockroaches can be baited or trapped, and, when combined with meticulous sealing of entry points, disruption of food supply and cleaning offer effective control. Sticky or mechanical traps can help to control other common pests. For termite control, a successful method not employing large amounts of pesticides is to prepare baits containing a gram of a chitin inhibitor; this can control colonies of termites occupying several hectares (35). Fewer chemicals are used, and they are targeted to the pests with less potential harm to the environment and the occupants.

Household Products, Office Products, and Other Point Sources

Among the many different products used inside homes, offices, and other nonindustrial buildings, those that may introduce contaminants into indoor air include cleaning agents, polishes, paints, deodorizers, and even pens and marking pens. Other potential sources are personal care products, moth balls (pesticides), and adhesives. These sources are ubiquitous and are frequently used in large quantity. A 1986 Danish database study shows that more than 60,000 tons (12 kg/person) per year of cleaning and maintenance products for hard floor covering and furniture alone were used from more than 700 different products in Denmark. Some of these products are used on a regular and long-term basis and others only episodically. Many household and office products have a large number of chemical constituents, including VOCs, SVOCs, surfactants, and polymers. Some products have perfumes added, either to mask other odors or to indicate their use. Some of these perfume constituents such as limonene are themselves VOCs. Laboratory testing has shown that substantial concentrations of VOCs can result from cleaning agents during their use. However, there are only sparse data on the contribution of these products to typical ambient levels of VOCs and other chemicals in homes and offices.

Despite the lack of data establishing that these products cause particular health symptoms, minimizing exposures to potentially harmful constituents is recommended. This may be achieved by substitution of different products or product selection by the consumer, elimination of perfumes from products, and the provision of information on appropriate use conditions. The voluntary product labeling used in Denmark and discussed in the previous section is an example of this last approach; it is intended to (*1*) improve indoor air quality in buildings, (*2*) provide a tool to stimulate the development of products believed to be more friendly in the indoor environment, and (*3*) provide manufacturers and users with comprehensible information about the products they manufacture and buy.

Other Point Sources in Homes and Offices

Materials used in crafts and hobbies can be significant sources of indoor air pollution, including solvents in glues and paints, adhesive components (acrylates), heavy metals (lead in solder and stained glass), isocyanates (polyurethane varnishes), and wood dusts and methylene chloride (furniture refinishing materials). Product labeling usually provides information on hazardous contents and appropriate precautions. In the home, exposures from crafts can be reduced by using materials in well-ventilated spaces. For dusts generated from hobbies, housekeeping practices are critical. Exhaust ventilation to the outdoors should be considered for using pottery kilns in the home, since glazes can contain toxins such as lead and sensitizing metals.

Equipment used in homes and offices includes copiers, printers, facsimile machines, blueprint machines, binding machines, cables, and VDTs. Such equipment may emit VOCs, including formaldehyde and particles, ozone, and NO_X. Emissions may depend on activity and can have concentrations that typically decline with distance from the machine. Some of this equipment is directly vented to the outdoors, but often it is not. Ozone and NO_X, can react with other substances in the air, producing reactive species such as aldehydes. Processed paper itself emits both particles and VOCs, as do carbon paper and carbonless copy paper. Emissions from these sources may be minimized by direct venting, segregation of equipment to isolate it from workers, and selection of lower-emitting products.

Control of pollution sources is incomplete if the odors from the occupants are not minimized. Perfumes are among the most difficult to control since they are perceived by their users as pleasurable. Personal rights and preferences for perfumed products must be evaluated against the discomfort that scents cause for some people. The odoriferous materials are highly volatile synthetic chemicals; in effect, they contribute to the total VOCs. Scented personal products are not limited to perfumes; they include residual scents on clothing from detergents and fabric softeners, soaps, shampoos, deodorants, skin lotions, and cosmetics. The only successful method of control is to eliminate these odors, either by avoiding their use, as with perfumes, or by using unscented products.

Design for Source Control

Several issues should be addressed in the design and retrofit of buildings to ensure good indoor air quality. Some of the discussion below was introduced previously; strategies are recommended here as initial methods of controlling sources of indoor air pollution.

Site characteristics. For all building types site characteristics should include a clean, well-drained soil. Soils should be examined for contaminants and, if present, cleaned or replaced prior to construction. Soils that are damp or subject to liquefaction should be drained, and surfaces under slab areas should have a gravel or well-draining sand sub-base.

Climate. A major consideration in the control of indoor air quality is climate. Buildings in regions with high relative humidity are subject to mold and mildew in envelope assemblies. The dew point in the wall should be reached on the cool side of the vapor barrier in a material or air space not subject to moisture degradation. Rainy climates require special attention to detailing at joints, connections, and roof parapet membranes so that they are continuous. Hot, dry climates with high air conditioning requirements should receive careful attention to potential moisture in drip pans caused by condensation. In a number of states, there are known areas of elevated soil radon levels. In such areas, basements and crawl spaces should have radon control systems installed or at least "roughed in" to facilitate mitigation in the event that high levels of radon are found in the building.

Building age. The age of the building may affect the type of problems encountered. Some new buildings have IAQ problems associated with emissions from the materials. Occasionally, microbial contamination may be a problem in a new building because of building envelope failure. In older buildings, asbestos may be present in building materials and ventilation systems may be inadequate or performance may have been compromised by changes in occupancy patterns. New construction in old buildings should be undertaken with care to ensure that airflow patterns will be either maintained or improved, local point sources of contamination are identified, and construction waste and dust are controlled.

Building construction. This may be a source of residual contaminants that continues to cause problems for the ventilation system during use. Construction sequencing should ensure that materials having high emissions are installed under well-ventilated conditions to limit absorption by adjacent soft materials. Dusty installations should not contaminate ventilation systems or lead to the collection of dust in plenum areas.

Building maintenance. Building maintenance should be directed at the products, materials, and systems specific to the building. Performance may suffer from poor operations and maintenance procedures that have a significant effect on ventilation rates, control of mold and mildews, and control of particulates, with a subsequent effect on IAQ.

Outdoor air quality. Outdoor air quality may have a significant effect on indoor air quality. ASHRAE Standard 62 (8) references consideration of outdoor air quality to standards of the Environmental Protection Agency. Cleaning of outdoor air may be needed for nonresidential buildings in polluted areas.

Building envelope integrity. This is a significant control factor in the maintenance of IAQ. The envelope should adequately control and restrict the airflow into the building. The envelope should also control moisture infiltration by a continuous vapor barrier on the warm side of the insulation system. The envelope integrity should include the roof, walls, and floor or slab system. The building should be operated at a slight positive pressure, if possible.

VENTILATION

Ventilation has been a long-standing cornerstone of the engineering approach to managing indoor air quality. When considered within the context set by the mass-balance formulation, pollutant concentrations depend on the strengths of the sources and the sinks within the building, the rate of removal of pollutants from the air, and the rate of dilution. Ventilation air affects dilution.

Standard 62 of the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) (8) defines ventilation air as "air delivered to a space to dilute airborne contaminants; the use of outdoor (makeup) air and appropriately cleaned recirculated air." (36) Whereas source control should be the first step in controlling indoor air pollution, sources can never be fully eliminated, and dilution by ventilation is an inescapably needed approach to managing indoor air pollution. By generally affecting concentrations of indoor air, ventilation inherently offers a solution to the multiplicity of pollutant sources and contaminants within a building.

Recommendations have been made for more than 100 years on the amount of ventilation needed for indoor environments (37). The basis for these recommendations has varied over time (Figure 2). The initial concerns that drove the choice of numbers related to control of infection—subsequently, the work of Yaglou and coworkers (38)—shifted the basis to maintaining odors from occupants at an acceptable level. More recently, the general rationale for selection of overall ventilation rates has shifted to assurance of health. The public expects that indoor environments should be healthful and assumes that residential and nonresidential buildings inherently pose no threat to health. There is now an attempt on the part of ASHRAE to provide ventilation standards that do provide healthy indoor air quality. Thus, Standard 62 of ASHRAE includes both comfort and health within its scope and purpose (8). However, other concepts of ventilation may be held by other professional groups and the general public as they respond to indoor environments. Notions of thermal comfort as well as access to direct entry of outside air through windows may also be included within the public's criteria for judging the acceptability of indoor air.

Control of Infection

Control of airborne infections, especially tuberculosis, was historically important in the setting of ventilation standards. Recently, because of outbreaks of tuberculosis in institutional settings, CDC/NIOSH issued official recommendations for ventilation rates in high-risk areas well above rates recommended for comfort (39). Because source control through case identification and treatment will never be fully effective in health-care institutions, exposures to the mycobacterium that causes tuberculosis will continue to occur in isolation rooms housing known or suspected cases, but, perhaps more importantly, from unsuspected cases housed throughout healthcare facilities. General levels of ventilation have limited value for reducing transmission of tuberculosis. High-risk exposure areas vary among institutions, but they include hospital isolation rooms, rooms where high-risk procedures such as bronchoscopy are performed, and common areas such as emergency wards and clinic waiting areas where persons with undiagnosed and contagious infections may expose others.

The economic consequences of controls for transmission of tuberculosis in health care facilities are substantial. The potential caseload varies by geographic location and type of facility. Institutions have reported the need to isolate as few as seven and as many as 93 suspected cases for every true case of tuberculosis; thus, a 200-bed hospital can be estimated to require as many as 75 isolation rooms, each providing six to 12 room-air changes per hour, exhausted directly to outside, and imposing a substantial energy penalty. For waiting areas and other large common places, high levels of ventilation may not be technically achievable in existing structures. Because we lack experimental or epidemiologic studies demonstrating that any particular ventilation rate provides effective protection against infectious diseases, mathematical modeling has been used to estimate the protection of various ventilation rates relative to exposures of varying intensity and duration (40). Models of transmission using data from epidemiologic investigations of tuberculosis outbreaks suggest that the protection reached by practically achievable ventilation rates is likely to be incomplete. It is necessary to supplement ventilation by other means of air disinfection such as filtration and upper room germicidal irradiation. A reasonable approach to environmental control of airborne infection would be maintaining a baseline level of ventilation and supplementing with additional disinfection of air throughout high-risk facilities.

For other infectious agents, there are limited epidemiologic data associating lower ventilation rates with higher prevalence of symptoms and illnesses in occupants of buildings (41). One study suggested higher rates of transmission of infectious pulmonary disease in more tightly constructed military barracks (42). Another recent study of pneumococcal infection showed increased transmission in jail areas with the lowest ventilation rates (43). It is thus plausible that lower ventilation rates in offices, schools, and other indoor environments may allow increased transmission of common infectious respiratory diseases such as influenza or colds.

Odor Control and Comfort

Historically, ventilation rate guidelines have been based on control of odors and comfort, and these remain the primary bases for the current guidelines. Prior to the era when complex effluents such as the odors from human bodies could be analyzed into their chemical constituents, the nose served as the best available detector. The presence of a notable amount of odor served as the criterion for insufficient ventilation. Now, although complex effluents can be analyzed chemically, the relationship between integrated odor as perceived by a person and the isolation and quantification of the odor-relevant ingredients in such effluents has proved a formidable challenge, as yet unmet. Over the decades, however, concern with odor as merely a source of discomfort has been replaced with concern for odor as a potential indicator of an unhealthy environment. Although ASHRAE has not explicitly justified its ventilation recommendations on the basis of odor control, those recommendations have resembled the requirements for control of occupancy odor derived from chamber studies in which judges rated the odor of persons who occupied a chamber. The data on control of occupancy odor and expert judgment together have been the foundation for ASHRAE's recommendations. The recommended rates also consider specific locations, offering higher values for such locations. ASHRAE recommendations reflect consensus of committees composed of HVAC engineers and other professionals, including health professionals.

In the past, when entry of outdoor air came principally from opening windows, one could argue that ventilation and thermal control (generally cooling) were almost inseparable and the relative contributions of the perception of freshness from dilution of indoor contaminants and of achieving comfortable temperature could not be identified. Chemosensory and thermosensory sensations interact, and cool spaces seem to engender fewer complaints than do warm spaces. While in a space that is too warm, a person may be more responsive to other noxious sensory input such as, for example, from an air pollutant. Thus, both thermal and atmospheric environments may affect ventilation requirements. In the modern era, buildings often provide comfortable thermal environments with or without the delivery of a given amount of outside air. However, occupants may be unable to specify whether lack of comfort has thermal or sensory origins.

The interaction between chemosensory and thermosensory stimuli may hold as strongly for irritation and warmth-cold as for odor and warmth-cold. Dryness-wetness should also be considered. In a warm environment, people may report dry eyes. Whether the feeling of dryness arises from actual loss of eye moisture, from sorption of chemicals onto the eyes, from warmth, or from dryness may not be known to the affected person, who may misattribute the source. The complexity of comfort responses to various dimensions of the environment should be considered in building operations and problem diagnosis.

Standards for comfort, regardless of how the dimensions of comfort are defined, should promote one or more of three goals: (*1*) "transparency" of the environment, so that the occupant takes no notice of warmth or cold, of the presence of any odors, of the occurrence of intrusive noise, and of other characteristics of the environment; (*2*) facilitation of human functioning, e.g., reading efficiently with unirritated eyes; (*3*) an acceptable trade-off between subjective costs and benefits; for example, the noise from a window fan-coil unit should seem an acceptable penalty for desired functioning along another dimension such as clearance of contaminants or control of temperature.

The health impact of the recommendations of ASHRAE Standard 62 has not been formally tracked, although energy impacts have been reported. However, experience over recent decades indicates that complaints about odor and sensory comfort are reasonably controlled with the current standard, absent strong and objectionable sources. Field experience indicates that ventilation at the specified rates also limits the transmission of airborne infection indoors. Of course, there is substantial variation in expectations and in willingness to pay for achieving acceptable indoor air quality, and expectations may change over time. In an environment with clean air, the introduction of even a level of minor contamination may prove less acceptable than in an environment with less clean air.

Health Assurance

There has been little awareness of ventilation practices and standards by the health community and of the implications of these practices and standards for the public's health. Although ASHRAE has had input from health professionals in developing Standard 62, the process leading to the standard does not involve formal cross-institutional or cross-discipline interactions to assure full engagement of the many relevant disciplines concerned with indoor air quality and health. In fact, no single organization or entity holds jurisdiction over indoor air quality. ASHRAE uses a committee process to develop its standard, and, in order to conform to the organization's consensus process requirements, committee membership includes a broad set of interests, particularly from the economic sectors most affected by the standard. However, there is no "consumer" or "public" representation on the committee. Currently, there are several health scientists and indoor air quality researchers and experts on the committee, as well as mechanical engineers, representatives of the heating, ventilation and air conditioning (HVAC) industry, building code officials, contractors, protobacco and antitobacco smoking interests, building products manufacturers, and others.

A consensus among such diverse interests tends to produce compromise and suppress innovation and major change from one version of the standard to the next. The imperative for ASHRAE 62, the ventilation standard, derives from the exigencies of engineering practice. Engineers need targets as they design the HVAC systems for buildings. In addition to health and comfort considerations, the engineer is faced with issues of cost and liability. ASHRAE's SSPC 62 reviews the basis for the standard and periodically revises it. The most recent version, 62-89, was released in 1989, and the process of revision is now underway. The recommendations for nonresidential buildings have been codified, but they have not been applied to the residential environment.

Paradoxically, the engineering community sets the only indoor air quality standard addressing healthy indoor air. ASHRAE uses a consensus approach in setting the ventilation standards, offering tables of recommended ventilation rates for various environments. Ideally, the choice of numbers should be based on an understanding of the full range of adverse health and comfort effects associated with indoor air contaminants. Information on exposure-response relationships would be used to identify "safe" or acceptable concentrations and, together, source control, air cleaning, and ventilation would be used to reach these concentrations. Of course, the requisite information is lacking for most indoor pollutants, and the authors of ASHRAE's SSPC 62 have drawn heavily on field experience and the evidence on odor in setting the standards. Uncertainties are evident and acknowledged but practicing engineers need this consensus judgment to have a target value for design.

Ventilation Rates

Ventilation capacity is typically set as a building is designed. However, it may be impossible to anticipate all future uses and the spectrum of susceptibility of occupants. Moreover, capacity is not synonymous with performance as the building is used and ages. Building uses and occupancy patterns may diverge from those originally intended, and inadequate maintenance may compromise performance. Consequently, the health impact of ventilation depends not only on the original design capacity but also on system operation and maintenance.

Ventilation rates are usually specified as cubic feet of outdoor air per minute per person (cfm/p). They may also be specified as cubic feet of outdoor air per minute per square foot of building area (cfm/sf), or as air exchange rate, usually given in air changes per hour (ach). Finally, total supply air, including both thermally treated outdoor air and recirculated air, is usually referred to as the supply air rate.

We lack the data necessary to specify ventilation rates using the mass-balance approach. We cannot identify health-based target concentrations for exposure to many indoor pollutants, and source strengths are known for only a small portion of the many pollutant sources typically found indoors. Sources may also change significantly over time in their emissions, and similar sources from different manufacturers may vary considerably in their emission rates. Even the same product from the same manufacturer may vary in emissions among production batches. For many chemicals, we lack information on toxicity, and we have little understanding of interactions among pollutants.

Numbers such as ventilation rates imply a degree of certainty that may be unwarranted. In fact, the range of numbers considered and adopted in recent decades varies more narrowly than the range of source strengths that can be found in indoor environments and the likely range of susceptibilities of the potential occupants. Because of the variation in pollutants and their source strengths, and in occupant populations, relying on ventilation rates alone in standards or in guidelines may not provide adequate indoor air quality for all buildings or for all occupant populations.

In reality, the ventilation rates most commonly used for design in the United States come from building codes and from the ASHRAE ventilation standards. There are variations in the codes throughout the country, and there are differences among the various versions of the ASHRAE standards. Therefore, depending on where and when a building is built, it may have been designed to a range of ventilation rates. Generally, these rates have ranged from 5 to 20 cubic feet per minute per person of outside air during the past 60 years (Figure 2). ASHRAE 62-89 specifies a minimum outside air ventilation rate of 15 cubic feet per minute per person (cfm/p). Certain types of spaces require more ventilation based on occupant activities or other factors than would be predicted by the nature and strength of the expected sources.

The federal government has not promulgated ventilation rate standards. To some degree, perhaps, the existence of the ASHRAE standards has reduced the need for the government to participate more actively in setting ventilation standards. During the previous two decades, wider recognition and acceptance of indoor air concerns have coincided with a trend

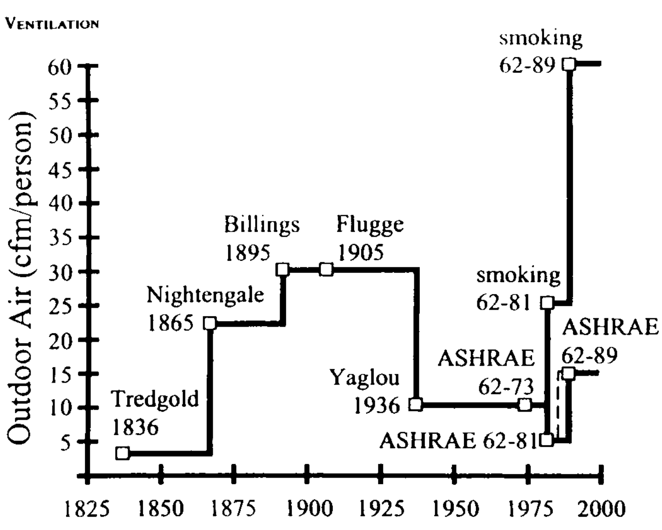

Figure 2. Historical ventilation guidelines (*see* Reference 57) (Used with permission).

toward deregulation, and the current climate is not favorable for national regulatory initiatives that would address indoor air pollution. However, some states such as California and Massachusetts have developed their own regulations regarding indoor air quality and ventilation. In California, the Occupational Safety and Health Agency has adopted a rule requiring operation of ventilation systems and creation of maintenance records (44). These records must be accessible to employees who request them.

Although much of the general information on ventilation applies to all buildings, the residential setting presents a separate, unique set of issues. There is essentially no purposeful ventilation in most residential structures in the United States; i.e., there is no structural or mechanical means designed into the structure for the explicit purpose of exchanging indoor and outdoor air. Rather, residential ventilation is provided by unintentional leakage, the goings and comings of occupants, and intentional opening of windows and doors for ventilation. Forced air heating and cooling systems—the predominant type of space conditioning systems used in United States residences—are often misconstrued as ventilation systems by the public. These systems run only periodically and are not typically connected directly to outside air, and therefore they cannot be counted on to provide for general ventilation needs and expectations. Similarly, local ventilation equipment such as kitchen and bathroom exhaust ventilators, although beneficial and now required amenities, cannot be counted on to satisfy the general ventilation needs for one entire structure. To date, ASHRAE has only addressed the residential ventilation issue in a cursory fashion: the 62-1989 Standard requires 0.35 air changes per hour or 15 cfm per person, whichever is higher. However, a note in the standard allows for windows and natural ventilation to satisfy this requirement, and consequently mechanical ventilation in residences is usually limited.

Is there a single "right" number for ventilation rate? The necessary ventilation could be calculated if one knew the relevant contaminants, their rates of generation, their concentrations in incoming air, their stability, and the acceptable maximal concentrations. In the absence of information on these fundamental components of the mass-balance equation, any general recommendation must be modeled and then used with appreciation of its uncertainty. The need to control for human occupants and their activities provides one basis for ventilation values per occupant in the space. This approach assumes that one person emits odors in the same way as another, that human occupants generate largely unique odors of strictly indoor origin, and that we can "measure" these odors qua odors psychophysically. From studies performed in chambers during the many previous decades, it appears that a ventilation rate of 15 to 20 cfm per sedentary, nonsmoking occupant will satisfy the aesthetic criteria of the large majority of visitors from nonpolluted spaces (37). Conceptually, this approach fits into the mass-balance model.

The odor-based approach, however, requires knowledge of the number of persons who will occupy a space. It also typically ignores levels of contaminants generated independently of occupants. Further, as typically used, it sets requirements based on impressions of unadapted visitors to a space; thus, it may lead to total ventilation rates for some densely occupied spaces such as theaters that seem too high and too energy-intensive and even too unachievable in certain geographic locations such as those having hot, humid climates. However, lowering rates in congregate settings such as theaters may predispose to increase person to person airborne infection unless alternate methods of air disinfection are added.

Ventilation is limited in maintaining a quality of indoor air that will be healthy and comfortable for everyone. There are ranges of expectations and potential susceptibility across the population; these ranges imply that one or a few recommended ventilation levels cannot provide health and comfort for all. In fact, the current ASHRAE standard 62-89 promises comfort for only a substantial majority (interpreted as 80%) of building occupants, recognizing that comfort cannot reasonably be assured for all occupants. The spectrum of sensitivity to pollutants implies that some persons may not tolerate reasonably achievable exposures, and for some pollutants, i.e., carcinogens, there may be no level of exposure that is not associated with some projected risk. Additionally, any ventilating system can have only limited flexibility and all future uses and associated needs for ventilation cannot be anticipated.

There are constraints on the amount of ventilation that can be used. Construction and energy costs mount with increasing ventilation rates. Additionally, the relationship between ventilation rate and health and comfort consequences may not be linear, and specifying higher ventilation rates may not have the intended consequences. Further, higher ventilation rates may lead to difficulty with moisture control, both with regard to excessive dryness that may affect occupant comfort and excessive moisture that may foster microbial growth.

Technology

Although questions remain about how much ventilation to supply, there are many proven ventilation technologies that can deliver adequate ventilation air for the maintenance of both contaminant control and comfort. These technologies are affordable for most types of nonresidential projects. The technologies can best be categorized as features that should be considered in the HVAC system design. Appendix B provides a listing and descriptions.

Maintenance

Even a well-designed ventilation system may perform inadequately if allowed to degrade over time. From initial operation and throughout its lifetime, the system must be inspected regularly and tested to assure continued proper operation. Before initial occupancy and after any remodeling, the system performance should be verified through a commissioning process as in conformance with the original design. The ventilation system in most commercial buildings is usually controlled by the temperature control system. Therefore, the temperature control operation should be verified in conjunction with commissioning the entire mechanical system. The outside air quantity and the airflow at each supply air diffuser should be measured by an independent test and air balance (TAB) contractor. The commissioning process must also include the provision of complete mechanical system documentation, including mechanical system drawings, control system diagrams, and the TAB report and maintenance manuals. Guidance for commissioning is provided in ASHRAE commissioning guideline No. 1 (10).

Proper ventilation system operation and maintenance (O&M) are critical for continued satisfactory performance. These activities must start with thorough training of the building maintenance staff as part of the original commissioning. HVAC systems can be very complex, especially in larger commercial buildings with sophisticated electronic controls interfacing with computerized building management systems; therefore, extensive hands-on training is necessary.

Maintenance needs to be performed according to a preventive maintenance schedule. The schedule should include frequent inspections that follow the manufacturer's recommendations. Although this schedule must include items such as regular filter changing, it must go farther and include "system" maintenance of the entire HVAC system.

Proper maintenance and regular calibration of an air economizer ventilation system are especially important. As described in Appendix B, an air economizer cools the build-up of internal heat in commercial office buildings by flushing the building with large amounts of cooler outside air. Inadequate ventilation is a clear signal that the economizer is operating incorrectly and needs maintenance.

If the economizer ventilation system is maintained correctly but the temperature control system allows the building to overheat, perceived inadequate ventilation with complaints of stale and stuffy air may occur even when commercial office buildings are operating with generous amounts of outside air. This is most common in the spring and fall in commercial buildings located in temperate climates that are operating with air economizer cooling; then the economizer will be supplying maximal outside air (in the range of 50 to 100 cfm/person).

A pattern often exists to the temperatures in these buildings. At the start of the day, temperatures are in the range of 67 to 70° F, and then gradually rise to overheated conditions of 75 to 80° F by 5:00 P.M. At the higher temperatures, the relatively dry air of the spring and fall can be perceived as stale and stuffy (45). To detect this swing of temperature, it may be necessary to measure the indoor air temperatures continuously for a week when the outside temperature is changing. The solution is a comprehensive ventilation and temperature controls system tune-up. A well-documented explanation of the maintenance required is provided in "Ventilation System O&M: A First Step for Improving IAQ" (46).

The costs of high-quality preventive maintenance for mechanical systems can be readily justified. Preventive maintenance protects and extends the life of the equipment; avoids crisis-causing breakdowns and expensive unplanned repairs; provides for better budgeting of building maintenance expenses; increases employee comfort by assuring proper ventilation system operation. Although HVAC system initial construction costs can be on the order of $12 per square foot (one-time cost), and personnel costs are on the order of $100 to $400 per square foot annually, HVAC operation costs are on the order of $2 per square foot annually.

General Recommendations for Ventilation of Buildings

- The institutional process that leads to the setting of ventilation standards does not include a sufficiently broad range of organizations and professionals. ASHRAE has responded to the needs of engineers in its Standard 62. However, the scope and purpose of Standard 62 have extended into the health domain, challenging the expertise and experience of an organization of engineers. Interactions among relevant organizations are needed to engage health, engineering, architectural, and other relevant groups in developing ventilation standards.
- Airborne disease transmission should be given more consideration in HVAC design. Items of specific concern include general air turnover rates, high efficiency filtration, and pressure relationships for isolation of air flow.
- In general, accountability of a building's indoor air quality and HVAC performance should be improved.
- There is a critical need to improve general knowledge for contractors, builders, and operators regarding the practical aspects of indoor air pollution control. Better approaches to identify sources of pollutants and to find solutions for controlling them are needed.

AIR CLEANING AND TREATMENT

Overview on Air Cleaning Devices

Air cleaning is a general term referring to the removal of particles and gases from the air by mechanical devices that may filter particles and/or chemically remove gases. (A technical appendix to this workshop report contains more detailed coverage of air cleaning and filtration. Appendix C was written after the workshop in order to provide additional background on air cleaners.) Portable devices are manufactured to clean air within rooms, whether in homes or offices. Large buildings typically have HVAC systems that remove some large particles from supply air; they may have additional systems to clean the air flowing through the system.

Air cleaning devices for rooms include a fan to move air through the apparatus; typically the devices contain elements to remove particles and gases, although some simple devices may only be intended to remove particles. The technologies for removing particles incorporated into the devices include mechanical filters; electrostatic precipitators, which charge particles and then collect them onto a surface with the opposite charge; and ion generators, which charge particles and thereby facilitate their deposition. There are several types of mechanical filters: flat panel filters, pleated filters, and high efficiency particulate air (HEPA) filters. Some small devices may contain a flat panel particulate filter, which is not efficient in removing particles. HEPA filters are highly efficient in removing particles of a wide range of sizes, and the acronym originally referred to High Efficiency Particulate Arrestor. Gases are not removed by the filters directed at particles, except for those gases and vapors that have been sorbed on to particulate matter. Charcoal or other sorbent materials may be incorporated into the device to remove gases and vapors. Such sorbents can become saturated and need to be replaced or reconditioned periodically to maintain performance and to assure that collected gases and vapors do not revolatilize to the air.

For persons with lung disease, air cleaning has particular appeal. Portable devices can be moved from room to room, possibly creating a more healthful environment for the allergen- or smoke-sensitive person. Centrally located devices carry the same potential appeal and possible benefits and afford the possibility of residence-wide air cleaning. Other types of cleaning such as duct and surface cleaning have also been proposed as beneficial to health.

Among the target sources for air cleaning in residences are cigarette smoking, airborne allergens, and volatile organic compounds (VOCs) from household products and materials. The major allergen sources indoors include dust mites in bedding, furniture, and carpets; fungi or bacteria growing on moist surfaces; cats, dogs, and other pets kept in houses; cockroaches; and outdoor allergens that have entered the home.

The potential benefits of air cleaners might be demonstrated indirectly by showing that their use reduces concentrations of pollutants and personal exposures or directly by showing health benefits; however, there is surprisingly little evidence for either indirect or direct benefits. Review of this evidence was the starting point for the evaluation of air cleaners by the working group. The group also considered the technical challenge of cleaning air in the presence of strong sources.

Consider the simplest of cases where a portable air filter appliance is used in a closed room that is not mechanically supplied with air. Mixing efficiency for the space will be ignored for this illustration. The percentage reduction in pollutant concentrations in a well-mixed room affected by using air cleaners is given by:

$$\% \text{ Reduction} = 100 \times \left(\frac{EQ}{NV + EQ}\right)$$

where N = air changed per hour (1/h), V = room volume (cu ft), E = fractional efficiency of the cleaner to remove particles in a specific size range, Q = flow through cleaner (cu ft/h).

Thus, the effectiveness of an air-cleaning device depends on the size and ventilation of the room where it is used, the efficiency of the cleaner, and the volume of air flow through the cleaner. For a substantial reduction of particle concentration, a very efficient and high airflow device is required. As an example, consider a room 20 by 12 ft and 8 ft high that has 10 air changes per hour. If a 90% reduction in airborne concentration of particulate matter present in the incoming air is desired, then a device with an airflow of 3,200 cu ft/min and a 90% efficient particle filter could be specified to meet this goal. For allergens, virtually complete removal may be needed, particularly for the most sensitive persons. Let us say that 99% removal was required for this small room. Closing windows and doors and running the air conditioner on recirculation (assume no additional removal) might reduce the air exchange rate to somewhere between 0.1 and 0.5 per hour. At 0.5 h^{-1} air exchange rates, the air cleaning device would need a flow rate of more than 1,500 cfm and a high efficiency filter (0.99) to clean to the desired level. At lower air exchange rates, only 350 cfm would be needed along with a moderately efficient filter (0.9) to meet the desired levels of airborne particles. These trade-offs between airflow and filter efficiency as well as the conditions of the intended space indicate the challenge faced by manufacturers and users of portable air cleaners.

Given this challenge, perhaps not surprisingly a review of the literature does not provide strong evidence for benefits of air cleaners. Few adequately designed controlled studies of portable air cleaners have been reported. These studies have had small sample sizes, which tempers their interpretation. They are further limited by their diverse locations—and hence the heterogeneity of exposure addressed—and by their participants' heterogeneity.

Other groups have also considered this evidence, including an ad hoc committee of allergists who met at the request of the Food and Drug Administration and the participants in the previous ATS/ALA workshop. The report of the allergists (47) comprehensively reviewed the literature through 1987. That group could not find sufficient sound evidence to support a firm recommendation for the use of air cleaners. Participants in the 1988 ATS/ALA workshop did not find new, major contributions to the literature that would provide a rationale for departing from the earlier view of the committee of allergists.

Since these earlier reports, some additional studies have been published, but these are still subject to the limitation of sample size as well as to other methodologic problems.

Recommendations on Air Cleaning Devices

Based on review of the earlier and most recent literature, the working group was in agreement with the 1988 statement of the American Academy of Allergy, Asthma and Immunology (47): "Absence of adequate data on the clinical relevance of indoor ambient allergen levels, as well as the effect of air-cleaning devices on these levels, plus a general lack of health effects by these devices in published double-blind studies precluded any firm recommendations for their use. It was clear, however, that use of room air-cleaning devices in the absence of other forms of environmental control was not reasonable." The evidence accumulated over approximately a decade has not been sufficiently abundant or conclusive to support an affirmative recommendation for use of the devices for control of allergen exposures. The National Asthma Education Program's *Guidelines for the Diagnosis and Management of Asthma,* and the *NHLBI/WHO Workshop Report: Global Strategy for Asthma Management and Prevention* (48, 49) state that environmental control measures should be the first measure for the treatment of asthma; physicians should instruct their patients in the appropriate hierarchy of control, beginning with primary source reduction. Health care providers should not prescribe, endorse, or tacitly accept use of air cleaners alone as an effective environmental control strategy.

These recommendations reflect the limited number of appropriately designed clinical trials on the efficacy of air cleaning devices for those with asthma and allergic diseases, as well as for other groups who might potentially benefit, e.g., persons with cystic fibrosis or chronic obstructive pulmonary disease (COPD). The group noted that the database for evaluating air cleaners had changed little since the publication in 1988 of the statement by the American Academy of Allergy, Asthma and Immunology. In addition to the obvious need for more clinical trials, the group recommended additional indoor air studies to characterize concentrations and size distributions for airborne allergens. Information is also needed on exposure patterns and the factors influencing exposures. Until research has further addressed indoor allergens and demonstrated clinical benefits, manufacturers should not imply that the devices have health benefits.

We conclude then, that if allergen sources are present in the space, commercially available portable air cleaners will not be 100% effective for all situations in reducing airborne allergen-containing particles to levels where effects will not occur. Strong intermittent sources are particularly problematic. Cats, for example, might shed allergens periodically and/or in areas where portable air cleaning devices might not be able to respond adequately. Furthermore, deposited antigens are not affected by air cleaners. Mites excrete allergens as larger particles on to surfaces (i.e., within carpet or bedding). These allergen-bearing particles become airborne sporadically by mechanical disruption. The relevant exposures may take place at times of close proximity to the source, e.g., lying on a couch or contact with bedding. Thus, transient conditions may produce short-lived exposures that evoke responses, whereas in the long-term, room or house-wide average airborne levels could be reduced by air filtration. Therefore, source control should always be the first choice for allergen control in residences.

The well-designed electronic air cleaner generates only a small amount of ozone. When the fan is off, the ionizer should go off as well. Electronic air cleaners will not present problems in homes or offices where air exchange rates are typically between 0.2 to 2 h^{-1}. The group expressed general concern that any electronic air cleaner, ionizer, ozone generator, office equipment, or motor should not generate ozone above the FDA limit of 50 ppb (50) in any occupied space. The group also considered removal of gases and vapors from indoor air. Sorption beds, with materials such as activated charcoal and permanganate/alumina, are widely used in removing organic compounds from recycled air.

Reactive catalytic materials that are effective in removing ozone, nitrogen dioxide, and carbon monoxide from ambient air at room temperature are under development. These reactors might also prove effective for aldehydes and ketones as well because these compounds contain the carbonyl group present in carbon monoxide. These catalysts may be useful for cleaning intake air in areas where ambient air quality standards are not being met. An unsolved problem with sorption or reactive beds is the lack of reliable means to determine the effective residual capacity while they are in use. The group recommended the development of an appropriate test method, perhaps by the American Society for Testing and Materials (ASTM).

Filtration in Residences and Large Buildings

Filters are usually part of residential forced air heating and cooling systems. Less expensive furnace filters are designed to capture dirt particles that might soil the mechanical equipment. The use of pleated filters that are 60% efficient for 3.0-μm particles (with an ASHRAE-rated efficiency of 95%) would significantly reduce particle accumulation within the building ventilation system. Higher performance filters are commercially available, and specifying that filters be capable of removing a minimum of 50% of the 0.3-μm size particles is reasonable. Figure C.4 in Appendix C shows the particle size fractional efficiency for pleated filters having different ASHRAE performance ratings. Note that minimal efficiency for these and most filters occurs between 0.1 and 0.5 μm.

For homes, residents should be aware of the following checklist, which might be asked of a furnace maintenance contractor.

1. Is the filter holder sealed and does it cover the furnace/air conditioner intake?
2. Do the air supply ducts leak into unoccupied spaces?
3. Are the return air ducts tight so they draw air from occupied spaces?
4. What is the efficiency of the pleated filter? Should you consider a more efficient filter?
5. Is the condensation drain clogged?
6. Is there mold growth on the walls of the air handler?
7. Is there visible dirt and/or mold growth on the ductwork? Does the air smell moldy, particularly at times when the basement or garage is damp?
8. If the filter or fibrous insulation has become wet, will it be removed?

Research needs include studying the effectiveness of different filtration modes on health end points; the particle characteristics of allergen-bearing particles, emission rates, exposure, and exposure/response relationships; and the efficiency of filters at the very low concentrations of particles that are characteristic of buildings.

Duct Cleaning in Residences

Duct cleaning is usually performed by one of three methods: (*1*) commercial-type vacuum cleaners that vacuum the surface of the ducts; (*2*) an air washing or air sweeping method using a compressed air hose upstream and a vacuum device downstream to dislodge and remove debris from the ducts; (*3*) a mechanical brush, often along with a compressed air driver rotary device, which moves down the duct dislodging debris, with HEPA negative air equipment placed downstream. The number of duct cleaning services has increased substantially. Although health claims are often made, no studies document any health benefit from duct cleaning. Case studies have, however, documented that ductwork can be cleaned and, in some cases, the cleaning has lowered fungal spore counts for long periods (51, 52). Anecdotal data support both positive and negative health impacts.

Clearly, ducts that are so filled with debris that airflow is restricted should be cleaned. Such soiling is likely to occur only on the return air end of the system if the supply system is protected adequately by filtration. Fungal growth in ductwork with fibrous lining is an indication that the lining should be replaced, not cleaned. Such growth is likely to occur in ductwork that is not adequately protected by filtration and where moisture control is ineffective.

Without additional research, we cannot recommend the efficacy of one method of duct cleaning versus another or specify the periodicity of preventive cleaning. In addition, the use of biocides in residential ductwork is not warranted. Sealing microbial growth within ductwork is also not advisable, especially where moisture problems are continuing. If a consumer does elect to have ducts cleaned professionally, the process should always include cleaning of the furnace blower blades and cabinet, and all furnace components of an air conditioning system, if present. If duct debris is contaminated with biologic growth, duct surfaces should be free of all dust after cleaning to avoid dispersal of potentially irritating particulates upon reactivation of the system. Professional duct cleaning for office buildings is expensive and lacking in performance standards. When contracting for cleaning surfaces, a wipe test of residual dust value should be specified (*see* Table C.1 in Appendix C for guidance).

Other Methods Proposed for Indoor Air Cleaning

The effectiveness of vacuum cleaning in removing settled or tracked-in dirt from surfaces varies by type of surface, characteristics of the dirt, and by the equipment and methods used. Currently there are no standard methods that inform consumers about vacuum cleaner effectiveness. Limited laboratory tests show substantial variation among vacuum cleaners in retention of a cat allergen charge placed in a bag. If possible, doubling the vacuum cleaner bag can improve retention of cat allergen. Other studies show that aggressive cleaning of rugs and carpet with a rotary brush generates substantial quantities of coarse size particles. Some vacuum cleaners have superior performance and HEPA-like bag filtration. Some methods of surface cleaning (steam injection, wet mopping) are likely to generate less suspended particulate matter than dry surface methods.

The scientific data are insufficient to support claims that plants improve or degrade indoor air quality. Plants can raise humidity levels and serve as reservoirs and supply nutrients for fungal growth. Although some plants have been shown to remove some organic vapors, it is unlikely that plants by themselves could be an effective control strategy.

POTENTIALLY SUSCEPTIBLE POPULATIONS

Overview

The general population is heterogeneous on a number of characteristics, such as atopy, bronchial responsiveness, and susceptibility to infection, that are determinants of susceptibility to the adverse effects of indoor air pollution. Whether these characteristics have a genetic basis or are acquired, their presence may affect the risk of disease in persons exposed to environmental agents. The diversity of the factors determining susceptibility and the myriad environmental exposures of concern imply that the population of potentially susceptible persons is large. Concerns about the effects of indoor air pollution on these special, susceptible populations have increased in recent years. The rising number of persons with a diagnosis of asthma, for example, has drawn attention to the possibly mounting exposures of allergic persons to indoor allergens.

For susceptible persons, there are abundant opportunities for exposure to potentially hazardous indoor air pollutants. Inhalable particulate allergens derived from pollens, dust mites, and fungal spores are of sufficiently small size to pass into the respiratory tract where the antigen-antibody reaction occurs. Additionally, exposures to some agents may also take place through ingestion and skin contact. For example, exposure to allergens may occur through ingestion of certain foods (e.g., milk, eggs, peanuts), and skin contact with certain substances (e.g., latex).

A seemingly increasing number of persons report being affected by odors. Organic solvents such as benzene and toluene, which are released by a variety of building materials (paints, finishes, and adhesives, for example), have characteristic odors. These and numerous other gaseous chemicals of increasing molecular complexity comprise the VOCs measured in indoor air. Some compounds such as mercaptans that are added to natural gas and perfumes are strong odorants (i.e., they have low odor thresholds). There has been speculation that low concentrations of odorant pollutants may have adverse effects, although only speculative hypotheses can be advanced concerning potentially involved mechanisms of pathenogenesis.

The Nature of Susceptible Populations

Susceptibility is multidimensional and can result from many factors, including disease status (Table 5), sociodemographic characteristics (age, sex, and socioeconomic status), genotype, and environmental exposures. Thus, occupational agents can cause increased bronchial responsiveness and asthma, and environmental tobacco smoke (ETS) increases risk for lower respiratory infections in young children. The distribution of susceptibility in a population is continuous for many factors, covering a broad range that extends from the most resistant and healthy persons to the susceptible, impaired, and diseased. Thus, a spectrum of resistance to infection exists with healthy persons at the most resistant end and immunocompromised persons (e.g., those with AIDS) at the most vulnerable; even among persons with AIDS, there is a wide range of impairment of host defenses against infection. For example, the counts of helper lymphocytes (CD4 cells) in persons with AIDS extend from normal levels to virtual absence.

Disease States

Decrements in immune system function range from minimal, as in most recipients of usual doses of oral steroid treatment for asthma, to severe, such as the lack of function of components of the immune system in AIDS. Along this continuum, persons with AIDS develop increasing susceptibility to infectious agents and become at risk from a broadening array of pathogens. For example, invasive aspergillosis occurs only in the severely immunocompromised. Immunocompromised patients are of special concern in hospitals, both because the most severely infected are congregated in hospitals, and because exposures to some infectious agents may be more likely in hospitals than elsewhere. Atopic persons make up another large, susceptible population, at risk for asthma and allergic

TABLE 5

SOME DISEASES THAT INCREASE SUSCEPTIBILITY TO INDOOR AIR POLLUTANTS

Disease	Susceptible to:
Cystic fibrosis	Infectious agents
AIDS	Infectious agents
Other immune deficiency diseases	Infectious agents
Asthma	Allergens, irritants
Allergic rhinitis	Allergens, irritants

rhinitis. Atopy has a genetic basis, but atopy-associated diseases are presumed to result from gene-environment interactions.

Some evidence indicates that allergen exposure in atopic people is a risk factor for the development of allergic diseases, although we lack evidence of reduced disease occurrences after implementation of environmental control measures. However, it is prudent for parents with a history of atopy to practice allergen control with the expectation of reducing their children's risks for allergic diseases.

Potentially Susceptible Populations: Persons with Asthma and Allergies

Primary prevention. Our knowledge of risk factors for asthma in susceptible infants and children is now sufficient to justify strategies for reducing exposures of those at high risk. A history of asthma and allergy in parents and siblings is strongly predictive of childhood asthma; a genetic basis for this association is assumed and is under intensive investigation. Allergen exposure has been shown to increase the risk for earlier onset of asthma.

Although controlled data on exposure avoidance and asthma risk are limited, recommendations for exposure control should be made for persons at high risk for asthma and to parents whose children are at high risk. Such persons should seek housing with characteristics associated with lower levels of allergen and irritant exposure. The following recommendations are considered most important by the working group participants.

1. Houses should have low levels of indoor humidity. In general, this is accomplished by using central air conditioning and avoiding evaporative coolers and humidifiers. In some climates additional use of dehumidifiers may be necessary to achieve the optimal relative humidity, levels of less than 50%, which do not support mite and mold growth. Reaching these levels may not be feasible in humid sections of the country.
2. Recognized reservoirs for house dust mites should be reduced. Carpets should not be placed directly on cement slabs or in the child's bedroom; mattresses and box springs should be encased with a mite-proof encasing, and pillows should either be covered or washed, as should bedding, in water at 130° F on a regular basis, preferably weekly. Blankets can be washed monthly in a similar manner. Waterbed coverings can become moldy because moisture can condense on them if they are not continuously heated.
3. There should be no warm-blooded pets kept in the home. It may be prudent to learn if recent occupants have had pets, particularly cats; it may be appropriate to avoid homes in which the previous inhabitants had warm-blooded pets.
4. Cockroach infestations should be eliminated and control maintained.
5. Exposure of a child to tobacco smoke should be avoided. Smoking by the mother appears to carry the highest risk.

Control of house dust mites. In addition to the general recommendation for low humidity (Item no. 1) and the specific recommendations for mite control given above (Item no. 2), other modalities may also assist in control of mite levels. Secondary measures to reduce exposure include control of mites in carpets and upholstered furniture, which are the other major sources of mite allergen. These measures include removing carpets and upholstered furniture from rooms and reducing potential dust-collecting items from the bedroom, which is the major site of exposure to mite allergens for most persons; avoiding lying on upholstered furniture; covering upholstered furniture with impermeable covering; and avoiding vacuuming with an unmodified vacuum cleaner, or being present in the room during such vacuuming.

Acaricides can be employed to reduce the mite population in carpets, and tannic acid can be applied to carpets to denature the residual mite allergen. These chemical treatments are only partially effective and the effect persists only for a few months, making repeated treatment necessary. In some studies, acaricide treatment has been shown to reduce mite allergen levels, whereas in others this treatment has been ineffective (53).

Controlling other indoor allergens. Animal dander and cockroach allergen are the other principal indoor allergens that have been implicated in causing allergic disease. Animal dander is shed by the animal and on to the reservoirs afforded by carpets, upholstered furniture, and bedding from which it becomes reentrained in the air through the effects of human activity. Cockroach allergen is present predominantly in inner city homes and homes in the warmer parts of the United States. The greatest concentration of cockroach allergen is found in the kitchen. The importance of indoor mold exposure is less clearly established for conditions of ordinary exposure, but it may be important where unusually high moisture is present, as in some basements or where flooding or leakage has occurred previously.

Of course, animal danders are best limited by not having pets in the home and cleaning thoroughly if animals were present in the past. Less effective is to limit the range of the pets in the house, particularly excluding them from the sensitive person's bedroom. Neither measure eliminates the reservoirs of dander, which have been shown to continue contaminating the environment for as long as six months. Tannic acid and injection steam carpet cleaning can be used to denature or remove residual allergen after pet removal, but the effects of both are limited. Because animal dander allergen is associated with particles that may remain airborne for prolonged periods, the allergen can travel throughout the house by movement of air, inside and outside of the HVAC system. Therefore, the bedroom door and heating vents should stay closed throughout the day. Opening windows in the bedroom will dilute the allergen and partially reduce the level of small respirable particles containing animal allergens that are in the air.

Cockroaches can be controlled by thorough cleaning, reducing the presence of food, paying careful attention to sealing the insects' entry points, and by trapping or using poisoned baits. In apartment buildings, cockroaches can move from one unit to another, and all possible entry points must be sealed. It may be prudent to avoid chemical pest control, if possible, because of potential exposure to fumes from pesticide applications and to residual pesticide in the indoor environment. Cockroaches are known to develop resistance to pesticides over time, making repeated use less effective.

Mold control is accomplished by reducing humidity, as molds, like house dust mites, thrive on high humidity. Removal of soft material that has become contaminated with mold growth may also be necessary.

Although there have not been prospective controlled studies that demonstrate the health benefits of reducing exposures to these allergens, there is little reason to doubt the effectiveness of reduction of exposures to animal dander or dust mites. For sensitive persons, benefits are also expected from reduction of cockroach and mold exposure.

Air cleaning devices can be effective only against allergens that are suspended in the air. Both mite and cockroach allergens are associated with large particles, which tend to fall rapidly from the air; therefore, air cleaners can contribute little to this natural clearing secondary to gravity. Air cleaners can remove fungal spores and animal dander allergens. However, the quantity of these allergens in reservoirs in carpets and upholstered furniture far exceeds the amount in the air. Furthermore, the allergen is readily reentrained from these reservoirs by human activity. Use of air cleaners should be considered only after sources of allergen exposures have been addressed.

Environmental tobacco smoke and other irritants. Patients with asthma have airways that are hyperresponsive to irritant stimuli. Exposure to environmental tobacco smoke (ETS) has been shown to exacerbate the status of children with asthma and possibly to increase risk for asthma (54). It has also been shown to increase symptoms in adults with asthma. It is prudent to recommend elimination of ETS exposures in the home for children and adults with asthma. Patients with asthma also report symptoms from other exposures of irritants in the home environment, and perfume is frequently reported to cause symptoms. Some asthmatics may also be adversely affected by other sources of irritants such as cleaners and polishes.

Potentially Susceptible Populations: Persons Affected by Sick Building Syndrome

In any building, there will be a *range of susceptibilities* among occupants to indoor air pollution exposures or other adverse conditions rather than a sharp distinction between susceptible and nonsusceptible persons. Thus, only a proportion of workers in an office building—those for whom exposures have exceeded a threshold of physiologic tolerance—would be expected to have physiologic responses to low level adverse exposures. As the distribution of human responsiveness to the responsible agents is likely to be a continuum, it is probable that, at higher exposure levels, a greater proportion of the exposed population would respond adversely. As an example, it is well recognized that generally less than 5% of those actually exposed to sensitizing microbiologic materials in indoor environments develop hypersensitivity pneumonitis, a recognized building-related illness, or complaints. The human response to thermal environments is so diverse that at any given temperature, a minimum of 20% of building occupants, and generally more, find thermal conditions to be unacceptable. Adverse health responses in buildings may involve parameters documented to cause building-related illness or thermal discomfort, including chemical (e.g., carbon monoxide or formaldehyde), biologic (e.g., fungi or dust mites), or physical (e.g., temperature, humidity, or air movement) factors. Appendix D provides a detailed account of an investigation of workers with possible building-related illnesses.

Symptoms that are apparently work-related should not be dismissed solely because etiologic factors cannot be identified. Levels of various environmental parameters currently considered acceptable may in fact not be. For instance, multiple studies have demonstrated that even *within* the indoor temperature range long considered acceptable, higher temperatures are associated with increased symptom prevalence. Because not all contaminants or conditions with adverse human effects are known or recognized (e.g., specific etiologic agents even for clearly documented outbreaks of hypersensitivity pneumonitis often cannot be identified), worker symptoms may result from exposures or conditions not yet causally implicated in building-related illnesses. These exposures or conditions, though quite plausibly causing adverse effects, may not yet be widely measured (e.g., endotoxins, various single or combined VOCs), or measurement methods may not be readily available (e.g., many mycotoxins).

Is there a relationship between occupants who report symptoms in buildings where adverse exposures or conditions cannot be identified, and those with multiple chemical sensitivity? Known as MCS, multiple chemical sensitivity is defined as long-lasting intolerance to chemicals and odors in the indoor environment. (See the next section.) As "problem" buildings are among the few environments that have produced simultaneous multiple claims of MCS development, sick-building syndrome (SBS) is considered by some to be synonymous with MCS. This is not the case, considering the very common occurrence of work-related symptoms among office workers in all buildings studied, compared with the relatively infrequent occurrences of MCS. There are also relatively small proportions of claimed MCS development even in severe "problem" buildings with very high proportions of workers having work-related symptoms.

Potentially Susceptible Populations: Persons with Multiple Chemical Sensitivity or Idiopathic Environmental Intolerance

Persons with this entity, generally termed multiple chemical sensitivity, or MCS, and recently relabeled as Idiopathic Environmental Intolerance by the World Health Organization (55), are usually self-described as hypersensitive to more than one, but not necessarily all, chemicals. Generally, such patients report more than one symptom, usually associated with multiple agents. Symptoms may include a burning sensation in the eyes or throat, cough, dyspnea, fatigue, headache, rashes, weakness, feelings of anxiety, panic, inability to think clearly, and related neurologic complaints. After a person's perceived exposure to an inciting agent, the symptoms may last for a brief time or for hours or even for days. An individual may become symptomatic and even debilitated by symptoms from alleged exposures even at levels generally considered inoffensive or innocuous to most people. The perceived cause-effect relationship between chemical exposure and symptoms is commonly defined by the patient based on perception of an odor or on perception of irritation. The person with MCS may believe that his or her own olfactory sensitivity exceeds that of the normal person.

The particular agents to which persons with MCS allege hypersensitivity vary from person to person, with the agents to which any patient claims susceptibility frequently varying over time, and possibly including substances such as fine fragrances that others may find desirable and pleasurable. The natural history of MCS has not been described. Anecdotal reports indicate that over long periods of removal from exposure to offending chemicals, persons with MCS may gradually return to normal. The role of avoidance in the condition has not been well-characterized.

The mechanisms leading to MCS remain uncertain, and exposure reduction may be the only relief from symptoms for many MCS sufferers. Control measures to improve indoor air quality for the population generally would also apply to this group of people. Specific approaches for home environments of persons with MCS would be person-specific and require individual guidance. Persons with MCS have formed their own support networks for exchange of information on managing symptoms by physical control of the environment. Typically, the home environments of many patients with MCS are sparsely furnished, and rigid dust control is maintained; as well, there is an absence of chemical products and of fleecy materials. Because of the ambiguous nature of MCS and the changing spectrum of substances to which the patient with MCS exhibits symptoms, there is little to make in the way of specific recommendations for exposures to particular agents. Systematic research using sound methods has been recommended to define and manage this poorly understood condition.

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APPENDIX A

Particle Reduction Strategies

The following is a list of recommendations for reducing particles in the indoor environment, and thereby reducing problems caused by indoor air pollution.

Ambient Particles
- Upgrade filters to $>$ 50% at 0.5 μm with target to improve removal efficiency.
- Relocate air intakes away from obvious sources.

Dust
- Clean exterior and entrance sites.
- Conduct high efficient particle removal by use of washable rugs and other surfaces at entranceway.
- Ensure enhanced cleaning of all internal surfaces.
- Reduce the use of textile covered surfaces, i.e., partitions/wall coverings/wall-to-wall carpeting.
- Advance development and application of cleaning performance standards.

Surface/Coatings
- Encapsulate, seal, and/or isolate all potentially friable surfaces.
- Direct duct supply and return air (i.e., do not use open ceiling plenum space).
- Specify abrasion resistant insulation material.

Combustion/Specific Equipment
- Isolate/zone ventilation where emissions can be identified and efficiently captured.
- Site exhaust filtration when it can be demonstrated that point of a source mitigation is more cost-effective strategy for reducing concentration, dust burden, or occupant exposure.

General Human Activity
- Improve efficiency of vacuums to reduce surface loadings and to reduce mechanical dispersion.
- Ensure that localized recirculation/filtration system is appropriately sized to the application.
- Upgrade air filtration efficiency on force air system/air conditioning.
- Identify sources and/or transport mechanisms and intervene appropriately (e.g., transport of latex on surgical clothing).

APPENDIX B

Ventilation Technology

Proven, affordable ventilation technologies that can deliver adequate ventilation air for the maintenance of both contaminant control and comfort should be considered in the HVAC system design. A listing and descriptions are below.

1. *Air Economizer.* This type of ventilation system offers a significant advantage for increased outdoor air ventilation over systems using a fixed minimum amount of outside air. In commercial buildings, heat from lights and people must be dissipated from the interior core year-round. With an air economizer, this is done by flushing with large amounts of outside air. For commercial buildings located in temperate climates, there will be generous amounts of outside air for the majority of hours of the year (in the range of 30 to 100 cfm/person), especially in the spring and fall. Therefore, economizers are much more forgiving to design inadequacies and building use changes. Occasionally, they are rejected because of the space needed for ductwork. However, with present emphasis on indoor air quality, an air economizer system may actually be more cost effective than alternatives.
2. *Direct Digital Control with Simple Graphic Interface.* Many HVAC systems have been controlled by computers in recent years. However, graphic interfaces now simplify the level of knowledge required to operate the HVAC system and drastically improve the likelihood of the system being operated correctly. All computer-controlled HVAC systems need periodic audits to assure that erroneous messages are not being given.
3. *Variable Air Volume (VAV) with Outdoor Air Injection.* These systems deliver variable airflow to spaces, depending on requirements. VAV systems can contribute to indoor air quality complaints if the airflow restriction is too great. Advances in equipment design and software controls now allow the amount of outdoor air delivered to the occupants to be maintained, even though the total supply of air is decreased to save on electrical consumption.
4. *Demand Control Ventilation and Reliable Carbon Dioxide Sensors.* We now have affordable sensors that can serve as indicators of the level of occupancy and thus be used to increase ventilation air delivery in proportion to the occupancy, thereby saving energy. When demand control ventilation is utilized, some baseline level of outdoor air ventilation is needed regardless of the carbon dioxide controller.
5. *Indoor Air Quality Air Conditioning Condensate Drain Pans.* Many companies are now marketing IAQ drain pans and IAQ air handling units. These systems are typically designed to avoid the build-up of stagnant water in the air handling system and to facilitate its hygiene.
6. *Low Pressure Drop High Efficiency Air Filters.* Recently, many air filter manufacturers have made available a selection of extended surface pleated air filters that allow much higher air filtration to be utilized without a significant increase in fan horsepower.
7. *Outdoor Air Preconditioning Units.* Until recently, removing the humidity from outdoor air in a hot and humid climate was very energy-demanding. Now, there are proven technologies for removing humidity before the outdoor air is brought into the building that are much less energy intensive. This type of system is preferable in any climate that is considered hot and humid, or even temperate and humid.
8. *Tight Building Envelopes and Air Conveyance Ducts.* Researchers in Florida and California have recently shown that tightening air ducts in both homes and commercial buildings, and reducing building shell leakage, can have a dramatic effect on both improving air quality control and reducing air conditioning energy bills.
9. *Unlined Air Conveyance Ducts and Nonpermeable Duct Liners.* Many designers have altered their design practice to eliminate porous duct liners from the HVAC ductwork because of the potential for accumulation of dirt and dampness to lead to mold growth. Some manufacturers have begun to make available nonporous duct liner.
10. *Return Plenum Design.* Because of difficulties encountered in cleaning ceiling plenums and maintaining adequate pressure con-

trol between different HVAC zones, some designers have eliminated the use of return air plenums. In general, when a return plenum is used, it is very important for the architect, engineers, and contractors to ensure that the perimeter of the plenum above the ceiling is very carefully sealed to prevent movement of unwanted airflow and air contaminants from one zone to the next.

11. *Vertical Displacement Ventilation Technology*. Although used in parts of Europe for many years, vertical displacement air supply has only been incorporated recently by designers in the United States to enhance the natural movement of air within a room. This type of system can reduce drafts, enhance air quality, and reduce energy consumption by fans. Often this type of system is used with a 100% outdoor air design and heat recovery, thereby preventing movement of contaminated air from one part of a building to another while achieving good energy efficiency. The potential electrical energy savings with this type of system are significant. Alternately, the electrical savings from reduced fan horsepower can be utilized to provide improved climate control with dehumidification and air conditioning in areas that may not have been previously air conditioned or dehumidified.
12. *Personal Work Station Control of HVAC Systems*. Some manufacturers have made available systems for personal control of airflow and temperature control at workstations. This approach may offer enhanced occupant comfort. Inherent in this approach is the need to maintain more dispersed HVAC equipment and controls. It is also important that the personal control equipment be accessible for preventive maintenance.

APPENDIX C

Air Cleaning and Filtration

Concepts and Definitions

The term "filtration" refers to processes in which individual suspended solid particles are separated from a fluid (vapor or liquid) phase, and collected on or inside a "filter." The filter is a medium that interacts with or exerts a force on particles dispersed in a fluid, attracts them to its surface, and retains them. The performance or *efficiency* of a filter or of a filtration process can be measured by the weight fraction of particles removed; that is, the percentage by weight of particles removed from the air. This term can be ambiguous and even misleading from the health perspective. Efficiency that is based on the weight fraction collected tends to emphasize disproportionately the removal of large particles, which are frequently not those of most concern for health. Other definitions of efficiency are based on the number of particles collected, or on the weight fraction of particles collected within a narrow size range. The passing of a fluid through a filter is also associated with consumption of energy; thus, another feasible efficiency concept may be that of energy expended per number or unit weight of particle collected.

The degree of air cleaned by filtration reflects a complex set of parameters including the chemical and physical properties of the particles, the filtering medium, flow rate, turbulence, mass loading on the filter, and other factors. A single term like "efficiency" is generally inadequate to describe the performance of a filtration process, unless qualified by numerous conditions. Solid particles vary widely in size, shape, and composition. Volume, number, and surface area of suspended particles have been characterized (*see* Figure C.1). Particle mass is typically bimodal, with two fractions characterized by coarse fraction and fine fraction. In Figure C.2, the bimodal distribution found in indoor atmospheres with the predominant constituents in each fraction are shown.

Sources of Particles

Sources of indoor air particles include penetration of outdoor air containing particles, resuspension of settled dust, cooking, combustion appliances, aerosol sprays and powders, cigarettes, vacuuming, motors, recondensed vapors from sources such as candles, oils, and lubricants, and copy machines. Biologic spores, pollens, dander, skin flakes, and mite allergens are typically larger than 1 μm in size and hence more easily removed by filtration. Nonviable fragments of cells, actinomycetes, viruses, and strains of DNA may very well be less than 0.1 μm in size (although viruses are quite small, they are often present in the air as a constituent of a droplet and therefore might be a few microns or so). The expected sizes for common indoor particles and the time required to fall 1 m or about half the height of a typical room are given in Table C.1.

Recent studies using sophisticated particle-size analyzers have shown that combustion events in the home produce abundant quantities of ultrafine particles (< 0.1 μm), which are carried by convective currents and disperse quickly as room air mixes and is displaced. Very small but high in number, the particles grow by agglomeration, diffuse to surfaces, or are removed from the indoors by air exchange. However, like all particles less than a few microns in size (5 μm), they settle out very slowly. Disturbing surface dust creates clouds of particles. Studies have shown that vigorous house cleaning resuspends particles greater than 5 μm in size. Even walking across a carpet will greatly increase particles 5 to 25 μm in size. Small sizes are not as likely to be resuspended (56). Although particles 100 μm in size or greater will settle quickly, convective currents and agitation by people and pets will keep many coarse-size particles suspended in the indoor air.

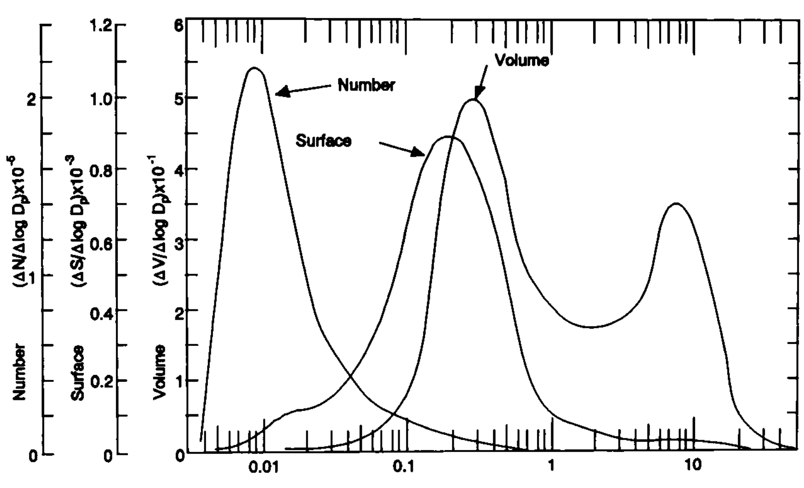

Figure C.1. Plots illustrating the relationship of particle number, surface area, and volume distribution as a function of particle size (Source: Whitby, K. T. 1975. Modeling of atmospheric aerosol particle size distributions: a progress report on EPA research grant No. R800971, "sampling and analysis of atmospheric aerosols." Minneapolis, MN: University of Minnesota, Mechanical Engineering Department: p.III-21; particle technology laboratory publication no. 253).

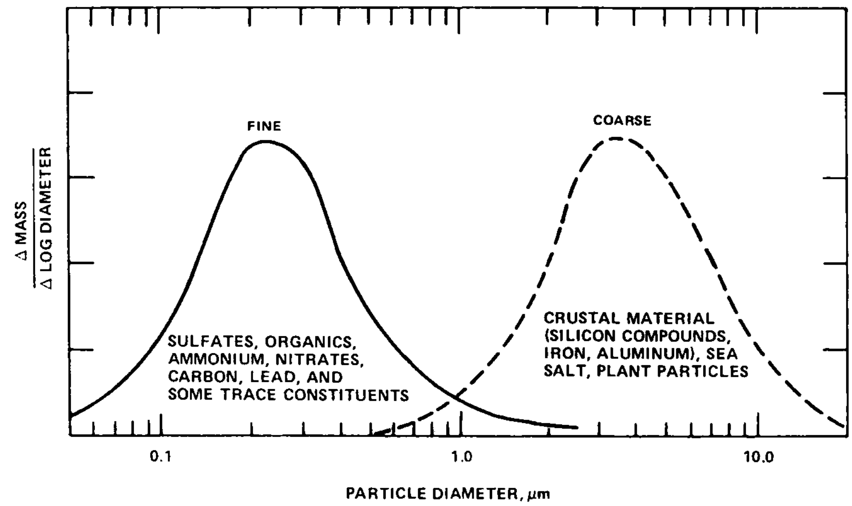

Figure C.2. Idealized representation of typical fine- and coarse-particle mass and chemical composition distribution in an urban aerosol. (Source: U.S. Environmental Protection Agency, EPA-600/8-82-029a, December 1992).

When activities in the home cease at night, particle measurements have clearly shown that PM_{10} concentrations decrease substantially.

Filtration of Particles

Different filtration media rely on different interaction mechanisms for the separation and collection of particles and have distinct efficiencies for particles of varying sizes and/or shapes; the collection efficiency of filters changes with time and is also affected by the flow rate of the fluid through the filter. Commonly, filtration processes are designed for collecting primarily one type or size-range of particles. The dust-holding capacity of the filter and the operating cost for the filtration system—energy requirements for moving the fluid phase through the filter and filter replacement costs—are also important parameters for the consumer. Thus, a single efficiency value, commonly cited in commercial literature to characterize the performance of a filter, may not be sufficiently informative for consumers.

The purpose of filters, even in general ventilation applications, may differ from case to case, and with it the performance criteria of principal interest. We return to the example of air filtration removing allergens (pollens, house dust mites, spores, etc.) from a home.

It should now be readily apparent that the actual effectiveness of any air cleaning device will depend on the proximity to the source, capture efficiency, filtration efficiency, air exchange rate, volume of the setting, and location of persons, among other factors. It is understandable that demonstrated health benefits of air cleaning are still elusive given the inherent difficulties in quantifying exposures. Manufacturers as well as users report favorable results, but an appropriately designed clinical trial on the efficacy of air cleaning devices for asthma and allergic diseases, as well as other groups who might potentially benefit, has not been conducted.

Filter testing methods. It follows from the general considerations above that the expected performance of a filter cannot be described without attention to many technical details. Accurate comparisons of different air cleaners (filters) can be made only on the basis of data obtained by standardized test methods. Unfortunately, testing by existing standards (e.g., ANSI/ASHRAE 52.1-1992) is not equally applicable to all filtration devices. For example, ANSI/ASHRAE 52.1 specifies as the material for challenge in its arrestance test a standard dust mixture that simulates typical dusts encountered in HVAC systems. However, this standard test dust contains graphite particles that will cause electrostatic (or "electronic") filters to malfunction in arrestance tests. Test dust is specified at 72% (wt) Arizona road dust, 23% powdered carbon, and 5% cotton lint. Performance based on this test dust says little about how the filters might remove particles in the respirable size fraction.

The ASHRAE 52.1-92 (or its previous version, ASHRAE 52-76) procedure tests filters in several important ways.

1. The weight arrestance test measures the collection efficiency for coarse particulates (those associated with HVAC system fouling) and is more appropriate for low efficiency filters (10 to 30%) such as those found on home furnaces and commercial HVAC systems.

TABLE C.1

APPROXIMATE PARTICLE SIZES AND TIME TO SETTLE 1 METER*

Type	Diameter (μm)	Time
Human hair	100–150	5 s
Skin flakes	20–40	
Observable dust in air	> 10	
Common pollens	15–25	
Mite allergen	10–20	5 min
Common spores	2–10	
Bacteria	1–5	
Cat dander	1 ± 0.5	10 h
Tobacco smoke	0.1–1	
Metal and organic fumes	< 0.1–1	
Cell debris	0.01–1	
Viruses	< 0.1	10 d

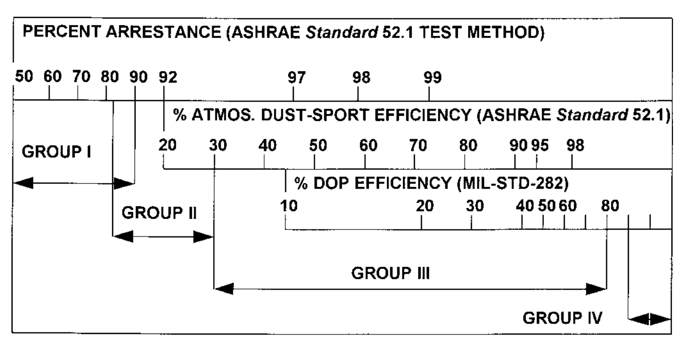

Figure C.3. Comparison of filter performance ratings. (Reprinted by permission of the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, Georgia. From the 1996 ASHRAE Handbook: Systems and Equipment.)

TABLE C.2

EXPECTED FILTER PERFORMANCE RATINGS FOR DIFFERENT FILTER TYPES*

Filter Type	Filter Media	Weight Arrestance (%)	Atmospheric Dust Spot Efficiency (%)	DOP Efficiency (%)
Panel-type filter	Spun-glass, open cell foam, expanded metals and screen, synthetics, textile denier woven and nonwoven, or animal hair	50–90		
Pleated panel-type filter	Fine denier nonwoven synthetic and synthetic-natural fiber blends, or all natural fiber	85–95	15–30	
Extended surface-type supported or nonsupported	Fine glass fibers, fine electret synthetic fibers, or wet-laid paper of cellulose glass, synthetic, or all-glass fibers	95–99.7	30–98	80
Extended-area pleated HEPA-type filters	Wet-laid ultafine glass fiber paper	99.99	> 98	99.97–99.999

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2. The dust-holding capacity test measures the expected life of the filter under given operating conditions.
3. The dust spot efficiency test is a semiquantitative measure of the filter's collection efficiency for fine particles—those associated with the smudging of the interior surfaces of buildings. The test is appropriate for medium efficient filters (20 to 98%). Upstream and downstream paper target filters collect particles and the opacity is measured (light transmission).
4. The measurement of resistance versus airflow is related to the energy required to operate a filter.

ASHRAE 52.1-92 fails, however, to address two important issues related to indoor air quality: the filter collection efficiency for "respirable particles" (those in the 0.01 to 10 μm size range) and the efficiency of removal of biologic materials (spores, fungi, bacteria, and viruses). To address the issue of rating filter efficiencies for respirable-sized particles relevant to the nuclear industry and for personal protective masks, another test was developed. Heating liquid dioctylphthalate (DOP) and then cooling it carefully can produce a uniform-sized aerosol. The DOP test uses 0.3 μm condensed droplets and light-scattering detectors for determining the particle retention properties of higher performance filters. Applications in microelectronics manufacturing now require filter efficiencies of 99.9995% in the DOP test. It can be seen in Figure C.3 how these three tests compare. To interpret the reported efficiencies of manufactured filters, it is important to note the reference test. A cheap furnace filter might state 90% efficiency when it is really less than 20% effective by the Atmospheric Dust Spot Efficiency test. (*See* Table C.2 for comparison of methods.)

A test procedure (ASHRAE 671-RP) recently developed by RTI under contract to ASHRAE utilizes fractional efficiency testing—"penetration measurements" on artificially generated aerosols—to characterize the efficiency of filters for the removal of particulates in the size range of 0.3 to 10 μm. This research was specifically commissioned for the purpose of developing a consensus standard method of testing (MOT), and this work is nearing conclusion. Standard 52.2 (Method of Testing General Ventilation Air Cleaning Devices for Removal Efficiency by Particle Size) is currently out for its second public review and is likely to be published by mid-1997. This new test procedure, if adopted as a standard, will provide a reproducible (± 2%) methodology for testing the particle removal efficiency of filters used for general ventilation. It is technically feasible to extend the fractional efficiency test to particle sizes less than 0.3 μm to include most viruses and combustion sources that vaporize oils, fats, and proteins in food to generating ultrafine aerosol.

The performance of four pleated filters is shown in Figure C.4 for particle sizes ranging from 0.01 to 3 μm in diameter. These pleated filters were rated by the ASHRAE Percent Weight Arrestance test as 95, 85, 65, and 40% efficient. The filter efficiencies for 0.1 μm size particles ranged from ~ 1 to 50%, which illustrates the importance of specifying particle size or at least test conditions when reporting efficiencies. It can be seen in Figure C.5 how the overall efficiency of a filter increases as it collects more dust. Dust loading increases the pres-

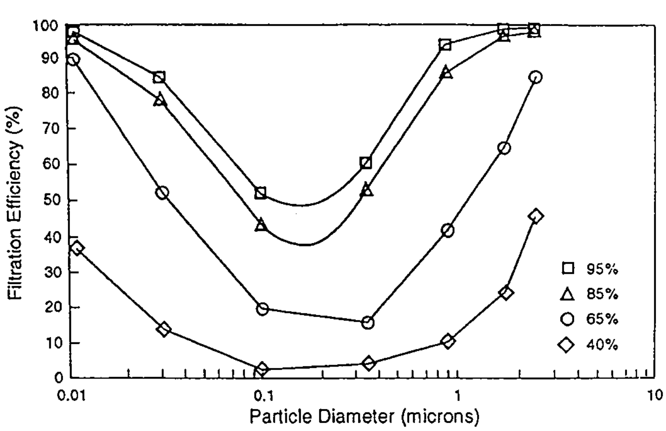

Figure C.4. Fractional filtration efficiency of four pleated filters having ASHRAE efficiencies ranging from 40 to 95% (Source: Hanley, *et al.* 1993. Fractional aerosol filtration efficiency of air cleaners. Proceedings of Indoor Air 1993: Sixth International Conference on Indoor Air Quality and Climate, Munksgaard International Publishers, Copenhagen, Denmark).

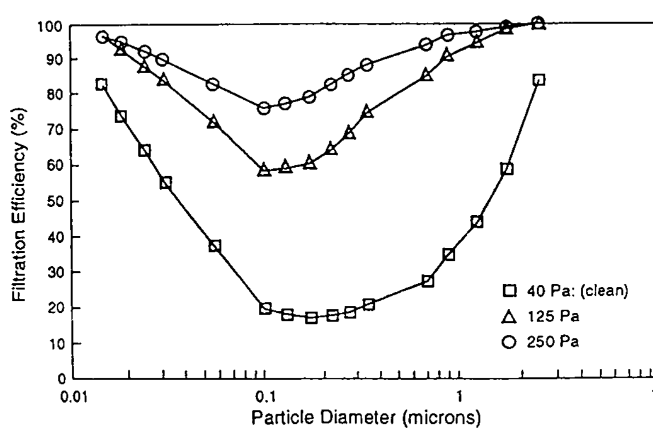

Figure C.5. Fractional filtration efficiency of a pleated-paper filter (65% ASHRAE efficiency) for clean and dust-loaded conditions (Source: Hanley, *et al*. 1993. Fractional aerosol filtration efficiency of air cleaners. Proceedings of Indoor Air 1993: Sixth International Conference on Indoor Air Quality and Climate, Munksgaard International Publishers, Copenhagen, Denmark).

sure drop, measured as Pascals$_{n,}$ across the filter and hence the fan power requirements. Another important parameter for comparing filters is the total recommended maximum mass loadings. New standard test methods will most likely require performance curves for different particle sizes over a filter's expected life. Other more sophisticated but not standardized filter tests have emerged as the result of needs in specialized industries (e.g., semiconductor manufacture and controlled hospital environments). The results of such tests, conducted with specific types of particles, may be misleading if extended to more typical environments. These and many other tests have been used and misused to characterize filter performance and to underpin claims that may be misleading when quoted out of context.

Electronic air cleaners. Electronic air cleaners (EACs) use electrostatic precipitators to remove particles from the air by giving them an electric charge. Units used in forced air systems in residences and commercial settings usually have two stages. A high voltage low current is supplied to wires that spew off positive or negative ions that quickly attach to particles. The second stage has oppositely charged collection plates that attract and hold the particles. Well-designed and well-operated EACs are quite efficient, usually achieving 95% removal of DOP 0.3 μm particles. Poor maintenance and loss of electric field potential in the EACs have been linked to secondary particle production. Also, ozone is formed when wires produce corona discharge. However, improved design lowers ozone generation so levels inside homes and offices are usually barely detectable, though one should be aware that operating some electronic air cleaners in small sealed rooms can result in unhealthful levels of ozone.

Sorbents for ventilation air. To remove gaseous contaminants, a variety of sorbent materials are used. Activated carbon, which is made from sieved coconut-shell carbon, removes many gases and vapors from an airstream by adsorption. The carbon granules have an enormous surface area per mass. Gas molecules diffuse to the surface where they are retained. Sorbent "filters" (charcoal, permanganate/alumina, or other materials) are typically available for HVACs in refillable 1 to 1 and 1/8-inch refillable panels. Depending on the packing and mesh size, sorbent panels can be 90 to 95% effective in removing most organic compounds.

There are several solid-phase sorbents available today. All sorbents have limitations that affect their performance and operating time; eventually the surface becomes saturated with vapors. Unlike particle filters, there is no direct way to know if adsorbing filters have exceeded their useful life. Water vapor competes for surfaces and will decrease performance. Charcoal-packed beds or panels that are less than 1/4-inch thick will not be effective. New matrix web fabric filters have carbon and glass fibers woven together and can be no more than 1/4-inch thick. They are effective for limited periods of time. Not all organic vapors or gases have the same adhering affinity, so careful attention to specific applications is advised. Air temperature will affect adsorption efficiency, and there is a potential for release of vapors.

APPENDIX D

Investigation of Workers with Possible Building-Related Illness(es)

Introduction

Investigations of illness among workers that may be related to the indoor environment in the building where they work have been initiated traditionally by two different mechanisms.

1. Building management receives "complaints" from occupants. These complaints may include symptoms (headache, mucosal irritation, etc.) that are attributed by the worker to the building environment, or perceptions of adverse conditions ("too dry," "stale and stuffy").
2. One or more workers seek medical attention for evaluation of symptoms that occur at work. After evaluation the physician attributes the health problems to the building in which the patient works.

Although this difference may appear unimportant, the process and outcomes of evaluation will be different because the focus of the investigation, and the training, experience, and perspective of those involved, will be very different. Building management has traditionally called upon engineers, architects, and, increasingly "IAQ consultants" —an emerging profession. These professionals take the perspective that the building is "sick." Therefore the building, particularly the HVAC system, is evaluated to identify conditions that could create occupant discomfort, dissatisfaction, or symptoms.

In the second mechanism, when a worker consults a physician, the evaluation is based on the premise that the worker is sick. The primary physician may call upon occupational or public health physicians or industrial hygienists in an effort to identify the specific illness and the causative exposure(s).

From the mid-1970s until now, the conceptualization, definition, and majority of investigations of this problem have been from the first perspective, i.e., problem-solving for buildings. Symptoms or other stated problems have often been considered as indicators of "problem buildings," and not directly evaluated. Cause and effect relationships

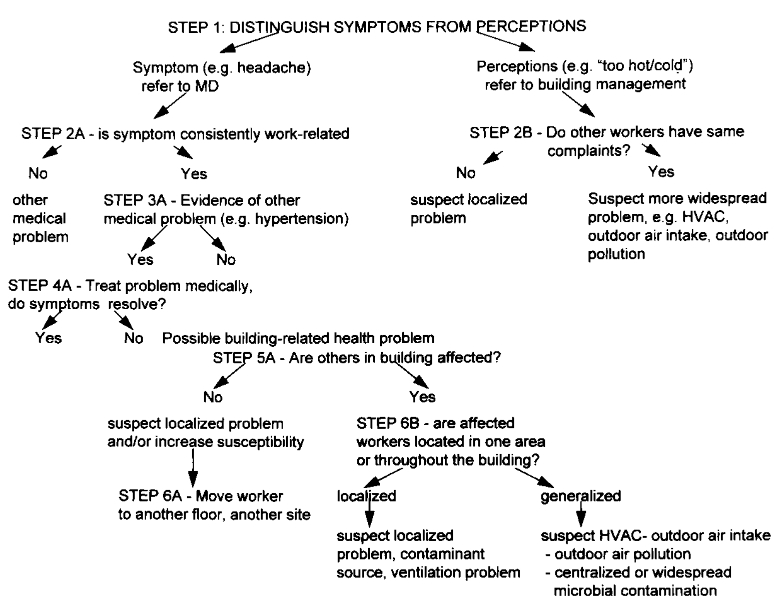

Figure D.1. Possible building-related discomfort, dissatisfaction, or symptom (directed to building management or personal physician) (Source: R. M. Menzies. Used with permission).

between health effects and environmental parameters have not been sought specifically. Instead, deficiencies in building operation and maintenance have been sought, and corrected if found. If remedial actions resulted in resolution or reduction of the workers' problems (as expressed in "complaints" to building management), then a cause and effect relationship was often concluded post-hoc.

Principles of Investigation of Possible Building-Related Illness(es)

Investigation of workers' discomfort, dissatisfaction, and/or symptoms would be improved by adopting a unified approach incorporating aspects of both perspectives (*see* Figure D.1). The following general principles are derived from experience of these two perspectives.

1. "Complaints" or problems identified by workers should be distinguished as symptoms (headache, chest tightness, wheezing, fatigue) versus perceptions ("too hot," "stale and stuffy"). Symptoms may indicate a health problem and these should be referred to a physician for evaluation no matter who is consulted first. For example, it is important to ensure that headaches are not indicative of a medical problem such as hypertension. On the other hand, perceptions of environmental problems should be directed to building management rather than to health professionals.
2. The symptoms should be categorized as work-related or not work-related. In occupational medicine the classic definition of work-related symptoms are those that begin after arrival at work and resolve upon leaving work. Occasionally, symptoms may begin many hours later. For example, hypersensitivity pneumonitis can manifest 12 to 24 h after exposure. Symptoms usually resolve rapidly, even within minutes after leaving work, but they may persist for weeks after a single exposure in those most severely affected. In more severely affected persons, work-related symptoms should resolve on weekends, vacations, or with other prolonged absences from the work environment.
3. The symptoms typically reported by workers in office buildings include headache, fatigue, difficulty concentrating, and mucosal irritative symptoms—none of which can be measured objectively. It is axiomatic that health professionals as well as building management accept that the symptoms experienced by the workers are real. Failure to identify a clear cause does not mean that the symptoms can be dismissed as psychologic. Such an attitude is potentially harmful because it denigrates the workers and reduces the likelihood of detecting and solving problems. In the long run this will worsen communication and exacerbate tensions between workers and building management.
4. Workers and their advocates should remain open to the possibility that work-related symptoms are not necessarily related to the building environment or to indoor air quality. Symptoms may be due to job stress, anxiety, or physical or ergonomic factors.
5. Evaluation of possible building-related illnesses requires expertise in architecture, engineering, and industrial hygiene as well as in medicine, and few persons have expertise in all these domains. Therefore, a team approach with good communication between persons with different expertise is essential. It is in everyone's best interest to evaluate and resolve symptoms among workers. Building management should be open to the possibility that symptoms among workers are related to the building environment and to solutions proposed by physicians on behalf of persons or groups of workers. Physicians should work with building management to review possible causes and solutions, and public health departments should provide assistance, including expertise and industrial hygiene measurements.
6. The symptoms considered typical of sick building syndrome are usually very heterogeneous. Therefore, if the symptoms reported by several workers are more homogeneous, the possibility of a single causative agent should be considered. In outbreaks of building-related illness caused by microbial contamination, many workers presented with similar respiratory symptoms, raising the suspicion of alert clinicians.
7. When the symptomatology of a group of workers is homogeneous, the nature of the symptoms reported may provide some indication of the likely problem. However, much of our current understanding of exposure response relationships in the office environment is derived from case series or from cross-sectional studies. Consistent relationships with symptoms have been detected for only a few of the possible causative agents in the office environment. Other parameters have been recognized to cause symptoms on the basis of studies in the home or outdoor environments.
8. The number and spatial distribution of symptomatic workers may provide important clues to the cause. For example, if a group of affected workers are all located on a single floor or in one section, a localized problem such as a strong contaminant source or ventilation malfunction should be suspected. On the other hand, if workers in many different parts of a large building report similar symptoms, this may indicate a generalized problem such as contamination of the HVAC system supplying these different areas.
9. The temporal distribution of symptoms may provide further clues. Seasonal variations suggest problems related to temperature or humidity, outdoor pollutants if outdoor air supply varies seasonally, or house dust mite or fungal allergen exposure, which may increase during seasons with higher humidity. Other problems may be specific to certain times of the week. For example, symptoms that occur each Monday morning may reflect accumulation of indoor contaminants over the weekend if ventilation systems are shut down during these unoccupied periods.
10. The traditional definition of "sick building syndrome" has encompassed many symptoms, including headache, fatigue, difficulty concentrating, irritation of the skin, eyes, nose, and throat, lower respiratory symptoms, and others. There is no evidence that these diverse symptoms represent a single disorder or syndrome. On the contrary, it seems quite plausible that "SBS" is made up of many different disorders, each with specific symptoms and causative agents.
11. Symptoms may be related to temperature, humidity, and air movement—the so-called comfort parameters. These parameters can vary significantly from building to building, but they also can vary substantially within a single building, from floor to floor or even from worksite to worksite. The spatial and temporal variations detected have, in turn, been associated with variation in symptoms reported by workers in a number of epidemiologic studies. Therefore it is important to investigate the "comfort parameters" first, as they may account for a significant proportion of all symptoms, and they are the most amenable to corrective action. These parameters should be measured directly at the worksite of affected workers, on repeated occasions. Fortunately they can be measured relatively easily and rapidly with direct reading instruments, allowing more accurate characterization of workers' exposure.
12. Measurement of many indoor air quality parameters, such as carbon monoxide, formaldehyde, volatile compounds, fungal spores, or respirable dust, is complex and expensive. It is not possible to measure all these parameters at the workstations of all symptomatic workers, so exposure must be estimated on the basis of measurements at a sample of sites. Because these parameters also show substantial spatial and temporal variation, workers' true exposure may be inaccurately measured. The difficulties of obtaining accurate environmental measurements may, in part, explain the failure to detect consistent associations between these parameters and workers' symptoms.
13. For a specific exposure, workers will develop symptoms, or other health effects, if they are susceptible to that level of exposure. At low levels of exposure only a few highly susceptible persons may develop symptoms. As the concentration of a contaminant increases, the number of persons affected may also increase. It is possible that a few workers may develop symptoms when exposed to contaminants at concentrations that the vast majority of workers can tolerate. Therefore, when a person has work-related symptoms for which the cause cannot be identified, changing worksites may resolve the problem. However this does not necessarily mean that the workers who move into this same site will develop symptoms because they may be less susceptible to the same, albeit unknown, exposure.

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