IAQ 91

#5897

Healthy Buildings

Postconference Proceedings

American Society of Heating, Refrigerating
and Air-Conditioning Engineers, Inc.

CONTENTS

Invited Papers

Designing Healthy, Energy-Efficient Buildings

H.T. Gordon, AIA

INTRODUCTION

The growing concern with designing and operating healthy buildings is sometimes perceived to be in conflict with energy conservation. From this perspective, sick building syndrome and other health-related building issues emerged from the tightening of building envelopes and the reduction of ventilation quantities. But materials selection, systems maintenance, occupant activities, and other elements are also critical factors affecting the interior environment. While there is a relationship between healthy buildings and energy conservation, the issues are not simple ones. Increasing ventilation quantities, one of the common measures used to improve the health of buildings, does require additional HVAC energy. However, there are many other opportunities to save energy in building design that easily offset this increase in ventilation energy.

The production of energy from fossil fuel and nuclear sources has decidedly negative environmental impacts. In some locations, the outside air has become sufficiently polluted that it is of limited value for ventilation. The escalating demand for energy throughout the world exacerbates acid rain, global warming, and other problems. From a global environmental viewpoint, energy efficiency must be regarded as one essential element of a healthy building.

Decisions regarding basic building design and the selection of materials and building systems establish the groundwork for healthy buildings. The responsibilities during design fall into the domain of architects, engineers, and interior designers and mandate careful coordination among the disciplines. Care is required during construction and commissioning of a building to realize the design intent. Those responsible for building operations must understand the importance of their actions in maintaining a healthy environment.

ATTRIBUTES AND RESPONSIBILITIES

Healthy buildings are those that support and enhance the activities for which the building was designed. The attributes of healthy buildings include:

- Air quality
- Lighting quality
- Thermal comfort
- Acoustic comfort
- Energy efficiency
- Responsiveness to the global environment

Designing a healthy building requires a coordinated effort among architects, engineers, and interior designers.

Architects must address:

- Site planning
- Envelope design
- Selection of base building materials
- Functional groupings (especially for special environmental requirements)
- Lighting and daylighting
- Building commissioning

Engineers must address:

- HVAC selection and controls
- Ventilation quantity and quality
- Effectiveness of air distribution
- Provisions for systems maintenance
- Lighting interface
- Building commissioning

Interior designers must address:

- Selection of finish materials
- Systems furniture—effect on HVAC distribution
- Requirements for material maintenance
- Light distribution
- Building commissioning

BUILDING ENERGY USE PATTERNS

To understand the importance of energy to healthy buildings and a healthy environment, it is necessary to examine current patterns of energy use. As illustrated in Figure 1, the building sector is responsible for more than 40% of the energy consumed in the U.S.; about 85% of this amount is for building operations, and the remainder goes into the construction of buildings. Lighting

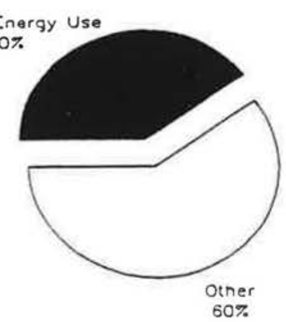

Figure 1 More than 40% of total U.S. energy use is for buildings.

Harry T. Gordon is a principal of Burt Hill Kosar Rittelmann Associates, Washington, DC.

is the single largest form of commercial building energy consumption, as illustrated in Figure 3 (National Energy Strategy 1991). When primary (or source) energy requirements are considered, commercial building energy use, especially of electricity, has increased substantially in the last three decades and is expected to continue doing so (Figure 2).

At present, more than two-thirds of primary energy use in commercial buildings is electricity. The proportion of building energy use that is supplied by electricity has been increasing for several reasons. There has been a substantial increase in equipment use in commercial offices, especially for computers and related components; the cooling load generated by these machines is normally met by chillers, fans, and other electricity-using components. For first-cost reasons, many commercial buildings are also heated with electricity. Offsetting these trends to a large extent is the great improvements in the efficacy of lighting, but the trend of electricity use is still upward. American businesses now spend in excess of $1 billion per year on electrical energy for buildings.

ENVIRONMENTAL CONSEQUENCES OF ENERGY USE

Inefficiencies in the production and transmission of electricity result in only about 30% to 35% of the primary energy value of the fuel used to generate the electricity being available for use at the building. More than 80% of electricity is generated from fossil fuel combustion, predominantly coal. The acid rain, global warming, and related environmental consequences of burning fossil fuels are beginning to be well known. However, the economic cost of these consequences is usually considered only in vague terms.

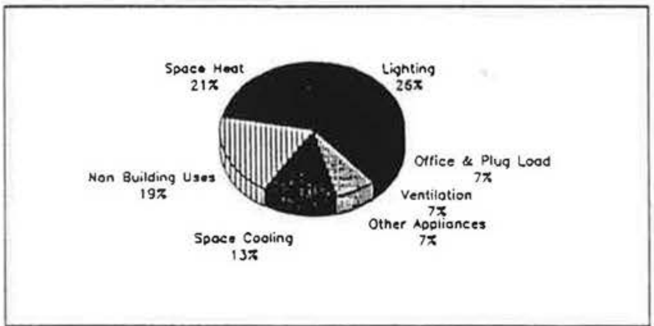

Figure 3 Lighting is now the single largest form of commercial energy consumption.

A recent study by the American Solar Energy Society attempted to estimate the "hidden" or societal cost of generating energy from conventional sources (ASES 1989). Among the energy-related costs that are not reflected in utility bills are:

Corrosion of structures	$2 b/yr
Agricultural crop losses	$3-8 b/yr
Health impacts	$12-2 b/yr
Treatment of radioactive wastes	$4-32 b/yr
Military costs—energy security	$15-54 b/yr
Fuel subsidies	$43-55 b/yr
Lost employment	$31 b/yr

While these costs are the estimates of experts, they are certainly not comprehensive. Yet the average total is almost $200 billion a year, which is at least one-half of the cost paid in the U.S. for energy each year. Other estimates put the hidden costs much higher. Regardless of the actual amount, the key point is that these costs are real and each of us pays them; most of the cost is paid from tax dollars, some from other funds. Only when we consider the economic and social consequences of these "hidden" costs will we begin to make realistic decisions about energy efficiency.

ENERGY EFFICIENCY AND INDOOR AIR QUALITY

One of the primary issues in describing healthy buildings is indoor air quality, which led to recent revisions in *ASHRAE Standard 62, Ventilation for Acceptable Indoor Air Quality.* For many occupancies, this establishes the quantity of outdoor air at 20 cfm/person, a figure that is four times as large as in the previous version of the standard for nonsmoking spaces. For normal office densities, this new standard amounts to about one air change per hour of outside air.

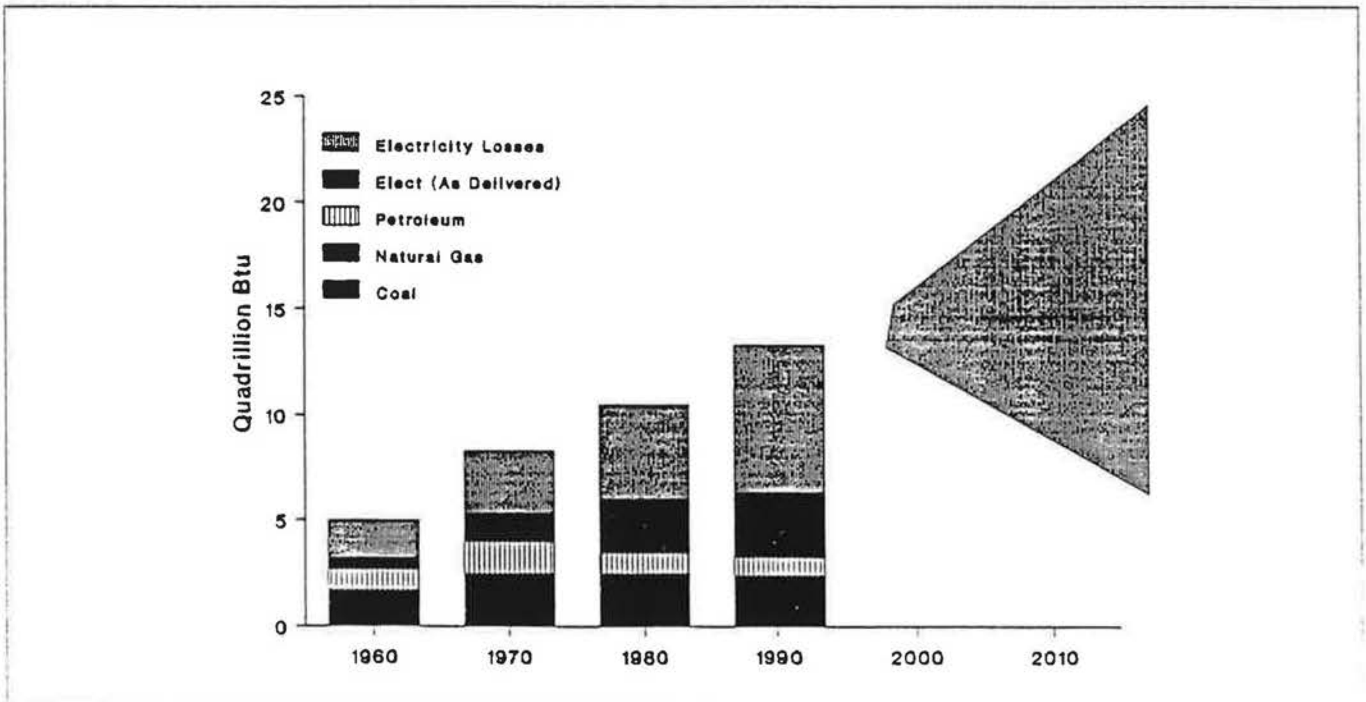

Figure 2 Commercial building energy use, especially electricity, is projected to increase substantially.

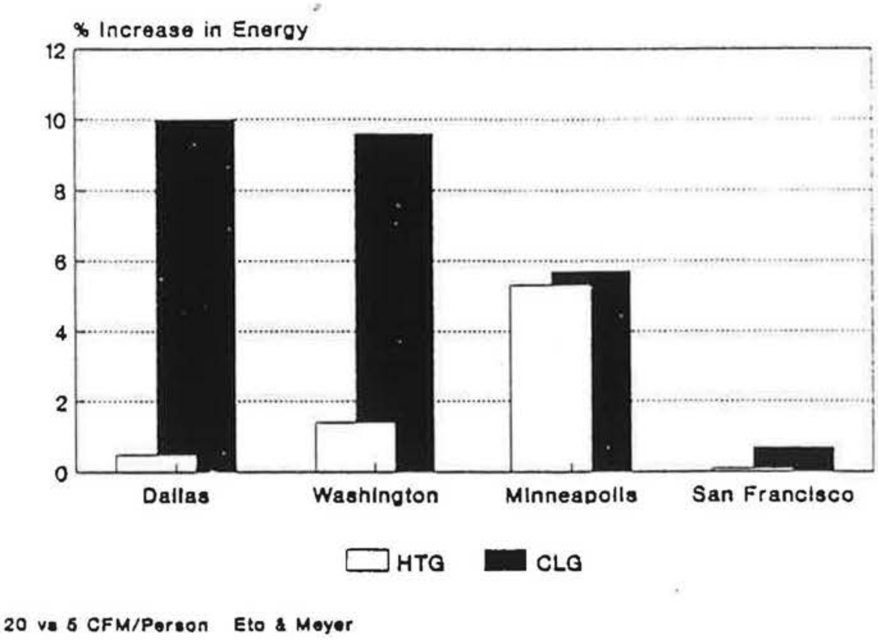

Figure 4 ASHRAE Standard 62-1989: Increased ventilation slightly increases operating costs in offices.

Concern has been expressed by some that this increase in ventilation requirements will result in a great increase in energy requirements. A recent study by Eto and Meyer (1988) indicates that, for large office buildings, the energy impact of increased ventilation is manageable. The authors examined the increase in energy use resulting from the change from 5 cfm per person to 20 cfm/person in 13 North American cities. The results for four of these locations are shown in Figure 4. While the researchers found increases in energy use ranging from less than 1% to about 8% for heating and less than 1% to almost 14% for cooling, the increases in operating cost are much lower, as shown in Figure 5. The maximum percentage increase in operating costs for all locations examined is less than 5%. Since space-conditioning energy costs are only a fraction of the total energy costs of operating the building, the impact of ventilation on operating cost is much less dramatic than it is when viewed in heating/cooling energy terms.

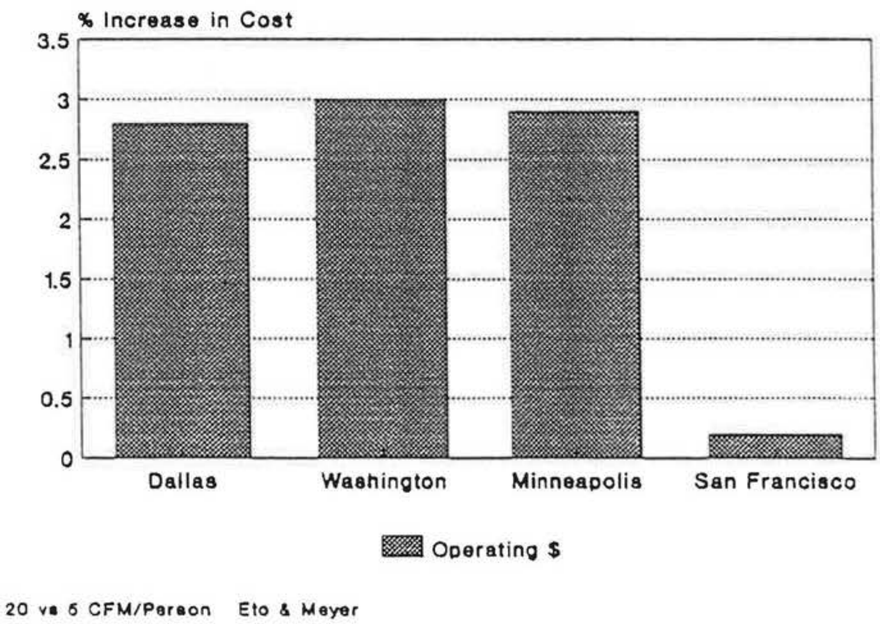

Figure 5 ASHRAE Standard 62-1989: Increased ventilation requires more energy in offices.

Other researchers have reported that the effect of increased ventilation is more significant in smaller buildings with reduced internal loads from people and equipment. For example, Steele and Brown (1989) found a 13% increase in total energy cost for a prototypical school.

SYSTEMS INTEGRATION AND ENERGY EFFICIENCY

Creativity in building design and an integrated A/E/ID approach can produce energy savings that easily offset increases in ventilation HVAC energy. Improvements in building envelope materials, lighting, HVAC and fan efficiencies, and controls create the opportunity for substantial reductions in energy requirements, with little or no increase in first cost.

For example, a 175,000-ft² office building in Pittsburgh, PA, uses a seasonally variable thermal chimney to control climate impacts on an atrium space (Figure 6). The atrium is conditioned with exhaust air from other portions of the building, resulting in an atrium with no increase in primary energy requirements. Similarly, the use of advanced glazing assemblies in the building envelope permitted offsetting reductions in HVAC equipment. The sprinkler system piping is used to serve water-source heat pumps, resulting in improved zone control and reduced construction cost. As a result, the building was constructed for a cost that is competitive with other office buildings but has a measured energy consumption of about 33,000 Btu/ft^2 per year, less than half that of similar contemporary office buildings, despite the fact that ventilation was based on 20 cfm/person.*

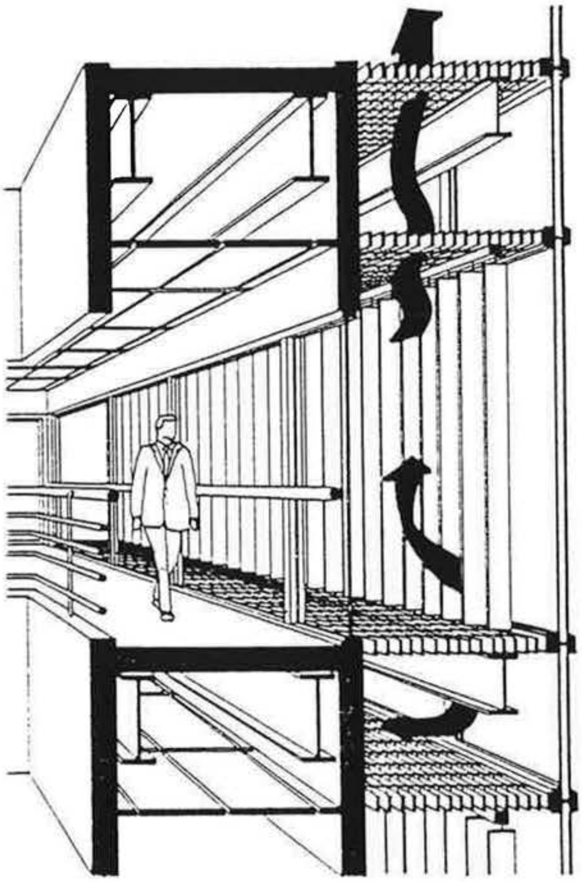

Figure 6 Diagram shows how west glazing/air shaft of atrium acts as a natural solar chimney, depending on the stack effect and temperature differential due to solar heat buildup at the vertical louvers within the shaft. The net effect is to eliminate solar heat, thus minimizing heat gain in the atrium.

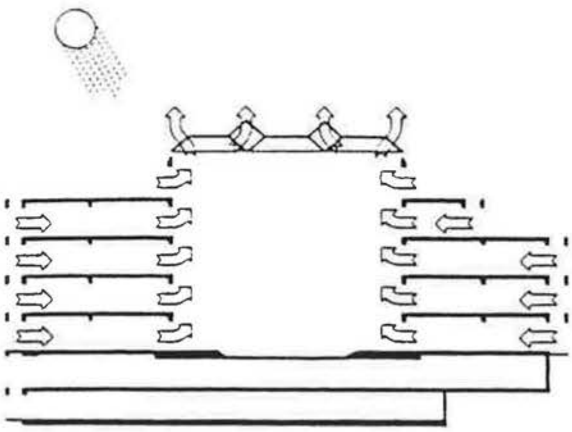

Figure 7 The London office building uses the atrium as a key element of a natural ventilation system, eliminating mechanical cooling.

Similarly, a building near London, UK, uses a large central atrium to induce ventilation through surrounding office spaces. The 150,000-ft^2 building was designed as the headquarters for paper manufacturers. The designers were asked to create a naturally ventilated building that would eliminate the need for a central cooling system. The operable roof glazing of the atrium creates a stack effect, drawing outside air through windows in the building perimeter, through the offices, and into the atrium (Figure 7). The building has operated successfully for seven years and has an energy use that rivals the best new office designs in the UK (646 MJ/m^2). The construction cost was only two-thirds that of a fully cooled office building built in the UK (IEA 1990).

CONCLUSIONS

- Energy efficiency is one key attribute of a healthy building. While increases in ventilation air quantities will require additional space-conditioning energy, there are many offsetting energy-saving opportunities.
- Design of a healthy, energy-efficient building requires a coordinated interdisciplinary effort among building professionals and the cooperation of building owners and managers.
- Commercial building energy requirements have been increasing for the last three decades, and are projected to continue doing so. Electricity is the largest component—more than two-thirds of commercial building energy consumption in source energy terms.
- Most electricity is generated from fossil fuels, predominantly coal. The adverse environmental effects of fossil fuel consumption are inadequately accounted for in utility bills and are largely paid with tax dollars. This creates an artificially low economic value for energy and discourages conservation.
- Creative commercial building designs, using a systems integration approach, can use ventilation effects to reduce building energy requirements and costs, while producing highly effective work environments.

*Comstock Engineering building, winner of 1986 ASHRAE Energy Award for New Commercial Building.

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Construction and Renovation for Healthy Buildings

A.E. Wheeler
Fellow ASHRAE

INTRODUCTION

The title of this paper implies that we adequately understand what makes buildings unhealthy. The chief thrusts of IAQ research and field investigations have been to identify specific contaminants that cause discomfort and symptoms of illness, measure the level of tolerance, determine their sources, and relate the distress they cause to other human stress factors, especially thermal, visual, and acoustical. While it would be presumptuous to believe the work and understanding is complete, the base of available information is sufficient to adopt techniques, concepts, and procedural safeguards into design, construction, and management that are likely to produce and maintain healthy buildings.

The place to begin our quest for healthy buildings is an examination of the building construction process. Typically, it begins with a recognized need by a developer, business, or institution for building space. This need is communicated to architects, engineers, and space planners who document graphic and verbal descriptions based on their understanding of the client's need. These documents, in turn, result in a construction contract, usually with the low and sharpest bidder in a highly competitive procedure. The contractor has developed his own understanding of the need, which must be regarded along with his own to make a profit. The building, when constructed, is transferred into the hands of building management with responsibility to operate, maintain, and modify, to fulfill not only the original objectives for the structure, but the new and changing goals of its tenants.

The baton has been passed three times. This is a well-established approach for creating the work and living environments for the occupants at the end of the delivery chain. The renovation process is often similar. The shifting of responsibilities from owner to designers to contractors to building management and weaknesses in link-to-link communication can make the process quite shaky.

While others in the link system are motivated to consider the occupants' well being, they are not represented in the chain. Moreover, entities such as the developer, architect, and HVAC and electrical engineers may be detached (or semi-detached) by intervening links from the end user.

Priorities of cost control (of fees as well as construction) and scheduling understandably push consideration of the comfort and health of the faceless occupants into the background. Building management itself seems at times divided into two camps—management and operation. Frequently, systems operation and building maintenance are left on their own by the building administrators, who, by virtue of their talents and interests, may have quite limited knowledge of the workings of the HVAC system and the skills, materials, and services vital to its successful performance.

Several compilations of "problem" buildings with sick building syndrome (SBS) reveal that building operation and maintenance is the leading underlying cause of environmental distress (Honeywell 1990). Design and construction practices are also contributors. In a real way, the failure of the building to provide a healthy and comfortable environment has an impact on us all. Should litigation result from such failure, who in the chain is immune from the suit?

DESIGN

Designers are becoming aware, although rather slowly, of the responsibility society is assigning them for the well being of building occupants. The enlightened are designing defensively and are actively seeking ways to improve indoor air quality through concept, equipment, and material selection. Let's touch on a few new ideas.

Work Stations

A common feature of office landscapes are the shoulder-high enclosures for work stations—sometimes known as "boxes without topses." Cubicle fever, spawned by poor ventilation effectiveness, temperature control, and visual strain from the reflected glare of undershelf lighting, assumes a place in the SBS lexicon. Several manufacturers have introduced products and concepts to avoid this condition. Ventilation integrated into the partitioning system (CC 1990) and displacement ventilation utilizing access flooring are two methods. Figure 1 illustrates how improved breathing zone air quality can be achieved (Mathisen 1990). This latter approach, more commonly applied in Europe and South Africa, offers individual volume and directional air control (Tate 1990). One U.S. survey reports a high degree of user satisfaction with this technique (Hedge et al. 1990).

New Control Strategies

Direct digital control promises greater reliability, flexibility, and improved strategies for enhanced HVAC performance. For variable-air-volume (VAV) systems, ASHRAE Standard 62-1989 (ASHRAE 1989) virtually mandates a constant outdoor ventilation rate in cfm (L/s) per person even as the total supply rate of airflow is changing in response to the demand of the space cooling load. Improved flow measurement techniques and transducer design are but two approaches to making this feasible. Direct closed-loop outdoor air ventilation control from commercial CO_2 sensors with reasonable recalibration requirements is now

Arthur E. Wheeler is president of Wheeler Engineering, Towson, MD.

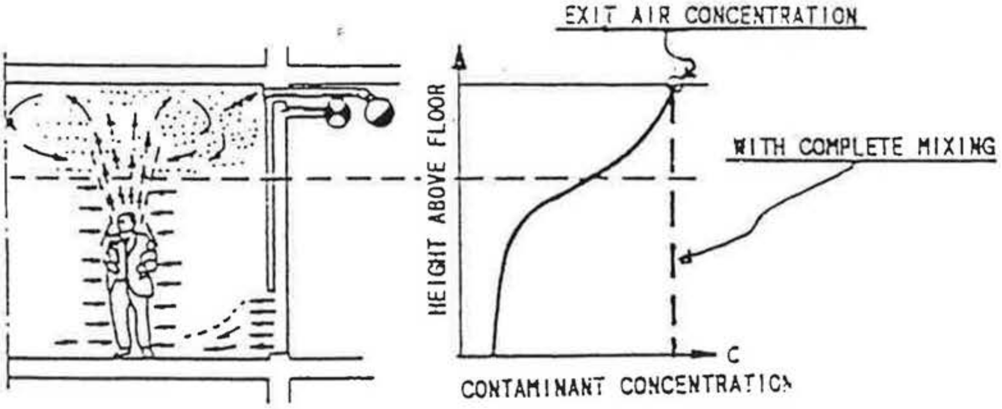


Figure 1 Stratification of contaminants from one person in a room with displacement ventilation

available. This development offers substantial energy cost benefits, especially in high-density, variable-occupancy applications.

DDC terminal control can be used to effectively isolate building areas under renovation to mitigate the spread of construction-generated contaminants into occupied space. Similarly, accidental (or deliberate) episodes of contaminant release can be contained through computer command.

Mineral Fiber Linings

Common in air-handling units, ductwork, and air terminal boxes, such linings have been impugned as harbors and amplifiers of microorganisms, especially in supply ducts that normally contain air with a relative humidity of more than 70% during the cooling season (Morey 1990). Linings are now being offered by several manufacturers with a nonflammable, nonpermeable surface without compromise of acoustical or insulating effectiveness.

Filtration and Air Filter Upgrades

In the past, air filters have frequently been selected for low cost chiefly to protect the heating and cooling components. Higher efficiency filters are necessary to clean up the outdoor air in many localities to meet the suitability requirements of ASHRAE Standard 62-1989 and prevailing codes. Designers have increasing knowledge of filter performance through the results of research such as the chart (Figure 2) presented at IAQ '88 (Ensor et al. 1988). Medium- and high-efficiency filtration of the recirculated air will reduce the particulates from environmental tobacco smoke, fungi spores, and bioaerosols (nucleated or on a host particle). This removal of particulates is not only dependent upon filter efficiency but on total air circulation (Wheeler 1990). A recent research report suggests a correlation between the airborne concentration of filterable endotoxins and the incidence of SBS (Rylander 1991). If confirmed, such a correlation would shift the emphasis from dilution by outdoor air to the importance of total air circulation and effective filtration. Total air circulation, while addressed in a limited way by ASHRAE Standard 62-1989, is given greater stress in the 1991 ASHRAE HVAC Application Handbook (ASHRAE 1991). A total supply rate at least five times the outdoor air rate prescribed by the standard is recommended by the handbook for office space. This importance can be demonstrated through the IAQ procedure of the standard.

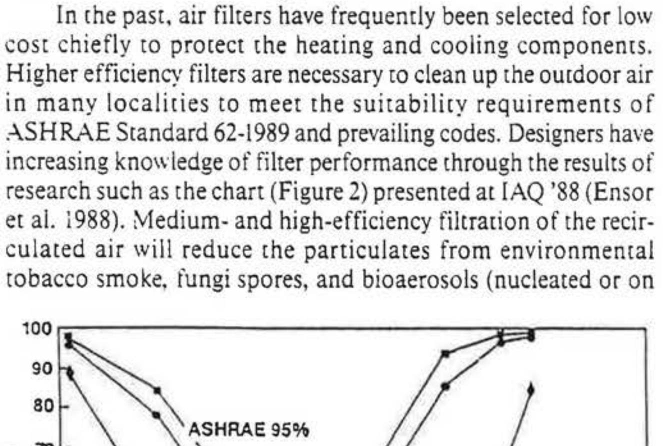


Figure 2 Particle-size-dependent dry media filter efficiencies

The concepts of substantial total air circulation and VAV can be integrated through application of fan-powered VAV air terminals or a twin duct system, as shown in Figure 3, in which centrally filtered recirculated air is supplied through dual-duct-type terminals.

An innovative concept of microorganism and VOC removal from the air supply through ozone oxidation is being introduced at this conference. Is this another promising resource with which to achieve healthy buildings?

Maintainability and Cleanability

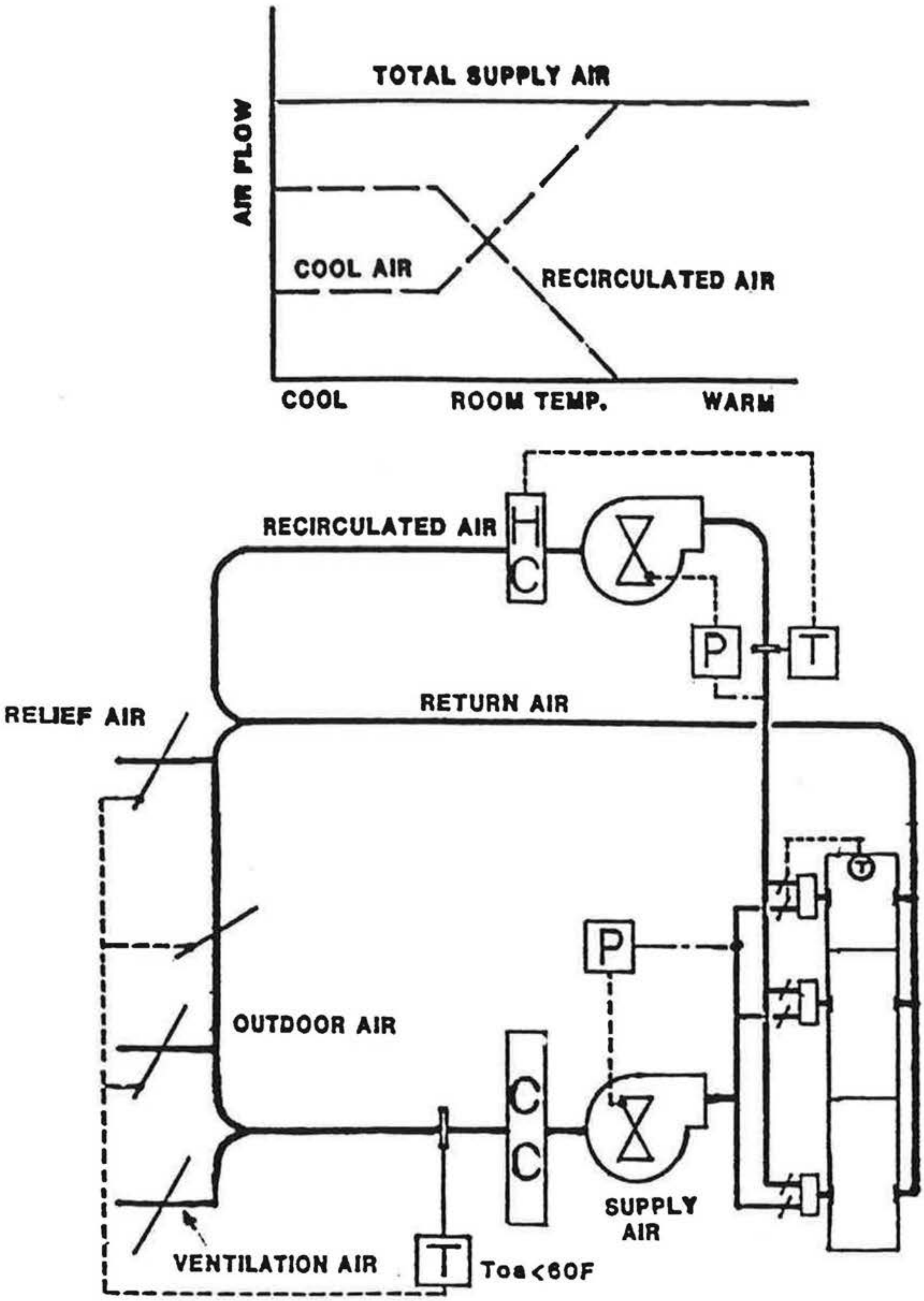
This provision must improve over common past design practice. All heat exchangers, fans, filters, control terminal boxes, and, to the degree practicable, ductwork must be accessible for maintenance and cleaning. The same must apply to unitary equipment. A new generation of unit ventilators to provide improved IAQ in classrooms and component-accessible central air-handling units has been developed with improved cleanability as well as more reliable control and balancing capability (Trane 1991). Locating air conditioners above the ceilings of occupied areas invites poor maintenance.

No doubt designers must always meet project economic constraints. However, the design goal to achieve healthy buildings not only serves the ultimate occupants, but affords legal protection for the designer as well.

CONSTRUCTION

Healthy building construction is best ensured by well-delineated design and thoughtfully controlled bidding procedures. Contractor and subcontractor prequalification and establishment of standards of quality for materials and equipment are more than designer responsibilities. It must be accepted by the owner as being in his own best interest. How much money is really saved in the

Figure 3 VAV twin-duct heating by VAV recirculated air



long run by cutting features intended to provide a healthy, comfortable environment?

Selection of materials used in mechanical construction, such as duct sealants, should consider their VOC emissive qualities—especially important in renovation work, where protection both to the construction workers and occupants must be considered.

Pre-occupancy ventilation of the completed construction to reduce VOC concentrations is imperative. Exhaust fans temporarily installed in windows can keep the construction area under negative pressure. Make-up air may be available from the building HVAC system or, if outdoor conditions are acceptable, through other open windows in the construction area. Some materials, such as carpet, may be effectively preventilated off premises.

Renovation work must be preceded by planning to protect people from toxic fumes. This may involve scheduling of the work, e.g., painting, construction equipment choice (electric or pneumatic motor vs. gasoline engine), and air barriers as well as ventilation strategies (Levin 1990).

A healthy building, a happy client, and a profitable project will usually be achieved only through solid supervision by the contractor and timely and systematic completion of all work. Occupancy of uncompleted building space is risky to all concerned—including the health and safety of the end user. Contractors and owners may be wise to avoid this as a condition of the construction contracts. Construction specifications should include, not subject to later compromise, balancing of air and water systems by an independent agency and commissioning following ASHRAE Guideline 1-1989. Although not foolproof, these post-construction efforts are a solid investment in obtaining the expected performance.

Some construction contracts call for training of the operating staff, supported by written operating instructions for the mechanical and electrical systems. This work may be better undertaken by the project design engineers, possibly in concert with the mechanical and electrical subcontractors. Certification that an operator is trained and duly qualified is another step toward building health.

Operator training should include formal followup by the designers and contractors after a reasonable period, a year perhaps, to resolve questions and to confirm proper operation. Strong operator training protects everyone involved with the project.

Post-design and post-construction designer services are essential to ensure that the design intent is carried out. Without their involvement during the entire building process, proper building system function is jeopardized.

BUILDING MANAGEMENT AND OPERATION

When one construction project is complete, another often is about to get under way.

A recent survey of facility managers indicates that office staff shifts between 40% and 70% annually (CC 1987). Work station layouts consequently are undergoing continuous change.

Alert management prepares for change in advance by maintaining a current building profile, including all pertinent information about the building and its systems, that will make the next project smoother. Documentation of design information concerning the ventilation of the building is required by ASHRAE Standard 62-1989. It is an essential part of the building profile.

No matter how smoothly the design and construction may have gone, management is going to receive complaints from occupants. The strategy for handling complaints should start before the first one arrives. Hallmarks of a good plan are prompt handling, intelligent consideration by a task force placed in responsible charge of all such issues, a documented plan of action, and written as well as verbal communication with the complainant. Problem prevention programs have been adopted by a number of major building management firms; these include periodic HVAC system inspections and measurement of contaminants or contaminant markers, such as CO_2 (White and Getman 1990).

Both lessee and lessor have IAQ interests, such as ventilation rates, number of occupants, space temperature, and hours of occupancy, that are best covered by lease provisions. Table 1 contains more specific guidelines pertaining to HVAC system management that will help ensure a satisfactory and healthy environment.

Healthy buildings do not just happen. They involve a combined effort of owners, designers, contractors, and building management. Complaints concerning air quality or any other aspect of the building environment are likely to rain on everyone. A solid building team provides solid support for a healthy building.

TABLE 1
Dos and Don'ts for HVAC Management

- Follow ASHRAE Standard 62-1989
- Keep It Clean
- Maintain Air Filters & Equipment
- Provide Thermal Comfort
- Ensure Proper Air Balance
- Ventilate Copier Areas
- Remodel HVAC to Suit Space Changes
- Don't Put People in Unventilated Boxes
- No Incentive Pay Keyed to Energy Cost Savings
- Select/Train Qualified Operators
- Contract Needed Services
- Practice Good Recordkeeping

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PROTECTING BUILDING OCCUPANTS DURING CONSTRUCTION AND RENOVATION

E. Light, CIH

J. Tiffany
Member ASHRAE

INTRODUCTION

In recent years, there has been increasing emphasis on upgrading existing space through major renovation. With regard to indoor air quality, renovation is the time when occupants are most vulnerable to major contaminant exposure. Despite this, IAQ professionals seldom become involved with non-asbestos aspects of renovation until after severe problems have occurred (Loftness and Hartkopf 1989).

For example, uncontrolled demolition activities caused the evacuation of a portion of a research and development center. Sources of exposure included exhaust from a gasoline-powered saw used to cut concrete and general dust and odor. Investigation showed that the work space was positively pressurized in occupied areas whenever the back exterior door was open and that attempts at protecting the HVAC system (which was left running) had been ineffective.

The purpose of this paper is to examine common IAQ issues that arise in the process of either conducting major renovation or completing construction in occupied buildings. It does not include post-occupancy concerns such as outgassing and ventilation adequacy, the health and safety of construction workers, or asbestos. Instead, the focus is on potential health and nuisance effects on occupants of demolition and construction activities. Approaches (both technical and administrative) to the control of these problems will also be explored.

CONTAMINANTS

Most contaminants generated during renovations are clearly assigned to either the vapor or particulate phase category and behave accordingly. Some, such as tar, overlap into both categories. The toxicology of renovation contaminants varies from low risk to extreme hazard. Representative categories include the following:

1. No known health effects at environmental levels in the general population. Could still be responsible for nuisance concerns and affect the extra-sensitive.
2. Could cause relatively minor, temporary effects at very high concentrations. No lasting effects are likely.
3. Chronic effects are considered likely.
4. Major acute effects are considered likely.

Considerable uncertainty and subjective judgment are involved in assigning potential contaminants to these categories.

PATHWAYS/VARIABILITY

Assuming that direct exposure of construction workers can be maintained within U.S. Occupational Safety and Health Administration (OSHA) standards, the potential effects of contaminants are of real concern only when they can move into occupied or public space. An understanding of such pathways is critical to controlling the IAQ impacts of renovation.

Direct movement of contaminants through the HVAC system can occur in at least three ways.

1. Contaminants enter through return grilles for recirculation into the rest of the air supply zone and any overlapping zones.
2. Contaminants enter the air-handling unit through leaks or openings in central HVAC equipment.
3. Exhausts or outside emissions are drawn into make-up air intakes.

The extent to which contaminants entering the HVAC system will become a problem is building specific. The dilution or filtration of recirculated air may be so great that the contaminants are not detectable.

Contaminants may be more noticeable when they move directly through the building from the renovation site driven by pressure differentials. Affected locations are generally close by and on the same floor, but this can also include movement to adjacent floors and (via stack effect) to remote locations on upper floors.

Direct tracking of dusts, solvents, and fibers from the worksite is another potential pathway. Workers and equipment "shed" contaminants, which can then be tracked into and around occupied space.

Levels of airborne exposure during renovation are typically episodic and can vary by orders of magnitude within short periods of time. Factors affecting such concentrations include

- the scheduling of specific operations,
- the work practices and materials employed,
- other determinants of pressure differentials (wind, etc.),
- temperature and relative humidity, and
- the effectiveness of control measures.

Ed Light is with Pathways Diagnostics and **John Tiffany** is at the University of Medicine & Dentistry of New Jersey-Robert Wood Johnson Medical School, EOHSI Centers for Education & Training. Mr. Light is chair and Mr. Tiffany is vice-chair and secretary of the Indoor Environmental Quality Committee, American Industrial Hygiene Association.

With the timing and location of peak IAQ exposures changing drastically, measurement of these impacts is often misleading, if not impossible.

TYPICAL PROBLEMS

Roofing

Periodic roof replacement is essential to maintaining the structural and sanitary integrity of buildings. A variety of roofing systems is now available, all of which can present significant IAQ problems during installation.

Fumes generated from holding kettles and freshly treated surfaces during the application of traditional built-up roofs can be a major source of irritation (potential carcinogens are also present). Coal tar pitch fumes heated onsite may be of greatest concern regarding exposure, but asphalt can also generate occupant complaints.

Newer rubber and plastic roofing systems release VOCs during installation, especially during the application of adhesives. Pathways of concern during all types of roof replacement are direct entry into HVAC intakes and the drawing of nearby emissions into negatively pressurized building areas through cracks or openings.

Combustion Products

Operations involving combustion can generate a variety of contaminants, such as carbon monoxide, oxides of nitrogen and sulfur, polynuclear aromatic hydrocarbons, and a range of VOCs. These same operations also produce other pollutants, such as nuisance dusts (during demolition) and ozone or metal fumes (during welding).

Emissions from power equipment depend on the type of fuel (gasoline, diesel, propane, etc.). Equipment of potential concern includes generators and gas-powered saws (e.g., for cutting concrete). The location and timing of equipment use and precautions taken for handling their exhaust will determine if these emissions become an IAQ problem.

Renovation commonly includes various forms of welding, along with brazing, soldering, and cutting with a torch.

Vehicles are sometimes in or under the building during renovation. These can include dump trucks, delivery trucks, passenger vehicles, excavators, and powered wheelbarrows.

For example, employees near the construction of a major addition complained of a variety of nonspecific symptoms. Propane- and diesel-powered equipment was operating within the building with no special provision for exhaust or containment. The work area varied from positive to negative pressure versus the occupied area, depending on the wind direction. Limited monitoring showed CO levels up to 9 ppm and RSP levels up to 150 μ/m^3 in a public corridor. A relationship between the complaints and exposure appeared likely, since they consistently correlated with construction activity and peak levels had not been measured.

Volatile Organic Compounds (VOCs)

Major sources of VOC emissions during renovation include paints, sealants, adhesives, caulks, and furnishings. Peak releases generally occur during application or installation. Other emissions take place from materials that are drying and from leaking products in storage. Products that can have significant short-term effects include lacquers, epoxy paints, adhesives, and curing concrete. Water-based substitutes reduce, but do not eliminate, exposures (Levin 1989).

General Construction and Demolition

While the demolition of building materials generally just creates a nuisance dust, there are at least two major exceptions (in addition to asbestos). Lead-based paint is common in many older buildings. Removal during renovation is the time when significant exposure can occur. Precautions similar to asbestos abatement procedures are needed during removal to minimize rising lead dust levels. Where unsanitary conditions have led to excessive growth of fungi and bacteria, demolition can also create a potential exposure hazard.

The potential hazards when tearing out moldy materials are illustrated by a project at a Maryland elementary school. When the source of allergy problems was traced to mold growth inside the wall cavities of one wing of the school, gypsum board and insulation were scheduled for removal. Because the school was to remain occupied, the following precautions were taken:

- Each work area was sealed in plastic and exhausted to the outside by a nonfiltered window fan.
- A buffer zone was maintained between work areas and school occupants.

During demolition work in each containment, bioaerosol concentrations rose 10 to 100 times over background. A similar increase was measured in the buffer zone when the fan was installed improperly or was shut off prematurely. Any contamination problems were resolved before areas were reoccupied (Light et al. 1989).

Minor Disassembly/Installation While the focus of this paper has been on the potential hazards of renovation, it should be noted that the majority of activities have very little environmental impact. For example, the installation of sheetrock or the disassembly of a suspended ceiling may not release any contaminants into occupied space.

Cleanup At some renovation sites, the greatest amount of airborne dust may be generated during sweeping. Failure to enforce good housekeeping in and around the work area can lead to excessive airborne dust. Cleaning agents are more likely to generate objectionable VOCs during renovations due to the more difficult cleaning problems encountered.

HVAC Disruption of the HVAC systems can impact the comfort and ventilation of building occupants. This might be the result of HVAC changes to accommodate renovation, contamination of the system (e.g., dust that clogs the heating/cooling coils), or accidental malfunctions.

Relocation Moving occupants to temporary quarters during renovation can lead to other environmental concerns. For example, occupants might move to modular units with possible formaldehyde outgassing and inadequate ventilation.

The bottom floor of a building was to be gutted for major rehabilitation while the upper floor, housing a television station, remained occupied. The building owner's concerns were (not necessarily in this order) the health of tenants, protection of the electronic equipment, and bad publicity on the nightly news. An industrial hygiene firm was retained to monitor nuisance dusts on a daily basis. Window exhaust fans were adjusted to maintain acceptable levels.

TECHNICAL CONTROLS

General Goals

1. Contain the work area and/or restrict critical emissions to off hours.
2. Protect the HVAC system from contamination (the return side is most critical).

3. Reduce emissions where needed to prevent contamination of occupied space.

Pathway Elimination

1. Contain and depressurize the work area.
2. Provide a buffer zone around the work area.
3. Attach flex ducts from point sources to the outside (filter as needed).
4. Shut down the HVAC in the work area (construction worker comfort is secondary to IAQ).
5. Protect the return air system.
6. Pressurize the occupied space and extend fan schedule.
7. Relocate emissions (e.g., move tar kettle away from intake).
8. Temporarily seal the outside air intake and/or the roof elevator shaft and roof access door.

Scheduling

1. Change the most offensive activities to evenings and weekends.
2. Delay occupancy until late morning to allow for completion of offensive activities.

Substitution, Reducing Emissions.

1. Reduce solvent content in products.
2. Add a direct capture/filtration system to processes that cannot be exhausted (e.g., HEPA/carbon filter).
3. Use an enclosed tanker versus open kettle for roofing.

Housekeeping

1. Upgrade the efficiency of HVAC filters and change them more often.
2. Suppress dust (wetting, etc.)
3. Change to a more efficient cleaning method (e.g., use HEPA vacuum rather than dry sweeping if microbial or chemical contaminants are present).

MANAGING RENOVATION

Air Quality Criteria

There are no standards applicable to IAQ aspects of renovation projects. When site-specific concerns arise, various guidelines have been used to evaluate measured contaminant levels. Such numerical guidelines have many shortcomings when assessing air quality during renovation. For example, worker protection standards (e.g., OSHA PELs, ACGIH TLVs) do not address nuisance concerns and extra-sensitivity. IAQ guidelines (e.g., 1/10 TLV, WHO) may be more applicable to occupants in general. However, measurement strategies often do not reflect the episodic peaks that characterize the release of contaminants from areas undergoing renovation.

Qualitative performance goals may be a more realistic way to regulate many renovation projects. First, work practices and conditions to control emissions can be specified. These can run the gamut from HVAC modifications to housekeeping. Second, gross indicators of contamination can be used to limit the movements of dusts and vapors. For example, renovation work shall not contribute visible haze, settled dust, or detectable odors to occupied building areas.

Planning

A pro-active renovation program should incorporate an early review of potential emissions from each phase of the project. Each operation should be categorized as to the potential severity of emission and the availability of controls. Where major problems are likely and controls may not be adequate, operations might be scheduled after normal business hours.

Where asbestos or lead-based paint removal is being planned as a first step, the sequence and scope of non-ACM demolition should be carefully considered. When heavy demolition can be accomplished inside a full containment work site, nuisance dusts and emissions from cutting equipment will be controlled better.

A typical team preparing specifications for a major renovation includes individuals with expertise in architecture, engineering, and construction. Air quality aspects may not be adequately considered unless an additional person, trained in the recognition and control of indoor air contaminants, is added to the team. Once the initial project requirements have been proposed, input from an environmental/occupational health scientist, such as an industrial hygienist, might involve

1. identification of hazardous materials such as lead-based paint or pathogenic bioaerosols;
2. identification of critical pathways for contaminant movement into occupied space;
3. control recommendations (ranging from HVAC changes and emission modifications to buffer zones, rescheduling, and housekeeping).

The planning team as a whole should then integrate these concerns into the project, taking into account logistical considerations.

Construction Management

Day-to-day oversight of most renovation is often done by a generalist (construction inspector) or an engineer. Where asbestos is involved, this function may be completely taken over by an industrial hygienist. Other IAQ concerns may also require the involvement of an industrial hygienist but to a lesser extent. Inspection of the air quality aspects of a renovation project might include

1. verification that work practices are being followed,
2. confirmation of pressure differentials,
3. observation of indicators such as dust and odors,
4. response to occupant complaints.

Air quality monitoring may play a role in larger or more sensitive projects. Although routine contaminant measurements may provide documentation and a baseline for the project, they are unlikely to identify or diagnose specific air quality problems. Regular oversight of work practices and inspection for air quality indicators may be more important in this regard.

Enforcement of work practices and air quality criteria should begin with education of contractors or in-house construction crews. Supervisors must be presented up front with a clean, practical, and concise view of the project's IAQ goals and the means for achieving them. On-site inspection, whether by a generalist or an industrial hygienist, must stress consistency and fairness in enforcing work practices. Criteria for warnings and job shutdown should be understood ahead of time. Since many contractors or construction crews may not be familiar with IAQ concerns, field inspectors should take a non-confrontational, cooperative approach when possible.

Communicating with Occupants

Building renovation is a disruptive and often traumatic period for occupants. Fear of environmental exposures may become a major factor, especially when episodic emissions of odor or dust occur in occupied spaces. This can lead to rumors and the spread of hysteria.

Preceding any major renovation project, potentially impacted occupants should be presented with a brief description of the work planned and precautions being taken for air quality protection. Any occupant concern should be discussed at this point and resolved, whenever possible. As demolition and construction progress, periodic updates, including summaries of environmental monitoring, should be presented to occupants.

Despite careful planning and oversight, environmental incidents are sometimes unavoidable. A contingency program, prompt response, and clear communication with occupants are essential at such times. Where exposures have only been in the nuisance category, this should be stated. Any health risks should be presented in perspective. Renovation work should be stopped until potentially significant health issues are resolved.

Case Study The basement of a large shopping mall was being converted to retail stores. Adjacent space remained occupied by a 300-person office. Operations in the work area included large trucks, excavation, demolition, and construction. Air quality considerations were limited to a few small exhaust fans. Soon after work was initiated, many of the office occupants began to complain of headaches, dizziness, irritation, and nausea. Mall management was not responsive until an investigation by the county health department found carbon monoxide levels up to 28 ppm and recommended major modifications to improve air quality. Subsequent improvements included the following:

1. Sealing of mechanical rooms that served as a return plenum and were now drawing in exhausts from several work sites.
2. Substitution of electrical for gas-fired generators and restriction of vehicular traffic in the building.
3. Suppression of dust on roadways and demolition areas.
4. Pressurization of the office with 100% outside air and depressurization of work sites by adding large exhaust fans.

Following these changes, complaints diminished and air quality measurements approached background levels.

IN-HOUSE ADMINISTRATION OF RENOVATION PROGRAM

The Fairfax County Public School (FCPS) System currently is in the middle of a major effort to modernize and expand a number of schools. Air quality has become an important part of this process as much of this work must be done while the buildings are occupied. The program considers IAQ early in the planning process and regularly during on-site inspections. Major goals include keeping dust and odor out of occupied space. Specifications for contractors include:

- use of low-solvent products,
- barriers for dust and fumes,
- dust suppression during demolition,
- daily cleaning of all areas.

Activities producing high levels of emissions are scheduled for after hours or summer. School custodians perform extra cleaning throughout the renovation period. In addition to regular inspections, personnel from the FCPS Risk Management (environmental) office conduct a weekly environmental inspection that includes measurement of dust (with a scattered light detector) and VOCs (with a photoionization detector). Compliance has generally been very good and incidents kept to a minimum.

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The Importance of HVAC System Commissioning in Achieving Satisfactory Air Quality

T. Cohen, P.E.

INTRODUCTION

The purpose of this presentation is to discuss how commissioning HVAC systems can help ensure satisfactory indoor air quality.

In the traditional commissioning process, the object is to perform all necessary inspections and performance tests during construction to verify that the design intent will be met. Adding IAQ procedures to this process is straightforward, requiring only that verified indoor air quality be added to the criteria for successful commissioning.

It is important, at the outset, to note that everything discussed here about IAQ procedures and commissioning applies equally well to renovations as it does to new construction—the format and procedures do not change.

ASHRAE makes this point explicitly in its *Guideline for Commissioning of HVAC Systems*, describing the need for a continuing commissioning process throughout the life of a facility:

> 9. POST-ACCEPTANCE PHASE
>
> 9.1 Introduction Post-acceptance commissioning is a critical step in ensuring the effective, ongoing functioning of a facility's HVAC system. As use and function of facilities change, HVAC systems need to be adapted to the changing requirements of occupancy and utilization. It is appropriate to maintain a history of the facility, recording changes and verifying the effect on the previously commissioned system.

If we were to add the phrase "and the IAQ procedures" after "HVAC system" each time it appears in this paragraph, we would establish the criteria for maintaining satisfactory IAQ performance throughout the life of the building.

There are four aspects of commissioning and indoor air quality to be considered.

1. Team leadership: Who should lead the team of IAQ investigators?
2. Indoor air quality procedures: Which IAQ testing and mitigation procedures should be performed?
3. The process of commissioning an HVAC system: How does one define a "comprehensive commissioning process"?
4. Testing responsibilities: What role can testing and balancing HVAC systems play in commissioning for acceptable IAQ?

Who Should Lead the IAQ Team?

Air-quality procedures often require the efforts of a knowledgeable, multi-disciplinary team. At a minimum, this team will include industrial hygienists, microbiologists, and test-and-balance (TAB) contractors.

With these divergent professions represented, it is essential to have a team leader who can apportion the work to best take advantage of the strengths of each discipline.

I believe that the individual best equipped to bring these groups together is the consulting engineer. The engineer has the best knowledge of how the HVAC system must perform to provide the required environment. The engineer also is the one who provides the design documents that guide the construction and commissioning of the HVAC system and the establishment of satisfactory air quality. This is true of both new construction and renovations.

Indoor Air Quality Procedures

The participants and leadership of the IAQ team greatly affect the type of procedures performed. For example, investigations led by an industrial hygienist can be expected to emphasize air sampling and source control. Likewise, a balancing agency might concentrate on ventilation analysis and testing and balancing the HVAC system.

This observation is not to find fault but to reaffirm the importance of having a capable team leader who, regardless of personal background, can ensure that all necessary procedures are performed and that all disciplines are properly represented.

Commissioning an HVAC System

Let us proceed now to see how the commissioning process can incorporate IAQ procedures.

I would begin with a definition of commissioning as I view it. I emphasize that this is my view (as well as the ASHRAE guideline committee's) because others may have different definitions.

Definition: Commissioning is a comprehensive process for bringing an HVAC system on line in a more effective manner in accordance with the design intent.

It will involve greater participation by the design engineer, the owner, and the operating and maintenance personnel. It will introduce a commissioning authority who will prepare, administer, and supervise the commissioning plan.

Let's go through the process and see how it could work with regard to the HVAC system and IAQ procedures.

1. The design consultant will have an increased role to play in the commissioning process. In addition to the normal plans and

specifications that have always been prepared, the consultant will prepare these additional contract documents:

A) A format for the commissioning plan.

B) The type and extent of the functional performance tests to be made.

C) The documentation requirements that will certify the as-built performance of the HVAC system.

D) A system operations manual.

The engineer must design into the system all of the provisions necessary to achieve the required air quality in accordance with the codes and the specific requirements of the facility being designed.

Code requirements for air quality are being developed. In New York City, an ASHRAE committee is being formed to work with the building department in an advisory capacity to include the recommendations of ASHRAE's Standard 62-1989 into the air-quality requirements of the building code. In general, we can expect increasing initiatives to regulate ventilation rates and effectiveness through code requirements.

The mechanical design will have to make provisions for the verification procedures to be implemented. For example, if the verification tests or the code require a direct measurement of the rate of fresh-air intake, the HVAC equipment will have to be arranged so that this measurement is possible.

The design documents will have to be clear on all of the air-quality requirements and the verification procedures so that the commissioning authority can prepare and implement the commissioning plan for the HVAC system to the full extent of the design documents.

The specifications will also have to be clear about the various contractors' participation in the verification (functional performance tests). The contractors so involved will have to include an allowance in their bids to cover the costs of these tests.

As far as air-quality procedures are concerned, there may be additional tests to be made beyond ventilation rates. It may also be necessary to determine the efficiency or effectiveness of the ventilation within certain spaces.

There is sophisticated test equipment available that uses tracer gases to evaluate the efficiency of the ventilation within a space. I expect that as the need to do these tests develops, new procedures will also develop. Let me give you an example of such a condition.

A room with a high ceiling has ceiling diffusers that distribute conditioned air in a nice horizontal pattern so that no drafty conditions develop. If the return-air inlets are also at the ceiling level, the ventilation in the upper portion of the room could be excellent, while in the lower part of the room, where occupants are breathing, ventilation could be poor. It is possible to maintain the required temperature conditions in a room like this and have inefficient ventilation at the breathing level.

All of the verification procedures will be included in the documentation of the commissioning process and become a part of the "as built" record of the commissioning of the HVAC system. It will also be necessary for the IAQ procedures to be certified by the agency responsible for implementing them and by the authority who witnessed and accepted the verification tests.

The completed documentation of the commissioning process will be submitted to the design engineer for review and acceptance. If the engineer is satisfied that the HVAC system and the air quality conform with design intent, he or she will recommend to the owner that the HVAC system be accepted.

After the HVAC system is accepted, any modifications that have to be made will use the commissioning documentation as a reference for the design engineer to determine whether the existing services are adequate for occupancy.

When the renovations are completed, the HVAC system will be recommissioned and the documentation brought up to date. This ongoing commissioning process should continue throughout the life of the facility.

The Role of Testing and Balancing in Commissioning

Why am I, a TAB engineer, so interested in the commissioning process and IAQ procedures?

There are two reasons. One is that the implementation of the commissioning process can increase the scope of work that we can do on a project. The services that we can provide have a direct effect on the commissioning of an HVAC system and in establishing the required air quality. I will mention these services in a moment, but let me introduce the second reason for my interest in these developments.

I have become convinced that a new approach to bringing HVAC systems on line is necessary. As the design of HVAC systems has become more complex, it is clear that the older methods do not provide the required results in a consistent, dependable manner.

Now let us look at the services beyond TAB that people like me can provide to the commissioning process:

1. Insight: Our normal TAB work has always been considered as part of the commissioning process, even before the word "commissioning" came into use. We have a built-in acquaintance with the process.

2. Experience: Many TAB firms are capable of and willing to carry out complete verification tests; we have been doing some of these tests for many years, including

a) Verification of the performance of the temperature control system;

b) Verification of the installed capacity of the major heat exchange components—chillers, pumps, and boilers.

3. Certification: TAB agencies that are members of the AABC certify their TAB reports and offer a warranty on each project.

It is certain that all air quality procedures will have to be certified. We are prepared to offer that service now.

CONCLUSION

In conclusion, I want to apologize for my continuous use of the word "verification." To a hands-on engineer like me, you cannot imagine the importance of this concept.

I will close with one more example. Imagine what would happen if a TAB contractor knew he would have to go back to the job after submitting his final report and remeasure air and water flow rates at random locations selected by the commissioning authority. Two things would happen. First, the TAB contractor would do a better job and, second, the TAB report as submitted would be an accurate record of the air and water flow rates. The TAB contractor would not want to be forced to repeat the balancing because the report was found to be in error.

The same analysis applies to air-quality procedures and to any other systems that are to be verified after installation is complete.

Commissioning can lead to improved indoor air quality and more effective operation of the HVAC system.

COMPREHENSIVE EVALUATION OF MATERIALS

W.G. Tucker, Ph.D.

This paper discusses the evaluation of indoor air quality impacts on materials used in buildings. The types of evaluations discussed will be of use to specifiers, such as architects, builders, or building owners; manufacturers; and standards organizations in both the private and government sectors. Most of what is said about evaluation of new or prospective materials also applies to the evaluation of materials from buildings with indoor air quality problems.

The paper has three parts. In the first part, I briefly discuss some of the causes of indoor air quality (IAQ) problems. The second part deals with evaluation of indoor materials in a conceptual way, then discusses the state of the technology for evaluating potential IAQ problems. The last part presents my view of how materials can be comprehensively evaluated for IAQ concerns. The key to this comprehensive evaluation will be the determination of probable health and comfort effects of the emissions from those materials.

Causes of IAQ Problems

IAQ problems occur in buildings either because the ventilation is inadequate or because there are unusually strong sources of indoor air contaminants. Ventilation can be inadequate because of design or operation; insufficient quantity or quality of outdoor air; ineffective distribution of ventilation air inside the building; or ineffective exhausting of air from the building. Unusually strong sources of air contaminants can either be building materials or material contents of the building; activities of people or machines in the building; operation of combustion devices; or contaminated outdoor air that is introduced into the building.

Material sources, the source type of particular interest in this presentation, comprise the following:

- Building materials
    - floor, wall, and ceiling materials
    - adhesives, sealants, coatings
- Furnishings
    - furniture, fabrics
- Consumable products
    - cleaners, solvents, treated paper products
- Office machines
- Ventilation system components

Comprehensive Evaluation of Materials

A truly comprehensive evaluation of materials used in buildings would, of course, go beyond indoor air quality concerns. The properties that influence selection of appropriate materials for buildings include those listed in Table 1. To be completely desirable, materials have to satisfy a wide range of requirements. Desirable aspects of the properties listed in Table 1, with particular emphasis on IAQ concerns, are listed in Table 2. From this point, I will discuss evaluation in a less comprehensive manner and will emphasize the evaluation of emissions properties of materials, since these are the properties that have the greatest impact on IAQ.

Comprehensive IAQ Evaluation of Materials

Today's state of technology for IAQ evaluation of materials has three basic steps:

- *Chamber studies of emissions.* These laboratory studies can evaluate emissions of chemical compounds, physical aspects of aerosols or fibrous particles, or microbials such as fungi and bacteria. Microbial emissions evaluations are seldom conducted, but more will be made in the future.
- *Mathematical modeling of the dispersion of the emitted substances.* This is done to estimate the indoor air concentrations of contaminants that result from the sources. Some of the existing mathematical models allow estimation of inhalation exposures by building occupants, given various time-activity patterns.
- *Comparison of estimated indoor concentrations and inhalation exposures to available toxicological data.* Available data are genrally limited to standards that have been developed for out-door air and to occupational health and safety standards that have been developed for industrial workplaces. In both cases, these data have been developed for single compounds.

TABLE 1
Properties Influencing Selection

Physical	Strength Durability Heat transmission Light transmission Maintainability Effectiveness (e.g., as a cleaning agent)
Aesthetic	Color Texture Odor Noise
Economic	Initial cost Maintenance cost Operating cost (e.g., energy)
Environmental	Emissions to air Other releases Support of microbial growths Life-cycle impacts

W. Gene Tucker is a visiting fellow and research scientist at the John B. Pierce Laboratory and Yale University, New Haven, CT, and chief of the Indoor Air Branch, U.S. Environmental Protection Agency, Research Triangle Park, NC.

TABLE 2 Desirable Properties	
Emission properties	Low emission rate Low toxicity of emissions
"Sink" properties	Non-sorbent If sorbent, not re-emitting If no re-emitting, non-nutrient
Microbial properties	Hydrophobic Non-nutrient Cleanable
Physical properties	As needed for the application
Aesthetic properties	As needed for the application
Cost	Reasonable

TABLE 3 Health and Comfort Effects/Symptoms	
Irritation	of eyes, nose, upper airways, throat, skin
Odors	
Decreases in respiratory function	wheezing, cough, chest tightness, shortness of breath
Neurological symptoms	nausea, dizziness, headache, loss of coordination, tiredness, loss of concentration
Immunological reactions	inflammatory reactions (delayed and immediate/allergic)
Asthma	(aggravation of)
Cancer	
Respiratory infections	
Increased susceptibility	to infections or to chemical substances

Figure 1 shows this testing procedure diagrammatically. Decisions on selection of materials using this procedure are based on exposures to emissions. Basically, the lower the exposure the better, but especially noxious compounds need to be considered regardless of their concentrations. This procedure represents the current state of technology and if conducted properly is a good one, but the question remains as to whether there could be something better.

The current technology for emissions testing is inadequate for a number of reasons. First of all, the emissions are almost always complex mixtures of contaminants, and very little is known about the toxicity of mixtures. Furthermore, not all emissions mixtures are equal, toxicologically. Therefore, low exposures do not necessarily lead to low health effects. So the question is: How do we do better?

In my opinion, the answer lies in some approach that makes combined use of the knowledge of engineers, chemists, and biological and medical scientists. Development of biologically based methods is needed to improve methods of material evaluation. Table 3 is a general look at the type of effects that will need to be addressed. It is a tabulation of effects or symptoms that have been reported in the IAQ literature. Materials-testing schemes that attempt to get a more direct measure of health and comfort effects will need to address the kinds of effects and symptoms listed in that table.

The basic approach to evaluating materials for the effects can be much the same as the chemically and physically based approach illustrated in Figure 1. Figure 2 shows an approach where evaluations, in addition to having chemical and physical analysis, involve exposure chambers where bioresponse testing using humans or animals or *in vitro* assays are done. These have the potential of giving a more direct measure or prediction of human response. Although Figure 2 shows parallel testing by chemical analysis and bioresponse testing, the parallel testing would not always be necessary. In some instances, one or the other would be appropriate by itself.

Relatively few bioresponse methods are in a sufficient stage of development that they have very much prospect of being used for material evaluations in the near term. Five possibilities of such methods are listed in Table 4. The odor test panels would be relatively simple "sniff" tests where one or two sniffs of emissions from a material would be made by human panels. These would give an indication not only of odor but in some cases immediate irritation to the mucous membranes.

Longer-term irritation of airways might be measured by a test that is based on respiratory frequency change in mice. This is a test that is an ASTM standard. Another type of test for airway irritation would be to look at the inflammation of mucous membranes in the upper airways. This can be done by washing fluids from the nasal cavities of either people or animals and analyzing for polymorphonuclear neutrophils (PMNs).

PMNs, which are cells that indicate an inflammation response, can also be examined in the tear fluid of the eyes to get a measure of eye irritation. Since PMNs are relatively time-consuming and expensive to analyze, other markers of inflammation that are easier and less expensive to measure might someday be found for tests of mucous membrane and eye irritation. The final type of method listed in Table 4 deals with electrical potentials that are evoked in either the central nervous system or peripheral nervous system when a person or animal is exposed to a stimulus such as breathing air contaminants.

The types of methods listed above are certainly not inclusive; they are simply potential methods for evaluating materials.

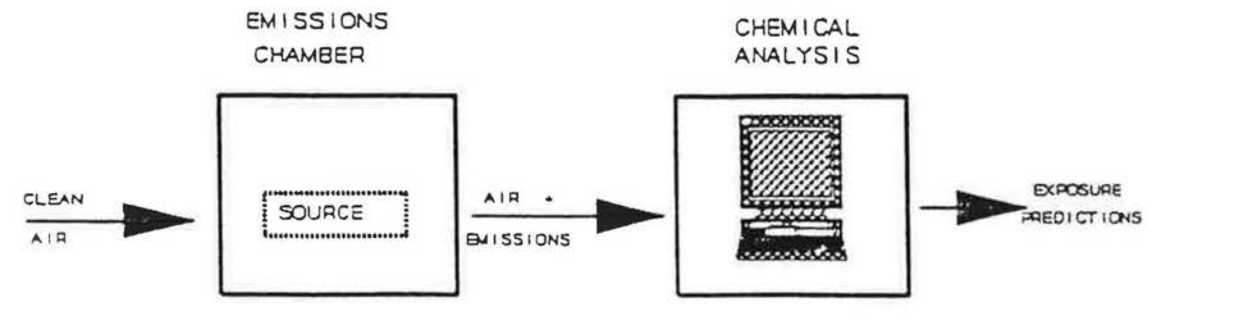

Figure 1 Evaluation of Emissions

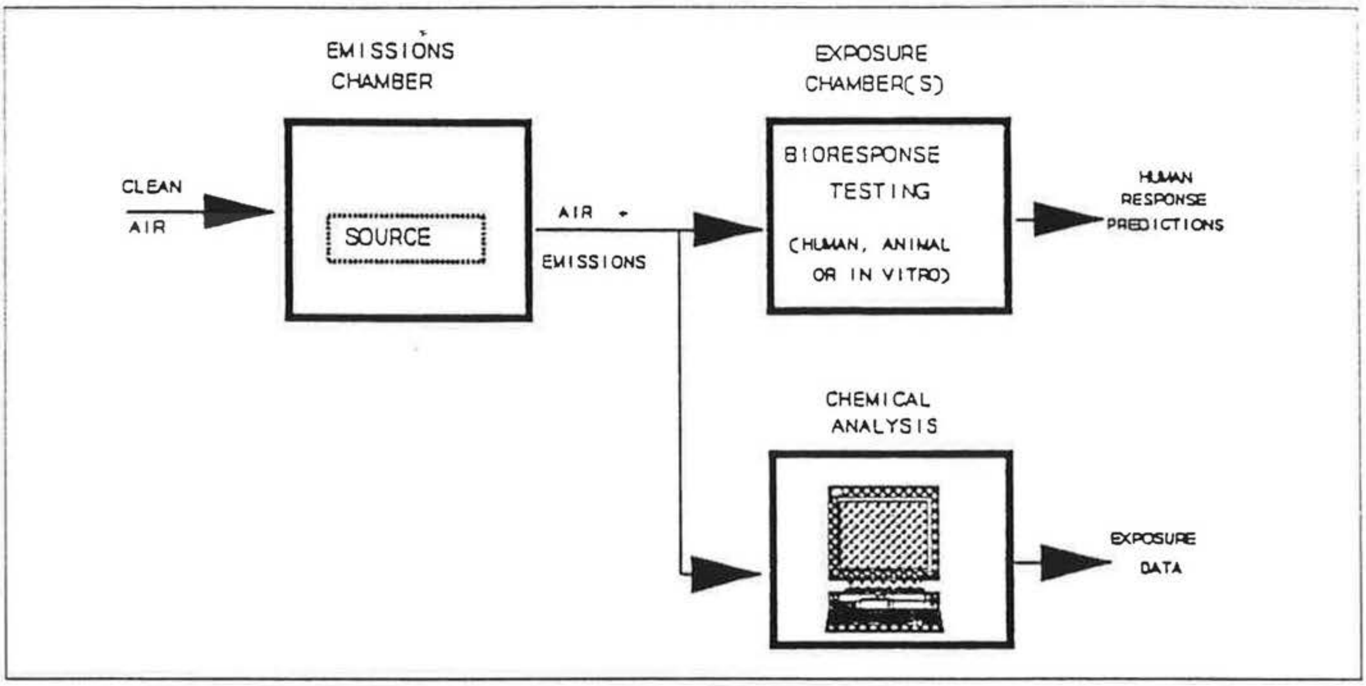

Figure 2 Evaluation of Effects

TABLE 4
Examples of Bioresponse Methods

Method	Effect/Symptom	Responder
Test panels	Odor/immediate irritation	Humans
Respiratory frequency change	Airway irritation	Mice
Mucous membrane inflammation	Airway irritation	Humans, animals
PMNs (e.g.) in tear fluid	Eye irritation	Humans, animals
Evoked potentials	Nervous system effects	Animals, humans

There is no doubt that some of them will not be feasible, and there are undoubtedly other methods that will be identified and developed in the years to come.

In summary, I would like to make the following points:

- Many IAQ problems are caused by unnecessarily strong sources of emissions of chemical, physical, and microbial contaminants.
- Methods for evaluating emissions rates and the compositions of those emissions are reasonably well developed.
- Methods for predicting emission dispersion and inhalation exposures are reasonably well advanced but further development is needed.
- Methods for directly evaluating the health effects of emissions are needed. We need to get closer to the bottom line (i.e., health effects) with our material testing methods.
- Bioresponse methods have potential for improving our prediction of health effects.

Measuring Respiratory Irritancy of Emissions

R.C. Anderson, Ph.D.

INTRODUCTION

The test method developed for evaluation of the potency of airborne irritant chemicals, ASTM E 981, is being used to evaluate the potency of outgassing from commercial products. The key to the test is in the observation that the fifth cranial nerve of most animals has specialized nerve endings that are activated by irritant chemicals.

The precise details of the reflex response to this activation are species dependent: in humans there is the well-known series of symptoms of eye, nose, and throat irritation, headache and fatigue, and the less well publicized changes of heart rate, blood pressure, and kidney function. The parallel response in mice is a change in respiratory rate and pattern. The mouse response is reproducible, stable, and proportional to the potency of the irritant.

The method being used is an established toxicological procedure that has been used for three decades to make predictions about the effects of these chemicals on humans. The validity of the test data for prediction of human responses has been thoroughly established and repeatedly published. The test animals (Swiss Webster mice) are somewhat less sensitive than humans, so an extrapolation from the animal data allows us to predict the response of the much more sensitive human. As a result, the amounts of material and concentrations used may be higher than immediately seems "realistic."

TESTS

The method is being used as published. The generation system for the test atmosphere, not specified by the ASTM procedure, is a closed glass chamber in which a test sample is equilibrated for 30 minutes before the collected atmosphere is delivered to the test animals by means of a peristaltic pump. The sample is typically heated to a temperature of 30°C by an external heat source.

To study any atmosphere, the baseline respiratory rate of the animals is first determined and set equal to 100% (Figure 1). The rate during a 60-minute exposure is described as a percentage of the baseline rate. To obtain a concentration response curve, a series of tests is conducted in which the sample size is varied (Figures 2 through 5). In order to summarize data, the point of maximum response is determined for each experiment and that percent change is plotted against the concentration on a log scale (Figures 6 through 9).

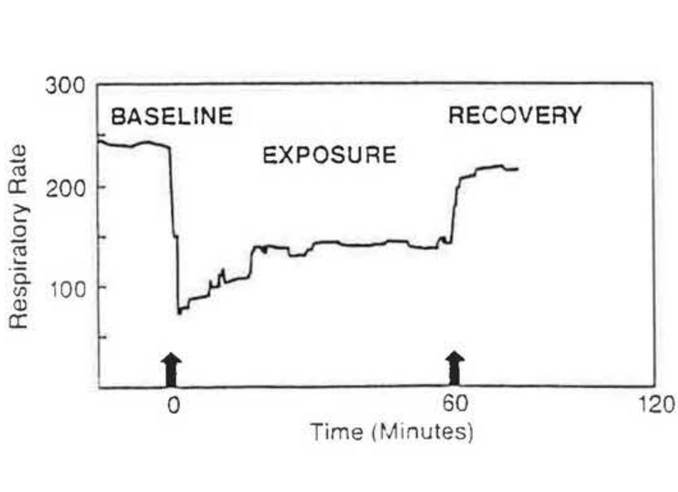

Figure 1 Respiratory response to irritant (mean of 4 mice)

Rosalind C. Anderson is president of Anderson Laboratories, Inc., Dedham, MA.

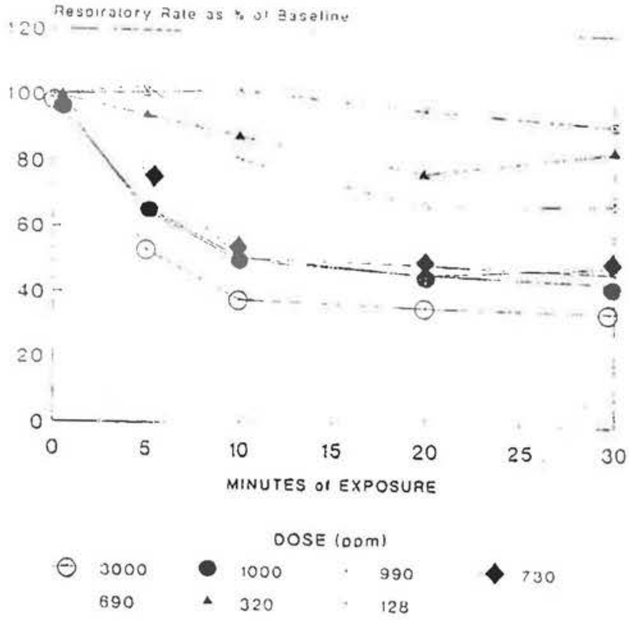

Figure 2 Sensory irritation from floor adhesive

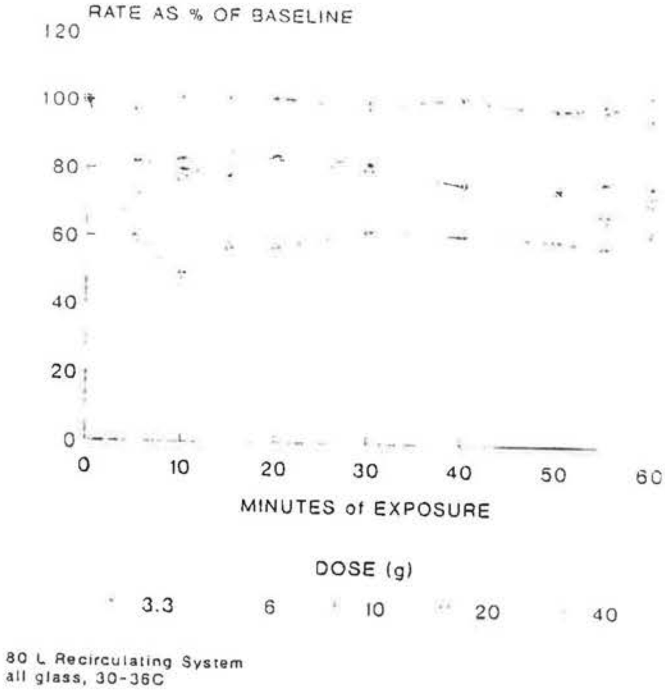

Figure 3 Sensory irritation from floor wax

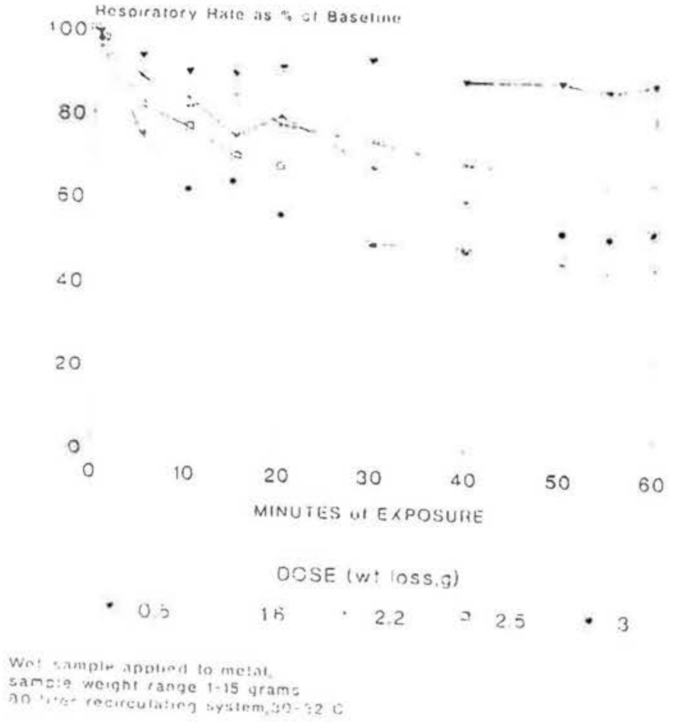

Figure 4 Sensory irritation from urethane finish

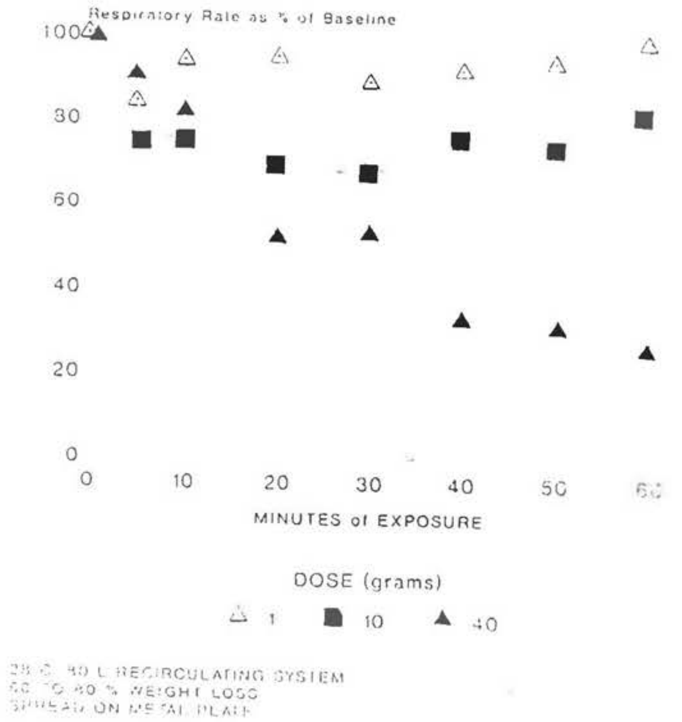

Figure 5 Sensory irritation from contact cement

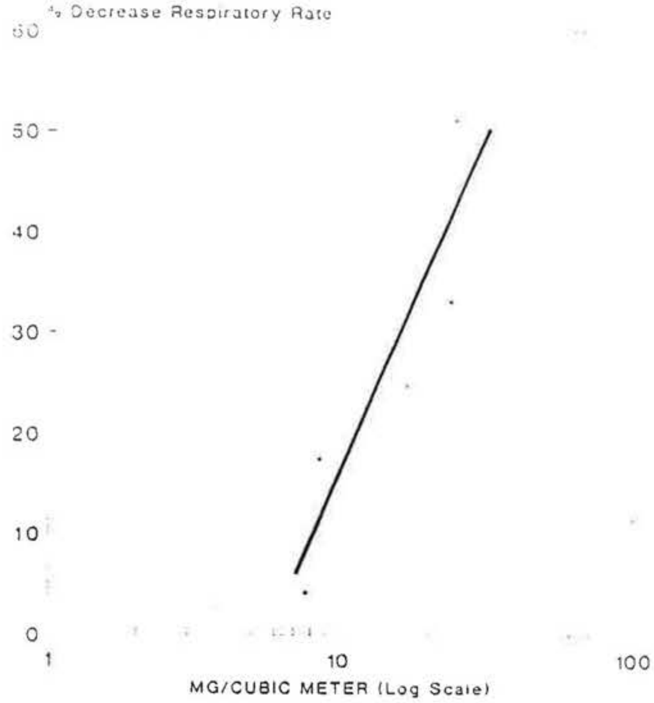

Figure 6 Sensory irritation—floor wax

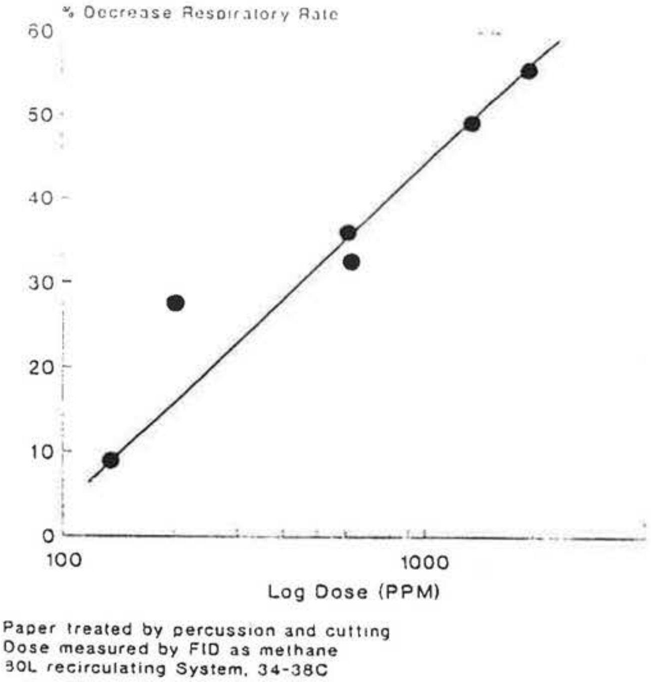

Figure 7 Sensory irritation—carbonless paper

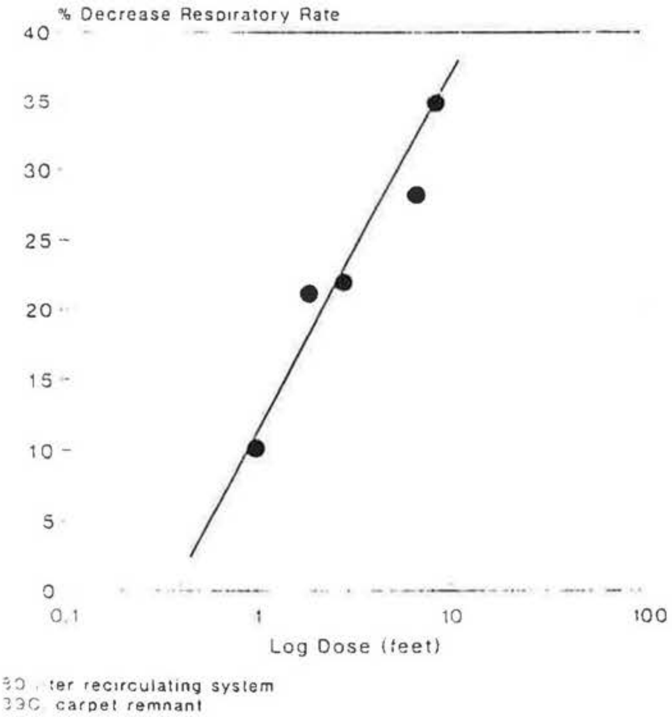

Figure 8 Sensory irritation—commercial carpet

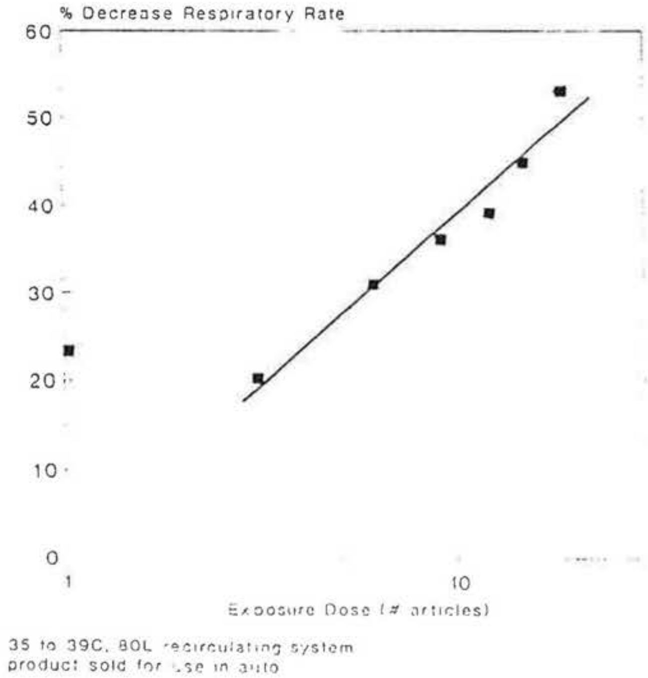

Figure 9 Sensory irritation—room freshener

RESULTS

Because the effects of fifth cranial nerve activation by irritant chemicals are very close to the symptoms reported in indoor air quality complaints, it seems relevant to investigate the use of this test method as a tool for looking at products used indoors. It could be very useful to determine in advance whether outgassing from a product was potent as a human irritant. To learn that after the fact can be an expensive education.

The products that have been tested during this exploration include a wide variety of wet and dry samples. The wet samples have included floor wax, paints, and several adhesives. Among the dry products, we have studied floor tile, vinyl wall covering, fabrics, carpet, carbonless paper, and room freshener with typical results presented in Figures 2 through 9. Several general observations have been made; the test is not sensitive to odor—1,000 grams of an aromatic fabric elicited no response over the 60-minute exposure period (Figure 10). The total hydrocarbon level of the test atmosphere is not indicative of the irritancy of the product under study.

The products tested were selected because they are often mentioned in connection with air quality concerns. Outgassing from some, but not all, products in each category has shown substantial irritant potency. There are significant differences between products for a single end use—see the comparison of two vinyl wall coverings in Figure 11. Clearly it would be possible to use these techniques to assist in the selection of products when the need is to minimize the potential for irritation in a specific end use. Since product data are not currently available in some great compendium in the sky, nor will generic data be useful, specific studies would need to be directed toward the question posed.

The test as it is being conducted is not directly linked to human irritation sensations without extrapolation that takes into

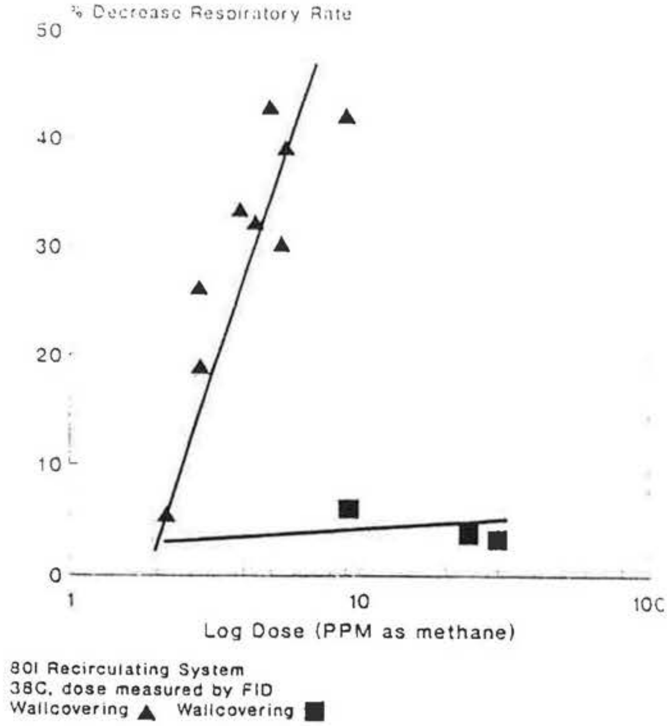

Figure 11 Sensory irritation—comparison of wall coverings

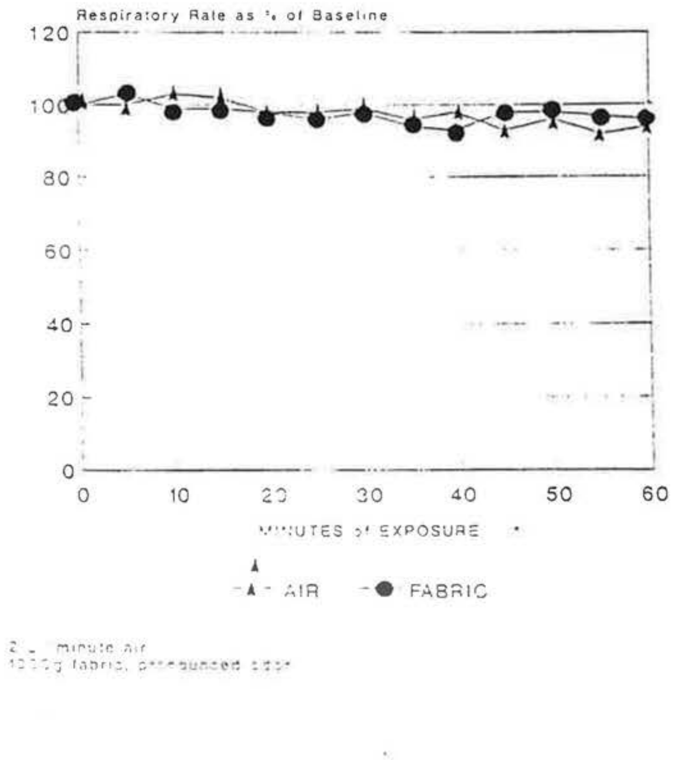

Figure 10 Effect of exposure to clean air or aromatic fabric

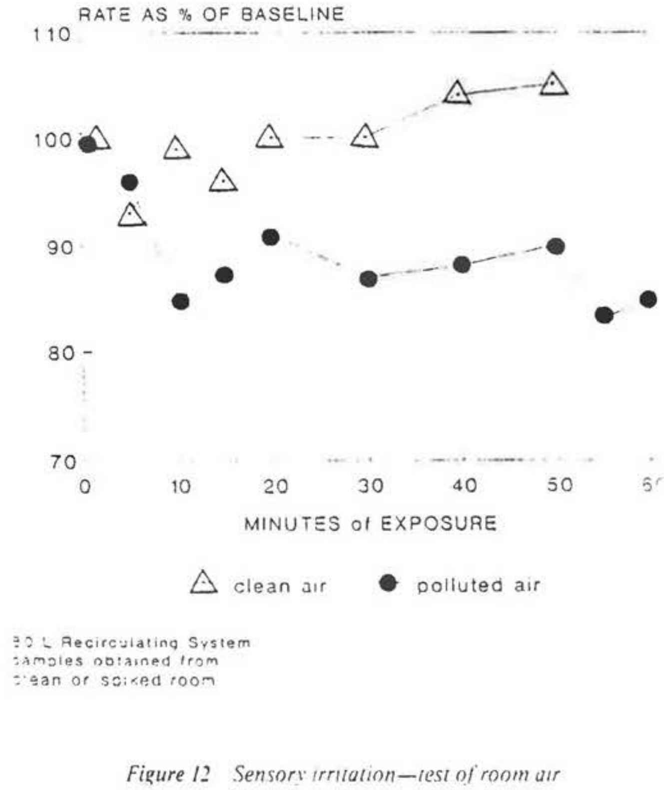

Figure 12 Sensory irritation—test of room air

consideration all details of specific product use. However, an application that would be easily applied to situations of actual use is to study room air for its irritant potency.

Gas samples from a contaminated room, collected by air bag, were compared for irritant potency against the atmosphere of a neighboring room (Figure 12). The difference from the baseline was significant (defined by ASTM E 981 as anything greater than a 12% change in respiratory rate), with the contaminated room causing a 20% change in respiratory rate of the test animals. In an additional experiment, air from a room having a mold contamination problem was found to be very active upon testing.

CONCLUSION

ASTM E 981 is a toxicology test method that was developed to evaluate the potency of airborne irritant chemicals. It has been adapted for use with commercial products and allows direct comparison of the irritant potency of outgassing from the products. We have demonstrated that, at least in some cases, it is possible to test air samples from contaminated spaces to numerically define an ambient irritancy level. The data can be extrapolated to predict the human response.

Ventilation Criteria, Effectiveness, Measurement

E. Skåret
Member ASHRAE

ABSTRACT

Ventilation for healthy buildings requires a holistic approach. Most important is source control. The penalty for not undertaking adequate and rational source control is high ventilation flow rates and high energy consumption. Source control is essential from the beginning, in planning, through all phases in the building process, and throughout the life of the building.

Ideally, ventilation requirements should be assessed based on residual emissions of pollutants and air quality criteria. Different approaches to ventilation criteria are discussed here. The rationale behind the discussion is NKB 41E, Indoor Climate—Air Quality, *recently published by the Nordic Committee for Building Regulations (NKB). Unambiguous air quality criteria apparently still belong to the future.*

INTRODUCTION

Apart from protecting us from nature, a modern building has to meet a range of requirements. The most important ones are functional, aesthetic, and environmental. Indoor air quality has a tremendous impact on the well-being of people and on work capacity, which, in turn, constitutes a substantial economic factor in our societies. Regarding the indoor environment, a building is healthy if the occupants (children as well as adults, including hypersensitive individuals) feel comfortable physically, emotionally, and socially. Because of these many aspects, creating a healthy building requires a holistic approach, not merely eliminating bad smells and harmful compounds, although this is one of the most important issues.

The history of buildings is thousands of years old. In spite of this, we still apparently cannot make and maintain healthy buildings.

The evidence and documentation regarding indoor air quality problems are in numerous reports in the international scientific literature. Apart from small local variations, the problems seem to be identical in the western industrialized part of the world. Sick building syndrome (SBS), building-related illness (BRI), building-related symptoms (BRS), multiple chemical sensitivity (MCS), radon, too low ventilation flow rates, and improper functioning of HVAC installations are common manifestations.

Regarding complaints, many investigations show that a range of factors not building related, such as sex, psychosocial conditions, social status, work content, and different forms of stress, influence the frequency of complaints among individuals. Ruling out such factors, however, does not rule out differences between buildings, meaning that buildings play a substantial role as the cause of human discomfort and sickness.

There is substantial literature regarding the characterization of indoor air quality. However, discussions about strategies or societal requirements to improve indoor air quality are more limited. One contribution to such discussions is *Indoor Climate—Air Quality*, recently published by the Nordic Committee on Building Regulation (NKB). This document,[1] based on the present state of the art, forms the background for this paper.

The ever-increasing frequency of problems is assumed to be related to a range of circumstances, such as switching to year-round building construction, industrialized building processes involving short times for drying out between the different construction phases, insufficient development of quality assurance in construction, and new technology and synthetic materials, which, for technical and/or economic reasons, achieved ready acceptance without proper prior testing/control regarding building hygiene.

To this must be added a tendency to reduce ventilation and tighten the building envelope as a consequence of the need for energy management and reduced energy consumption and other factors. NKB especially draws attention to:

- Materials, furnishings, and furniture that emit pollutants of different kinds are used in buildings.
- Materials and construction sensitive to moisture are used while at the same time insufficient remedial action is taken to prevent moisture loading.
- Ventilation and air-conditioning installations in some cases provide insufficient outdoor airflow rates, either because they have been designed incorrectly or are not used properly, or because the supply air on its way through the ventilation plant becomes contaminated because of the use of materials and components that emit pollutants or because maintenance and cleaning are neglected.
- Coordination (quality assurance) in the building process is unsatisfactory with regard to the indoor climate. Buildings are constructed, operated, cleaned, and maintained in an unsatisfactory or faulty manner.

In addition to the above list, attention should be drawn to the contamination given off by people, cooking, smoking, and office processes and the introduction of new, improperly tested and approved chemicals in the cleaning process. There is also a tendency in our society to neglect housekeeping and cleaning.

Ventilation is only one of several factors to be considered in creating healthy buildings. Nevertheless, it is, by its nature, the most essential one and should not be underestimated. The main

E. Skaret is a professor and senior research fellow at the Norwegian Building Research Institute, Oslo, Norway.

reason for this is that the building itself prevents the necessary fresh air exchange. The amount of supply air and its quality are crucial for the well-being of the people occupying a building and their capacity to work, a substantial economic factor in our society. On the other hand, it is of primary importance that the building itself not be a polluter, as the many SBS manifestations in our day frequently demonstrate. However, sick buildings are not a new occurrence. In the book of Moses in the Old Testament, we find both a description of a sick building and a cure for it. In the worst cases, the cure was to demolish and remove the whole building. We should learn from that. Obviously, their sick buildings were caused by mold, fungi, and microbial growth caused by moisture, which evidently is also a most important factor in the modern sick building mystery.

We have at present a contradictory situation. On the one hand, there is great knowledge today of indoor pollution. On the other hand, because most of the research has been of a survey character and not the kind that permits conclusions to be drawn as to which factors have significance for what regarding the incidence of ill health, it is not possible at present, other than in exceptional cases, to pinpoint "guilty" substances or factors.

In light of this uncertain state of knowledge, philosophy must be of a general nature. That is to say, we must not only avoid certain substances/factors but generally keep the number and intensity of pollution sources at a level low enough to secure a reasonable ventilation standard and adequate indoor air quality.

Ventilation for healthy buildings requires the following steps: (1) employing an adequate source control procedure, (2) quantifying the resultant "worst case" of contaminant generation, and (3) specifying the ventilation flow rate necessary to obtain acceptable indoor air quality in a worst-case situation. A strategic approach may be:

- Select the building location.
- Plan the building.
- Select construction materials, processes, etc., for the lowest possible contaminant exposures from the building and its use.
- Select a proper HVAC system.
- Predict its performance based on current criteria.
- Construct the building, including all HVAC installations.
- Commission and start to use the building.
- Verify its performance through experiments.

VENTILATION

The main subject in building ventilation is source control. The penalties for not undertaking adequate and feasible measures to reduce emissions to a practical minimum are high ventilation flow rates and high energy consumption. Source control is essential from the beginning, in planning, through all phases in the building process, and throughout the life of the building.

Building Requirements in Planning, Design, and Construction

Regarding the building site and ground conditions, special attention should be paid to moisture and radon exposure, waste deposits, and deposits from industrial activities that may create a substantial air quality problem if remedial action is not taken to prevent them. A recommended action is to prevent the substances from leaking into the building by sealing.

Outdoor air quality is considered because pollutants from the outside air may be a significant risk factor in town centers, near industrial sites, or near traffic routes. Guideline values for outdoor air quality have been set up by WHO. The trouble with these guidelines is that they do not consider the fact that there are also indoor sources of pollutants, which means that the outdoor air, complying with the guideline values, has no ventilation potential for these substances.

In construction, the risk of moisture damage is specifically underlined, especially with regard to its harmful influence on building materials with the risk of emission of contaminants to the indoor air. Moisture and temperature may cause microbial growth and chemical degradation of the materials with great risk of impaired air quality.

Building Materials and Surface Finishes, Fixtures, and Fittings

Ideally, building materials should not contribute to the ventilation demand. However, this is not a realistic assumption, neither today nor for the near future. Building materials pollute, either more or less, and there is a great variety of materials in the market that have not been through a realistic emission, health risk, or building hygiene test.

The client should demand an indoor-climate-related product description of the material. Such declarations currently are not common. Testing techniques and standards are in the process of being developed and harmonized between different countries. It will take time both to establish control/certification procedures that are internationally agreed on and practiced and to rule out low-quality materials. Particleboard is a good example of such a process. From being a primary polluter 10 years ago, this material has been developed in Scandinavia to emit less formaldehyde than pine wood when properly handled, stored, and used. But there are still low-quality products in the international market, and faulty handling and use, especially with regard to moisture and cleaning chemicals, can degrade any material.

Processes and Activities

When processes and activities that pollute the air are necessary, they should be encapsulated as much as possible, provided with a local external air supply, and/or limited to times when few people are exposed. When smoking occurs, special measures should be taken to prevent the risk of passive smoking. In many office environments, copy machines and laser printers may cause problems of ozone emission and dust generation.

HVAC Pollution

HVAC systems can be a major source of indoor pollutants. It is important that these systems be clean and cleanable with proper filtration of the outdoor air and that they consist of nonpolluting materials and be designed to prevent accumulation and condensation of water.

Cleaning of the Building

Cleaning of buildings is important. It is especially important that the building be prepared for cleaning, i.e., all surfaces that are in contact with room air or supply air are easily accessible and possible to clean. One should bear in mind that cleaning itself, through methods and agents, can deteriorate materials and air quality. Methods and agents need documentation showing both hygienic properties and suitability.

VENTILATION CRITERIA

Ideally, ventilation requirements should be assessed based on residual emissions of pollutants and air quality criteria. There is no doubt that in contrast to earlier ventilation codes, which regarded humans as the principal polluters, we have to consider other sources more carefully. Some codes have recognized the building itself as a polluter, but only to a minor extent. It was not suggested earlier to add together the different demands, although this has been common in the field of occupational hygiene.

However, much knowledge is still needed before a dose-response can be quantified in relation to a certain exposure or any specific pollution source in a normal building. It is only in exceptional cases that it has been possible to relate symptoms of ill health of the SBS type to the concentration of specific air pollutants or combinations of these.

Correlation between airflow rates and symptoms of the SBS type is, as can be expected, ambiguous. However, it has been found that, for a specific building, the frequency of complaints decreases as ventilation rates increase.

Humans are, of course, still an important pollution source. As early as the 1850s, Pettenkofer could give good criteria for ventilation rates for the control of human effluents based on the CO_2 content.

Perceived Air Quality

A classic measure of air quality is the extent to which odor and/or chemical irritation is perceived as acceptable by visitors directly on entry into the premises. The measure was used by Yaglou in his classic studies and has in recent years been developed by Fanger et al., manifested by the olf and decipol concepts. One olf is equivalent to the emission of the perceived air pollution (bioeffluents) by a standard person. One decipol is the perceived air quality due to one olf ventilated at 10 L/s of fresh (clean) air. The decipol is further geared to PPD (predicted percentage of dissatisfied persons). The new line is to quantify actual pollution sources in buildings, such as tobacco smoke, building materials, surface coverings, furnishings and furniture, processes, etc., in olfs. In theory, the ventilation criterion for comfort could be to specify the air quality in decipols. The ventilation requirement is then calculated from the olf load. Fanger has shown that there is a considerable variation in pollution load in olfs between buildings. The variation was on the order of 1:50 with an average of 0.3 olf/m^2, equivalent to approximately four persons per 10 m^2 floor area. Most remarkably, he found in some cases that the ventilation system contributed most to the olf load. It is believed that the load can readily be lowered to 0.05 to 0.1 olf/m^2 in new buildings by careful selection of materials and HVAC systems.

There are a few questions. One is how to mathematically treat olfs from different sources (should it be simple, hypo, or hyper addition). Fanger, based on his findings, suggests as a best choice, until we know more, that olfs be added arithmetically ($1 + 1 = 2$). The other question concerns adaptation. Some adaptation of occupants will take place after a while, especially in the case of human bioeffluents, although it is less pronounced for typical building materials. On the one hand, adaptation with regard to perceived air quality does not guarantee there will not be other health effects, such as fatigue, headache, heavy-headedness, lack of concentration, sore eyes, irritation of the mucous membranes, etc. On the other hand, the adaptation effect will quickly disappear when the exposure stops, as in leaving the premises. In a typical office environment, people are quite mobile, so it seems right to use the visitor concept when criteria are assessed. Last but not least, we have the question of to what extent dissatisfaction with regard to perceived air quality upon entry can be connected to health effects and discomfort during occupation. More knowledge is needed in this field.

A working group under COST 613, convened by Fanger,[4] is preparing a document on ventilation requirements based on perceived air quality.

Chemical Air Quality

The odor and chemical senses react when exposed to chemicals although not to all substances that may be harmful to human health. In theory the best criterion is to express air quality in safe concentration levels for the different contaminants when the health risk criteria and source intensities are known. For a few substances, guidelines are given by WHO (Air Quality Guidelines for Europe), but for the great majority of substances and for a number of interacting substances, knowledge is insufficient, and very little is known about the source intensities. To this must be added allergens and mycotoxins related to microorganisms and fungi.

However, volatile organic compounds (VOC) as a mixture are not reflected in the WHO document. At concentrations that can occur indoors, reactions of irritability and hyperactivity can be expected to some of the substances. Such reactions and toxic effects can occur at very low concentrations of single substances, and it can be very difficult to identify the "guilty" substance. It is probably not the total level of indoor air pollution but the occurrence of certain substances or combinations of them that produces health effects. There is, however, very little information about the contribution of single and/or combinations of substances to health effects. Dose-effect/dose-response data are completely lacking. In spite of this lack of data, a working group under the Norwegian Public Health Department of the Ministry of Social Affairs has decided to give a guideline value of exposure to TVOC of 400 μg/m^3, formaldehyde and carcinogens excluded. This value was chosen partly because it is readily obtainable in practice by careful selection of source control measures, and partly because an elevated presence of symptoms is not generally found at such concentrations. Other suggestions are 300 μg/m^3 TVOC, proposed by Seifert.[3] Values here depend on how they are measured. Elevated concentrations are generally caused by specific contaminant sources for which specific remedial actions should be taken.

The Norwegian document further proposes:

- **Formaldehyde** should not exceed 60 μg/m^3.
- **Suspended particulate matter** in the indoor air is probably not a ventilation matter, but is related to certain remedial actions such as filtering, avoiding material-generating particles, avoiding conditions favorable for microbial growth, etc. A high content of certain particles will carry VOC into the respiratory system, intensify the feeling of dry air, or intensify symptoms such as irritation of the mucous membranes and dry skin. The suggestion here is **40 μg/m^3 for the fine fraction (<2.5 μm)** and **90 μg/m^3 for total dust (<10 mm).**
- **Asbestos fibers** should have a target value of zero.
- No level of health effects is documented for **MMF**, but these fibers should not be present indoors.
- **Tobacco smoking** should not occur indoors.
- **Mites** should have a target value of less than 50 mites/g dust.
- Regarding **microorganisms**, no pathogens should be present indoors. Others should be as low as possible, and there should be no smell of mold.
- **Radon** should not contribute to ventilation requirements but be subject to a source control such as sealing and/or subfloor ventilation.
- **Humidity** in the indoor air may directly or indirectly have an impact on the occupants. High humidity may stimulate the growth of fungi and microorganisms and may cause condensation and building damage. High humidity may also enhance the emission of chemicals from building materials. Low humidity per se seldom causes a problem. To suppress the growth of dust mites, it is important to avoid high relative humidity, especially in the bedrooms. Humidity may be a ventilation criterion, and relative humidity should not exceed 70%.

In theory, the different guideline values could be criteria for calculating ventilation flow rates. ASHRAE Standard 62-1989[6] proposes such an air quality procedure. The conclusion is, however, that at present too little is known about the sources for such procedures to be employed as a whole. The use of low-polluting materials is encouraged. Otherwise, ventilation requirements are given based on person load. ETS is not considered specifically (see table for comparison).

Scanvac recently published a guideline[2] for classifying indoor air quality, introducing a calculation model based on emission rates from building materials. This is a good model of current thought. However, lack of knowledge is a barrier, as mentioned previously, both with regard to quantifying emission rates and to relating and quantifying health risks with concentrations of contaminants. In spite of the lack of data, Scanvac introduces three different emission classes for building materials in the document and has tried to group building materials into these three classes. Instead of using exact emission data and threshold values, it gives formulas linking the amount of square meters used of the different material classes to ventilation flow rates. The document also gives restrictions in the use of the worst class if the aim is a high air quality level. The use of low-polluting materials is encouraged.

The IEA reported "minimum ventilation rates" in 1987.[5] The work behind the report was motivated mainly by energy conservation. Different aspects of air quality (pollution sources) were thoroughly discussed, such as smoking, radon, and formaldehyde. The conclusion for building-related contaminants, such as volatile organic compounds, microorganisms, and many particulates, was that current knowledge is limited, but there are, nevertheless, indications that they may be associated with significant health effects. Further research is required to characterize the sources and to investigate the effects of the pollutants, which may be particularly important for offices and similar buildings.

The report concludes, not unexpectedly, with relatively conservative ventilation requirements related mainly to persons and prescribes sealing, removal, and elimination as actions to control contaminants not covered by person-related requirements. ETS is considered to some extent (see table for comparison).

The Norwegian Directorate of Labour Inspection recently published a revised edition of *Guidelines for Indoor Climate and Air Quality in Work Environment.*[7] In the new edition, three categories of pollution sources are defined: person load, building fixtures and furnishings, and activity and processes. It suggests these different demands be added (see table for comparison).

In the new Nordic air quality guideline, NKB61E,[1] neither the perceived air quality comfort equation of Fanger nor an air quality procedure is employed in full, simply because too little is known at present about the characteristics and intensities of sources indoors, measured in any quantity for such procedures to be applied. However, these theories as a whole have formed the background for professional judgment regarding proposed ventilation requirements. NKB61 has adopted the addition principle, not as normal addition but as hypo addition, where the building materials and other sources unrelated to persons have a weighting factor of 1 and the person load a weighting factor of 0.5. Effective source control is the prerequisite for the specified flow rates (see table for comparison).

One should bear in mind that total ventilation flow rates in practice may differ significantly from the requirements discussed regarding air quality. In the case of many buildings, other factors,

Comparison of Different Guidelines for Ventilation Requirements

Source Room	Notations	NKB61	ASHRAE Standard 62 - 1989	IEA	The Norw. Direct. for Lab. Insp.	
Person non smoking	l/sp	7	10	5.5 - 8	7 - 10	
Person smoking	.l/s p	sep.room. 20	sep.room. 30	8 - 20	Not allowed	
Building-material.	l/s m²	0,7 1) 3)			0,7 1) 2,8 3)	
Buildingrel Office	l/s m²	> 0,7 2)			>1.7 2)	
Polluting activity	l/s	Consid.	Include	Consid.	Calc. and add	
Kitcen	.l/s Exhaust	20	50 mech 25 nat			
Bathroom	l/s Exhaust	15	25/10			
Dwellings	l/s m² ach	0,35	7,5 l/s p 0,35	0,5		
Toilet priv " public	l/s Exhaust	10 15	10 25			

1) After one year, low-emitting materials
2) New building/redecorated building
3) Lack of documentation of low-emitting materials

such as the need for maintaining thermal comfort by cooling, may call for much higher flow rates.

Energy consumption may be lowered and comfort even improved when employing demand-controlled ventilation. Such a strategy should be based on air quality sensors. In many circumstances, it can be based on user patterns or individual requirements. The need for developing air quality sensors and other sensors and/or control devices in this field is great. The IEA has an annex working with this issue.

EFFICIENCY

The ventilation flow rates discussed presuppose complete mixing between contaminants generated in the space and the room air. The air quality is generally not the same throughout a ventilated space. What really counts is the air quality in the breathing zone. The objective for an efficient ventilation process is to aim at the lowest possible contaminant concentrations in the breathing zone compared with the concentrations in the return air terminal, which, in contrast to the concentrations in the occupied space, are indifferent to how ventilation is accomplished. Inhomogeneity in air quality is connected to ventilation efficiency and has an impact on the ventilation requirements.

The air quality may be poorer in the breathing zone than in the return air terminal for two reasons:

1. Inefficient air distribution, causing an inefficient purging of ventilation air through the breathing zone, meaning that some of the ventilation air is short-circuiting to the exhaust.
2. Ineffective removal of contaminants, causing an accumulation of contaminants in the breathing zone.

The penalty is increased flow rates.

The efficiency of an air distribution system and the purging flow rate are connected to the age of the air in the breathing zone. This age is taken as the time elapsed since the air at a point entered the space.

The overall effectiveness of the contaminant removal is connected to the age of the contaminant at the return air terminal. This age is taken as the time elapsed from the moment the contaminant was released at the source. The younger the air and the younger the contaminants are in this context, the more efficient the ventilation process is.

However, the breathing zone conditions regarding pollutants cannot be characterized by the local age of the contaminants. The procedure is simply to compare local concentrations with the return air concentration.

The air quality in the breathing zone may be better than in the return air terminal when efficient ventilation has been a design goal. This introduces a potential for lowering the ventilation flow rates.

In general, any ventilation system can be regarded roughly as a two-zone flow pattern. One zone is the air supply zone and the other zone comprises the rest of the room. In mixing ventilation, the supply zone is usually above the breathing zone. The best efficiency is achieved when the mixing is so effective that the two zones are transformed into one zone. In displacement ventilation,[8] there is generally a supply zone occupied by people and an exhaust zone above. The best efficiency (and higher than for complete mixing) is achieved when there is minimal mixing between exhaust and supply zones.

A unidirectional flow pattern for both air and contaminant is the most efficient. An example of this is a unidirectional flow from floor to ceiling, as can be accomplished in a clean room because of the high flow rates. In spaces such as office rooms, the efficiency is a function of the location and characteristics of the terminal devices and of the pollution sources. It is further a function of the temperature and flow rates of supply air. Ceiling-mounted terminal devices in combination with supply air heated above room temperature may be very inefficient. In displacement ventilation, the aim is to create a flow pattern with a tendency to unidirectional flow. These systems are generally more efficient than systems aiming at complete mixing. In most of these applications, the main flow direction is from floor to ceiling, relying upon upward convective currents to carry contaminants out of the breathing zone.

The efficiency can be calculated by numerical simulation, measured experimentally, or determined from experience. The first two methods are not widely used in the design phase, mostly for economic reasons. IEA Annex 20 is dealing with this topic.

The air exchange between rooms and time-varying flow rates also have an impact on ventilation effectiveness. Multiroom and temporal ventilation effectiveness are also dealt with in IEA Annex 20.

MEASUREMENT

Generally, apart from ventilation flow rates, not many parameters are specified in design documentation. However, this is in the process of being changed. Builders and clients are now encouraged to require, and are also more conscious of, specification of rational air quality parameters connected to present guidelines.

The process of verifying the performance of the ventilation system then is to measure the parameters specified in the design and compare measurements with specified values. Such specifications include ventilation flow rates, ventilation efficiency, and air quality parameters.

Ventilation Measurements

Total ventilation flow rates delivered by the mechanical ventilation system and the distribution of it through the ducting system and the terminals can readily be measured using well-known and well-described methods. However, an important prerequisite for a meaningful outcome is that the ventilation system be designed and constructed for such measurements. If there is no mechanical system, one has to rely upon certain tracer gas methods, such as PFT passive sampling,[9] the active constant-concentration method, or the classic tracer gas decay method. The CO_2 from people can also be used as a tracer in these contexts.

What counts next are the purging flow rates and the ventilation efficiency in the different spaces. Building infiltration will also be encountered in these measurements. Such measurements can most readily be accomplished by applying one or more tracer gas methods that measure the age of the air in the occupied zones and at the return air terminal. Practical measurements involve either injecting tracer gas in the main ventilation system at a constant rate or injecting a certain amount of tracer gas in the occupied spaces and mixing it well with the room air before starting measurements. The tracer gas concentration is measured as a function of time. From this, the different quantities can be calculated.[10]

For contaminants generally, the local contaminant-removal effectiveness or the local ventilation index, defined as the ratio between the contaminant concentration in the return air terminal and the concentration at a local point, is readily measured directly by measuring the concentrations of the different contaminants. Methods are given by Nordtest[13,14] and AIVC.

Air Quality

As already stated, there are a large number of agents in the indoor air that can be measured. What is meaningful to measure is, first of all, all parameters that have been used as design criteria or guidelines. The most important factors that should be determined are the perceived air quality, TVOC, suspended particulate matter such as dust and fibers, and, in special cases, radon and microorganisms.

Perceived air quality can be measured in different ways. The method most widely used presently is probably the one developed by Fanger et al. using trained panels judging the air quality in decipols or untrained panels also resulting in a decipol estimation.

Regarding measurements of chemical substances, there are many situations and pollutants in the different types of indoor spaces that call for quite a large set of sampling procedures to be established. However, there are general considerations that apply in most circumstances. These general considerations cover the dynamics of the indoor environment (which is very important) and the questions of why, when, how long, how often, and where sampling should be carried out. The publication of COST 613 Report No. 6,[11] *Strategy for Sampling Chemical Substances in Indoor Air*, covers all these questions.

There is currently no strong rationale for measuring chemical substances other than TVOC and specific irritants, including particulate matter. Perceived air quality and questionnaires currently constitute the most meaningful measurements.

All measurements should be preceded by a standardized questionnaire, such as the one described in COST 613 Report No. 4,[12] *Sick Building Syndrome—A Practical Guide*. Air quality measurements should be carried out the first time soon after the building is in use, the second time after one year, and later every third or fifth year.

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Air Exchange Effectiveness of Conventional and Task Ventilation for Offices

W.J. Fisk D. Faulkner R. Prill

ABSTRACT

Air quality and comfort complaints within large buildings are often attributed to air distribution problems. We define three parameters for air exchange effectiveness related to air distribution. The first two indicate the indoor airflow pattern (i.e., the extent of short-circuiting, mixing, or displacement flow) for an entire building or region. The third parameter is most useful for assessments of the spatial variability of ventilation. We also define the air diffusion effectiveness, which indicates the airflow pattern within specific rooms or sections of buildings. The results of measurements of these parameters in U.S. office buildings by the authors and other researchers are reviewed. Almost all measurements indicate very limited short-circuiting or displacement flow between locations of air supply and removal. However, a moderate degree of short-circuiting is evident from a few measurements in rooms with heated supply air. The results of laboratory-based measurements by the authors are consistent with the field data. Our measurements in office buildings do indicate that ventilation rates can vary substantially between indoor locations, probably due to variation in air supply rates between locations rather than variation in the indoor airflow patterns. One possible method of improving air distribution is to employ task ventilation with air supplied closer to the occupant's breathing zone. We have evaluated two task ventilation systems in a laboratory setting. During most operating conditions, these systems did not provide a region of substantially increased ventilation where occupants breathe. However, both systems are capable of providing substantially enhanced ventilation at the breathing zone under some operating conditions. Therefore, task ventilation is a potential option for using ventilation air more effectively.

INTRODUCTION

There seems to be a fairly widespread belief among the ASHRAE membership that substantial short-circuiting of air between ceiling-level supply diffusers and ceiling-level return grilles is common, resulting in poor ventilation at the locations of occupants. Air exchange effectiveness (AEE), more commonly called "ventilation efficiency," is an indicator of the nature of the indoor airflow pattern between locations of air supply and removal within buildings or rooms. The indoor airflow pattern ranges between two hypothetical extreme cases. At one end of the scale, all supply air immediately short-circuits to the return or exhaust grilles. At the other end, a perfect displacement (piston-like) pattern of air flow occurs between the locations of air supply and removal. In between is the case of perfect instantaneous mixing of all indoor air. Several sources of air motion in real spaces, including natural convection plumes from internal heat sources, natural convection at warm or cool walls, the use of fans, and the motion of people, tend to mix the indoor air and prevent complete short-circuiting or perfect displacement flow. One of the objectives of this paper is to present and discuss data on indoor airflow patterns in office buildings.

The indoor airflow pattern has implications for indoor air quality (IAQ) and building energy use. A short-circuiting flow between ceiling-level supply diffusers and return grilles is generally inefficient in removing pollutants and heat generated in the occupied lower regions of rooms; hence, with short-circuiting, more outside air is required to maintain acceptable IAQ and more total supply air may be required to remove heat. However, when pollutant and heat sources are located in the path of the short-circuiting flow, this flow pattern may be efficient because the pollutants and heat also short-circuit to the exhaust. In contrast to short-circuiting, a displacement flow pattern in the floor-to-ceiling direction is generally more efficient in removing heat and pollutants generated in the occupied space than the "perfect mixing" pattern because the exiting air has a pollutant concentration above the building average and, in some cases, an above-average temperature.

The local AEE, as defined in the next section, has a different significance. This parameter is most useful for comparing the rate of ventilation (or age of air, as defined later) measured at different individual locations. In a large multi-room building, the local AEE is influenced by both the amount of air supplied locally (e.g., to the room in question) and by the indoor airflow pattern. Therefore, individual values of local AEE are not useful indicators of the extent of short-circuiting (an occasional point of confusion). The second objective of this paper is to discuss the spatial variability of ventilation as indicated by the local AEE and other parameters.

AEE parameters are useful for characterizing the ventilation performance of task ventilation systems. These systems, described in greater detail subsequently, permit individuals to adjust the rate and direction of a local air supply that serves their work space (primarily so occupants can fine-tune their thermal comfort).

William J. Fisk, **David Faulkner**, and **Richard Prill** are with the Indoor Environment Program, Applied Science Division, Lawrence Berkeley Laboratory, Berkeley, CA.

Ideally, these systems will provide a region of increased ventilation where the occupant normally breathes. The third and final major objective of this paper is to discuss the extent to which two task ventilation systems provide this enhanced ventilation.

DEFINITIONS

We use the age of air, usually denoted by the symbol τ, as the basis for defining AEE parameters. The age of a sample of air is the average amount of time that has elapsed since molecules in this sample entered the building. One can consider the local age of air at a specific location within the occupied space, the age in various airstreams (such as the exhaust), and the spatial mean age of all air within a building. We use the symbol τ_{BL} represent a local age of air measured at the typical breathing level of a seated person. Age of air is measured using tracer gas techniques described by numerous authors (Sandberg and Sjoberg 1983; Fisk et al. 1985, 1988, 1989; Persily 1985). For brevity, we do not repeat the descriptions of measurement techniques in this paper.

The nominal time constant, denoted τ_N, is used in the definitions of AEE parameters and equals the indoor volume divided by the flow rate of outside air supply. τ_N is the reciprocal of the air exchange rate and is usually expressed in units of hours. τ_N equals the local age of air exhausted to outside (Sandberg and Sjoberg 1983) and is determined from measurements in the main return or exhaust duct(s).

The spatial average age of air within the entire building, usually referred to as the mean age of air, is denoted by the symbol $<\tau>$ and is also determined from measurements of tracer gas concentrations in the exhaust airstreams. We also use the average of the measured local ages of air at breathing level, denoted $<\tau_{BL}>$ to calculate an AEE.

We define three AEE parameters via the following equations:

$$AEE_{GLOBAL} = AEE_G = \tau_N/<\tau> \qquad (1)$$

$$AEE_{BREATHING\ LEVEL} = AEE_{BL} = \tau_N/<\tau_{BL}> \qquad (2)$$

$$AEE_{LOCAL} = AEE_L = \tau_N/\tau_{BL} \qquad (3)$$

AEE_G is representative of the entire building because both the numerator and denominator of this parameter are indicative of the entire building. The parameter AEE_{BL} is more relevant to human health because it is based on the average measured age of air at breathing level $<\tau_{BL}>$ rather than the spatial average indoor age $<\tau>$. However, multipoint measurements are required to obtain a representative average value of τ_{BL}. The local AEE is based on a comparison of the nominal time constant (a whole-building parameter) to the age at a single indoor location, and, as noted previously, the range of AEE_L is useful for assessing the spatial variability of ventilation.

The reference for all three AEE parameters (i.e., the case with AEE equal to unity) is perfectly mixed indoor air. The maximum possible value of AEE_G is 2.0 for a perfect displacement flow. There are no theoretical upper limits for the other two parameters. Values less than or greater than unity for AEE_G and AEE_{BL} indicate short-circuiting and displacement flow patterns, respectively. Larger deviations from unity indicate more pronounced short-circuiting or displacement flow.

We define another related parameter, the air diffusion effectiveness (ADE), which is a better indicator of the airflow pattern in a specific indoor region (e.g., a room).

$$ADE = \tau_{RG}/\tau_{BL} \qquad (4)$$

where τ_{RG} is the age at a return grille located near the τ_{BL} measurement location. If low-age supply air short-circuits to the return grille, τ_{RG} should be significantly less than τ_{BL}; hence, the ADE will be less than unity. The converse is true with a displacement flow pattern. The advantages of ADE as an indicator of local short-circuiting or displacement flow are as follows: (1) both the numerator and denominator of the ADE are representative of the same general region (e.g., room) and (2) the residence time of air in return-air ceiling plenums and the leakage of supply air into return plenums will have a small effect on ADE but may substantially affect the other three parameters (thus, ADE is more indicative of the flow pattern in the room). The ADE will equal unity if the room is perfectly mixed. One could compute an ADE parameter based on an average of several measurements of both τ_{BL} and τ_{RG} in the same region; however, in this paper we use a single measured value of each parameter.

CONVENTIONAL AND TASK VENTILATION

Supply of air through ceiling-mounted diffusers or high wall supply grilles and removal of air through ceiling-level or high wall return grilles is conventional practice in U.S. office buildings. Air is supplied in high-velocity jets that entrain room air, promoting mixing. Complete mixing of the indoor air is the usual design goal. Indoor temperature control is achieved by regulating the supply temperature, supply flow rate, or both of these parameters. The regulation of supply temperature or flow is controlled by a thermostat. Generally, there are many more occupants than thermostats, and occupants are not able to adjust the thermostat setting.

In contrast to conventional ventilation, we define task ventilation (TV) as a method of ventilation that permits the occupants to adjust some local air supply parameter, such as supply flow rate, temperature, or direction. The potential for improved thermal comfort, because occupants can (to some extent) adjust their local thermal environment, is a major impetus for the use of TV. Improved indoor air quality is another potential benefit because the supply air can be delivered more directly to the region around the occupant. TV systems may also, in some situations, result in a displacement (pistonlike) airflow pattern in the floor-to-ceiling direction because slightly cool air, more dense than room air, is supplied at floor or desk level and air is typically removed from the room at or near the ceiling. Displacement flow can result in lower pollutant concentrations at the breathing level and higher concentrations in the ceiling-level exhaust air (see, for example, Holmberg et al. 1990).

We consider two task ventilation systems that are being introduced in the U.S. We call the first system the "floor supply system." Air supply modules are installed in an raised panel floor. Each module contains a fan that draws air from the subfloor supply-air plenum and discharges this air into the room through slots (inclined 40° from vertical) in four plastic grilles each 0.13 m in diameter. Using a recessed thumb wheel, the fan speed and, thus, airflow rate can be adjusted between approximately 40 L/s and 90 L/s, resulting in maximum air supply velocities of 2 to 6 m/s (or the fan may be turned off). The direction of the air supply can be changed by rotating any or all of the four grilles. Occupants cannot control the supply air temperature, which, to reduce the potential for cold drafts, is typically about 18°C or 5°F higher than the supply temperature of many conventional U.S. ventilation systems. Air is typically withdrawn from the occupied spaces through ceiling-level return grilles.

We refer to the second task ventilation system as the "desk-supply system." Air from either a subfloor supply plenum or from supply ducts is drawn into one opening of a fan/control unit that fits under a desk. Air is also drawn directly into another opening of the fan/control unit from the room. A mixture of the air from both sources is supplied to the room through a pair of nozzles with movable vanes located at the desktop. The nozzles may be rotated

360° in a horizontal plane, and the vanes may be angled ±30° in a vertical plane. The temperature of air supplied through the nozzles is a function of the ratio of recirculated room air versus supply air in the air exiting the nozzles, which, in turn, is determined by the position of two dampers in the fan/control unit. Damper positions are controlled by the air temperature setting on a desktop control panel. The control panel also gives the occupant the ability to set the air supply rate (via adjustment of fan speeds) and to control operation of a radiant heating panel, a task light, and a white noise generator. The control panel also contains an occupant sensor that will turn off power to the fans, heater, light, and noise generator if no occupant is detected for 10 minutes. When an occupant is detected, the system resumes operation at the previously set conditions. The maximum flow rate of supply air with fans operating is approximately 70 L/s. With no power to the propeller fans and 25 Pa positive static pressure provided by the main air handler, approximately 10 L/s will flow through each nozzle.

MEASUREMENT RESULTS

Field Measurements with Conventional Ventilation

The authors have measured the three AEE parameters and the ADE in several office buildings located in the San Francisco area. All of the buildings used conventional methods of air supply and return. Supply air temperatures were lower than indoor temperatures. In most buildings, we completed measurements with both minimum and maximum percent outside air supply (i.e., maximum and minimum recirculation of air by the air handler). The measurement method involves labeling each stream of outside air with a unique tracer gas via constant tracer gas injection and monitoring tracer gas concentrations in major airstreams and also at multiple locations within the occupied spaces (see Fisk et al. 1988, 1989, 1991 for details on measurement and data analysis procedures). Table 1 provides the key results (some have been published previously).

First consider the AEE_G. The majority of measured values are within the range 1.0 to 1.2 and three of the four values outside of this range are equal to 1.3. Based on an evaluation of measurement precision in a laboratory setting (Fisk et al. 1991) and our estimate of the magnitude of additional errors in field settings, the 95% confidence limits for measurements of AEE_G are at least ±20%. Within this confidence limit, most of the AEE_G values are indistinguishable from the value obtained with complete mixing. However, because we use different tracer gases to simultaneously label the outside air entering buildings through each air handler, we know that the indoor air throughout these large buildings is often not perfectly mixed (Fisk et al. 1988, 1989). Thus, our measurement of an AEE_G value close to 1.0 does not indicate perfect mixing throughout a building but does indicate minimal short-circuiting or displacement flow, on average, for the entire building. (In theory, displacement flow in some locations could counteract short-circuiting elsewhere, resulting in a value of 1.0 for AEE_G.)

With three exceptions, the values of AEE_{BL} in Table 1 are also indistinguishable (i.e., within 0.2) from 1.0. We suspect that values of 1.4 and 1.3 for both the fifth and sixth floors of Building No. 1 are due to a primarily one-way flow between the office regions (where air was supplied) and the bathroom/janitorial regions that contained the only exhaust grilles (see Fisk et al. [1988] for details). The elevated value of 1.4 in one test of Building No. 5 may have resulted from the very large spatial variation in age of air during this test, leading to an inaccurate determination of the true average age at breathing level.

Next consider the ADE. Based on multipoint measurements in a well-mixed room, we have calculated 95% confidence limits for an ADE measurement of 12% to 20% (confidence limits varied with test conditions; we assume 20% for the subsequent discussion). Forty-two measured values of ADE are provided in Table 1. None is below 0.8, i.e., none is significantly below unity with 95% confidence. Only six measured values exceed 1.2. Thus, the ADE data also indicate that there is minimal short-circuiting or displacement flow at the majority of measurement locations within these buildings. The average of the 42 measured values is 1.1, which is significantly greater than unity. (The 95% confidence limit for the average of 42 measurements is ±0.03.) Thus, these measurements indicate a very slight tendency toward displacement flow.

The local air exchange effectiveness values frequently deviate substantially from unity. Because of the evidence of minimal short-circuiting or displacement flow, the large deviations from unity must result from variable air supply rates throughout the buildings. The relative standard deviations (RSD) in the age of air at breathing level within these buildings must also reflect these variations in air supply rates. The RSD is typically 0.1 to 0.2 in tests with minimum percent outside air (maximum recirculation) but is as high as 0.5 in tests with maximum percent outside air.

The final column of Table 1 provides the outside air supply rate per occupant during these tests. In Building No. 1, the 10 L/s per occupant supply rates are equal to the minimum rates specified for offices in *ASHRAE Standard 62-1989* (ASHRAE 1989). In other tests with minimum percent outside air, the outside air supply ranged from 16 to 45 L/s per occupant—substantially above the minimum value specified in this standard. Thus, if a moderate degree of short-circuiting did occur in these buildings, the "effective" outside air supply rate (e.g., product of actual outside air supply rate and AEE) would generally still exceed the value prescribed in the ASHRAE standard. However, rooms with a very low local air exchange effectiveness could be underventilated relative to the rate prescribed in the ASHRAE standard.

There are only a few additional measurements in U.S. office buildings. Our general findings of limited short-circuiting or displacement flow are consistent with results of tests in a three-story office building by Persily (1986). In three tests, the global air exchange effectiveness ranged from 1.04 to 1.12 and the averages of several measurements of local air exchange effectiveness during each test (the average is similar to AEE_{BL}) ranged from 0.73 to 1.02.

Persily and Dols (1990) also completed nine tests in a large office/library building, and the averages of seven to eight measurements of local air exchange effectiveness during each test ranged from 0.92 to 1.05.

Offermann (1988) completed two tests within an isolated room in an office building with conventional ceiling diffusers and a ceiling-level return grille. The room was heated with the supply air during these tests. The breathing-level air exchange effectiveness was 0.66 and 0.73, respectively; thus, these two tests do indicate significant short-circuiting. Possibly the elevated supply air temperatures were a reason for the short-circuiting.

Rask and Sun (1989) describe results from three spaces; however, they use a different definition of air exchange effectiveness that precludes comparison of their results to ours. Their definition results in an air exchange effectiveness less than unity even in a room with perfectly mixed air if the room volume exceeds the volume of the occupied zone as defined by ASHRAE. (*ASHRAE Standard 62-1989* defines the occupied zone as the region between 0.075 and 1.8 m [3 and 72 in.] above the floor and greater than 0.6 m [2 ft] from walls.) The largest volume of published data (that we identified) from field measurements outside the U.S. is based on measurements in 23 offices within Finland (Seppanen 1986). The global air exchange effectiveness always exceeded 0.82 and was typically near 1.0 except in office buildings with air supplied to the hallway and exhausted from the office area. With this ventilation configuration, which is unusual in the U.S., the global air exchange effectiveness ranged from 0.72 to 1.0.

Laboratory Measurements with Conventional Ventilation

The authors have also measured air exchange effectiveness (see Bauman et al. 1991a) in a laboratory called the Controlled Environment Chamber (CEC), which is 5.5 m by 5.5 m by 2.5 m high. Although a flexible research laboratory, the CEC closely resembles a modern office space. For the tests described in this paper, the CEC was subdivided into three workstations separated by partitions. Each workstation contained typical office furniture (desks, side tables, chairs, bookcases). The chamber also contained sources of heat and air motion typical of real offices, including overhead lights, task lights, and personal computers with a small cooling fans plus monitors. A seated mannequin that released heat in a manner similar to a real person was located in one or two of the workstations. Airflow in the cavities of the exterior walls and between window panes maintained wall and window temperatures close to the indoor temperature during tests with the CEC cooled. Consequently, these exterior walls and windows were not a source of strong natural convection but affected indoor air movement like interior walls. During tests with the CEC heated, the exterior walls and windows were cooled (to create a heat sink); thus, during heating tests these surfaces were a stronger source of natural convection airflow. Air was supplied through a single perforated diffuser mounted in the ceiling either centrally or near the center of one wall. Air exited through a ceiling-level return grille.

Table 2 provides the primary results of AEE measurements in the CEC. Only two of ten values of AEE_{BL} are significantly different from unity with 95% confidence. In all seven tests with the CEC cooled, the AEE_{BL} is greater than unity, but only one deviation from unity is significant. In all three tests with the CEC heated, AEE_{BL} is less than unity, but again, the difference is significant in only one case. The results of these laboratory measurements are very consistent with the previously discussed results of measurements in actual buildings. In general, the air exchange effectiveness is close to unity. The data indicate a very slight tendency toward displacement flow when the CEC is cooled and a slight tendency toward short-circuiting when the CEC is heated. At least during these tests, the partitions do not interrupt the airflow (a commonly expressed concern) and cause significant short-circuiting. In addition, the data in Table 2 on age of air vs. height (and the individual measurements that are not included in the table) indicate that the ventilation within and above the partitions is nearly identical; hence, the partitions do not create "dead spaces" with poor ventilation. Thermal comfort and air velocity measurements by Bauman et al. (1991a) lead to the same conclusion.

Laboratory Measurements with Task Ventilation

The air exchange effectiveness of the two previously described task ventilation systems has also been measured via laboratory experiments in the furnished CEC. Some results were reported in Arens et al. (1991), Bauman et al. (1991b), and Fisk et al. (1991). Twenty tests have been completed with the floor supply system operating. Test variables have included the direction of air supply (e.g., toward the occupant or toward the center of the floor supply module), location of the floor supply module, rate of air supply, and supply temperature (cooling or heating of the CEC), with and without recirculation by the main air handler (100% outside air was supplied during most tests). In general, AEE_{BL} was within 0.15 of unity. (The 95% confidence limits for this series of tests is $\pm$15%.) Consequently, the system did not usually provide a region of significantly enhanced ventilation where occupants breathe. Directing the air from the floor supply toward the occupant's breathing zone resulted in slightly (e.g., 15%) lower ages of air in the breathing zone than at the return grille. However, the results of one unique test are promising. We have completed only one test with minimum supply flow rates and two floor supply modules operating simultaneously. In that test, AEE_{BL} was approximately 1.5. The multipoint measurements indicate a significant increase in age of air with height, which is indicative of a displacement flow pattern. Therefore, with a low air supply rate, this system can provide highly effective ventilation.

We have completed only five tests with the desk-supply system operating; thus conclusions regarding the air exchange effectiveness of this system are only tentative. With the air supply nozzles supplied by the manufacturer, the supply flow rate at each workstation was maintained below approximately 20 L/s and the air was directed toward the occupant's breathing zone. Under these conditions, the measured AEE_{BL} ranged from 1.1 to 1.3. The value of 1.3 is a significant but still moderate enhancement compared to the case of complete mixing. To permit higher supply flow rates without high velocities at the occupant's face, we fabricated a set of larger air supply nozzles that reduced exit velocities by approximately a factor of three. In a single test with 42 L/s supplied at each of two workstations, AEE_{BL} was 1.6. Hence, this system can also provide highly effective ventilation.

CONCLUSIONS AND DISCUSSION

The number of measurements of air exchange effectiveness in U.S. office buildings or realistic laboratory mock-ups of offices is limited. The large majority of available data from conventionally ventilated spaces indicate very limited short-circuiting and limited displacement flow between the locations of air supply and removal. We suspect that these results are due to the mixing of indoor air caused by both high-velocity jets of supply air and natural convection. We do not claim that short-circuiting is minimal in all or a very high percentage of U.S. office buildings—the available data are too sparse for such a claim. In fact, some data indicate a moderate degree of short-circuiting of supply air to return grilles when the supply air is heated. We believe that additional measurements are required. However, based on the available information, short-circuiting is not the pervasive problem assumed by many engineers and indoor air quality specialists.

The available data do indicate that the ventilation rate within U.S. office buildings can vary substantially with location. Based on measurements by the authors, the relative standard deviation in the age of air at breathing level was typically 0.1 to 0.2 when minimum outside air was supplied and as high as 0.5 with maximum percent outside air supplied. Local air exchange effectiveness values reported here ranged from 0.3 to 3.6 (i.e., local ages of air at the breathing level were 30% to 330% of the nominal time constant for the entire building). We suspect that this variation is caused primarily by spatial variations in air supply rates.

Based on a preliminary examination of the performance of two task ventilation systems, we conclude that these systems do not produce a region of substantially (i.e., more than 25%) increased ventilation where occupants breathe for most of the operating conditions considered. However, under certain operating conditions, both task ventilation systems are capable of producing an age of air in the occupant's breathing zone that is approximately 65% of the age of air at the return grille. Thus, task ventilation is one potential option for using ventilation air more effectively that deserves further study.

ACKNOWLEDGMENTS

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building and Community Systems, Building Systems Division of the U.S. Department of Energy (DOE) under Contract No. DE-AC03-76SF00098. The research reported here was also funded in part by the California Institute for Energy Efficiency (CIEE), a research unit of the University of California. Publication of research results does not imply CIEE endorsement of or agreement with these findings, nor that of any CIEE sponsor. We thank Ed Arens and Fred Bauman from the U.C. Berkeley Department of Architecture for permitting us to conduct experiments in their Controlled Environment Chamber and also David Pih and Pleasant J. McNeel IV for their assistance in performance of experiments.

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Classified Indoor Climate—A Way to a New Indoor Climate Technology

U. Rengholt

GENERAL BACKGROUND

The dissatisfaction among consumers with indoor climate and ventilation is widespread and deep. In Sweden, about 40% to 50% of all employees complain about the indoor climate where they work. The number of complaints concerning dwellings is also high. The frequency of so-called "sick" houses is even more serious. Up to 30% of all houses are estimated to be "sick" in the sense that buildings and their indoor climate give rise to considerable discomfort, symptoms of illness, or bad health.

Practically no industry can survive if it delivers products that fail to satisfy nearly half the number of consumers. However, the building and indoor climate industries have managed to do that, partly because they have been shielded by official standards and regulations that have limited or eliminated their responsibility for how their products work. Another contributing factor has been that consumers used to make rather low demands on the products (indoor climate).

The problems of poor indoor climate and sick houses have deep roots. They indicate a number of serious shortcomings in the whole building process, a sign that there are no functioning quality systems for the building industry. The problem of sick houses cannot be remedied solely by limited measures such as better ventilation, even though that is an important part. The only solution is to remove the faulty elements in the actual building process, to create a new building process applying new and better quality systems.

One important consequence will be a need for an improved technology for indoor climate and ventilation—what I call "a new indoor climate technology"—based on a stronger awareness among consumers, high demands on indoor climate quality, and application of modern theories of quality systems. Its real goal is consumer satisfaction.

As a step toward this goal, the Scandinavian organization Scanvac has worked out new common guidelines for indoor climate quality declaration and specification, the so-called "Scanvac guidelines for indoor climate." Those guidelines represent a way to transform the knowledge about indoor climate and quality technology into useful information for the ordinary builder or consulting engineer in practical work.

THE NEW INDOOR CLIMATE TECHNOLOGY—SOME CHARACTERISTICS

It is not my intention to discuss the means and ends of the new indoor climate technology, but as background to the Scanvac guidelines, I would like to present some of its most important characteristics.

- The new indoor climate technology recognizes the importance of the indoor climate for people's well being, health, and performance ability—in other words, the productivity of the indoor climate.
- The new indoor climate technology expresses the indoor climate and its effect on human beings in terms that enable us to make an economic estimate of its importance. In that way, both decision makers (clients, managers, etc.) and consumers can get a clear view of and put a price on the indoor climate.
- The new indoor climate technology considers the indoor climate to be a complex factor. Different people perceive the indoor climate differently depending on age, sex, activity, etc. It is influenced by many different technical factors, such as pollution sources and thermal loads inside and outside the building. The indoor climate in each case must rest on the basis of the prevailing conditions and with respect to who is going to use it. In other words, the indoor climate must be "individualized." Thus, the new indoor climate technology is far removed from the view that has dominated up to now, namely, that the indoor climate is a fixed entity that is the same for most people and can be based on rigid standards valid for most types of buildings.

These characteristics of the new indoor climate technology are sufficient as an explanation of the background to the new Scanvac guidelines.

PRINCIPLES BEHIND THE INDOOR CLIMATE GUIDELINES

The Scanvac guidelines are built on the following principles, derived from the new indoor climate technology.

- The quality of the indoor climate is characterized according to the effect of the indoor climate on people's comfort and well being (also health aspects) by means of frequencies of dissatisfaction, so-called "PPD values."
- The quality specifications are classified by a limited number of different quality levels, which enable the customer (the house owner) to choose a suitable (but to some extent standardized) indoor climate in each individual case.
- From a technical point of view, the quality of the indoor climate is defined by a number of indoor climate factors (air quality factors, thermal quality factors, etc.) and by specifications of acceptable values for them in the various classes.
- The quality of the indoor climate is regarded as separate from the technical solutions that are applied to establish it.

These principles will be discussed in concrete detail in the following section.

Ulf Rengholt, Swedish Society of Heating and Air-Conditioning Engineers (Swedevac).

THE STRUCTURE OF THE CLASSIFICATION SYSTEM

The purpose of the Scanvac guidelines is to indicate a new way of thinking that enables us to *understand* the indoor climate, *evaluate* it in economic terms, and *adapt* it to the various conditions—technical and consumer-oriented—in the individual case.

In accordance with these guidelines, the indoor climate is divided into different quality classes with respect to thermal comfort, air quality, and noise level. Each class is characterized by a statistically determined value of the percentage of dissatisfied persons that the class is estimated to yield, the so-called "PPD value."

There are three thermal classes, two air quality classes, and two noise level classes. Each thermal class and each air quality class is composed of a number of indoor climate factors, the values of which are given in Tables 1 and 2. The noise level classes are directly defined by the noise level values allowed (see Table 5).

A PRACTICAL APPLICATION OF THE CLASSIFICATION SYSTEM

The indoor climate is determined by thermal, air quality, and noise level classes. Within the 12 combinations possible (see Figure 6), that which agrees most closely with the type of building, use, etc., is chosen for each individual object.

A classified quality system of this kind has many effects on the practical work. The builder or the building owner must consider and specify which indoor climate quality he needs. He must choose a quality level before the projecting or design stage.

The functions of the building, its ventilation, and other factors will be better adapted to individual needs instead of following a rigid standard that is taken for granted in every case.

The choice of quality level is documented. If the building owner has chosen a lower quality than is justified, that is documented, and the information is preserved for the life of the building.

The consulting engineers are given clear specifications of demands to follow and use as a basis for the choice of technical solutions that meet the quality demands in the best possible way.

CALCULATION OF AIRFLOW WITH REGARD TO EMISSIONS

In order to create an air quality in accordance with air quality classes AQ1 and AQ2, the major indoor pollution sources must be identified and their source strength determined (calculated). The correct airflow should be determined on the basis of the generated quantity of pollution—the so-called "source control principle." Major pollution sources are people (emitting carbon dioxide), building materials and surface materials (emitting VOCs), and office equipment.

Up to now, the necessary airflow has been calculated only with regard to people (carbon dioxide) as a source of pollution.

TABLE 1 Thermal Quality—Acceptable Values of Different Factors in Various Quality Classes

The table indicates values for the normal case.

Item	Indoor climate factor	Factor value in quality class			
		TQ1	TQ2	TQ3	TQX
1*	**Operating temperature (to)**				As specified
1.1	Winter mode				
	highest value °C	23	24	26	
	optimum value °C	22	22	22	
	lowest value °C	21	20	18	
1.2	Summer mode				As specified
	highest value °C	25.5	26	27	
	optimum value °C	24.5	24.5	24.5	
	lowest value °C	23.5	23	22	
2*	**Air velocity within the occupation zone**				As specified
	winter mode m/s	0.15	0.15	0.15 (0.25)	
	summer mode m/s	0.20	0.25	0.40	
3*	**Vertical temperature difference, summer/winter mode °C**	2.5	3.5	4.5	As specified
4*	**Radiant temperature asymmetry**				As specified
	to warm ceiling °K	4	5	7	
	to cold wall (window) °K	8	10	12	

*This table does not cover the guidelines completely and only gives instances of how indoor climate factors vary between classes.

TABLE 2 Indoor Air Quality—Acceptable Levels of Pollutants in Indoor Air of Different Air Quality Classes

Item	Pollutant		Maximum permissible quantity mg/m^3 in class		
			AQ1	AQ2	AQX
1	Carbon monoxide, total				
		MV 0.5 h MV 8 h	60 6	60 6	As specified
	—from tobacco smoke	MV 1 h	2	5	As specified
2	Carbon dioxide	MV 1 h (in ppm*)	1000 600	1800 1000	As specified
3	Ozone	MV 1 h	0.05	0.07	As specified
4	Nitrogen dioxides	MV 1 h MV 24 h	0.11 0.08	0.11 0.08	As specified
5	Volatile organic compounds (VOC) —total —formaldehyde	 MV 0.5 h MV 0.5 h	 0.2 0.05	 0.5 0.1	As specified
6	Particles from tobacco smoke, inhalable	MV 1 h	0.1	0.15	As specified

**This table does not cover the guidelines completely and only gives instances of how indoor climate factors vary between classes.*

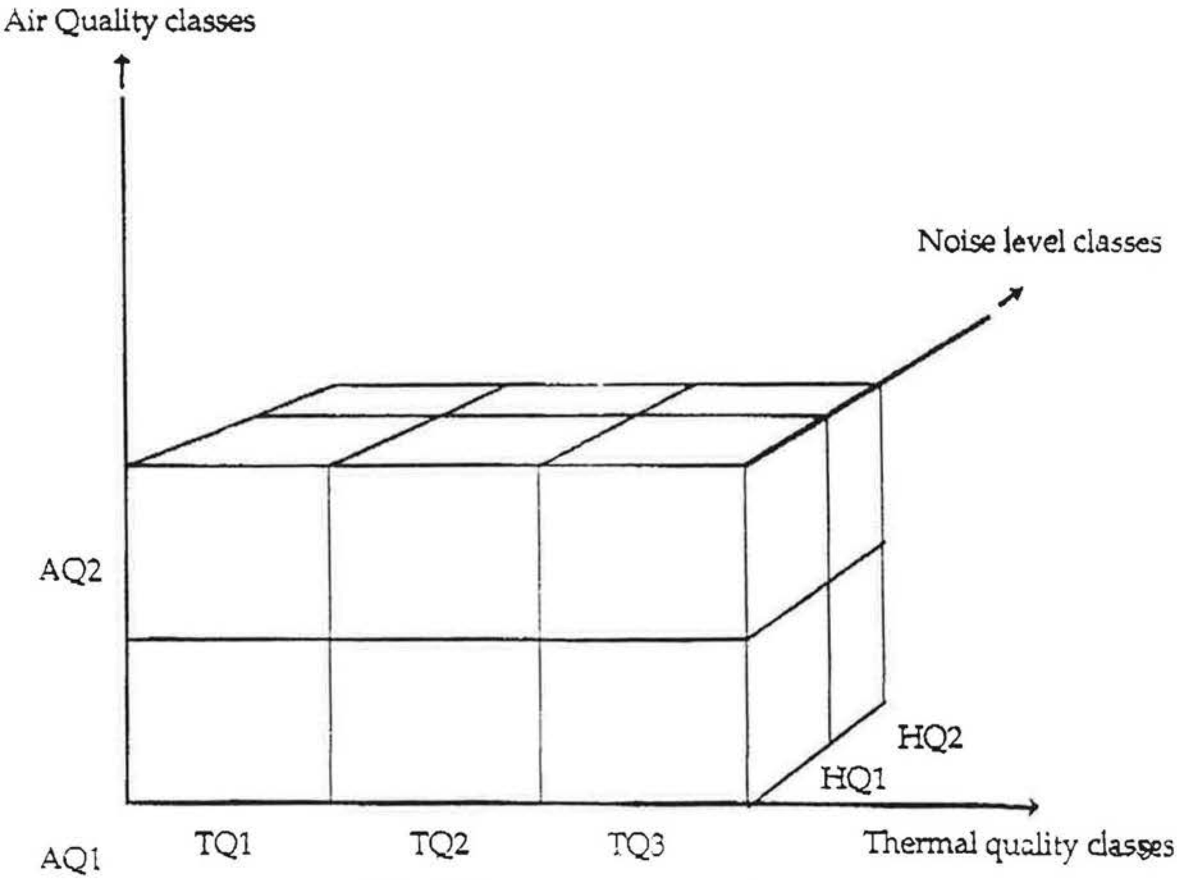

Figure 1 Possible combinations of indoor climate classes

Now, that is an unacceptable simplification. Emissions from building materials often prove to be more serious.

The indoor climate guidelines therefore indicate new methods for calculating the airflow, taking into account pollution both from people and from building and surface materials. These methods rest on building materials being divided into three different emission classes, defined by emissions under operation (low, medium, and high emissions).

The calculation has been simplified to a diagram, indicating the necessary airflow as a function of the percentage of medium or high emission materials prevailing and the person load (number of persons per square meter of floor surface) (see Figure 7).

These new calculation methods give considerably higher airflows than has been customary. An airflow of 0.7 to 1.0 L/s m^2 (1.4 to 2.0 cfm/ft^2) proves sufficient only if low-emission material is used. When high-emission material is used, 5 to 10 times that figure is required.

Airflows of that magnitude are unrealistic. For that reason, the use of high-emission building materials must be limited if an air quality in accordance with the Scanvac guidelines is to be obtained. By demonstrating the results of the use of high-emis. building materials, the guidelines indicate a method for choo. suitable materials with regard to the indoor climate, in other w to limit emissions from building materials.

COOPERATION

The quality of the indoor climate is established by a comp interrelationship between factors of building technique, vent: tion technique, and external environment loads. This requi cooperation between many different professional groups.

AN ECONOMIC ESTIMATE OF THE INDOOR CLIMAT

The guidelines open a possibility of estimating the quality the indoor climate in economic terms on a statistical basis. T: PPD values for each class are then used to calculate the over: costs for bad indoor climate in a building with respect to dissa isfaction, health problems, and lower productivity. Such calc lations had been made in the Scandinavian work. They indica. that bad indoor climate has a big price tag. Indeed, it is not th mission of this paper to discuss that issue.

TABLE 3 Noise Level—Acceptable Values for Continuous Noise Levels in Different Quality Classes

Item	Factor	Highest level in class		
		NQ1	NQ2	NQX
1	**Sound pressure level dBA**			As specified
1a	—dwelling room —bedroom —kitchen —bathroom —WC	— — — — —	30 30 35 40 40	As specified
1b	—office premises —conference premises	— —	30 35	As specified

The percentage of dissatisfied people those classes will produce, statistically seen, is given in Tables 4 and 5. In the thermal classes, the percentage of dissatisfied varies between 10% and 20%. In the air quality classes, the values vary between 1% and 50% depending on which factor is regarded.

TABLE 4 Thermal Comfort (TQ)—Percentage of Dissatisfied for Different Quality Classes and Indoor Climate Factors

Item	Indoor climate factor	Quality class				
		TQ1*	TQ2	TQ3	TQX	Notes
1	Operative temperature	<10%	10%	20%	As specified	
2	Air velocity	10%	10%	20%	As specified	
3	Vertical temperature difference	<10%	10%	20%	As specified	
4	Radiant temperature asymmetry	<10%	10%	20%	As specified	
5	Floor temperature	<10%	10%	20%	As specified	

**This class requires individual control of temperature and airflow.*

TABLE 5 Indoor Air Quality (IAQ)—Frequency Values for Different Quality Classes and Indoor Climate Factors

Item	Indoor climate factor	Quality class			
		AQ1	AQ2	AQX	Notes
1	As determined by toxicological assessment	—	—	As specified	
2	Adverse reaction	0-1%	5%	As specified	
3	Mucous membrane irritation	0-1%	10%	As specified	
4	Dissatisfaction with subjective air quality	10%	20%	As specified	
5	Odor detection as first impression	10%	50%	As specified	

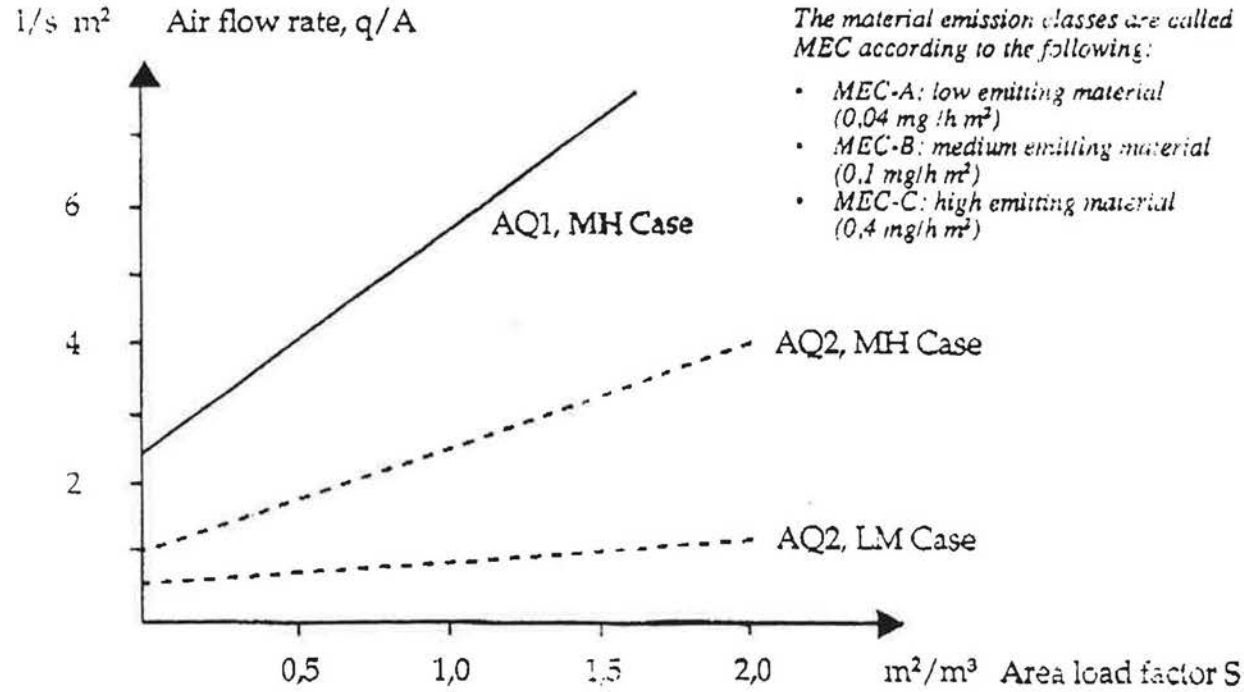

Figure 2 Hygiene airflow rate for n = 0.1 person/m² and low/medium (LM) and medium/high (MH) emission categories in accordance with Standard Method II, 0% smokers

ASHRAE Standard 62-1989: Building Ecology by Voluntary Industry Consensus

K.Y. Teichman, Ph.D.

ABSTRACT

In 1989, the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) revised its ventilation standard, ASHRAE 62-1989, Ventilation for Acceptable Indoor Air Quality. *This voluntary industry consensus standard, subsequently approved by the American National Standards Institute, will likely have a greater impact on the design (and, indirectly, operation and maintenance) of buildings than its predecessors. This increased impact will not be the result of any significant departures from the requirements of previous versions of the standard, but rather an increasing awareness of indoor air quality and its associated economic and legal ramifications. This paper briefly describes some of the significant features of* ASHRAE Standard 62 *and the impact it will have on both energy consumption and indoor air quality in buildings.*

"FOREWORD THINKING"

To understand the requirements specified in Standard 62, one must first understand the format of most ASHRAE standards. The body of an ASHRAE standard includes the purpose, scope, definitions, procedures, and references necessary to comply with the requirements of the standard. Importantly, the foreword and any appendices to a standard are provided for informational purposes and do not comprise requirements for compliance. Appreciating these distinctions is essential to understanding Standard 62.

For example, the foreword to Standard 62 includes the following statement relating to the operation and maintenance of healthy buildings:

> ". . . the conditions specified by this standard must be achieved during the operation of buildings as well as in the design of buildings if acceptable indoor air quality is to be achieved."

Healthy buildings address both energy efficiency and environmental concerns (indoors and outdoors) throughout the life of the building (Levin and Teichman 1991). Therefore, the inclusion of the statement quoted above in the foreword to Standard 62 (as opposed to the body of the standard) renders the achievement of acceptable indoor air quality a desired goal, not the result of solely complying with the standard's requirements.

Similarly, some coments on the standard have questioned the removal of the distrinction between ventilation rate requirements for buildings where smoking is prohibited and buildings where it is allowed. (The 1981 version of the standard, ASHRAE Standard 62-1981, distinguished between these two building types and required larger amounts of ventilation in buildings where smoking was permitted [ASHRAE 1981]). To partially address this concern, the foreword to Standard 62-1989 states:

> ". . . with respect to tobacco smoke and other contaminants, this Standard does not, and cannot, ensure the avoidance of all possible adverse health effects, but it reflects recognized consensus criteria and guidance."

Those favoring stricter control of tobacco smoking in buildings have argued that this statement should be included in the body of the standard (as opposed to the foreword) to give it greater prominence.

"STANDARD FEATURES"

Within the body of the standard, Standard 62 defines "acceptable indoor air quality" as:

> "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction."

There are several important features contained within this definition. First, acceptable indoor air must meet two criteria—an objective, health-based criterion and a subjective odor/irritation criterion. Second, with respect to the health-based component, ASHRAE relies on the determination of harmful concentrations by cognizant authorities, i.e., others whose primary responsibility is public health. Finally, the 80% or more requirement in the subjective criterion has been the subject of much discussion among those who favor increasing this value to address sensitive populations, those who believe achieving 80% satisfaction is ambitious based in part on surveys of occupant-reported symptoms, and those who propose different classes of acceptable indoor air quality with varying percentages of the population exposed anticipated to express dissatisfaction.

How does a designer achieve acceptable indoor air quality? Standard 62-1989 provides two alternative procedures for achieving acceptable indoor air quality—the ventilation rate procedure and the indoor air quality (IAQ) brochure.

In the ventilation rate procedure, acceptable air quality is achieved by providing ventilation air of specified quality and quantity. It is important to stress that, although not a departure from ASHRAE Standard 62-1981, the quality and not just the

Kevin Y. Teichman, Ph.D., U.S. Environmental Protection Agency, Washington, D.C.

quantity of air is specified. For example, among other requirements, the outdoor air used for ventilation must meet the National Ambient Air Quality Standards (NAAQS) set by the U.S. Environmental Protection Agency. Although frequently neglected by many designers, the ventilation rate procedure explicitly prescribes the outdoor air quality acceptable for ventilation and when outdoor air treatment is necessary.

In addition, the ventilation rate procedure lists ventilation rates for residential, commercial, institutional, vehicular, and industrial spaces. These ventilation rates, contained in Table 2 of the standard, are provided in cubic feet per minute (cfm)/person or cfm/square foot (ft^2) for different applications. For example, in office spaces, 20 cfm/person is required.

The ventilation rates listed have been chosen to control carbon dioxide (CO_2) and other contaminants with an adequate margin of safety and to account for health variations among people, varied activity levels, and a moderate amount of smoking. As such, the ventilation rates in Table 2 are derived from physiological considerations, subjective evaluations, and professional judgments. In addition, the values in Table 2 define the outdoor air requirements in the occupied zone for well-mixed conditions (ventilation effectiveness approaches 100%).

Following the ventilation rate procedure, indoor air quality is considered acceptable if the required rates in Table 2 are provided for the occupied space except where unusual indoor contaminants or sources are present or anticipated. In these situations, these emissions are to be controlled at the source or the alternative indoor air quality procedure is to be followed.

The indoor air quality procedure achieves acceptable air quality by controlling known and specifiable contaminants. As opposed to the ventilation rate procedure, the IAQ procedure provides a direct solution to the control of indoor contaminants by restricting the concentration of all known contaminants of concern to specified acceptable levels. This procedure includes both a quantitative and a subjective evaluation.

In the quantitative evaluation portion of the IAQ procedure, acceptable indoor contaminant levels are listed for the NAAQS, CO_2, chlordane, ozone, and radon. Other potential contaminants are discussed in Appendix C. This appendix provides standards, guidelines, and levels of concern for common indoor contaminants from U.S., Canadian, and World Health Organization sources, including information on asbestos, carbon monoxide, lead, nitrogen dioxide, chlordane, ozone, radon, sulfur dioxide, organics (including formaldehyde), particulate matter (including environmental tobacco smoke), water vapor, CO_2, and mineral fibers. However, since these guidelines are provided in an appendix, they are not requirements of the standard.

The IAQ procedure also includes a subjective evaluation portion. In this procedure, the judgment of acceptability derives from subjective evaluations of impartial observers. Appendix C provides one approach to meeting this requirement: air can be considered acceptably free of annoying contaminants if 80% of a panel of 20 untrained observers deem the air to be not objectionable under representative conditions.

POLLUTANT AND ENERGY IMPACTS

How will the adoption of ASHRAE Standard 62-1989 into building codes likely change both guidelines for pollutant levels and energy consumption in buildings? Relative to ASHRAE Standard 62-1981, Standard 62-1989 changes the following pollutant guidelines. First of all, Standard 62-1989 removes the distinction between buildings in which smoking is permitted and those in which it is prohibited. Second, the new standard reflects changes in the NAAQS that have occurred since the 1981 version of the ASHRAE standard, namely ambient standards for carbon monoxide, nitrogen oxides, and particulate matter less than 10 microns in (aerodynamic) diameter. In addition, guidelines for specific pollutants identified in the IAQ procedure portion of the standard are revised as follows: carbon dioxide is reduced from 2,500 parts per million (ppm) to 1,000 ppm; radon is increased from 0.01 working levels (WL) to 4 picoCuries per liter (approximately 0.02 WL); and the 0.1 ppm formaldehyde guideline is removed from the body of the standard and included among other guidelines provided in Appendix C. The net effect of this last change is to remove the pollutant guideline requirement for formaldehyde from the standard, since matter included in the appendices to ASHRAE standards is provided for information only (see discussion above).

With respect to building energy requirements, ASHRAE Standard 62-1989 raises the minimum ventilation rate in buildings currently specified in many building codes from 5 to 15 cfm per person (20 cfm/person in office spaces). What are the energy costs of providing this increased ventilation to promote acceptable indoor air quality?

Using building simulation, researchers at a national laboratory have shown that the increased annual energy costs associated with increasing the minimum outside air ventilation rate from 5 to 20 cfm/person is only about 5% of the total annual energy cost to operate a typical office building (Eto 1988). They also showed that the increase in first costs would be on this order. This permits two important conclusions. First, dramatic increases in ventilation do not result in correspondingly dramatic increases in total annual energy and initial construction costs. Second, buildings should be designed, constructed, commissioned, operated, and maintained to optimize energy conservation and indoor air quality.

The benefits of healthy buildings can also be viewed from the perspective of the trade-off between increased energy costs for ventilation and enhanced building occupant health and comfort. Assume that the total energy costs for an office building are $2/$ft^2$/year, the average employee salary is $20,000/year, and the building occupant density is 100 ft^2/person. With these assumptions, an energy conservation measure that saves 25% of the building's annual energy costs (i.e., $0.50/$ft^2$/year) represents only about 1 minute per day or 5 hours per year of the building employee's time. Therefore, energy cost savings at the expense of acceptable indoor air quality are less than the resulting increased costs associated with reduced worker productivity and compromised employee health.

CONCLUSION

In summary, ASHRAE Standard 62-1989 has already become an important contributing factor to the realization of improved indoor air quality in buildings. This is particularly true because the U.S. federal response to indoor air quality is nonregulatory, i.e., one of research and information dissemination. In addition, the standard will likely have a greater impact on the design (and, indirectly, operation and maintenance) of buildings than its predecessors. Ironically, this increased impact will not be the result of any significant departures from the requirements of previous versions of the standard, but rather an increasing awareness of indoor air quality and its associated economic and legal ramifications.

DISCLAIMER

The opinions expressed in this paper are those of the author and do not necessarily reflect those of the U.S. Environmental Protection Agency, nor is any official endorsement to be implied.

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The Ergonomics of Healthy Buildings: Overcoming Barriers to Productivity

D.P. Wyon

ABSTRACT

A healthy building must provide what each individual user of the building requires of it. As there are innumerable reasons for different users to have different requirements, and almost as many reasons for a given user to have different requirements at different times, this implies that the user must have a degree of control over what the healthy building provides for him. Even intelligent buildings cannot act intelligently unless they are given all relevant information, and there is no way that this can be done other than by involving the user. Interindividual differences can be due to age, sex, skinfold thickness, personality, physical handicap, allergy, or hypersensitivity. Differences between occasions for the same user can be due to clothing, activity, fatigue, thermal history, recent exposure to pollutants, or current state of health. No building control system, however computerized, has access to any of this information. The user is in possession of this information but is often poorly informed about the building. He often has no idea of how the building is supposed to work, no information about how well it is working, and no means of affecting the environment it provides. Thus both the building and the user lack information that is potentially crucial for the user's health. This is why most buildings are not healthy buildings, and often present barriers to productivity. The solution lies in designing the building to provide channels for the communication identified above as being necessary for health; as the building cannot be given the relevant information about each user, the user must be given the relevant information about the building. Healthy buildings must provide the user with insight, information, and influence. Active steps must be taken by the building operator to give users more insight into the possibilities and limitations of the building systems, more information about what is happening (including ways of inspecting the air intake of the building, ways of sampling the quality of the air at various points on its way through the airways of the building toward their own airways, and more influence, that is, more degrees of freedom to experiment until they themselves find out how to remove barriers to health and productivity).

INTRODUCTION

Imagine the following future scenario: research has led to the development of a "nutritional index" that takes account of the major parameters by which diet can be described—energy, protein, carbohydrates, fiber, cholesterol, vitamins, trace elements, and even flavor and texture can be quantified as discrete dimensions—and an equation has been derived, based on the replies given by literally thousands of experimental subjects who experienced a wide variety of diets, and in each case were able to ask for "a little more" or "a little less" until they were unable to decide which they would prefer. The nutritional index equation can predict what proportion of a given group will be satisfied with a given diet. Under the well-controlled conditions of the experiment, no differences in preferred diet were found as a function of age, sex, race, time of day, etc., although the activity level of the subjects and the clothing insulation they wore naturally had large effects. For any given combination of activity and clothing insulation, it is therefore possible, with the help of the equation, to define a range of diets that will satisfy, say, 80% of the population. It has been decided that in view of the importance of food conservation for the economy, the currently very large differences in food consumption between individuals and between families that are, for all intents and purposes, identical cannot be allowed to continue. Optimal food conservation can best be achieved by removing all individual choice and serving a diet with PPD (predicted percentage dissatisfied) equal to 20%. The various components of the diet can be adjusted to use available raw materials while maintaining PPD = 20% for each combination of clothing and activity level applicable to a given consumer group. It has been suggested that in buildings where clothing and activity levels are known, the equation could be used to program food dispensers in each room. The "intelligent building" could then ensure an optimal diet for all while maximizing food conservation at all times.

The above prescriptive approach is in fact already in operation in buildings. This paper will argue that it is as ludicrously wrong for energy and thermal environment as it is for food and diet in the above analogy.

BARRIERS

The following barriers to health, comfort, and productivity will be identified:

1. User substitution by simple rules (USSR, for short).
2. The dictatorship of the group.
3. Prescriptive standards.
4. The 80% tolerance zone.
5. "Intelligent buildings."
6. The GIGO principle of computer science (garbage in, garbage out).

USSR

Even very sophisticated control apparatuses for energy use in buildings, for the "optimization" of the thermal environment, must act on the basis of crude assumptions and models of group behavior that were incorporated at the design stage. To the extent

David P. Wyon, National Swedish Institute for Building Research, Gavle, Sweden.

that these are wrong or inadequate, energy use will always be suboptimal, often causing unnecessary discomfort, inconvenience, and reduced performance and even health for individual occupants whose activities and requirements differ from those assumed. Design-stage energy conservation can work well only if individual differences in behavior and in response to indoor climate are small. Where they are large, as in the case of allergies or hypersensitivities, or where basic assumptions are wrong, as in the case of people working late or on weekends, USSR is a barrier to health, comfort, and productivity.

Group vs. Individual

The dictatorship of the group can have serious consequences for the individual, as in the operation of USSR. The "simple rules" are, of course, based on studies of group behavior and group requirements. Demands for individualization are called "utopian" on the grounds that "information on individual requirements cannot be made available to building systems computers" and, in any case, "buildings cannot affect individual micro-climates unless each person has his or her own room. Thus, individuals must be treated as identical members of a group. Practical, nonutopian solutions to these difficulties will be outlined below.

Prescriptive Standards

Prescriptive standards in the building field are often formulated as minimum standards, but have come to be used as target standards. In the absence of other quality guidelines, builders need only ensure that their product "fulfills building standards" and can then proceed to compete in terms of price. The result is often that users have to contend with buildings that are designed to operate at the minimum standard, with no margin to accommodate user requirements that sometimes or always would require a higher standard. Prescriptive standards should therefore also prescribe margins of individual adjustment, and a group optimum as well as a group minimum standard.

80% Tolerance Zones

McIntyre (1978) has estimated that thermal comfort responses are as variable between occasions for the same person as they are between people. The fact that 80% of a group is predicted to be satisfied within a calculated range of conditions does not necessarily mean that most people will always be satisfied, the implication being that there is no satisfying some people. On the contrary, most people will at some time be dissatisfied with the 80% tolerance zone. The factors leading to individual differences, and to individual variation, are set out below.

Intelligent Buildings

The current trend in so-called "intelligent" buildings is not toward better ways of accommodating individual differences, but in the opposite direction, toward the irrational, frustrating imposition of prescribed thermal environments administered by computers oblivious of our individual differences and beyond our control.

The GIGO Principle

Even if the simple rules that substitute for users in the minds of intelligent buildings are correct, even if they were to be made so complicated that they were theoretically adequate, the input information would be based largely on assumptions about individual users. The GIGO principle states plausibly enough that if the data input to a computer is garbage, the output will also be garbage.

INDIVIDUAL DIFFERENCES

Human requirements of the indoor environment differ because of age, gender, skinfold thickness, personality, physical disability, allergy, hypersensitivity, and habit. Interpersonal differences in environmental effects on performance have been reviewed by Wyon et al. (1982). The building systems computer knows nothing for certain about these characteristics of its users.

INDIVIDUAL VARIATION

Individual requirements may differ between occasions for the same person because of clothing, activity, fatigue, recent thermal history, recent exposure to pollutants, and current state of health and mood (e.g., frustration and hostility toward the building, and boredom or interest in the work to be performed). The building systems computer knows nothing of these factors. The application of simple rules to arrive at user requirements will therefore often result in a mismatch between calculated and actual user requirements.

DECREASED PRODUCTIVITY

Productivity is decreased by 100% in the case of death or absence from work. Both may be caused by accidental injury resulting from human error, the risk of which is increased under unsuitable working conditions. Sickness absence, due to building-related illness, and voluntary absence due to intense dislike of working conditions similarly lead to a 100% decrease in individual productivity. Long before an individual gets sick or stays home, productivity may be substantially reduced due to the sick building syndrome (SBS), which includes such aspects as lethargy, fatigue, and headache, any one of which can lead to productivity decrements above 50%. Similarly, a preoccupation with staying well, safe, and comfortable despite a difference of opinion with the building systems computer can amount to a full-time secondary task that demands up to 50% of available effort, initiative, and ingenuity. Finally, decrements in performance in the region of 10% to 30% can result from the distraction of thermal discomfort, the lethargy and reduced motivation accompanying an environmentally induced state of low arousal, or the overarousal induced by certain other combinations of environmental factors, such as noise, heat, excessive illumination, or mucosal irritants.

MEASURES OF PRODUCTIVITY

Experiments will eventually have to be performed to demonstrate the magnitude of indoor environmental effects upon productivity. This will require the use of measures of productivity. The recording of accidents and injuries is very time-consuming, and experiments using such measures come close to being unethical even if all of the experimental changes introduced are for the better. Why then were not such changes also introduced in the reference conditions? Studies of discomfort and of SBS are once removed from the expected decrease in productivity, although Raw et al. (1990) were able to derive a relationship between SBS symptoms and self-estimates of productivity. Studies of sickness absence due to SBS are valid to the extent that the diagnosis is correct, and Preller et al. (1990) showed that this measure of productivity loss was decreased by 34% in offices where individual control of the thermal climate was possible. Direct measures of performance, focusing on component skills crucial to productivity, are valid to the extent that key activities can be identified. There are numerous studies showing thermal effects on performance, summarized by Wyon (1986), though apparently none as yet using air quality parameters as the independent variables. Overall measures of productivity tend to be affected by so many extraneous factors that the effects of naturally occurring variations in environmental conditions would be difficult to distinguish, and the possibility that productivity really would be decreased by experimentally introduced changes is a financial disincentive to allowing such direct field experiments to take place. For the present, therefore, sickness absence and measurement of component skills seem to be the only viable alternatives to subjective self-estimates of productivity, which are fatally flawed in that they will always reflect users' own expectations of cause and effect, in addition to any actual causation. The removal of barriers to productivity must, in the meantime, proceed on a rational basis, pending a demonstration of the quantitative size of effects on productivity.

OVERCOMING BARRIERS

If the prescriptive group approach is unable to accommodate individual differences in human requirements of the indoor environment and gives rise to the six barriers to health, comfort, and productivity identified above, it must be replaced by another approach. It should be adequately clear from the above analysis that the building cannot be supplied with all the relevant information regarding individual differences, but the building and its systems will always be the effective determinant of individual microclimatic conditions. The user must therefore be given the relevant information about the building, especially about its possibilities and its limitations. A measure of control can then be delegated to the user. However, the user at present often has no idea even of how the building is supposed to work, no information on how well it is in fact working, and no influence on any aspect of its function, except, residually, the anarchic possibility of opening a window, which is often against the rules. Overcoming barriers to productivity therefore requires the building operator to take active steps to provide the user with more insight, more information, and more influence. How this might be achieved is outlined in the following sections.

Insight

User insight into the building systems can be increased by means of an introductory course and the provision of a handbook. Vehicles are very similar to each other, but no one expects to be able to drive one without an introductory course or to buy one without a comprehensive handbook. Even VCRs come with bulky handbooks. Buildings are usually very different from each other, but handbooks and introductory courses are not usually provided for them, although they cost many times more than a vehicle or a VCR. Information on the building should also be displayed on bulletin boards, properly formulated for the lay user, showing perhaps the location of the airways of the building and the sampling ports referred to below. Cutaway models of the building, its air-handling system, and individual heating and ventilating devices would increase user insight into their possibilities and limitations. Visits to the plantroom and the air-intake site would similarly increase user insight.

Information

Users should have access at any time to a display of on-line information about the relevant aspects of building system operation, including room temperature, supply and exhaust temperature for the room, relative humidity, CO_2 ppm, liters per second of air supply, and fresh air proportion. The display could be in a lobby or corridor or available on any networked VDU. This feedback information is a pre-condition for any learning of the consequences of user influence, and is essential for user experimentation with available degrees of freedom.

Users should always be able to inspect air ducts and the air intake site. Sampling ports should be provided at various points in the building and their location clearly marked on planes displayed on a bulletin board to enable users to sniff the air on its way through the airways of the building toward their own airways. Allergics can have thresholds of sensitivity a million times lower than those of normal people and can be relied upon to use these early-warning sources of information. They will voluntarily fulfill the warning function of the miners' canary, and may then be viewed by building operators as an asset rather than as a liability. Users should also be informed of the design limits of each room, perhaps by means of a mandatory notice by the door, analogous to those in elevators. Users expect and respect notice of an elevator's design limitations: they do not expect one to lift twelve people safely if it is rated for six. They might then cease to expect a room designed for "6 people or 600 watts" to cope with 12 people and as many computers. It is understood that the elevator is guaranteed to lift the specified number of people, but the room specification should guarantee to maintain room temperature and CO_2 levels, at the very least, within stated ranges for the specified loading. Users could then use the on-line display to perform simple checks on building system function. The formulation of user-verifiable guarantees of this kind would open new channels of communication between building users and operators, whereas guarantees of the small-print variety would provide more work for lawyers than benefit for the user.

Influence

User influence is increased by the appointment of a user representative whose function is to be more informed than the rest, and to enhance communication between building operator and users, in both directions. User representatives with this function are already in place at all Swedish places of work: they are known as "skyddsombud," and are a kind of lay safety engineer. Users turn to them for practical help and information in all matters regarding safety, including thermal climate and indoor air quality. Users should also have a list of telephone numbers so that they can report building faults and initiate maintenance, repair, and cleaning as and when it is required, instead of having to complain ineffectually until routine inspection also discovers the need. Users should have as much control over their microclimate as can reasonably be devised, and should know how to operate the controls. They should be able to inspect the nearest upstream filter, be able to check the pressure drop over it, and initiate a filter change if one is required; they are the people actually breathing the air. It should not be impossible to design filters that users themselves can change as required. Although this sounds impossible, users should also be able to add air inlets and outlets as required, and to move them around so as to furnish the room with air, thus avoiding drafts where they wish to work. They should similarly be able to install point exhaust, as in a factory, so that machines such as computers, copiers, and fax machines do not load the room system by contributing heat or air pollution. The air used by these machines to remove excess heat often smells of hot plastic and the fire retardants used to coat electronic components: it should not reenter the room, but should be removed by a point exhaust duct, wherever it is situated in the room. Impossible in an office? Raised-floor systems offer the possibility of siting air inlets and outlets freely and of installing point exhaust ducts discreetly connecting each machine to the floor. Users should be able to requisition the appropriate inlet, outlet, and point exhaust devices and move floor-tile-mounted units around as they see fit. Workstation HVAC, otherwise known as an environmentally responsive workstation (ERW), the ultimate in individual microclimate control, is also easier to install in combination with a raised-floor ventilation system.

INDIVIDUAL MICROCLIMATE CONTROL

As soon as two people must share the same room, conflicts arise that can be barriers to productivity. Whereas one person may be draft-sensitive, another may be allergic. The former wants less fresh air, the latter wants more. One may feel cold, the other hot, for perfectly understandable reasons as set out above. Even if the room has its own climatic system, it will be impossible to agree on the control settings. Other conflicts may exist even for one person: as warm air rises, it is difficult to keep a cool head without getting cold feet. That is, the thermal profile has the wrong slope. Workstation HVAC can address these problems, providing each user with additional sources of heating and cooling power, arranged so as to correct the thermal profile experienced by the user, and to provide the option of additional fresh air delivered to the breathing zone. These options must be completely under user control, and so arranged that they neither affect the microclimate of any other user in the room nor the room climate itself to any extent. The room system is then relegated to a background function, which it can perform better. Workplace HVAC systems should shut down automatically when the user is absent. A system with these characteristics has been developed within the Swedish National Board of Public Building (Byggnadsstyrelsen, the Swedish GSA) and has been described by Wyon et al. (1991).

CONCLUSION

Barriers to productivity can be removed in healthy buildings by adopting a radical alternative strategy based on getting the user back into the system, rather than engineering him out. Arguments for this approach were put forward by Wyon (1988), some of which, including the food analogy, have been repeated here. Practical means exist today for implementing this strategy. The continuation of the present prescriptive, group-based approach that ignores individual differences will result in many more sick buildings and more barriers to productivity.

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Workshop Summaries

IAQ and Thermal Comfort in the Design of Healthy Buildings

Facilitator: J. Woods
Reporter: O. Seppanen

1. *Is there a unified standard for IAQ ventilation and thermal comfort?*
   - There is insufficient information to develop such a standard.
   - We should continue to develop individual standards.
   - We should proceed with unified guidelines.
2. *Design and operational parameters vs. standards and codes.*
   - Design and operation should be more for occupants.
   - Feedback is missing.
   - Buildings do not meet standards.
   - Values of design parameters for good IAQ and climate do not exist in codes.
   - Code makers should be encouraged to adopt ASHRAE standards.
3. *Does lowering the room temperature reduce the amount of outside airflow required for acceptable air quality?*
   - No.
4. *Are ventilation rates seasonal?*
   - There is seasonal variation in practice.
   - Requirements may also vary seasonally (emissions, humidity, temperature, outdoor air quality).

Questions 5 and 6 were not addressed.

Materials in the Design of Healthy Buildings

Facilitator: J.R. Girman
Reporter: J. White

In this workshop we were asked to answer six questions. The first of these was *whether natural materials are healthier than synthetic ones and does it matter whether a material is natural or synthetic?*

The answer was "not necessarily." To say that natural materials are healthier than synthetic materials may currently be a good marketing strategy but is also a sweeping statement that lacks foundation. Certain materials are viewed as healthier based upon past experience, but results from systematic testing are not available. It was also pointed out that some natural products, e.g., cedar, have strong emissions that create problems for some individuals. More information on emissions and health effects would be needed to support the notion that natural materials are healthier. Individuals with MCS would especially benefit from such knowledge.

Two additional research questions emerged during this portion of the workshop:

1. Is sorption different for natural and synthetic materials? Only limited information was available. It is known that wool is a stronger sink for some pesticides than many synthetic fabrics and that it also absorbs more water, which may enhance the growth of microbials.
2. Are emissions from natural and synthetic materials that are used for the same purpose significantly different and, if so, do these differences affect health?

Our second question was, *"Is emission testing useful for the design of healthy buildings?"*

It was generally, but not universally, agreed that emission testing serves a useful purpose. However, there were questions about how this can be achieved and what is the state of the art. There were concerns as to whether chamber data could be reliably extended to larger, more complex indoor environments. Some wondered if single-material tests could represent emissions when materials were combined into assemblies or systems and, if so, how that could be done. It was suggested that whole assemblies should also be tested.

A question emerged as to what result should be reported from emission testing—TVOC or selected, individual chemical species. There was concern that use of TVOC could conceal important information, such as the presence of a carcinogen, which could certainly affect material selection. Detailed knowledge of individual chemical species is necessary for assessment of potential health effects. However, there was also recognition that testing for TVOC was relatively inexpensive, would allow for more materials to be tested, and could be appropriate for some comparisons of materials in the same category. For many materials, speciation of emissions would be moot since health effects data are lacking.

In fact, the most prevalent concern was about the lack of health effects data. There is a clear need to link emissions testing with biological responses so that an architect or designer can specify a healthier material because its use would produce a lower concentration of a particular compound and, therefore, reduce the probability of occurrence of a specific health effect.

"How can emissions tests be presented to designers and consumers?"

The preferred method appears to be reporting the concentration of a specific chemical or mixture and an associated health effect.

To address concerns about whether small chamber emission rates are appropriate to whole-house scenarios, it was stated that the linkage was well established. However, it was noted that it is crucial that the chamber studies be done correctly (that is, dynamically). Furthermore, successful extrapolation of the data to a specific environment requires detailed knowledge of the environment (that is, volume, air change rate, airflow characteristics, presence of sinks, etc.). Knowledge of the time history was emphasized since many sources vary over time.

The question of the applicability of TVOC emerged again but with no further resolution.

However, an important question was asked: Who should be responsible for testing materials—government or industry? The response was mixed. Most believed that the government should take the lead in developing standardized methods. Some participants believed that government should also take the lead in the testing as well, either by an active program of testing or by requiring testing by other parties. It was pointed out that the latter was currently a component of the indoor air bill in the U.S. House of Representatives and would apply to GSA specifications. It was believed that this would lead others to do the same. Suppliers of products were urged to request information from manufacturers.

With respect to industry testing (i.e., by manufacturers), it was pointed out that, to an unknown extent, many in industry already conduct emissions testing on their own and competitors' products. However, because of concerns about liability and maintaining a competitive advantage, they do not release the data. The concern for competitive advantage argues for one of two possible approaches. Either a level playing field for all manufacturers must be provided so that there is comparable information for use by consumers and designers, or manufacturers need to utilize the indoor air issue as a means to gain a competitive advantage in the marketplace. With respect to liability, it was pointed out that manufacturers have the obligation to produce healthy products and that, if legal action is brought against a manufacturer, all records, technical as well as anecdotal reports of adverse health effects from complainants, would be subpoenaed, resulting in disclosure.

Finally, it was suggested that perhaps all materials data could be presented in terms of odor acceptability. It was noted that designing occupancy schedules of new buildings on the basis of odor has been done successfully. It was argued that the end point is distinct—either it smells unpleasant or it does not. However, some participants observed that odor is only one aspect of human response.

We were asked, *"Is low-emitting material healthy?"*

Clearly, what makes one material healthier than another is the human response. Therefore, low-emitting material must be interpreted in terms of an undesirable health end point. TVOC may not be the best measure of this. It was suggested that TVOC data must be well qualified and used only to compare emissions from similar materials. In this use, substantial differences in TVOC could be interpreted as having a potential difference in effect.

But is low-emitting material healthy? There was no real answer. It depends on what is being emitted. This argues for chemical speciation in emissions data to provide a firmer linkage with health effects. In the absence of health effects data specific to the individual VOCs emitted and at the appropriate concentrations, TVOC may provide additional information on one consideration that can be used to select products.

"Are people willing to pay for lower-emitting materials?"

There was not a strong response to this question. It was argued that if source control, as it relates to odors, was presented to a user in terms of the cost savings accrued through lower ventilation requirements, the user world be more willing to pay for lower-emitting materials. It was pointed out that individuals with MCS already pay for lower-emitting materials to preserve their health. A key point here, however, is in identifying who pays versus who accrues the benefit. This can be a major obstacle. For example, a building owner must be convinced that it is profitable for him before he will agree to the use of a lower-emitting but more costly material.

This issue was not resolved. It could well be that lower-emitting materials are beyond the reach of some users. On the other hand, some materials could be produced as low emitters at little additional cost, if manufacturers were convinced there was a market for them.

Our final question was *"should ASHRAE standards, especially the ventilation standard, address contaminant source controls in more detail than in the current Standard 62-1989?"*

There were very few comments on this issue and, perhaps, little consensus. The standard appears to be amenable to such an inclusion and already has discussion on biological contamination. However, except in the case of materials used for construction of the ventilation system, there did not appear to be much support for modifying Standard 62-1989 to address contaminant source controls.

Designing Healthy Energy-Efficient Buildings

Facilitator: D. Grimsrud
Commenters: J. Ventresca
T. Lindvall
Reporter: A. Persily

The facilitator began this workshop with the basic question of whether energy-efficient building design and good indoor air quality are compatible. He pointed out that conventional wisdom and popular perception, even among some experts in both fields, are that energy-efficient building design and good indoor air quality are not compatible. The workshop participants quickly responded that this viewpoint was an oversimplification and was simply not true. Referring to Harry Gordon's talk earlier in the morning and Eto's study of the additional energy costs of increasing ventilation rates, it was noted that while these increased costs are always large, they are real. The extra cost may or may not be large, depending on the building type, its occupancy characteristics, climate, and building systems, and one's perspective. But even when the energy cost increases are significant, it was pointed out that there are numerous opportunities to offset these increases through design strategies such as daylighting, controls, and improved equipment efficiencies.

Some of the confusion arises when energy efficiency is erroneously equated with closing the outdoor air intake dampers. Such an action is obviously detrimental to indoor air quality, and it was pointed out that it may not save as much energy as one might anticipate due to increased envelope infiltration rates when dampers are closed. Regarding indoor air quality, it was pointed out that outdoor air intake rates are just one factor affecting indoor air quality. There are many other important factors to consider, such as source strengths and thermal comfort parameters, which in many cases are more important than ventilation rates.

The discussion of the compatibility of energy efficiency and good indoor air quality can be summarized by two important questions:

How important are outdoor air intake rates to indoor air quality and the perception of the indoor environment?

How important are outdoor air intake rates to energy consumption?

Outdoor air intake rates are important to both, but are not the most important factor in either case. For example, occupant perceptions seem to be more closely related to indoor temperature and humidity than the per person rate of outdoor air intake.

The discussion of energy efficiency and air quality quickly focused on other issues. It was pointed out that designing for energy and air quality is only part of the story. The important issues of operation and maintenance remain, and shortcomings in these areas were repeatedly cited as key reasons for both poor air quality and excessive energy costs. There are many good designs and technologies that are not being used properly due to bad operation and maintenance. There is a need to improve the capabilities of users (operators) through training in these technologies and in the specific approaches being employed in the buildings they are operating. There is also a need to educate owners and managers that improved operation and maintenance save money through decreased operating costs, lower liability, and improved comfort and productivity. By improving operation and maintenance, one can save energy, increase the outdoor air intake rate if necessary, and improve air quality and overall occupant satisfaction with the indoor environment.

One of the questions posed at the workshop was how outdoor air pollution affects the healthiness of energy-efficient buildings. Outdoor air quality is obviously an important issue, but it is not exclusive to energy-efficient buildings. It was pointed out that technology exists to clean outdoor air, and that indoor air quality will be degraded when outdoor air intake rates are increased when the outdoor air quality is poor. Cases in which indoor air quality complaints increase during the spring and fall, when economizer cycles are in effect, may be caused by the increased outdoor air intake rates when outdoor air quality is poor. On the other hand, these complaints may be due to temperature control problems, particularly those associated with low perimeter loads during these same seasons. The poor quality of outdoor air was discussed in more general terms as reflecting larger societal problems associated with transportation and development.

Thomas Lindvall made a very interesting point during the workshop when he stated that the energy savings realized in newer buildings may need to be used in older buildings to improve their environments. This may result in no net change in the energy use in the building sector, and he pointed out that this suggestion is often not a popular one.

Measures to Achieve Good IAQ in Occupied Buildings during Construction and Renovation

Facilitator: E.L. Besch
Commenters: J. Tiffany
E. Light
Reporter: S. Rose

Issue No. 1: *How should construction/renovation activities be conducted in the occupied building (i.e., to maintain morale, productivity)?*

1. Identify a project leader.
2. Conduct an inventory prior to initiation of work to determine what will be removed and what will stay in place (e.g., hazards, odor, noise).
   a. Is HVAC isolated to renovation space or not?
   b. Can dust from renovated areas be spread to nonrenovated areas?
   c. It is important to know which substances can potentially be spread.
      (1) Develop premodeling (i.e., baseline) information.
      (2) Identify components that may be disturbed.
      (3) At the conclusion of renovation, compare actual noise, odor, etc., with baseline values.
      (4) Project leader should possess knowledge of pertinent regulations, codes, and guidelines.
3. Inform occupants if potential risk exists; be prepared to move occupants to other areas; time work for unoccupied hours.
4. The best approach is to minimize all risk to employees throughout the renovation process.
5. Carry out all activities in a responsible and legally aware fashion.
6. Maintain direct, clear, open, and regular—including written—communications (concerning disruptions, noise, odor) with employees, occupants, unions, etc.
7. Develop timely responses to occupant complaints.
8. Always be proactive.

Issue No. 2: *How can disruptions and loss of productivity be minimized for all parties?*

1. Develop actions on a case-by-case basis (e.g., occupied hours can be rescheduled only in some places).
2. Planning and communications are important.
   a. Identify a project leader early.
   b. Utilize a permit system.
      (1) Limit access to ceilings; remove occupants below.
      (2) Know and approve welding activities in advance.
      (3) Establish and maintain good coordination between all parties (e.g., workers, occupants).
3. Maintain credibility through good planning and communication.
4. Do not be a firefighter—this approach does not work. Planning and teamwork do work.
5. Maintain clear, direct, open, and regular—including written—communications with employees, occupants, unions, etc.
6. If possible, alter employee hours on a case-by-case basis but prevent disruptions to support services.
7. Monitor progress of renovation to ensure no "surprises" are occurring; monitor what is being added to renovated spaces.
8. Do not move occupants to unacceptable temporary quarters.

Issue No. 4 (includes Issue No. 3): *How does one ensure that the building functions as designed?*

1. Develop a quality assurance plan that can be validated at the end of the renovation.
   a. Design must match intended occupancy.
   b. Identify and test new products prior to introduction.
   c. Follow protocol; no shortcuts.
2. Utilize second party involvement; this may contribute to problem identification and resolution.
   a. Develop (architect) list of IAQ expectations.
   b. Validate (second party) that the list of expectations is fulfilled.
   c. Retest after completion.
3. Ensure that primary and secondary parties (e.g., architect, engineer, industrial hygienist) are team players.
4. Require and perform an annual checkup.
   a. Utilize team (i.e., architect, engineer, industrial hygienist) approach.
   b. Utilize summer-winter rotation for validation measures.
5. Ensure an ongoing, effective preventive maintenance program.
6. Maintain good communications between all parties.

Construction and Renovation during Partial Occupancy

Facilitator: P. Morey

Panelists: H. Eisenstein
J.R. Girman
H. Levin
J.E. Woods, Jr.

Reporter: P. Morey,
notes transcribed by H. Levin

Consensus was reached on the following:

Acceptable IAQ can be maintained during build-out in a new building or during renovation in an old building primarily by isolation of the construction-renovation zone from the occupied spaces. Many of the techniques used in the asbestos abatement industry can and should be applied to isolate dusts and VOC emitted during construction/renovation. Special actions that should be used to control air contaminants associated with construction/renovation include:

- Isolate HVAC of construction zone from all occupied spaces.
- Isolate construction zone from all occupied spaces by physical barriers (i.e., polyethylene sheeting).
- Exhaust air from construction zone to outdoor air via fans in windows or other building openings. Negative pressurization of construction zone must be demonstrated by manometers in physical barrier or other measuring devices. Exhaust fans must have sorbents for VOCs and fabric filters for particulate matter.
- Verification that construction contaminants do not enter occupied spaces can be demonstrated by compliance testing for TVOCs and airborne particulate.
- The HVAC must be recommissioned for all affected zones after construction is complete.
- Personal protective equipment (e.g., respirators) may be necessary to protect workers in construction zones.
- Excellent communication of actions being taken by the building operator to protect occupants from airborne construction contaminants is essential.
- Construction workers must be trained with regard to action needed to prevent contaminants from entering occupied spaces.

Any action to remediate possible airborne construction contaminants at their source is always beneficial in proactively preventing IAQ problems. For example, the use of sealants and adhesives that emit lesser amounts of VOCs is advised. Sealants and adhesives used in construction work should be chosen based on the absence of irritating/malodorous chemicals among their ingredients.

The presence of an HVAC economizer adds flexibility to enable the building operator to control VOC construction emissions through dilution ventilation.

Practitioners are now on notice that the current standard of care requires that building occupants be protected from renovation/construction air contaminants through source isolation (steps noted above) and source substitution.

Consensus was not reached on the following discussion items:

More discussion and work are needed to decide if large central air-handling units (supplying air to many floors at the same time) are more desirable than small air-handling units (distributed system), each supplying air to only one floor or a portion of a floor. Thus, large units that should be more easily maintained cannot be easily operated in a building so as to isolate and restrict VOCs to the construction floor. Some discussion ensued on the use of a fire/smoke control system in large buildings to positively pressurize occupied floors from construction floors. The use of distributed air-handling units on each floor, while in theory perhaps the best approach for isolating air in various parts of the building, suffers from the absence of preventive maintenance commonly given to small units. Poor IAQ is almost always associated with inadequate maintenance.

Human perception of odors and the visual occurrence of settled construction dusts in occupied spaces can be used as simple tools to monitor acceptable IAQ.

Source Assessment

Facilitators: D. Moschandreas
H. Levin

Reporter: H. Levin

Dr. Moschandreas began by summarizing the progress made since the 1988 Healthy Buildings conference in Stockholm. Dr. B. Tichenor of the U.S. EPA said we had developed standard methods for emissions measurements in small chambers (EPA Guide, ASTM Standard); we have conducted information dissemination. He suggested that we should discuss sinks as well as primary sources; everything absorbs and re-emits, he said.

Define Acceptable Materials

Dr. P. Wolkoff of Denmark said it is hard to identify "acceptable" materials. We must go beyond measurement of emissions; we have to find out which VOCs are important, which ones cause the effects of concern to us. The Danes have used multi-phased testing including the mouse bioassay for irritation, odor panels, chemical emissions testing and evaluation, and observable changes in the human subject's eye (tear film quality). This panel of tests provides more useful information than the sum of the individual test results.

Dr. Moschandreas suggested that we will never find a perfect material or combination of materials because of additive and synergistic effects among their emissions. An architect said that building type and use dominate the decision-making process. Building use is what drives the decision on material selection. He asked: How will sources have their VOC content reduced?

Source Control vs. Ventilation

Regarding the issue of source control vs. ventilation, there are two basic phases or modes: (1) the initial emissions during construction, when one must maximize ventilation to avoid loading up the sinks with emissions from wet materials, and (2) the long-term emissions from dry and "dried" products when ventilation is used in combination with sinks.

Dr. Tichenor said that the wet sources are "huge"—one cannot provide enough ventilation to control them. Therefore, source control must be used. He suggested management of the occurrence of maximum concentrations in an acceptable (occupied or vacant) time period with the use of ventilation for faster removal so the VOCs cannot go to sinks.

A ventilation engineer said we are leaning toward ventilation as the control option of choice. Local exhaust as a method of control should also include isolation of the source whenever practical. It was suggested that source control can best be accomplished by designers, specifiers, and building owners applying pressure to the manufacturers of the products they purchase.

Initial installation procedures are important features of source control; guidelines and standards should be available for various product types and specific products. One participant suggested that we need a different approach to contaminant control. Building materials all decay over time, but office machines, appliances, consumer products, etc., are continually generating contaminants throughout their useful lives.

Isolation as a form of control differs for gases and physical contaminants. For example, moisture is another contaminant that needs to be controlled, but its control is different from control of VOCs or of particulate matter.

Maintenance is important; there is a need to learn how to better control dust in carpets and on other soft (fleecy) surfaces.

HVAC Systems as Sources

Ventilation systems themselves, including their filter, sound absorbers, and insulation, can be a source and a sink. Man-made mineral fiber is a dust collector.

Source Testing

Source testing has occurred, but there are few published reports. One participant asked, "Why aren't there more published data?" There is a need to get the results of source testing into the hands of those who make the decisions in buildings.

A scientist with a major materials manufacturer stated that most manufacturers know what is coming out of their products; they use the information as a development tool. But testing is an evolving technology; it is expensive and time-consuming. Not many commercial laboratories can do it, but as time passes, more of it will happen.

Dr. Tichenor said that the cost of testing is related to the number of samples that must be analyzed. Through comprehensive testing, we can reduce the number of samples required and, therefore, the cost of testing. Analytical costs are huge, and other forms of testing, such as the mouse bioassay, are not cheap either.

Dr. Wolkoff asked, "What do you want to measure?" That, he said, is the critical question. Unless you know what you are trying to learn, you cannot answer that question. He also suggested that we consider how well each of the available test methods performs in terms of what it attempts to measure.

One of the architects said it is difficult for the practicing architect or engineer to take something home from this kind of discussion and use it in his/her practice.

Important Sources to Control

Discussion was focused on where VOCs come from in buildings. Janitorial activities were identified as an important source. Wet products are quite different from dry ones in terms of their emission profiles.

The following sources were identified as important by various participants:

- Wet or high-solvent-content products.
- Aerosol products.
- Magazines and newspapers.
- Porous insulations.
- Humidifiers; VOC from corrosion inhibitors.

The following specific types of products were named as important sources:

- Cosmetics.
- Toiletries.
- Filters for air cleaning.
- Occupants.
- Dust on carpets and open shelves, ducts, and filters.
- Oils in fans.
- Dust as a sink and a secondary source for volatile, especially semi-volatile, compounds.
- Auto exhaust.

Finally, the workshop participants ranked source categories in order of importance as follows:

1. Building operations: housekeeping and maintenance activities and products.
2. HVAC system components.
3. Refinishing and refurnishing operations within occupied buildings.
4. Dirt, debris, and moisture (primary or contributing sources).

Performance Guidelines for Controlling Indoor Air Quality by Ventilation

Facilitators: E. Mayer, CIB Indoor Climate Working Group
J. Talbott, U.S. Department of Energy
K. Teichman, U.S. Environmental Protection Agency
G. Yuill, Pennsylvania State University

Two concurrent workshops were held on the topic of "Performance Guidelines for Controlling Indoor Air Quality by Ventilation," and both workshops addressed the same questions (identified below). This report summarizes the opinions expressed in both workshops in response to these questions and also includes "along the way" comments, which greatly enriched these sessions.

Question 1: To what extent are existing ventilation standards or guidelines being used in building design?

Workshop participants agreed that ventilation standards are receiving increasing attention, especially when they are incorporated into building codes. However, it was duly noted that new ventilation standards can set the "standard of care" for building design (and *operation* in California), even if they are not part of the appropriate building code.

Designers appear to be using only portions of ventilation standards. For example, most designers do not address outside air *quality* considerations, even though this requirement is not new. Similarly, participants felt that many building designs do not give proper attention to ensuring ventilation air is supplied to the occupant's breathing zone.

Finally, workshop participants agreed that the ASHRAE Standard 62-1989 indoor air quality procedure is rarely used.

Question 2: Is compliance with ventilation standards enforced? If so, how and is the enforcement effective?

Workshop attendees universally agreed that the enforcement of ventilation standards is ineffective. This opinion was held independent of geographic borders. Reasons offered included the absence of an easy, standardized protocol to check compliance and the concern that competent code checking is unusual. For example, participants were divided on both the usefulness of carbon dioxide tracer decay studies and the use of flow hood measurements in combination with techniques to determine the percent outside air in air-handling units.

Health and safety inspectors only have time to inspect problem buildings. Therefore, although desirable, buildings are not spot checked to ensure compliance.

Finally, some participants expressed the opinion that improved education and certification efforts may be a better way to address the issue of ensuring compliance.

Question 3: How can ventilation standards or guidelines be improved?

How should ventilation standards address smoking?

No clear consensus was achieved on how ventilation standards should address smoking. For example, some participants felt that smoking should be explicitly addressed in ventilation standards; others thought smoking should be the subject of a separate, global guideline. Similarly, attendees were split on whether environmental tobacco smoke is a problem in recirculated air. Finally, some participants view tobacco smoke as only one of many pollutants to be concerned about, while others view it as an easily identified and controlled source.

One participant discussed the Swedish experience with this issue. In Sweden, there is a ban on smoking in buildings with susceptible populations, e.g., schools and hospitals. In addition, it is recommended that there be a ban on recirculating air in buildings where smoking is permitted or, at a minimum, signs posted to inform building visitors (and occupants) when tobacco smoke is included in recirculated air. Another participant reported that the American Industrial Hygiene Association has recommended that, in addition to establishing smoking cessation programs, employers should set aside a work and/or lounge area for smoking if all employees assigned to the area agree to the designation and the air exhausted from such an area is vented to the outside.

How should ventilation standards address other indoor pollutants?

Some workshop participants expressed the opinion that it was a lost cause at this time to list more than the pollutants currently identified in ASHRAE Standard 62-1989. Other participants thought that the recent Scandinavian efforts to identify pollutants of concern and acceptable levels within different classes of air quality merited consideration. All participants felt that additional research on the health effects of both individual pollutants and pollutant mixtures is needed.

What is the role of ventilation standards or guidelines in the construction, commissioning, operation, and maintenance of buildings?

Workshop attendees strongly endorsed the application of ventilation standards or guidelines in all phases of a building's life, from design through construction and commissioning, operation and maintenance, and renovation. Participants noted that California's ventilation standard already applies to building operation and maintenance. In addition, attendees stated that consideration should be given to providing a section on compliance in ventilation standards.

Other Questions

Workshop participants were asked three additional questions related to improving ventilation standards or guidelines. Due to the ambitious set of questions prepared for discussion, these questions received relatively less time and attention and are summarized as a group below.

With respect to how air-cleaning technologies should be considered in ventilation standards, some workshop participants expressed the opinion that ASHRAE's filter standards should address health implications in addition to engineering performance. Separate ventilation standards were deemed appropriate for residences and large buildings, although this opinion was not unanimously held. Finally, with respect to whether standards should provide minimum and recommended criteria, attendees felt that Scandinavian thought on different classes of air quality was an intriguing concept that merited serious consideration.

Additional Comments

Along the way, participants made comments that enriched the workshop discussions. These opinions are presented below in bulletized form:

- The IAQ procedure of ASHRAE Standard 62-1989 is good, but designers need emissions data, a model to predict exposures, and a method to evaluate IAQ performance before the procedure will be widely used.
- Outside airflow percentages should be increased as variable-air-volume systems reduce total flow. Maintaining outside airflow rates at a constant percentage of supply airflow is inadequate.
- Outside air should be provided by a separate, independent system.
- Ventilation effectiveness should continue to be a consideration in ventilation standards or guidelines, but it may only be a ±10% effect. Rather, pollutant removal effectiveness should be stressed.
- Federal buildings should serve as examples of good indoor air quality.
- Ole Fanger's example of a building with good indoor air quality (no smoking, low-emitting materials, good ambient air quality) requires about 20 cfm/person!
- Designers need practical information on engineering approaches to achieve good IAQ. Operation and maintenance personnel need similar information.
- Standard 62-1989 and its related energy requirements are still an issue. The relationship varies with building location, function, and HVAC system type.
- Standard 62-1989 should characterize what is meant by an "unusual" source.
- Standard 62-1989 was the product of extensive committee deliberations. Those charged with revising the standard should take it easy and not rush to prepare a hurried revision.