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Critical Building Design Factors for Indoor Air Quality and Climate: Current Status and Predicted Trends

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Abstract

In recent years, some building design professionals have become more aware of the indoor air quality concerns of owners and occupants and as a result, they have made some important changes to improve indoor air quality and climate. These changes include improvements in site planning and design; overall building design; ventilation and climate control systems; and materials selection and specifications. In addition, changes that limit the chemical contamination of building air during the construction process and during occupancy of buildings are also occurring; some of these changes are specified or controlled by design professionals. However, the majority of design professionals have little or no awareness of indoor air quality considerations. There is inadequate dissemination of building science research results to design professionals. There is a need for a useful general body of knowledge, theory, and practice regarding building-environment-occupant interactions. The lack of such knowledge, theory, and practice is an impediment to developing the necessary professional design tools and practices to address effectively indoor environmental quality and energy conservation issues.

KEY WORDS:
Design, Architecture, Site planning, Materials selection, Building ecology

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Introduction

Important changes in building design have taken place in recent years and many of these changes can improve indoor air quality (IAQ) and climate significantly. These changes are being made in response to heightened awareness and concerns of occupants, building owners, and the design professionals themselves. Additionally, building products and materials manufacturers are making and marketing products to improve IAQ (Levin, 1989, 1990a, 1990b).

The changes tend to fall into four major categories: site planning and design; overall architectural design; ventilation and climate control; and materials selection and specifications. Additional design and building professional responsibilities related to the commissioning of newly constructed or renovated facilities have developed. Table 1 lists the major phases and subcategories of critical building design control.

Major IAQ Control Measures by Design

Many design approaches to IAQ control have been used in various projects. In this section we identify some of the dominant trends and approaches to provide an overview of the field. Not all of the IAQ control methods described in this paper are used by even the most air quality conscious designers. Some of them are no more than pro-

Table 1 Major phases and subcategories of critical building design control

Site planning and design
Ambient air quality
Local source control

Overall architectural design
Vehicle access
Building openings
Operable windows
Pollutant-generating activities
Mix of users in building
Envelope and structural materials
Penetration of volumes
Basement dehumidification
Smoking lounges

Ventilation and climate control
Dilution by outdoor air
Air intakes
Exhaust locations
Air cleaning
Space air distribution
Heat recovery
Microbial control
Standards development

Materials selection and specifications
Low-emitting materials
Preventive installation procedures
In-place curing

Construction process and initial occupancy
Design documentation and commissioning
Special ventilation
Initial occupancy period

posals and have not, to our knowledge, been used at all, although each has been developed within the context of some actual building design process. We have made an effort to identify the nature and extent of use of most of the design IAQ control measures described.

Site Planning and Design

During site planning and design, a few design professionals address sources of indoor air contaminants in ambient air. These sources may originate at a distance from the site or locally. They include gaseous and particulate contaminants generated by motor vehicle, power generation, and industrial process combustion; particulate matter from agriculture, road dust, and wind-generated soil erosion; and ozone formed by the combination of NO_2 and hydrocarbons in the presence of strong sunlight. Soil gas contaminants including radon and organic chemical compounds can enter buildings through gaps in construction elements in contact with the soil or by direct migration through semi-permeable building materials. Table 2 lists the major elements of IAQ control during site planning and design.

There are several control measures that building designers use to control indoor air quality by site planning and design. They evaluate sites prior to acquisition and project planning to avoid problem sites. They locate

Table 2 The major elements of IAQ control during site planning and design

Pre-design site evaluation
- Analyse regional and local ambient air quality data

Analyse adjacent and nearby pollutant sources
- Vehicular traffic
- Industrial sources
- Commercial sources
- Agricultural sources

Analyse soil and groundwater sources
- Radon and other radioactive decay products
- Volatile and semi-volatile organic compounds

Determine prevailing weather and wind patterns
- Diurnal variations
- Seasonal variations
- Microclimate

Site planning
- Site selection for suitability
- Building location and orientation
- Vehicular circulation

Local source control
- Landscape and architectural buffers
- Soil depressurization
- Drainage
- Site preparation and imported soils

the building and appurtenances on a site distant from pollution sources or pollutant plumes. They plan vehicular circulation and parking to minimize pollutant concentrations at the building edge, especially air intakes and other openings (Levin, 1988, 1989).

Designers and project planners can review and evaluate ambient air quality data and local contaminant sources during feasibility studies. Data are obtained on air quality and climate from local agencies. Soil and water samples are analysed for potential sources of contaminants. Activities in adjacent and other nearby structures are identified to determine potential pollutant emissions. If necessary, air monitoring is performed to evaluate outdoor air quality and proximate pollutant sources. Soils and gaseous soil emissions are tested for volatile organic chemicals (VOC) and radon. Where warranted, mitigation measures including pressure relief systems and more effective sealing of pathways into the building are designed to reduce soil gas or groundwater penetration into the structure (Levin, 1988).

Overall Architectural Designs

The overall architectural concept (or "schematic" building design) includes basic decisions about building shape and size, orientation, layout of floor plans, location of pollutant-generating activities, envelope and interior materials, fenestration, and general ventilation. Experience shows that many IAQ problems result from decisions made at this stage of the project. Although problems resulting from such decisions can be mitigated by subsequent control measures, it is often more cost-effective to consider good IAQ from the outset and to design for it already at the schematic design phase. Very few designers have considered IAQ in the development of the design concept, although the number is growing. Table 3 lists the major categories of overall architectural design considerations.

Table 3 The major categories of overall architectural design considerations

Location of vehicle access	Separate from air entry points
Vehicles in buildings	Provide air supply and exhaust removal, negative pressure to building
Building openings facing clean air	Consider sources, wind, building pressure
Operable windows for backup ventilation	Occupant-controlled for comfort
Isolate pollutant-generating activities	Separate rooms, negative pressure, no recirculation
Durable envelope and structural materials	Minimize emissions, maintenance, refinishing
Basement dehumidification, pressurization	Prevent microbial contamination, pests, soil gas entry
Separate smoking lounges	Exclude polluting behaviour from general space

Building Openings

Openings through which contaminants might enter should be located distant and not downwind from identified pollutant sources outside the building. Interior building areas adjacent to such potential sources of exhaust fumes are positively pressurized to reduce possible entrainment of exhaust. Relationships of spaces with adjacent functions must also be considered.

Operable Windows

In a reversal of the trend toward sealed windows that dominated building designs from the 1960s well into the 1980s, buildings designed recently have often included operable windows. In some instances these are provided as an "emergency ventilation" system in the event of inadequate ventilation by mechanical means. In many such instances occupants are not actually permitted to open the windows; in some cases they are locked in the closed position. When mechanical ventilation is operated to create positive pressure inside a building, opening windows might not provide additional outdoor air.

Some designers provide operable windows to allow occupants the psychological benefits of direct visual access to the outdoor environment as well as to actually allow air to enter occupied areas directly. The installation of a sensor "interlock" for window operation and the ventilation system controls can maintain a "balance" in the ventilation system while permitting occupant operation of windows. The sensor sends a signal to the ventilation system controls which then compensate for the change in pressure. Such a system has been proposed for the new United States Environmental Protection Agency headquarters facility (Levin, 1988).

Pollutant-Generating Activities
Activities such as food preparation, printing, art, tobacco smoking, certain health care, and others can be sources of contaminants inside buildings. These activities are identified and located away from sensitive areas or occupants. Airflow is controlled to avoid transferring contaminants to adjacent spaces or into a recirculating mechanical ventilation system. Direct exhaust without recirculation is the preferred solution. These IAQ control design measures are being used more frequently and by growing numbers of designers, although consideration is still insufficient in the vast majority of projects.

Envelope and Structural Materials
Materials are chosen that are known to have low pollutant emission characteristics. When such materials are not suitable, alternative means of controlling the contamination of air in the completed building are used including temporary ventilation, in-place curing, and encapsulation or isolation of materials from the building occupants' air. Where glazing permits direct sunlight to strike interior materials, darkened glass or shading devices are used to minimize such sun entry. This reduces surficial heating of materials and associated episodic elevation of VOC emissions. Increasing numbers of designers are concerned about emissions from building materials, but relatively little has actually been done to consider material emissions in most projects.

Vehicle Access
Motor vehicle access to garages, loading docks, and pedestrian drop-off points are located away from air intakes and building entries when designers consider indoor air quality. Where openings do occur near vehicle access points, positive building pressure is maintained inside the opening to keep exhaust fumes out. Spatial relationships of vehicles and occupied building areas must also be considered. This addresses one of the most widely recognized sources of IAQ problems, and growing numbers of designers are considering vehicle access in relation to building openings.

Basement Dehumidification
Control of microbial contamination in basements is accomplished by reducing humidity. Some designers have developed and tested full-scale installations of sophisticated systems to control humidity as well as soil gas entry into basements in Canadian houses. The Canadian system has also been designed to reduce water leakage and cold floors (Walkinshaw, 1990). Further research and development activities are likely to produce refinements and alternative systems to improve IAQ and climate in basements.

Special Provisions for Polluting Activities
During overall building design, identification of occupant activities likely to be sources of indoor air pollutants allows planning for their containment and control. Printing, cooking, art and hobby activities,

and other common building occupant functions can be addressed by locating them where their emissions will not adversely affect other parts of the building. By providing separate, dedicated, and properly ventilated spaces, their impacts can be minimized.

Other activities such as photocopying, food preparation, and graphic arts have also been provided with increased ventilation, no recirculation, and additional exhaust systems to minimize exposure of building occupants to the contaminants they emit. Special exhausts with inlets close to the pollutant source have been proposed to control indoor air contaminant levels effectively (Levin, 1988). Dedicated exhaust systems and spaces with direct exhaust ventilation impact the flexibility of interior space planning resulting in an expanded definition of building core. Considering the control of emissions from polluting activities is becoming increasingly common in building design and is, to some degree, practised by most design professionals. Improved information on sources and their control will enable more adequate consideration.

Smoking Lounges

Public awareness and new laws have resulted in the design of separate spaces for smoking in some public access buildings. One-pass ventilation with no recirculation is usually provided to eliminate exposure of non-smoking occupants to environmental tobacco smoke. There is a strong trend in the United States to limit smoking to designated areas or to prohibit it within the building. Nevertheless, there are still many buildings where the issue remains unaddressed by the designers.

Ventilation and Climate Control

Ventilation is viewed by many as an essential design strategy for IAQ control. They argue, that there are too many sources, the sources are too diverse, and they change over time making it impossible to avoid them by design. In particular, contaminants emitted from occupant activities, personal hygiene products, clothing, and other sources are outside the control of the design professional or builder. Therefore, ventilation including dilution of contaminants with cleaner air (either outdoor air or filtered, recirculated air) is used to control contaminant concentrations to acceptable levels. Table 4 lists the major ventilation design considerations for good IAQ.

Questions exist as to the suitability of outdoor air for such dilution, about the proper approach for strong contaminant sources, about contamination from the ventilation system itself, and about distribution of ventilation air within the building. Filter and air cleaner manufacturers are actively involved at present in developing effective air cleaning methods to remove gaseous contaminants. Virtually no designers thoroughly evaluate outdoor air quality and devise means to control contaminants when required to provide acceptable air quality for supply air used for ventilation. ASHRAE Standard 62 (both 1981 and 1989) requires consideration of the quality of outdoor air used for ventilation, and widespread adoption of the standard by code-promulgating authorities is likely to stimulate attention to this requirement.

Dilution by Outdoor Air

Dilution and removal of contaminants by ventilation continues to be the principal approach to indoor air quality control. The quantity of outdoor air used for this purpose is the subject of much investigation and is a driving force in ventilation system design. The issuance of the revised ASHRAE ventilation standard (Standard 62-1989, "Ventilation for Acceptable Indoor Air Quality") has resulted in some changes, mostly increases, in the quantity of outdoor air required for the ventilation of various types of occupancy (ASHRAE, 1989a). This is the primary, if not the only means of controlling indoor air quality in the majority of building designs.

Table 4 The major ventilation design considerations for good IAQ

Dilution by outdoor air ventilation
Outdoor air per occupant (OA CFM/p)
Outdoor air exchanges per hour (OA ACH/h)
Ventilation based on contaminant source strengths
Direct exhaust from polluting activity spaces
Air intake locations, design
Avoid plumes from known and suspected sources
Avoid standing water and cooling tower drift
Prevent bird roosting or animal entry at intakes
Building exhaust locations
Avoid contamination of ventilation air intake by re-entrained exhaust
Increase height and distance from air intakes
Air cleaning and filtration
Outside air meets ambient air quality standards:
- particles: media, electronic filters
- gases: chemisorption, scrubbers
Recirculated air meets guidelines/standards
Space air distribution
Prevent/eliminate "dead zones" and stratification
Deliver ventilation to occupant breathing zone
Maintain effective pressurization control
Balanced supply and return air systems
Heat recovery
Energy-conserving outdoor air ventilation
Transfer air for high ventilation rate areas
Use heat recovery devices where practicable
Microbial control
Avoid fleecy materials in air stream including ductwork
Eliminate standing water in drip pans

Even so, delivery of the required quantity of outdoor air to the occupants' breathing zone as required by the ASHRAE standard has not been addressed explicitly in the majority of projects to date.

Ventilation standards based on outdoor air supply per occupant have been shown to be insufficient to control unusual or strong contaminant sources. Adequate ventilation rates must be based not only on the human occupant density but also on the activities that will take place, the types and strengths of contaminant sources, the ventilation system distribution scheme, and the volumetric dimension of the spaces in the building. These are explicit requirements of the Standard 62-1989, but their application has been vigorous in only a small number of building designs to date. It is often difficult to identify most or all of the sources during the early stages of design. A review at the time the actual occupancy is clearly defined might be necessary in order to implement the requirement.

Air Intakes

The known sources of potential contaminants for outdoor air intakes include exhausts from other buildings, motor vehicles, industrial and agricultural processes, and exhausts from the building itself. Many building designers have begun locating building air intakes distant from various building systems including plumbing stacks, kitchen and toilet exhaust air vents, and the ventilation system itself. In large buildings, cooling towers are located distant from air intakes to avoid entrainment of drift containing water treatment chemicals or microbial contaminants.

Exhaust Locations

The location of the building system exhaust is related to that of the air intake. Designers reduce potential re-entrainment of exhaust air by locating outlets downwind and distant from potential intake sites. However, the impact of the exhaust location on IAQ is not considered sufficiently in most projects.

Air Cleaning

Where outdoor air is contaminated, designers specify the use of air cleaning and filtration as appropriate. Designers are choosing more efficient media filters or using electronic air cleaners to reduce concentrations of particulate matter in ventilation air. Gaseous contaminants have been largely ignored until now. However, growing consciousness of outdoor air contaminants and their entry into buildings is leading to the investigation and specification of adsorbents for improving ventilation air quality. When indoor air is recirculated with little outdoor air being introduced, air cleaning and filtration are used to remove contaminants from indoor sources. Particles and gases are removed by the means mentioned above. These air cleaning and filtering devices have been used both in central HVAC components and locally (within or near the occupied space).

Space Air Distribution

Considerable differences of opinion exist among researchers and engineers regarding the extent to which ventilation supply air mixes within building spaces. Designers in some areas have begun introducing supply air through the floor, at desk top, and from sidewall diffusers to improve space air distribution. Return air registers are being carefully placed to avoid short-circuiting of supply air to the exhaust system. Supply and return air systems are being carefully balanced to improve space air distribution.

Partial-height partitions in open-space offices can block the airflow, especially under low flow volume and velocity conditions. Some designers raise partition bases above floors to improve the airflow and ventilation space air distribution. Others have used supplemental fans to improve space air distribution. Desktop supply inlets and inlets mounted in raised floors have also been used to improve space air distribution as well as energy efficiency of ventilation systems.

Induction units, fan coil units, and local (personal) fans have been used. "Personal" or individual control of such supplemental units has provided occupants with more access to airflow and comfort.

Heat Recovery

In order to maintain indoor air quality without unnecessary loss of energy efficiency, heat recovery systems are now being used. When designed to remain in service during maintenance, a high level of performance can be achieved (Greim et al., 1990). This technology is not widely used at present, but increasing pressures for improved indoor air quality and energy conservation are likely to stimulate its use.

Microbial Control

Designers have focused considerable attention on reducing potential microbial amplification within ventilation systems. This has been done by selection of materials to minimize absorption of dirt and moisture that provide niches for microbial colonization. Fibrous insulation has been a particular concern due to the large number of instances in which microbial amplification has been observed on its surface in problem buildings.

Control has been achieved by eliminating or reducing the use of exposed fibrous materials for acoustic control, by placing thermal insulation outside of ductwork, and by thoroughly sealing insulation from circulating air. Many designers are now specifying these measures. The ASHRAE Standard 62 calls for attention to potential problems stemming from man-made mineral fibre insulation. Research has shown that as it accumulates dirt, it becomes more hygroscopic, and when wet can easily host microbiological organisms (West, 1989).

There is a need for improved acoustic and thermal insulation materials for use in mechanical systems so that both insulation and air quality goals can be achieved (Levin, 1990b). Insulations exposed to the air stream can be completely covered with mylar or another vapour barrier to minimize the potential for contamination.

Drip pans for cooling coils have been designed for positive drainage to eliminate standing water contributing to microbial growth. Ductwork, mixing chambers, and plenums are being designed for ready inspection and cleaning to control contamination. Humidifiers are now specified using "dry steam" rather than cold water sprays to minimize the likelihood of microbial contamination. While these practices are not yet widespread, increasing numbers of architects, mechanical engineers, equipment manufacturers, and contractors are implementing them.

Standards Development

ASHRAE's recently published revised standard for ventilation and indoor air quality is widely regarded as the most authoritative guide for designers. However, its actual application is almost always limited to use of the prescribed quantities of outdoor air supply during design of building ventilation systems. Other important requirements such as outdoor air quality or the control of unusual pollutant sources are generally ignored by architects and HVAC system designers.

There is no universal agreement regarding the quantities of outdoor air supply required to maintain good indoor air quality. In fact, a very wide range of values for recommended or required outdoor air supply rates exists; the values appear partly to depend on the purpose of the indoor environment and the type of occupants anticipated in it. Thomas Lindvall of Sweden has presented a range of values for outdoor air supply rates from various authorities (Lindvall, 1989). Table 5 lists various recommended and adopted ventilation rates.

Currently there is discussion about revision of the ASHRAE standard and possible integration of thermal comfort criteria into a single, unified indoor environmental design standard. Due to the complexity of the issues, such an integrated standard is not likely to be developed quickly, if at all. Yet building design professionals must resolve the issues even though the standards writers may not be able to do so. It is likely that the ventilation standard will be revised. The revised standard may include more detailed, specific guidance on acceptable contaminant levels and system design requirements, although a scientific basis for guidance on most contaminants is lacking (Grimsrud and Teichman, 1989).

Table 5 Various recommended and adopted ventilation rates (Lindvall, 1989)

(l/s)[a]	Basis or recommending/adopting group and year
>0.3	2% CO_2 (respiration)
>0.5	1% CO_2 (performance)
>1	0.5% CO_2 (TLV)
>3.5	0.15% CO_2 (Pettenkofer Rule, 1858; body odour)
2.5	ASHRAE Standard 62-1981
3.5	Swedish Building Code 1980
4	Nordic Building Regulation Committee 1981
5 - 7	Berglund et al. (body odour)
8	Fanger et al. (body odour)
7.5	ASHRAE Standard 62-1989
5 - 10	Swedish Building Code 1988
10 - 30	Swedish Allergy Committee 1989
10, 20	Nordic Building Regulation Comm., preliminary 1989
16 - 20	Weber et al.; Cain et al. (Tobacco smoke annoyance)
14 - 50	Fanger et al. (total odour)

[a] 1 litre per second ~ 2 cubic feet per minute

Materials Selection and Specifications

The selection and specification of materials has been the subject of enormous interest, particularly by designers who believe that source control is the most effective strategy for controlling IAQ. Some designers and authors have suggested reducing VOC emissions into indoor air by the careful selection and installation of building materials and furnishings. Some data are available to allow comparison of emissions from various products. However, no comprehensive set of data exists nor is it likely to in the foreseeable future due to the large number of products and the variations in them over time. Some designers and their consultants have attempted to evaluate the toxic and irritant properties of emissions in order to choose less harmful or irritant chemicals (Levin, 1989; Girman, 1989). Table 6 lists the major steps in conducting such an evaluation.

Material emission testing has been done by a few research institutions and is beginning to be done by product manufacturers as well (Tucker, 1990). Manufacturers are now advertising products as "low-polluting," "non-toxic," "environmentally safe," and other such claims (Levin, 1990a). While such trends are only in their infancy, significant changes are already occurring.

Some designers are requiring the submission of emissions data by manufacturers before specifying or approving the product for use in a building. Included among the projects where such requirements are imposed are several major governmental projects that are "visible" to manufacturers. This has stimulated the development of testing in laboratories and the writing of standards for the conduct of such testing (Levin, 1990a; Tichenor, 1989; ASTM, 1990).

Table 6 Material selection and specification

Specify IAQ concerns in bid documents: - health, safety, and comfort of occupants - manufacturer responsibility for review and assurance
Require submittal of product contents and emission tests
Select low-emitting materials and products
Criteria for evaluating emissions data: minimize - odorants - irritants - systemic toxins - carcinogens, teratogens
Specify minimal required use of adhesives
Minimize use of fleecy (high surface area) materials
Utilize preventive installation procedures - ventilation during and after installation - in-place curing: ventilation, bake-out

Authorities have proposed guidelines for maximum emissions for low-emitting materials and products (Seifert, 1990). Some researchers are now planning to evaluate emissions in terms of various biological responses to them (Tucker, 1990). Others have used sensory responses of the anticipated occupants as a screening technique. In one case, the occupants of a home included two chemically sensitive children. After chemical screening, the children judged the products on the basis of brief exposures (Salares, 1990).

The maintenance requirements and projected life-cycle of materials are design considerations with important implications for indoor air quality. Too often these considerations are not adequately addressed during design. Some designers have developed materials and products that consider these factors, with positive effects on indoor air quality. Evaluation of the results indicate that such efforts can be successful in improving indoor air quality (Fredriksen, 1990). Only a few examples of such efforts have been described in the professional and scientific literature.

Problems remain in adequately characterizing emissions from the thousands of available products. Testing is expensive, time-consuming, and not standardized. Interpretation of results is difficult due to lack of knowledge regarding health effects. Trade-offs between the significance of toxicity and irritation must be determined. Nonetheless, the concern of designers is leading to the development of cleaner products and the elimination of some of the strongest emitters from the market (Levin, 1989; 1990a).

During the coming years it is likely that the marketing of materials will become increasingly competitive while regulatory initiatives increase pressure on reluctant manufacturers. The likelihood is that some of the strong emitters will be replaced by other products. Researchers will increase our understanding of the factors necessary to select "clean," less harmful building products and furnishings.

Controlling Emission Impacts through Ventilation during Installation
Ventilation procedures are specified to reduce the adsorption of VOC emitted from building materials during installation. These procedures involve one-pass, all outdoor air ventilation continuously during installation of strong emitting materials. This reduces the contamination of "fleecy" materials by adsorption of the solvents and other volatile components of adhesives, caulks, sealants, plastics, and other building materials. It is specified that painting and carpeting be done under maximum ventilation conditions. Continuous ventilation during and after installation is required by designers (Levin, 1988; 1989; 1990a).

Construction Process and Initial Occupancy

Design Documentation and Commissioning
Table 7 lists the major steps available to designers to control IAQ during construction and initial occupancy. Designers wishing to control IAQ now document design assumptions thoroughly and provide clear, detailed descriptions of building systems. This documentation is used to evaluate the completed construction during the "commissioning" phase before occupancy. The building is tested against the design criteria to assure its suitability for occupancy (ASHRAE, 1989b). This procedure is rapidly being adopted by a growing number of designers and owners to provide assurance of good IAQ and other building design specifications.

Table 7 Construction and initial occupancy

Prepare design documentation and commissioning plan
Document design assumptions
Document systems characteristics, function
Plan commissioning process
Special ventilation
During and after installation of strong sources:
all outdoor air, continuous ventilation
seal return air plenum, ducts
Commissioning process
Complete operation and evaluation of HVAC system
Challenge system under full and part loads
Initial occupancy period
All outdoor air ventilation, extended hours
Respond to occupant complaints
Monitor occupant responses to reduced ventilation

Special Ventilation
Designers have begun to specify extra ventilation immediately before and during initial occupancy of newly constructed or renovated buildings. All outdoor air, 24-hours per day ventilation is used to minimize occupant exposure to emissions from new materials and furnishings. Such extra ventilation also reduces the potential for under-ventilation by incompletely balanced HVAC systems, often characteristic of new buildings with poor indoor air quality.

A special procedure known as a "bake-out" has been used in many buildings, and some initial research results have been reported. The procedure involves raising the building temperature for 48 hours or more while maintaining at least minimal ventilation. The elevation of temperature results in more rapid emission of VOC and a correspondingly reduced contaminant load. The research results indicate that the method has potential to reduce contaminant air concentrations, that the process is not a trivial one in terms of technical requirements, and that there are some significant additional costs associated with its use. It would appear that pre-treatment of materials prior to installation would be a more efficient approach for many materials. However, for adhesives, paints, sealants, and other products applied on location, it may not be possible to reduce emissions adequately in a reasonable time period without the use of a procedure such as the "bake-out" (Girman, 1989).

Initial Occupancy Period

Due to the presence of many newly installed materials and furnishings, the initial occupancy period is often accompanied by the presence of strong emission sources. In order to control the concentrations of indoor air pollutants from these sources, ventilation protocols are modified. Ventilation systems are set to provide maximum outdoor air (up to 100% where possible) during operating hours to reduce airborne concentrations of VOC. Additional hours of operation are provided, sometimes continuously (24 hours/day) until emission levels have tapered off. This might be from three to six or eight weeks after installation. Buildings are thoroughly flushed before re-occupancy after any period of vacancy and reduction of ventilation – evenings, weekends, holidays (Levin, 1988). Extra ventilation is often used as a solution to air quality problems. Recently building operators have begun to use it as a preventive measure.

Construction during Occupancy

The occurrence of construction during occupancy is common both in newly completed buildings and during renovation, relocation, or adaptive re-use in older buildings. These situations present challenges to designers, constructors, and building management to avoid exposing occupants to fumes and dusts from construction activities when these contaminants are strongly generated and can produce high concentrations. The problem is especially challenging when the construction area cannot be easily isolated from the occupied areas. The contamination migrates either directly or is circulated by the ventilation system.

Care must be taken to identify the sources of contamination and control them. This can be accomplished, at least in part, by providing temporary ventilation in the construction area while thoroughly isolating it from the occupied zone. Management strategies can provide significant reductions in potential occupant exposure by carefully scheduling both construction and occupant activity as well as temporary occupant relocation. Asbestos or lead abatement projects provide examples of the types of barriers, temporary ventilation equipment, and management strategies that can be employed. These measures are likely to be employed more in the future.

Building Science Research Needs

In spite of a few examples of building design that consider indoor air quality, the majority of design professionals have little or no awareness of indoor air quality considerations. Neither codes nor legal requirements have altered sufficiently to create the necessary awareness and changes in practice.

Part of the problem originates from the fact that there is inadequate dissemination of building science research results to design professionals. Ultimately, it is the building design professional's client who decides whether to address indoor air quality, especially where there are no regulatory or financial requirements to do so.

Information Needs

There is a long time lag in the translation of building science research and related fields into building design professional practice. In most instances, the results from building science research are incorporated into codes, standards, and new products. Additionally, research results are adopted by specialized consultants in new and emerging areas of practice. But economic and institutional factors slow the transfer process (Schon, 1967).

Building design professionals do not normally read technical and scientific publications. Much of their technical information that does not come from consultants is provided by manufacturers and suppliers of building products and materials. Newly qualified professionals provide another source of information when they have acquired new information or learned new methods during their education.

There is a general lack of information available to design professionals regarding indoor air quality. Architects and their consultants who may wish to incorporate low-polluting materials in their designs do not have available to them clear, simple means of obtaining information on products under consideration. They are not trained or qualified to evaluate "healthy" products; they must rely on some sort of industry standards for testing and labelling or rating systems. They need information on the performance of products with respect to durability, life-cycle costs, maintenance requirements, and health effects.

Table 8 Key actors in the building process

Institutional interests
- Codes and standards organizations
- Professional associations
- Industry and trade associations
- Lenders
- Insurers

Designers/builders
- Designers (architects, engineers, interior designers, consultants)
- Product/material manufacturers and distributors
- Builders
  - contractors
  - trades people
  - equipment suppliers

Owners/occupants
- Owners
- Tenants
- Occupants
- Visitors

Building operators
- Building managers
- Building operators
  - janitorial or custodial staff
  - repair personnel
  - maintenance personnel
  - service personnel
- Contract service and supply organizations

Diverse Interests

There is a complex set of actors involved in the process of making and using buildings. Table 8 lists four major groups of individuals with different perspectives, needs, and relationships to the buildings they affect (or that affect them). Controlling energy consumption, indoor air quality, and other environmental factors involves the complex task of coordinating their diverse inputs and resolving differences in their needs.

Need for a Theory of Building Ecology

The absence of a useful general body of knowledge, theory, and practice regarding building-environment-occupant interactions is an impediment to developing the necessary professional design tools and practices to construct and operate low-pollution, energy-conserving buildings. Design professionals and facilities operators are not equipped to analyse buildings as dynamic entities with important impacts on occupants as well as a dependence upon the outdoor environment.

Borrowing from the approach in the biological science of ecology, we have suggested that researchers and practitioners develop a systems approach to understanding building-environment-occupant interactions. We have coined the term "building ecology" to describe this concept or approach to understanding buildings (Levin, 1981). The concept requires application of a systems approach to understanding, designing, and operating environmental control systems in buildings. It also requires consideration of the building as a dynamic and complex entity that continually changes in response to external conditions, occupant activities, and operator interventions. Finally, it requires understanding the complex chemical, physical, and biological processes of a building that influence occupant health and well-being.

Conclusion

Much progress has been made toward improving environmental quality and energy conservation through building design and operation. Site planning, architectural design, ventilation, materials selection, and commissioning have all made contributions. Yet there are still numerous technical problems challenging researchers and professionals alike. The next few years are likely to produce further improvements in indoor air quality by design.

An overall approach to building design involving consideration of the interrelationship of the building, the larger environment, and the building occupants in a complex, dynamic system can contribute much to continued improvement of building environments by architects, engineers, and interior designers. This overall approach, called "building ecology," can also provide the foundation for theoretical advances in the building design professions.

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