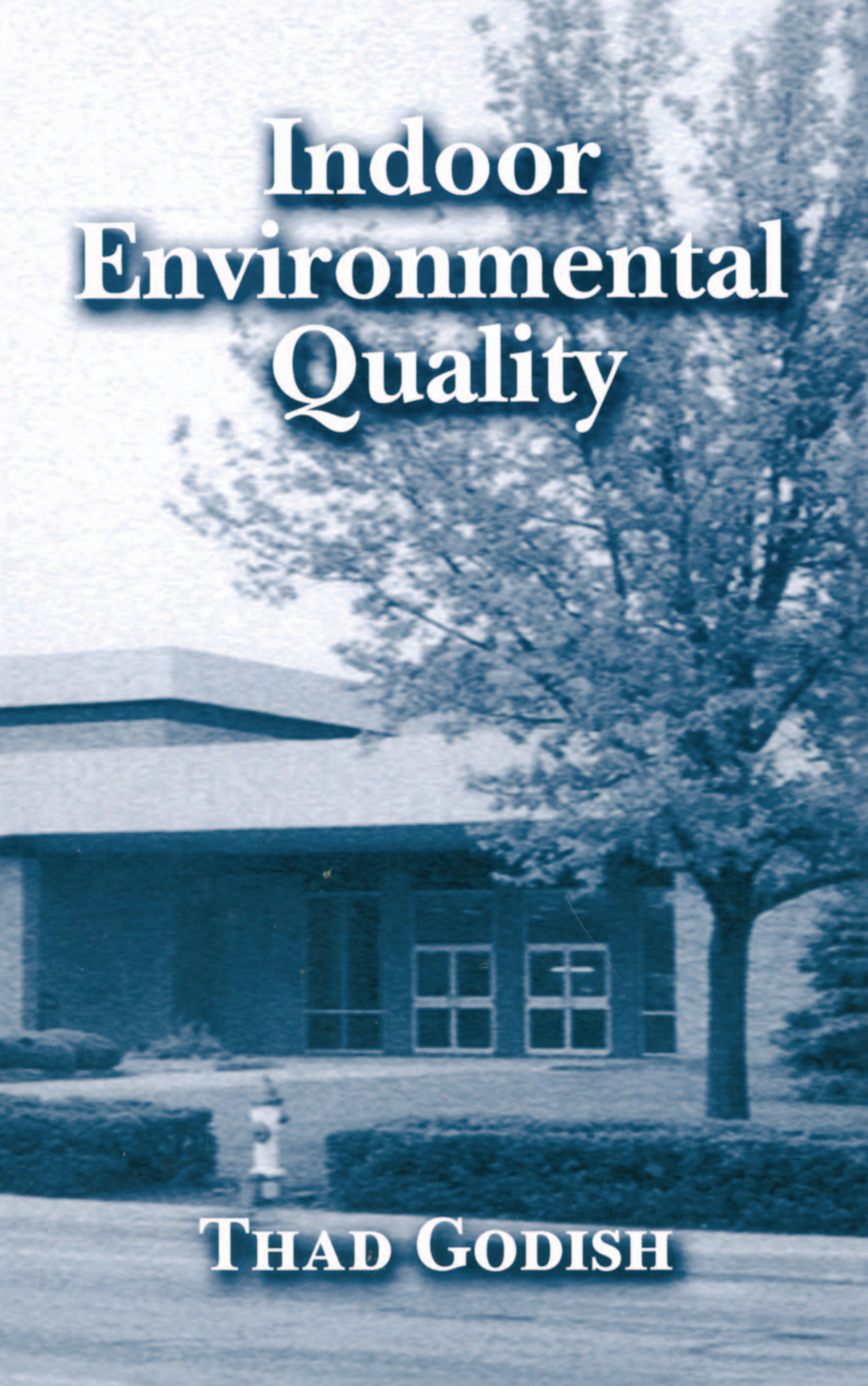

Indoor Environmental Quality

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Preface

Indoor Environmental Quality is the third in a series of books written by the author over the past decade and focuses on environmental problems and issues associated with our homes, office buildings, schools, and other non-industrial indoor environments. This book differs in several ways from the author's previous works, *Indoor Air Pollution Control* (1989) and *Sick Buildings: Definition, Diagnosis, and Mitigation* (1995).

Most important, *Indoor Environmental Quality* reflects the success of research scientists and other investigators in defining the nature and causes of indoor environmental health and comfort problems, and the measures used to investigate and control them. It reflects an increasingly mature field of study. The published results of well-focused, careful research of colleagues around the world are the lifeblood of the author who labors to distill their findings and thoughts into a review article, reference book, or a text designed for use in the classroom.

The author has previously published review articles and reference books whose purpose was to describe major indoor air quality/indoor environment concepts and issues and associated research results. *Indoor Air Pollution Control* focused on the broad area of indoor air quality and the measures used to control indoor contaminants. *Sick Buildings: Definition, Diagnosis, and Mitigation* was more narrowly focused on problem/sick buildings, an area of intensive public health and scientific interest.

Indoor Environmental Quality is written in the style of a textbook, much like *Air Quality* (3rd edition), also by the author. It is anticipated that it will serve as the genesis for the establishment of indoor environment courses in environmental health and industrial hygiene programs in North America and other parts of the world.

Indoor Environmental Quality is intended as a primary resource for individuals who are entering, or are already in the field, whether their interest be research, governmental service, or private consulting. It accomplishes this purpose by defining the major issues and concepts and providing supporting facts in a highly readable manner. Its readability makes it suitable for use by educated laypersons who want to learn about specific indoor environmental problems and how to diagnose and mitigate them, or indoor environmental problems in general.

By its title, the book seeks to go beyond the historical focus on indoor air quality and inhalation exposures to indoor contaminants. Though most indoor environment health and comfort concerns are associated with the indoor air environment, in several major cases air appears not to be the primary route of exposure. This is particularly true in pediatric lead poisoning, which appears to be primarily due to exposures associated with hand-to-mouth transfer of lead-contaminated house dust and soil particles. Similar childhood exposures, including dermal exposures, may occur with pesticide-contaminated house dust. Exposures to office materials such as carbonless copy paper and other printed papers may cause indoor air quality-type symptoms that might be due to dermal and not inhalation exposures. As such, the book attempts to expand its focus beyond "indoor air quality" issues.

Readers of *Indoor Environmental Quality* will notice that many of the concepts and issues treated in previous reference works are included in this new work. That is due in good measure to the fact that concepts and principles continue to be important over time while the facts used to elucidate them may change.

About the author

Thad Godish is Professor of Natural Resources and Environmental Management at Ball State University, Muncie, Indiana. He received his doctorate from Pennsylvania State University, where he was affiliated with the Center for Air Environment Studies.

Dr. Godish is best known for his authorship of Lewis Publishers' *Air Quality*, a widely used textbook now in its third edition; two well-received reference books on indoor air quality: *Indoor Air Pollution Control* (Lewis, 1989) and *Sick Buildings: Definition, Diagnosis, and Mitigation* (Lewis, 1995); and his research, teaching, and public service activities in various areas of indoor air/indoor environmental quality. He maintains a weekly updated web site entitled Indoor Environment Notebook (www.bsu.edu/IEN), which provides expert answers and advice on a wide variety of indoor environmental quality concerns.

Dr. Godish continues to teach a variety of environmental science courses including air quality, indoor air quality management, occupational/industrial hygiene, asbestos and lead management in buildings, and hazardous waste operations and emergency response. He is a Fellow of the Air and Waste Management Association and the Indiana Academy of Science, as well as a member of the American Industrial Hygiene Association, American Conference of Governmental Industrial Hygienists, and International Society of Indoor Air Quality and Climate, and has served as chairman of the East Central section and Indiana chapter of the Air Pollution Control Association. He has been Visiting Scientist at Monash University, Gippsland, Australia, and at Harvard University, School of Public Health.

Contents

Dedication

To the scientists, engineers, architects, and other professionals whose efforts make our indoor environments healthier and more comfortable.

chapter one

Indoor environments

Humans in developed countries have, in the past few millennia, advanced from depending on rock shelters, caves, and rude huts to protect themselves from the elements to modern single- and multifamily dwellings and other buildings that provide amenities and conveniences far beyond the basic needs of shelter — conveniences that ensure comfort whatever the vagaries of weather and climate.

Our world is one of the structures that shelter our many activities: the small to grand shells that house a myriad of industrial processes and activities; institutional buildings such as schools, universities, hospitals, and government buildings; automobiles, trains, planes, and ships that provide transportation as well as shelter; shopping malls and office complexes where we trade goods and services; and cinemas, theaters, museums, and grand stadia that provide venues for entertainment.

Built environments comprise a diversity of functions, magnitudes, and, of course, forms. In addition to functional aspects, built environments reflect human aspirations and creativity. They also reflect more fundamental factors, such as the diversity and availability of construction materials, climate, cultural tastes, and human foibles.

We attempt to keep rain, snow, and wind out of our indoor environments; provide and maintain warm thermal conditions in seasonally cold climates; provide cooler and more acceptable conditions in hot climates; and mechanically ventilate our larger buildings to reduce odors and discomfort associated with human bioeffluents. Our ability to control thermal comfort and other aspects of indoor environments requires the application of a variety of climate-control technologies and a commitment to operate them properly.

The built environments of man are fragile artifacts. They are in constant peril from forces by which the earth renders all things unto itself. Just as water, ice, and wind level the mountains with time, so too do they act to level what man has built. Though the forms of ancient temples and buildings remain after millennia, they have long ceased to shelter humans and their activities. Wooden structures that housed humans for much of our history have been turned to mould. Indeed, the contagion of decay, fed by neglect and the forces of wind and water, constantly imperil even our newest structures. They may even affect our health and make our dwellings unclean. The book of Leviticus in the Old Testament of the *Bible* describes a "leprous" house and what is to be done about it.

> "If the priest, on examining it, finds that the infection on the walls of the house consists of greenish or reddish depressions which seem to go deeper than the surface of the wall, he shall close the door of the house for seven days. On the seventh day, the priest shall return to examine the house again. If he finds that the infection has spread on the walls, he shall order the infected stones to be pulled out and cast in an unclean place outside the city. The whole inside of the house shall be scraped, and the mortar that has been scraped off shall be dumped in an unclean place outside the city. Then new stones shall be brought and put in the place of old stones, and the new mortar shall be made and plastered on the house."

Though we design buildings and other structures to provide shelter from an often hostile outdoor environment, the shelter they provide is less than perfect. They are subject not only to the forces of nature, but also to the randomness inherent in the second law of thermodynamics or its derivative, the law of unintended consequences.

As we attempt to provide both shelter and those many amenities and conveniences that make life more comfortable, we, in many cases inadvertently and in other cases deliberately, introduce a variety of contaminants that have the potential to diminish the quality of our lives or pose moderate to significant health risks to occupants.

Indoor environments are often contaminated by a variety of toxic or hazardous substances, as well as pollutants of biological origin. When early humans discovered the utility of fire and brought it into rock shelters, caves, and huts, they subjected their sheltered environments to the enormous burden of wood smoke (not much different from modern cooking fires in developing countries) and attendant irritant and more serious health effects. Biological contaminants such as bacteria, mold, and the excretory products of commensal organisms (e.g., dust mites, cockroaches, mice, etc.) have caused human disease and suffering for most of human history. However, viewed within the context of infectious and contagious diseases such as tuberculosis and bubonic plague, illness caused by asthma and chronic allergic rhinitis can be seen as relatively minor.

In advanced countries, increasing concern has developed in the past several decades about contaminants in our building environments and potential exposure risks to occupants. These have grown out of previous and contemporary concern for the health consequences of ambient (outdoor) air pollution, water pollution, hazardous waste, and the general pollution of our environment and food with toxic substances such as pesticides, PCBs, dioxin, etc.

Other factors have also "conspired" to increase our awareness that contamination of built environments (particularly indoor air) poses potentially significant public health risks. These have included: (1) recognition of the health hazards of asbestos and its widespread presence in schools and many other buildings, and the regulatory requirements for inspection of public and private schools for asbestos as well as its removal prior to any building renovation/demolition; (2) recognition of the significant exposure to formaldehyde (HCHO) experienced by residents of mobile homes, urea–formaldehyde foam-insulated (UFFI) houses, and conventional homes in which a variety of formaldehyde-emitting urea–formaldehyde resin-containing products were used; (3) recognition that residential buildings and some schools have elevated radon levels (thought high enough to carry a significant risk of lung cancer); (4) the apparent consequences of implementing energy-reducing measures in response to increased energy prices in the mid 1970s, including reducing ventilation air in mechanically ventilated buildings, using alternative space heating appliances such as wood-burning stoves and furnaces and unvented kerosene heaters, and reduced air infiltration into buildings; (5) an eruption of air quality complaints in hundreds of buildings in the U.S. following changes in building operation practices; (6) progressive awareness of the problem of childhood lead poisoning and its association with house dust from lead-based paint; and (7) an increasing understanding that biological contaminants of the indoor environment, e.g., mold, dust mites, pet danders, cockroach excreta, etc., play a role in causing human asthma and chronic allergic rhinitis.

I. Indoor contamination problems

The contamination of indoor air and horizontal surfaces (by dusts) is common to all built environments. Such contamination is most pronounced in industrial environments where raw materials are processed and new products manufactured. These environments pose unique exposure concerns and are subject to regulatory control and occupational safety and health programs in most developed countries. Though industrial and other occupational exposures are significant, they are not included in discussions of indoor air quality and indoor environmental (IAQ/IE) contamination concerns in this book.

Indoor air quality as it relates to residential, commercial, office, and institutional buildings, as well as in vehicles of transport, is its own unique public health and policy issue, as is the contamination of building surfaces by lead, pesticides and other toxic, hazardous substances. As such, IAQ/IE concerns are, by definition, limited to nonindustrial indoor environments.

Indoor environment problems, as they are experienced in residential and nonresidential structures, tend to have their own unique aspects. In nonresidential buildings, occupants have little or no control over their environments, which are owned and managed by others. In theory, homeowners and lessees have some degree of freedom to modify (for better or worse) the environments in which they live. Because of the nature of activities conducted within, and how buildings are constructed and maintained, residential and nonresidential buildings often differ significantly in the nature of IAQ/IE problems and associated health risks. These building types also differ in how problem investigations are conducted and, in many cases, who conducts such investigations. Because of the differences described above, IAQ/IE problems treated here are described in the context of both residential and nonresidential built environments.

II. Characteristics of residential buildings

Residential buildings can be characterized in the context of (1) the population they serve, (2) ownership status, (3) building types, (4) construction characteristics, (5) heating and cooling systems, (6) site characteristics, (7) occupants and occupant behavior, and (8) exposure concerns.

A. Population served

Residential dwellings are different from other built environments because they must provide shelter for everyone, i.e., an enormous population. This includes individuals ranging in age from infants to the elderly, individuals whose health status varies from healthy to a variety of ailments, illnesses, and infirmities, and who spend anywhere from a few to 24 hours per day indoors. In the U.S., on average, individuals spend 22 hours/day indoors, with approximately 14 to 16 hours at home.

Those who spend the most time at home are the very young, very old, ill or infirm, or those not employed outside the home.

B. Ownership status

Approximately 70% of the U.S. population resides in occupant-owned dwellings, while 30% lease their residence from private individuals or government agencies. This significant private ownership of individual dwellings is unique among nations.

Ownership status is an important factor as it relates to IAQ/IE concerns. It is widely accepted that home ownership carries with it both individual responsibility and pride. Such responsibility and pride can be expected to result in better building maintenance, reducing the potential for problems such as extensive water damage and mold infestation. On the other hand, home ownership can, in many cases (because of human attitudes and foibles), increase the probability that home contamination problems will occur (e.g., indiscriminate pesticide application or storage of toxic/hazardous materials; or engaging in commercial activities or hobbies, e.g., hair dressing salons, silk screening, or wood refinishing, that could cause significant air or building surface contamination).

Home ownership is a significant decision-determining factor when IAQ/IE issues arise. If a dwelling is discovered to have excessively high radon levels, significant mold infestation, or a high potential for lead dust exposure to young children, homeowners have the opportunity to mitigate such problems at their own expense. If the dwelling is owned by a second party, occupants must convince an often reluctant lessor to mitigate the problem, seek alternative housing, or "live with it."

C. Building types

There are two basic types of residential structures: single-family and multiple-family dwellings. Typically, single-family dwellings (Figure 1.1) are detached from other residential structures (although some row houses and condominiums blur the line); multifamily dwellings are constructed as single large structures that provide 2 to >1000 leased individual apartments. Single-family dwellings are characteristic of American rural and suburban areas and older parts of cities. Multiple-family dwellings are characteristic of urban areas and are becoming increasingly common in other areas as well. Because of the limited availability of building sites, multifamily dwellings are the primary form of housing used by families in cities and densely populated countries.

Single-family residences may be site-built or manufactured and placed on site. In the U.S., manufactured houses (Figure 1.2) comprise approxi-

Figure 1.1 Single-family owner-occupied home.

Figure 1.2 Mobile or manufactured home.

mately 10 million housing units. These are often described as trailers, mobile homes, double-wides, modulars, and, increasingly, prebuilts. Most are described as mobile homes because they are transported on a frame and wheels which are part of the structure. The construction of manufactured houses differs significantly from that of site-built houses because the former are designed to provide lower cost, more affordable housing. They often employ lower cost materials and have, in the past, been less well-constructed than site-built houses. They are more vulnerable to wind and weather-related damage and are usually less well-insulated. Prebuilts are erected on substructures and differ from site-built homes primarily in their simplicity of design.

Multifamily dwellings (Figure 1.3) vary from single-story to multistory structures. In most instances, ownership is second-party. Multifamily dwellings are always site-built, with building materials that reflect cost and engineering considerations.

Figure 1.3 Multiple-family dwelling.

D. Construction characteristics

Residential buildings vary enormously in their construction characteristics, including size, design, building materials used, substructure, cladding, use of insulation, quality of construction, and site conditions. They vary in size from simple shanties, to nice single- and multifamily homes, to palatial mansions. They vary in design from the simple rectangular boxes of manufactured houses, to the diversity of home designs of middle-income individuals, to the more complex and architecturally inspiring homes of the Victorian era and the present.

All residential buildings have similar construction requirements. They include a substructure, sidewalls, flooring, windows, roofing, attic and crawlspace ventilation, plumbing, electrical wiring, attic and wall insulation (depending on climate), and roof and site drainage. They also include interior furnishings such as storage cabinets, closets, and finished wall and floor surfaces. These reflect construction practices that depend on regional climate, site characteristics, design preferences, and availability of construction materials. They also reflect evolving builder and homeowner preferences and new amenities in the marketplace. Construction characteristics are much influenced by cost, the most important factor in residential building construction.

1. Substructures

Most residential buildings rest on a substructure that supports their weight and anchors them to the ground. There are three common types of substructure: slab-on-grade, crawlspace, and basement. Some residences have combinations of these.

House substructures reflect regional preferences (in general, basements are preferred in the northeastern U.S.); contractor preferences (assuming equal costs, some contractors prefer to build houses on crawlspaces, while others prefer slab-on-grade); soil characteristics (poorly drained clay soils are unsuitable for basements); and cost and construction time (this is a major contributor to the increasing construction of slab-on-grade, single-family dwellings).

Substructure type often has significant effects on building IAQ/IE problems. Houses with basements or slab-on-grade tend to have higher radon levels (given the same soil radon-emitting potential). Basements tend to have problems with water penetration and excess humidity, factors that contribute to mold infestation and attendant exposure and health risks. Such health risks may also exist in dwellings with crawlspace or slab-on-grade substructures when constructed on poorly drained sites (as is often the case).

2. Roofing

Roofs are constructed to protect building interiors from rain, snow, and wind. They are designed to intercept rain and snow and carry their waters from the roof edges to the ground, either directly or through guttering. Climatic factors determine the nature of roof construction and the use of guttering.

Roof construction also reflects resource availability and cultural preferences. In new U.S. residential construction, roofs are typically constructed with oriented-strand board decking on wood trusses. Decking is then covered with asphalt felt and shingles. In the southwestern U.S., as in some other parts of the world (Europe, Southeast Asia, Japan, Australia), terra cotta roofing is preferred. In some parts of the U.S. (South) and Australia, painted galvanized steel is the most common roofing material.

Roof construction and materials used are important. The roof must carry away water without leakage, lest significant internal structural damage and mold infestation occur. In cold, snowy climates, the roof must be strong enough to support the weight of heavy snow. In regions with severe storms, roofs must be securely anchored lest they experience serious damage. The cavity between the roof and ceiling timbers must be adequately ventilated to prevent the build-up of excessive moisture, which in cool/cold climates may result in condensation and even freezing. Poorly ventilated attics may result in structural damage and mold infestation.

3. *Sidewalls and walls*

The exterior sidewalls of dwellings are typically constructed using structural timbers, fiberglass insulation, Styrofoam or polyurethane sheeting to provide additional low-cost insulation, oriented-strand board sheeting in corners and around windows to provide extra strength, an external semipermeable membrane (e.g., Tyvek), and one or more types of external cladding. Typical cladding includes, or has included, aluminum or vinyl siding, wood or fibrocement weatherboard, stucco over concrete block, and brick or stone veneer. Cladding is an important factor in protecting the building from the vagaries of weather and climate. All cladding types indicated above provide reasonable protection from wind, water, and snow. From a structural standpoint, houses constructed with brick/stone veneer are less prone to damage from wind gusts which can tear off small to large pieces of vinyl and aluminum siding. Wood weatherboard must be painted repeatedly and, with time, can deteriorate as a result of weathering and inadequate maintenance. In many older houses, wood weatherboard was painted with lead-based paint and represents a potentially significant source of lead contamination of the soil surrounding the building, as well as interior dust. Old weatherboard-clad houses are often a major public health concern because of their potential to cause lead poisoning in young children.

As in the story of the three little pigs, an all-brick or stone house would seem to provide the best shelter. However, such houses are not without problems. Brick/stone veneer houses constructed on unstable soils develop small to large settlement cracks which provide an avenue for rain to enter building cavities. Here both liquid water and water vapor can cause structural damage and mold infestation. In the absence of settlement cracks, many brick/stone veneer facades pass water through porous mortar and brick, and through small holes. If constructed properly, rain water will drain down the interior surface of the mineral facade and seep out through properly functioning weep holes at the bottom. If brick/stone veneer facades are poorly constructed (without weep holes and the removal of excess mortar), rain water will be carried into walls, again causing mold infestation and structural damage.

Timbers on wall interiors are covered by polyethylene plastic, which serves as a vapor barrier. It is designed to prevent warm, moist air from passing into building cavities where it may condense and cause structural damage and mold infestation.

4. *Windows*

Windows in dwellings differ in style, size, placement, and materials. They are designed to keep wind, rain, and snow out, allow light in, and provide a means of natural ventilation during moderate to hot weather. Windows are a major source of energy loss because of their thermal energy transmitting properties. On single-pane windows (found in older houses), moisture on interior surfaces cools and condenses, causing damage to interior window surfaces (and in many cases significant mold infestation). Windows also break the continuity of building cladding. These breaks must be provided with flashing or be caulked to prevent water from penetrating wall cavities during heavy rains. Water penetration into wall cavities around windows is common as houses age and maintenance is neglected.

5. *Flooring*

Materials used in both exterior and interior house construction change with time. In older houses (>40 years), softwood boards were commonly used to construct floors. In many cases these were overlain with hardwood oak flooring. Because of the high cost of such flooring, it became common to construct floors using CDX plywood sheeting. Later, contractors used a combination of softwood plywood sheeting as a base, with $^5/_8$″ (1.6 cm) particle board underlayment above it. This was inexpensive and provided a smooth surface for attachment of wall-to-wall carpeting. Between 1960 and 1990, over 10 million homes were constructed in the U.S. using particle board underlayment, a very potent source of formaldehyde (HCHO). Emissions of HCHO from underlayment have significantly declined in the last decade or so (1988 to 2000). It is little used in modern site-built construction and has declined to approximately 50% of new manufactured house construction. Particle board flooring has been displaced by oriented-strand board (OSB), a composite wood material that has better structural properties and very low HCHO emissions.

The main floor surface of slab-on-grade houses is, of course, concrete, with wall-to-wall carpeting and other floor coverings overlaying it. This concrete–ground contact provides a cool surface, which may result in optimal humidity levels for the development of high dust mite populations. Slab-on-grade substructures also provide (through cracks) a mechanism for the conveyance of radon and other soil gases (most notably water vapor) into building interiors.

6. *Decorative wall and ceiling materials*

A variety of materials are used to finish interior walls and ceilings. Base materials have historically included plaster over wood or metal lath, or gypsum board panels. Because of cost factors and ease of installation, gypsum board has dominated the construction market for interior wall and ceiling covering for the past four decades, with plaster found primarily in older homes. Gypsum board in itself appears to pose no direct IAQ/IE concerns. However, during installation, spackling materials are used to cover gaps between individual panels. Prior to 1980, most spackling compounds contained asbestos; therefore, many older homes with gypsum board wall covering contain a limited amount of asbestos fibers. In other older homes, acoustical plaster containing 5 to 10% asbestos was sprayed on ceiling surfaces to provide a decorative finish with sound-absorbing properties.

Gypsum board has become increasingly associated with *Stachybotrys chartarum* infestations in residences and other buildings. *S. chartarum* is a fungus that produces a potent mycotoxin (see Chapter 6 for an expanded discussion of *S. chartarum*). It grows readily on the cellulose face of gypsum board when it has been subjected to a significant or repeated episodes of wetting.

Residential buildings have a variety of exterior and interior surfaces that have been coated with paints, stains, varnishes, lacquers, etc. These coatings may have significant emissions of volatile organic compounds (VOCs) and semivolatile organic compounds (SVOCs), particularly when newly applied. Old leaded paints (pre-1978) may pose unique indoor contamination problems (see Chapter 2).

Base gypsum board materials are usually finished with the application of latex, or in some cases oil-based, paints. In the early history of a dwelling, latex paints, though water-based, emit a variety of VOCs and SVOCs, with significant emissions of VOCs and polyvalent alcohols from oil-based and latex paints, respectively. Though these emissions diminish with time, high initial emissions from walls and other painted surfaces represent a significant source of odor, and in some cases irritant effects, in the early days of home occupancy. Notably, some manufacturers have recently included biocides in their latex paint formulations that emit significant quantities of formaldehyde in the first weeks after application.

In some dwellings the base gypsum board may be covered, in whole or in part, with decorative materials other than paint. These may include wallpaper, hardwood plywood paneling, hardboard, vinyl, fabric, etc. Hardwood plywood paneling may be used to cover walls in single rooms or, as was the case in mobile homes, most rooms. Though gypsum board panels with a paper or wallpaper overlay are now used most often, decorative hardwood plywood paneling covered most interior walls of mobile homes constructed in the U.S. prior to 1985. Hardwood plywood paneling was a potent source of HCHO and a major contributor to elevated HCHO levels reported in mobile homes constructed in the U.S. in the 1970s and early 1980s.

7. *Energy conservation*

Modern dwellings are being constructed to be more energy efficient. Energy efficiency is achieved, in part, by using insulating materials such as fiberglass batting in sidewalls and attics and blown-in cellulose in attics and wall cavities. In the latter case, wet cellulose is often used to insulate wall cavities in new construction. Intuitively, the practice of applying wet cellulose to building sidewalls could cause significant mold infestation problems and even structural decay. In some cases, wall cavities are being insulated with a combination of foamed-in-place polyurethane and fiberglass batts. Contamination of building interiors with diisocyanate and other compounds from polyurethane foam has been reported.

In addition to the use of insulation, dwellings are being constructed more tightly; i.e., modern construction practices are designed to reduce infiltration of cold air in the cold season and exfiltration of cool air during the cooling season. Concerns have been raised that such construction practices result in reduced air exchange and, as a consequence, increased contaminant concentrations and attendant health risks.

8. Furnishings

Modern dwellings are provided with a variety of furnishings and amenities. These include wall-to-wall carpeting, floor tile, furniture, decorative wall and ceiling materials, fireplaces, etc. The use of wall-to-wall carpeting in modern dwellings in the U.S. is now nearly universal.

Wall-to-wall carpeting is a highly attractive home furnishing. It absorbs sound, diminishes the perception of cold floor surfaces, is aesthetically attractive, and provides a comfortable playing surface for children. Wall-to-wall carpeting has negative attributes that are not as apparent as its attractions. Until recently, new carpeting was characterized by emission of a variety of volatile and semivolatile compounds that have caused odor problems (e.g., the rubbery smell of 4-PC associated with latex binders) and, in some cases, health complaints.

Wall-to-wall carpeting is an excellent reservoir for a variety of inorganic and organic particles, particles that are often difficult to remove even with regular cleaning. These include human skin scales, which serve as a food source for a variety of mold species and dust mites, and mite excretory antigens, which are the most common cause of chronic allergic rhinitis and asthma. They also include cat and dog dander, cockroach antigens, etc. These antigens are significant causes of inhalant allergies and many cases of asthma.

In addition to being a reservoir for a variety of dirt particles which are allergenic, carpeting produces a microenvironment favorable to dust mites and a variety of mold species. The high relative humidity needed to sustain development of large dust mite populations (see Chapter 5) is present in homes as a result of favorable conditions produced by the combination of carpeting and cool floor surfaces. Environmental concerns associated with carpeting are described in detail in Chapter 7, Section F.

Most houses are furnished with wood furniture. Most modern wood furniture is constructed with HCHO-emitting pressed-wood materials, and even solid wood furniture is coated with HCHO- and/or VOC-emitting finish coatings.

9. *Storage*

Residential building interiors are designed to provide a variety of storage capabilities. These include bedroom and hallway closets as well as kitchen and bathroom cabinetry. Most modern cabinetry is constructed with various pressed-wood products. These include hardwood plywood, particle board, medium-density fiber board (MDF) and OSB. With the exception of OSB and softwood plywood used for shelving and counter tops, respectively, most wood components are constructed from urea–formaldehyde resin-bonded wood materials that have the potential to emit significant quantities of HCHO. Formaldehyde emissions also occur from acid-cured finishes used on exterior surfaces of hardwood cabinets and good quality furniture.

10. *Attached garages*

Many single-family residences have attached garages. These provide an enclosure for motor vehicles and utilities such as furnaces, and a storage area for the varied needs of the building's occupants.

Because of diverse uses and their physical attachment to occupied spaces, garages may be a source of a variety of contaminants. Because occupied spaces are negatively pressurized relative to garages, motor vehicle emissions, gasoline and solvent vapors, etc., are readily drawn into living spaces.

11. *Heating/cooling systems*

In many parts of the world as well as the U.S., seasonal changes in outdoor temperature require that some form of heating and cooling appliance or system be used to provide more acceptable thermal conditions than occur outdoors. In addition, appliances provide hot water for bathing and other washing activities.

Energy sources and appliances used to heat residences or provide other heating needs (such as for cooking and supplying hot water) vary widely. In developing nations where population densities are high and resources limited, building occupants rely on biomass fuels to cook food over poorly vented fires, which during cold seasons also provide some degree of warmth.

In developed countries, a variety of manufactured appliances are used for cooking and others for space heating. Cooking appliances include natural gas or propane-fueled stoves and ovens, electric stoves and ovens, and microwave devices. Gas stoves and ovens are not vented to the outdoors and, as such, are a potentially significant source of indoor air contamination.

Single-family dwellings in the U.S. are typically heated by some form of appliance. These include vented furnaces fueled in most cases by natural gas, propane, or oil, or, less commonly, wood or coal. Other vented fuel-fired appliances include wood or coal stoves and, in parts of northern Europe, fireplaces. In the U.S., fireplaces serve primarily an aesthetic and decorative function.

Home space heating is accomplished primarily by the use of modular, freestanding, unvented natural gas or kerosene space heaters in the warmer regions of the U.S. and in countries such as Japan and Australia. These devices are designed to emit only limited quantities of carbon monoxide (CO) and do not pose an asphyxiation hazard. They may cause significant indoor air contamination with a variety of combustion by-products (see Chapter 3). Such space heaters are commonly used to "spot heat" individual rooms to reduce energy costs.

Electrical devices or systems are often used for home space heating in the U.S. These include cable heat, with elements in the ceiling, or electric heat pumps. In the latter case, energy is extracted from outside air or groundwater, with a heating coil supplement during very cold weather. Electric heating devices do not produce any combustion by-products and do not, in theory, pose any indoor air contamination risks.

Indoor space heating can be provided by central systems which forcibly or passively distribute heat from a combustion or electrical appliance to attain and maintain desired thermal conditions. Such systems heat all spaces, including those that are unoccupied. In forced air systems, heat is distributed through duct systems. In radiant heat systems, hot water is pumped to radiators distributed in various parts of the house.

In forced air systems, a fan draws air through a filter into the appliance, where it is heated and then delivered through ducts to building spaces through supply air registers. Air is returned to the furnace to be reheated through a second duct system described as a cold air return.

Duct systems in residences can cause or contribute to indoor air contamination problems. Historically, ducts (both supply and return) were constructed of galvanized steel. Increasingly, ducts are being fabricated from fiberglass materials. These include duct board, which is fashioned into supply and return air trunklines on-site, with polyethylene-lined, fiberglass-insulated flex duct serving to deliver conditioned air to supply air registers. Duct board may release contaminants such as methylamine, which is both an odorant and an irritant. Porous surfaces of duct board are deposition sites for organic dust, which may serve as a medium for mold growth and subsequent indoor air contamination.

Return air ductwork, which is under a high negative pressure, is typically located in attic, crawlspace, or basement areas, or attached garages. Wet crawlspaces and basements are often heavily contaminated with mold, and the usually leaky ductwork located in these spaces serves as a conduit for mold spores, moisture, and even radon into living spaces.

In many dwellings, cooling is provided either by window or whole-house systems that are integrated into heating systems.

12. Plumbing

Most houses have plumbing systems that carry water into them, then heat (and in many cases soften) it and distribute it to kitchen and bathroom sinks, toilets, showers/tubs, laundries, and external faucets for lawn and garden use. They also carry away cooking and bathing waters, toilet wastes, condensate from air conditioners and high-efficiency furnaces, and, in some cases, food wastes. In most cases, plumbing systems perform their functions well. Good maintenance, however, is required to prevent damage from leaks (which are relatively common) and entry of sewer gases through drains that develop dry traps. Plumbing-related problems that result from improper installation or maintenance are common in many residences.

13. Other utilities

Other utilities that are integral parts of housing structures include electrical wiring and, in many homes, pipe systems for natural gas or propane. Except for the potential to cause structural fires, electrical wiring poses no environmental concerns. Gas utility systems are subject to leakage and may cause an odor problem; the odor is designed to warn homeowners that leaking fuel gas may pose an explosion hazard.

E. Age and condition

Buildings vary in age and condition, so they vary in the types and magnitude of IAQ/IE problems associated with them. Because lead-based paint was used to cover exterior surfaces prior to 1978, and both interior and exterior surfaces prior to the 1950s, older houses are more likely to be contaminated with lead-containing dusts. This problem is exacerbated by the fact that many older houses are not well maintained; many are dilapidated.

Older houses are more likely to have had problems such as water intrusion, flooding, and condensation on windows and walls during their history than new houses. As a consequence, they are at much higher risk of being infested with mold.

Older houses are more likely to be less insulated, and therefore better ventilated, than newer houses. As such, they have higher air exchange rates. They are also more likely to have hardwood floors and less likely to have wall-to-wall carpeting.

F. Site characteristics

Inadequate site drainage bedevils many homeowners. Many building sites were historically poorly drained and remain so after building construction. Dwellings constructed on such sites are subject to a variety of water-related problems, including: basement seepage or flooding; episodically wet crawlspaces; water in heating/cooling ducts in slab-on-grade houses; and infestation of slab-on-grade ducts with moisture-loving crustaceans (sow bugs), spiders, insects, and mold. The periodic incursion of moisture into basements, crawlspaces, and slabs poses major IE problems. It may cause wetting of materials and subsequent mold infestation; high indoor humidity which increases the risk of condensation on cold window surfaces and a variety of mold infestation problems; and a favorable indoor climate for development of large dust mite populations, with their associated antigen production and exposure risks.

Other site characteristics also contribute to moisture and IE concerns. Heavily shaded sites tend to retard drying of exterior building surfaces as well as the site itself. Well-drained sites with sandy or gravelly soils reduce risks associated with moisture-requiring biological contaminants. On the other hand, high soil permeability may be associated with elevated radon levels.

G. Occupants and occupant behavior

Once a dwelling is occupied, it is subject to a number of contaminant-generating activities. These include: production of bioeffluents by occupants as well as odors associated with food preparation and use; emissions from personal care and clothing/home cleaning products; smoking of tobacco products (and possibly other weeds); emissions/by-products of hobbies, crafts and in-home enterprises; fragrant emissions from candles, potpourri and decorative items, as well as combustion by-products from the frequent use of candles; pet odors and danders; production of organic debris that serves as food for antigen-producing dust mites, cockroaches, mice, etc.; both proper and improper use of pesticides to control common household pests; building interior renovation activities; improper/ inadequate care and maintenance of building combustion, plumbing and other systems; introduction of furniture and other materials which may be a significant source of contaminants; and introduction of particulate-phase contaminants on shoes and clothing from the building site (e.g., lead-based paint dusts and pesticides) as well as work environment (e.g., industrial dusts, starch and talc from hair care establishments, etc.).

H. Exposure concerns

Occupants of dwellings are exposed to indoor air and other environmental contaminants in ways that are different from other nonindustrial buildings. As indicated previously, occupants of residences can be exposed to potentially toxic indoor contaminants 12 to 24 hours/day. Exposed populations include infants/children, healthy adults, the aged, and the infirm.

Contaminant exposure concerns that are unique in residences include: radon; HCHO; environmental tobacco smoke (ETS); pesticides; unvented combustion appliances; biocontaminants such as dust mite and cockroach antigens, mold, and animal danders; lead-based paint-contaminated dust; emissions from personal and home-care products, and arts and crafts activities; and contagious disease.

Exposure concerns in residences are increased due to limited dilution/ventilation potential when windows are closed during heating and cooling seasons. Residences, unlike other nonindustrial buildings, are not, in most cases, mechanically ventilated.

Figure 1.4 Retail building.

III. Characteristics of nonresidential buildings

Nonresidential buildings can be characterized by (1) the functions and populations they serve, (2) access and ownership status, (3) building types and construction characteristics, (4) building operation and maintenance, (5) occupant density/activities, and (6) health and other exposure concerns.

A. Building functions and populations served

Nonresidential buildings are designed and constructed to serve a variety of human needs. These include retail and other commercial activities (Figure 1.4), private and public office space, education, health care, imprisonment/detention, worship, entertainment, etc. These buildings vary in the populations they serve. In office buildings (Figure 1.5), prisons, colleges and universities, and many commercial establishments, most of the building

Figure 1.5 Office building.

Figure 1.6 School building.

population is comprised of adults; in schools (Figure 1.6), children age 5 to 18 dominate; in health-care facilities (Figure 1.7), the building population consists of the infirm, as well as care givers and a variety of service personnel; entertainment and sport facilities serve populations that reflect the popularity of the entertainment provided to various age groups. Unlike residences, nonresidential buildings tend to serve diverse populations. As such, IAQ/IE exposure concerns differ in many cases from those that occur in residential buildings.

B. Access and ownership status

Although many nonresidential buildings are owned and operated by government and a variety of not-for-profit entities, most are privately owned by individuals or corporations. Because these buildings are open to the public for at least a portion of the day, they can be described as public-access

Figure 1.7 Health-care facility.

buildings. Occupants of public-access buildings as well as "visitors" depend on building management to provide a comfortable and low-health-risk environment. Occupants and visitors usually do not have any control over building environment conditions.

C. Building types and construction characteristics

Building type, design, and construction characteristics reflect the needs served by individual buildings, resources and desires of the owner, preferences of architects and contractors, resource and material availability, climate, etc. Office buildings, for example, vary in size from small structures no larger than a residence to giant towers providing hundreds of thousands to millions of square feet of floor space. They vary from wood-framed with a variety of cladding types to structures with ribs of steel and facades of glass and stone.

Like residences, nonresidential buildings have similar basic structural and furnishing requirements. These include a substructure or building base; a skeletal frame; external cladding; windows; a roof; insulating materials; interior wall coverings; flooring; finish coatings; and interior furnishings such as floor coverings, furniture, storage cabinets, room dividers, etc.

1. Substructure/structure

Because nonresidential structures tend to be large, they are constructed to reflect structural demands. The building base must support the weight of the building whose structural components are steel and concrete. Substructures therefore are slab-on-grade or have one or two subgrade levels, with structural members often anchored to bedrock or stabilized ground. The building frame may be constructed of steel or reinforced concrete columns. In multistory buildings, structural steel is sprayed with fireproofing insulation, which reduces the risk of warping and building collapse in a fire. Before 1973, such fireproofing contained asbestos.

2. Walls

Exterior walls may include extensive glass or cladding of limestone building stone, brick, etc. As in residences, they are often insulated (depending on climate) with materials manufactured for the walls and roofs of large buildings. Such buildings may or may not have vapor barriers. In warm climates, such as Florida, severe mold infestations on interior wall materials have occurred as a result of thermal-enhanced movement of water through the building envelope (without vapor barrier) and subsequent condensation on cooled wall surfaces. Interior walls are typically covered with gypsum board, with other materials used for decorative purposes.

3. Flooring/floor covering

Floors of nonresidential buildings are usually poured concrete, often covered with vinyl tile, terrazzo, or carpet. Vinyl asbestos tile was widely used in schools and other nonresidential buildings prior to 1980. Increasingly, in new buildings, floor coverings are glued-down industrial-grade carpeting. Emissions from carpeting and associated adhesives have been the subject of IAQ complaints in a number of buildings. As in residences, carpeting in nonresidential, nonindustrial buildings becomes a sink for a wide variety of organic particles.

4. *Ceilings*

Ceilings of many nonresidential buildings serve several functions. They need to provide an aesthetically acceptable appearance and, in many cases, a cavity through which utilities such as wiring, plumbing, and mechanical systems are extended. These cavities often serve as plenums through which return air is conveyed to air-handling units (AHUs) to be reconditioned. Suspended ceiling tile commonly serves as the plenum base. In other cases, decorative acoustical plaster may be sprayed on ceiling surfaces. Prior to 1978, acoustical plaster containing upwards of 10% chrysotile asbestos was commonly used in foyers and hallways in schools, auditoria, and other buildings.

5. *Roofs*

Roofs of a large percentage of nonresidential buildings are flat. A flat roof is considered more aesthetically pleasing by architects and serves as a platform for heating, ventilation and air conditioning (HVAC) system AHUs, exhaust vents, etc. Flat roofs require design and construction care to assure proper drainage of rain and snow melt, and maintenance to prevent water intrusion into building interiors. Flat roofs are often plagued by water leaks that damage ceiling tiles and other interior materials. Such water intrusion is a common problem in school buildings. Because HVAC system AHUs as well as exhaust vents are often located on flat roofs, re-entry of flue and other exhaust gases is also a common problem.

6. *Furnishings/equipment*

Nonresidential buildings are provided with a variety of furnishings, e.g., chairs, desks, storage cabinets, office dividers, etc. These furnishings can emit a variety of VOCs and SVOCs which contaminate indoor spaces. Steel desks and storage cabinets have low emissions. Wooden desks, storage cabinets, counter tops, and office dividers may be constructed from HCHO-emitting pressed-wood products, and thus serve as a source of HCHO and potential irritant effects.

Nonresidential buildings also contain a variety of equipment types including computers, printers, photocopying machines, etc. Such equipment can be a source of indoor contaminants (see Chapter 7).

7. *Heating, cooling, and ventilation systems*

Nonresidential, nonindustrial buildings vary considerably in how they are climate-controlled and ventilated. Climate control in seasonally colder climates may be limited to providing heat by radiant heating elements, forced air furnaces, boilers plus forced air heating coils, heat pumps, etc. The systems used reflect the building's needs and often its age. Ventilation may be provided by mechanical systems or, as in many older buildings, by opening windows (natural ventilation).

In seasonally hot climates, the primary focus of climate control is cooling. Again, ventilation may be provided by mechanical means or by opening windows.

The trend in most developed countries is to design and construct buildings with year-round climate control. In these buildings, windows are sealed and cannot be opened to provide natural ventilation. Ventilation must be provided by mechanical systems. Because ventilation is integrated into the heating and cooling systems, they are described by the acronym, HVAC (heating, ventilating, air conditioning). HVAC systems vary in design and operation (see Chapter 11).

HVAC systems control thermal conditions and air exchange with the ambient environment, so their operation is a major determinant of occupant comfort and satisfaction with the indoor environment. Well-designed and operated HVAC systems are essential to provide occupants with ventilation air sufficient to dilute human bioeffluents to acceptable levels and, to a limited degree, control levels of other contaminants as well. Inadequacies in design and operation of HVAC systems are the primary cause of air quality complaints in mechanically ventilated buildings.

8. Plumbing

Plumbing systems are designed to provide a potable water supply, heated (hot water or steam) or chilled water lines serving AHUs, sprinkler water supply for fire suppression, static water supply for emergency fire use, and waste water lines. Heated or chilled water lines are typically insulated. A variety of insulating materials have been used, including molded gypsum-containing asbestos. In many older buildings, the plumbing system is the major site of asbestos-containing materials. Modern plumbing is insulated with a variety of materials including fiberglass, foamed rubber, molded gypsum, etc.

Plumbing in nonresidential buildings is subject to a variety of leakage problems that cause minor stains (and mold infestation) to major flooding. The former are common; the latter rare. Both are environmental quality concerns.

9. Other utilities

In addition to heating, cooling, ventilating, and plumbing, nonresidential buildings are provided with a variety of utilities including lighting fixtures and electrical, telephone, and computer wiring. Wiring is typically arranged to minimize space and resource requirements and is co-located in wiring runs, pipe chases, hallway plenums, etc.

D. Building operation and maintenance

Nonresidential buildings such as office, commercial, and institutional buildings are typically large, with relatively complex systems (plumbing, lighting, HVAC) that need to be properly operated and maintained. Many buildings and their systems are often poorly operated and maintained and are therefore subject to a variety of problems, including poor thermal control, inadequate ventilation, inadequate cleaning, recurring roof and other structural leaks, and mold infestation. Poor building and building systems operation and maintenance may be due in part to the complexities involved (particularly HVAC systems), inadequately trained or motivated facilities service staff, lack of commitment by building management, and inadequate building operation/maintenance resources. School buildings, in poor (and sometimes not-so-poor) school districts, are particularly subject to resource limitations. In such instances maintenance is often deferred. As a result, poorly operating mechanical systems, water damaged/mold infested materials, and inadequately cleaned surfaces are common.

E. Occupant densities and activities

Nonresidential buildings are distinguished by varied occupant densities and activities. Projected occupant densities are a major building design factor. They determine space requirements and ventilation needs. Highest occupant densities occur in school buildings and sports arenas.

Occupant activities vary from building to building, as well as within a single building. In office buildings, these may include general clerical work, using office equipment, preparing/serving/eating food, printing, etc. They may also include maintenance activities such as cleaning floors and other horizontal surfaces, repainting, repairing problem systems, and pest control, among others. In schools, they include teaching/learning, clerical/administrative work, food preparation/eating, athletic activities, art and shop projects, and maintenance activities such as floor waxing and pest control.

Occupant activities may, in many cases, be a source of contaminants that affect IAQ and the cleanliness of building surfaces. They may also affect the health and well-being of occupants engaged in such activities and/or the general building population.

F. Exposure concerns

Nonresidential buildings are subject to a number of contamination, exposure, and health concerns. These include: elevated bioeffluent levels associated with high occupant densities and inadequate ventilation; emissions from office equipment and materials; cross-contamination from contaminant-generating areas; re-entry of building exhaust gases; entrainment of contaminants generated outdoors; contamination of AHUs by organisms/biological products that can cause illness, e.g., hypersensitivity pneumonitis, humidifier fever, and Legionnaires' disease; transmission of contagious diseases such as flu, colds, and tuberculosis; exposure to resuspended surface dusts; exposure to ETS where smoking is not restricted; etc. With some exceptions, radon, unvented combustion appliance emissions, pesticides, and lead-based-paint-contaminated dusts are not major exposure concerns; radon, pesticides, and lead-contaminated dusts are, however, concerns in school buildings.

Health concerns, as indicated above, include diseases such as Legionnaires' disease, hypersensitivity pneumonitis, and illness symptoms often described as "sick building syndrome."

IV. Other indoor environments

Because humans spend so much time indoors, most IE concerns have focused on buildings. Nevertheless, exposures to airborne or resuspended surface contaminants occur in other environments as well. These include interiors of motor vehicles, airplanes, trains, ships, submarines, and space capsules.

A. Motor vehicles

Motor vehicles represent unique IAQ/IE concerns. Contaminants such as VOCs and SVOCs may be emitted from materials used in vehicle interiors, e.g., vinyl plastics. They may also become entrained in the interior compartment from the vehicle's own exhaust or the exhaust of other vehicles. Air-conditioning systems may also be a source of contamination. Exposures may be brief, varying from minutes to hours per day, and possibly repeated daily.

B. Commercial airplanes

Travel in commercial aircraft (Figure 1.8) is a relatively infrequent occurrence for most individuals (except flight crews). Airplanes are in some ways similar to nonresidential buildings. They are characterized by high occupant densities (2 m^3/person) and mechanical systems that use both recirculated and

Figure 1.8 Commercial aircraft.

outside air; uniquely they have interior pressures comparable to an altitude of 8000 feet. Despite the fact that ventilation standards for aircraft have been revised to increase outside air, aircraft designs limit outside air delivery capacities to environmental control systems. In a filled-to-capacity airplane, the amount of outside air provided to passengers and crew is half that recommended for office buildings.

Commercial aircraft personnel and passengers are subject to a variety of contaminant exposures. These include human bioeffluents, VOC emissions from seats and other interior materials, entrained fuel combustion by-products, ETS on smoking-permitted flights [respirable suspended particulate (RSP) levels are approximately 20 times those on nonsmoking flights], and elevated ozone when flying at high altitudes (circa 30,000 to 40,000 feet). Passengers and crew are often subject to low relative humidity (5 to 25%) as well.

C. Trains

Trains are used for both surface and underground transportation. Tens of millions of individuals, in North America and other parts of the world, use train transportation daily. Such use is particularly heavy in large cities. Underground transportation includes two indoor environments, the train and underground tunnels and platforms. Underground systems require ventilation that occurs passively or by mechanical means.

Contaminant exposures in train compartments may include human bioeffluents, emissions from interior materials, entrainment from combustion-driven systems, entrainment of contaminants from underground sources, etc.

D. Ships

A ship can be likened to a hotel. It contains sleeping/living quarters, dining areas, food-handling areas, lounges, theaters, etc. It also includes an on-board, combustion-driven propulsion system, and waste handling and storage systems.

Many modern passenger ships are mechanically ventilated and air conditioned. Like land-based nonresidential buildings, such systems vary in the degree of thermal comfort provided, as well as ventilation adequacy.

Exposure concerns on ships may include human bioeffluents, emissions from ship materials, ETS in smoking-permitted areas, entrainment from combustion systems, and cross-contamination from high source areas. Of special concern have been the transmission of contagious diseases, such as influenza, and outbreaks of Legionnaires' disease.

E. Submarines and space capsules

Submarines and space capsules represent truly unique indoor environments and exposure concerns. In both cases, ventilation is not possible. Air/oxygen, which is quite limited, has to be continuously recycled. In submarines, special air cleaning systems must be used to maintain acceptable CO_2 (<1%) and VOC levels.

Exposures to crew members in both cases include human bioeffluents, emissions from interior materials, and combustion by-products. Crew members in early space flights reportedly experienced symptoms similar to those associated with poor IAQ in buildings.

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Questions

1. What factors have contributed to our recent concerns about IAQ/indoor environment problems?
2. How are IAQ/indoor environment problems in residences different from those experienced in nonresidential buildings?
3. What is the significance of ownership status relative to preventing and mitigating indoor environment problems?
4. Describe differences in substructure types and their potential roles in indoor environment concerns.
5. How do site-built homes differ from manufactured homes?
6. Describe sidewall components and their function.
7. Describe problems experienced with cladding that might cause structural and indoor environment problems.
8. Describe environmental problems in residential buildings associated with windows.
9. Describe residential flooring materials and potential indoor environment problems associated with them.
10. Describe energy conservation practices and potential associated indoor environment problems.
11. What kind of environmental problems have been associated with the use of gypsum board?

12. Describe the nature of storage in residences and how it may be related to indoor environment problems.
13. How are site characteristics related to the indoor environment of residences?
14. A variety of mechanisms/appliances are used to heat our food and make our dwellings comfortable. How may these affect the indoor environment and human health?
15. How do occupants in residential buildings affect their indoor environment?
16. Describe contaminant exposure concerns in residential buildings.
17. What are public-access buildings?
18. How do roofs on nonresidential buildings differ from those on residential buildings? What unique problems are associated with roofs?
19. Describe the nature of ceilings in many nonresidential buildings.
20. Describe the use and operation of HVAC systems in public-access buildings and how they differ from residential buildings.
21. Describe the nature of building operation and maintenance concerns in nonresidential, nonindustrial buildings.
22. Describe health and exposure concerns in nonresidential, nonindustrial buildings.
23. How do occupant activities affect the indoor environment in nonresidential, nonindustrial buildings?
24. What human exposure concerns are associated with the interiors of motor vehicles?
25. What human exposure concerns are associated with commercial air travel?

chapter two

Inorganic contaminants: asbestos/radon/lead

Inorganic substances such as asbestos, radon, and lead are major indoor contaminants. Though very different, they have in common a mineral or inorganic nature. Exposures may pose significant health risks.

Lead is of concern because it is a common surface contaminant of indoor spaces, and contact with lead-contaminated building dust is the primary cause of elevated blood levels in children under the age of six.

I. Asbestos

Potential airborne asbestos fiber exposures in building environments and associated public health risks were brought to the nation's (United States) attention in the late 1970s by both public interest groups and governmental authorities. This attention was a logical extension of exposure concerns associated with the promulgation of a national emission standard for asbestos as a hazardous pollutant (NESHAP) by the United States Environmental Protection Agency (USEPA) in 1973. The asbestos NESHAP banned application of spray-applied asbestos-containing fireproofing in building construction; there was a subsequent ban of other friable asbestos-containing building products in 1978. Under NESHAP provisions, friable (crushed by hand) asbestos-containing building materials (ACBM) must be removed prior to building demolition or renovation. Such removal must be conducted in accordance with Occupational Safety and Health Administration (OSHA) requirements to protect construction workers removing asbestos, as well as building occupants. As a consequence of these regulatory actions, asbestos in buildings, particularly in schools, became a major indoor air quality (IAQ) and public health concern.

The ban on friable asbestos-containing materials used in building construction and requirements for removal prior to demolition or renovation were intended to minimize exposure of individuals in the general community to contaminated ambient (outdoor) air. Potential exposures to building occupants from fibers released from building products in the course of normal activities had not been addressed. In 1978, public attention was drawn to the large quantities of friable or potentially friable ACBM that was used in school construction as well as other buildings.

A. Mineral characteristics

Asbestos is a collective term for fibrous silicate minerals that have unique physical and chemical properties that distinguish them from other silicate minerals and contribute to their use in a wide variety of industrial and commercial applications. These include thermal, electrical, and acoustic insulation properties; chemical resistance in acid and alkaline environments; and high tensile strength, which makes them useful in reinforcing a variety of building products.

Asbestos comprises two mineral groups which are distinguished by their crystalline structure: serpentine and amphiboles. Serpentine chrysotile (Figure 2.1), the most widely used asbestos mineral, has a layered crystalline structure with the layers rolling up on each other like a scroll or "tubular fibrils." The amphiboles, which include amosite, crocidolite, anthophyllite, actinolite, and tremolite, have a crystalline structure characterized by double-chain silicate "ribbons" of opposing silica tetrahedra linked by cations.

Individual asbestos fibers have very small diameters, high aspect (length:width) ratios, and smooth parallel longitudinal faces. Asbestos fibers are defined for exposure monitoring as any of the minerals in Table 2.1 that have an aspect ratio ≥3:1, lengths >5 μm and widths <3 μm. In actual practice,

Figure 2.1 Chrysotile asbestos fibers under microscopic magnification. (Courtesy of Hibbs, L., McTurk, G., and Patrick, G., MRC Toxicology Unit, Leicester, U.K.)

Table 2.1 Asbestos Minerals Used Commercially or Found in Asbestos Products Used in Buildings

Mineral	Commercial name	Chemical formula	Building occurrence
Chrysotile	Chrysotile	$(Mg)_6(OH)_8S_{14}O_{10}(\pm Fe)$	*
Grunerite	Amosite	$Fe_7(OH)_2S_{18}O_{22}(\pm Mg, Mn)$	**
Rubeckite	Crocidolite	$Na_2(Fe^{3+})_2(Fe^{2+})_3(OH)_2S_{18}O_{22}(\pm Mg)$	X
Anthophyllite	Anthophyllite	$(Mg, Fe)_7(OH)_2OS_{18}O_{22}$	***
Actinolite	Actinolite	$Ca_2Fe_5(OH)_2S_{18}O_{22}(\pm Mg)$	***
Tremolite	Tremolite	$Ca_2Mg_5(OH)_2S_{18}O_{22}(\pm Fe)$	***

* Very commonly found in ACM products.

** Commonly found.

*** Uncommonly found.

X Typically not used in ACM in North America.

Source: From Health Effects Institute–Asbestos Research, *Asbestos in Public and Commercial Buildings: A Literature Review and Synthesis of Current Knowledge,* Cambridge, MA, 1991. With permission.

asbestos fibers have the following characteristics when viewed by light microscopy: (1) particles typically having aspect ratios from 20 to 100:1 or higher, and (2) very thin fibers (typically <0.5 μm in width). The parallel fibers often occur in bundles. The very fine individual fibers are best seen using transmission electron microscopy. Chrysotile asbestos fiber diameters have been reported to range from 0.02 to 0.08 μm, amosite between 0.06 and 0.35 μm, and crocidolite between 0.04 and 0.15 μm. The smaller the diameter, the higher the tensile strength.

B. Asbestos-containing building materials

Commercial and industrial use of asbestos has a relatively long history. Asbestos fibers have been used extensively, with well over 3000 applications. Generic uses have included fireproofing, thermal and acoustical insulation, friction products such as brake shoes, and reinforcing material.

Materials made of asbestos, or having asbestos within them, are described as asbestos-containing materials (ACM). When used in building construction, they are identified as asbestos-containing building materials (ACBM). Types of ACBM, their characteristics, asbestos content, and time period of use are given in Table 2.2.

1. ACM in nonresidential buildings

For regulatory purposes, asbestos-containing building materials are classified as surfacing materials (SM), thermal system insulation (TSI), and miscellaneous materials (MM). Surfacing materials include spray-applied fireproofing (Figure 2.2) and spray-applied or troweled-on acoustical plaster. Asbestos-containing fireproofing was sprayed on steel I beams in multistory buildings to keep buildings from collapsing due to structural fires. Acoustical