Indoor Air Quality Guide

Best Practices for Design, Construction, and Commissioning

American Society of Heating, Refrigerating and Air-Conditioning Engineers
The American Institute of Architects
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Sheet Metal and Air Conditioning Contractors' National Association
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PART I—Summary Guidance

Overview Information for Design, Construction, and Commissioning for IAQ

Part I of this Guide provides a convenient summary of the key elements of design for indoor air quality (IAQ). These are grouped into eight Objectives:

Objective 1 – Manage the Design and Construction Process to Achieve Good IAQ
Objective 2 – Control Moisture in Building Assemblies
Objective 3 – Limit Entry of Outdoor Contaminants
Objective 4 – Control Moisture and Contaminants Related to Mechanical Systems
Objective 5 – Limit Contaminants from Indoor Sources
Objective 6 – Capture and Exhaust Contaminants from Building Equipment and Activities
Objective 7 – Reduce Contaminant Concentrations through Ventilation, Filtration, and Air Cleaning
Objective 8 – Apply More Advanced Ventilation Approaches

Overview text provides an introduction to each Objective. The overviews are followed by descriptions of the Strategies that can be employed to achieve each Objective. An objective graphic for each Objective identifies major Strategies related to that Objective. In the electronic version of this Guide, each objective graphic in Part I contains blue interactive links to the Strategies for that Objective in Part I.

For each Strategy, there is an overview, both tabular and graphical guides to the detailed information in Part II, one or more case studies, and occasionally a sidebar. The overview explains why the issue is important for IAQ, how to determine whether it needs to be considered for a particular project, and potential design solutions to the problem. In Part I, each Strategy's tabular guide to the detailed information in Part II identifies the elements that need to be addressed in meeting each Objective and can be modified to be used as a checklist in project planning. Each Strategy's graphical guide to the detailed information in Part II provides a visual overview of the issue. In the electronic version of this Guide, both the tabular and graphical guides in Part I contain blue interactive links to the Part II detailed guidance.

Manage the Design and Construction Process to Achieve Good IAQ

The single most important step an owner or design team leader can take to reliably deliver good IAQ is to use effective project processes. Lacking these, even the most sophisticated suite of IAQ technologies may not deliver the desired results. Using effective project processes, however, even simple designs can avoid IAQ problems and provide a good indoor environment.

- Strategy 1.1 – Integrate Design Approach and Solutions describes approaches to integrate design across disciplines, enabling achievement of IAQ and other performance goals at lower cost. Many IAQ problems occur because building elements are designed by different disciplines working in relative isolation. Even design elements that do not appear to be related can sometimes interact in ways that are detrimental to IAQ.
- Strategy 1.2 – Commission to Ensure that the Owner's IAQ Requirements are Met provides guidance on commissioning (Cx) as a quality control process for IAQ, from establishment of the owner's IAQ requirements at project inception to construction observation and functional testing. For buildings as for any other product, quality control in design and execution is necessary to achieve the desired result.
- Strategy 1.3 – Select HVAC Systems to Improve IAQ and Reduce the Energy Impacts of Ventilation explains how the type of HVAC system selected can constrain the level of IAQ achievable by limiting the capability for filtration, space humidity control, building pressurization, or separation of intakes from contaminant sources. It can also have a major impact on the energy required for ventilation. Yet the type of system is often selected by the architect before the engineer is involved or chosen based on cost, space required, or other factors without adequate consideration of IAQ implications.
- Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ highlights the importance of construction processes to IAQ. A project schedule that is too compressed or improperly sequenced can jeopardize IAQ. Likewise, failure to manage contaminants and water during construction can have a detrimental effect on occupants in buildings undergoing renovation and on long-term IAQ in new buildings.
- Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ explains how the design team can help O&M staff deliver performance consistent with the design intent through appropriate system selection, system-oriented documentation, and system-oriented training.

Objective 1

Objective 1

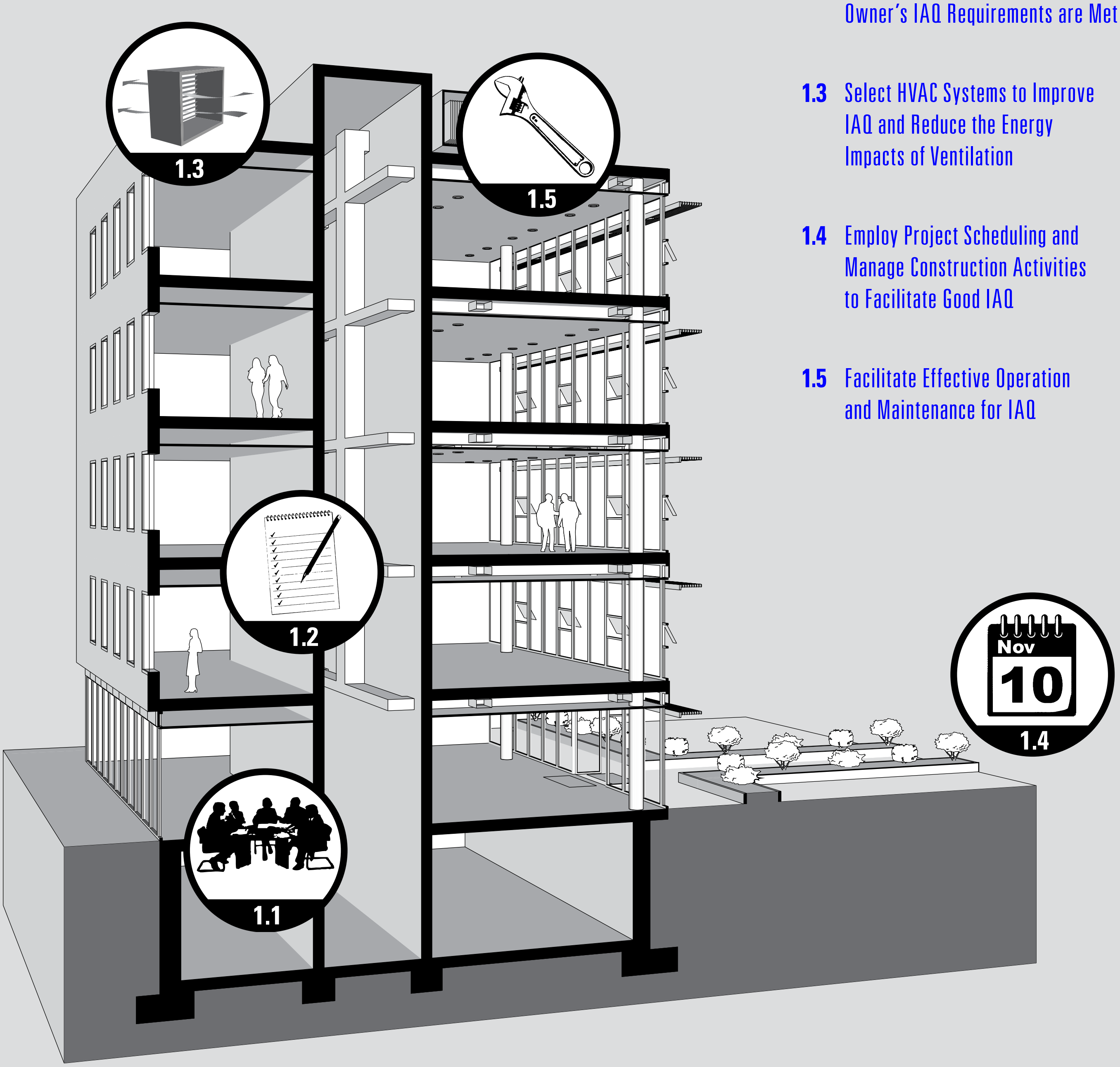
1.1 Integrate Design Approach and Solutions

1.2 Commission to Ensure that the Owner's IAQ Requirements are Met

1.3 Select HVAC Systems to Improve IAQ and Reduce the Energy Impacts of Ventilation

1.4 Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ

1.5 Facilitate Effective Operation and Maintenance for IAQ



Integrate Design Approach and Solutions

Integrated design is one of today's buzzwords in "green" and "sustainable" building design, but nowhere is it more important or valuable than in relation to IAQ. Most if not all of the design approaches and solutions that are important for achieving good IAQ are also important for thermal comfort and energy efficiency. They also have very strong connections to illumination and acoustics.

Thermal comfort and good IAQ are intricately bound together both in the characteristics of the indoor environment and in the way building occupants respond to the indoor environment. Occupants' perceptions of the indoor environment and the indoor environmental quality (IEQ) impacts on occupant health have strong interactions and, in reality, cannot be separated. Beyond environmental control systems, IAQ is strongly determined by the building structure and envelope, so all key members of the design team play a role in determining the potential for achieving good IAQ in your designs.

The team members responsible for the ventilation and thermal control solutions affect and are affected by the acoustic and illumination requirements and solutions. Noise from mechanical systems, waste heat from electrical illumination sources, or heat loss or gain through glazing are as important to the selection of ventilation solutions as the pollutant loads coming from building materials, occupant activities, building equipment, appliances, or any other sources. Only by considering all of the potential loads can the optimal solution for ventilation, material selection, and envelope design be made effectively.

The easiest and most effective way to accomplish integrated design is to assemble the entire design team at the beginning of the project and to brainstorm siting, overall building configuration, ventilation, thermal control, and illumination concepts as a group. The give and take of the initial design charette with the key members present will help each team member to appreciate the specialized concerns of the others and enable the group to develop a solution that best integrates everyone's best ideas.

Once the initial design concept is agreed upon, then the evolution of the design through its various stages can occur with a shared concept and the potential for direct interaction among team members as challenges arise later in the process. The design team leader ultimately must make decisions when conflicts arise, but starting with a concept shared by the whole team will minimize the number and importance of those conflicts later in the process.

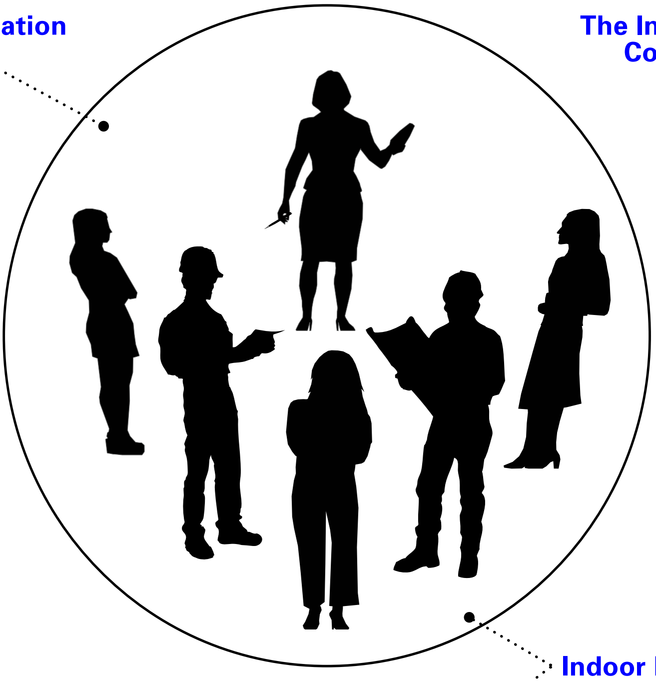
In typical design processes, lacking such a collaborative effort to produce an overall design concept, the building's basic concept ends up reflecting only some of the important considerations. Then the remainder of the design process looks more like an effort to retrofit the design concept to accommodate the concerns ignored initially. It is also true that many of the most environmentally responsible design solutions can work together to produce a synergy that is not achieved when such collaboration and integration is absent. Reducing loads—whether of pollutant emissions or of heat gain or loss—reduces demand for ventilation and conditioning of outdoor air and results in lower first costs for equipment as well as lower operating costs.

Building design professionals understand that the design of virtually every building element affects the performance of other elements, so it makes sense to integrate various design elements of a building. Unfortunately, the prevailing design process of our time tends to create design elements in a compartmentalized and linear process rather than jointly designing these elements in an interactive process. Figure 1.1-A depicts the traditional design team; Figure 1.1-B depicts the integrated design team.

Strategy 1.1

Current Trends call for Integrated Design

Leadership and Communication with Integrated Design



The Importance of the Conceptual Design Phase

IAQ Considerations During Conceptual Design

Laying the Groundwork for an Interactive Process

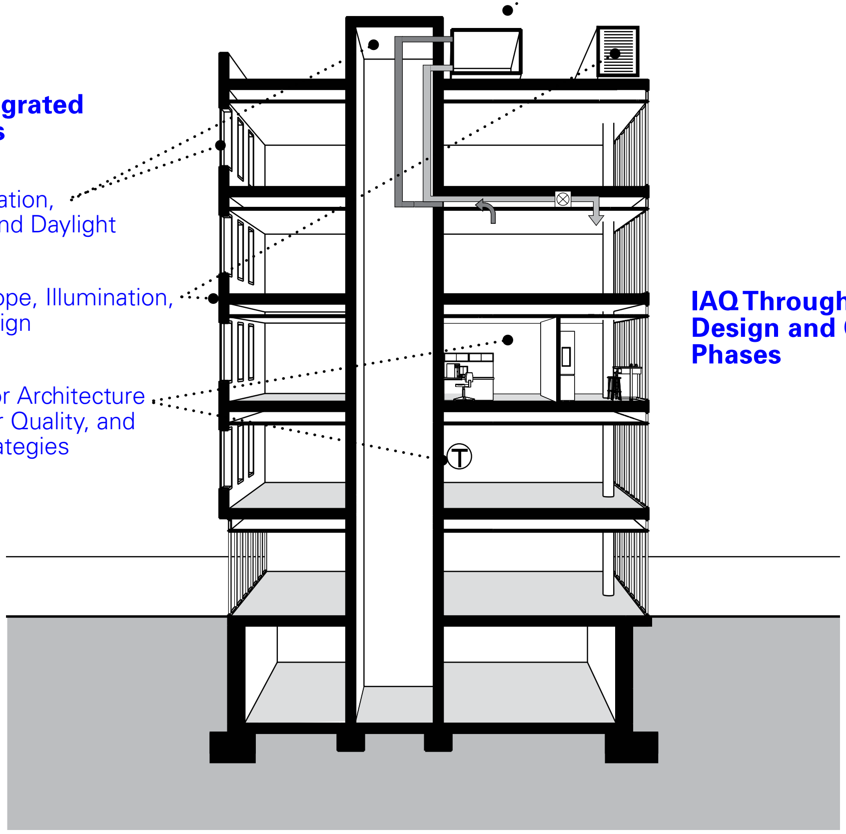
Indoor Environmental Quality is Best Served by Integrated Design

Examples of Integrated Design Solutions

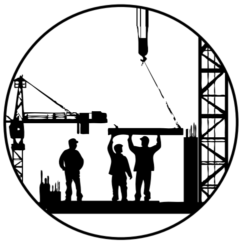
Use of Hybrid Ventilation, Occupant Control, and Daylight

Integration of Envelope, Illumination, and Mechanical Design

Integration of Interior Architecture with Illumination, Air Quality, and Thermal Control Strategies



IAQ Throughout the Design and Construction Phases



Strategy 1.1

Traditional

Hierarchical Organization
Owner - Architect - Engineer
Transactional Design Process
Boundaries / Boxes
Percentage Based Fees

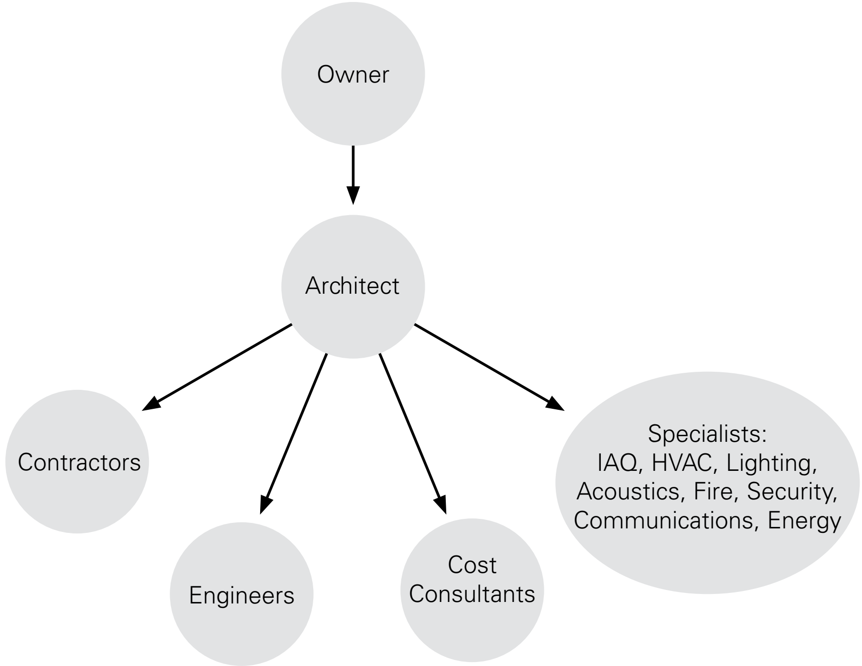


Figure 1.1-A Traditional Design Team

Integrated

Holistic Thinking
Team Based
Organic design Process
Larger Inclusive Team
Users, Operators, Code
Innovations Encouraged by Client

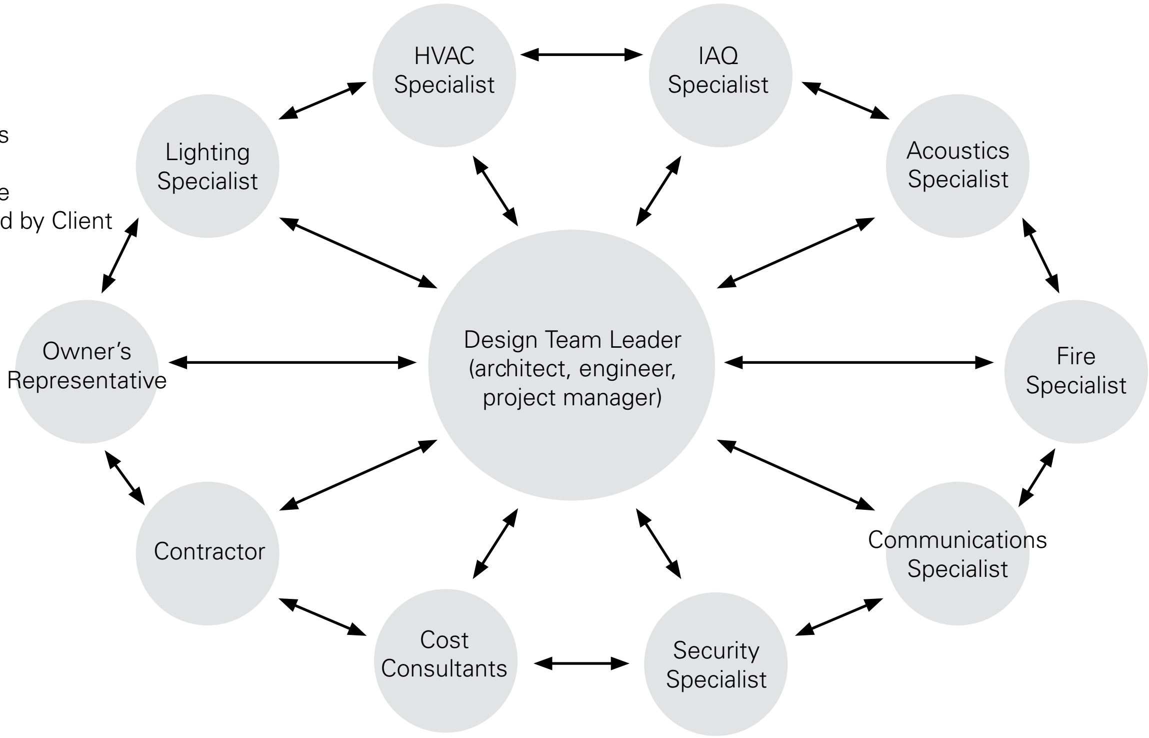


Figure 1.1-B Integrated Design Team

Strategy 1.1

Integrated Design Process

Typically, an integrated design process begins with a "charette"—a gathering of the major players, often including the client or future occupants. A design charette may also be a gathering of the key members of the design team including all major consultants. When the focus is on environmental performance, indoor environment, energy, and environmental impacts, it is common to identify the major issues and establish goals very early in the process, ideally during the generation of the conceptual or schematic design.

An example of this process is much of the work of architect Bob Berkebile, FAIA, principal of the firm Berkebile Nelson Immenschuh McDowell Architects in Kansas City, Missouri. Berkebile founded the American Institute of Architects (AIA) Committee on the Environment and has long been one of the leading practitioners of environmentally responsible design including IEQ, energy performance, and general environmental impacts. Figures 1.1-B and 1.1-C show typical gatherings in the integrated design practice of BNIM.

Figure 1.1-B Designers Choosing Materials at a Typical Charette
Photograph copyright BNIM.

Figure 1.1-C Design Team Studying a Model of an Early Design Concept at a Charette
Photograph copyright BNIM.

Commission to Ensure that the Owner's IAQ Requirements are Met

What is Commissioning and Why Is It Needed?

Few manufacturers today would consider producing a product without a formal quality control process. Yet the majority of buildings are built without the use of systematic quality control procedures. As a result, buildings may be turned over with undetected deficiencies, and key assemblies or systems may fail to function as intended. IAQ may suffer due to any number of problems in design, material, and equipment selection or construction. To address these problems, a growing number of building owners are incorporating commissioning (Cx), a quality-focused process that is used to complete successful construction projects (ASHRAE 2005).

Commissioning Starts at Project Inception

It is a common misconception that Cx is a post-construction process. In fact, Cx needs to start in the pre-design phase to maximize its effectiveness and cost-effectiveness. During this phase, the owner should select a commissioning authority (CxA) and establish the Cx scope and budget. The design team's responsibilities related to Cx need to be defined in their agreements with the owner.

During pre-design, the CA helps the owner identify and make explicit all functional requirements for the project. These requirements then become the focus of the Cx process. For example, every owner expects his or her building to be free of condensation and mold problems, be properly ventilated, and provide good-quality ventilation air, but the team can lose focus on these Owner's Project Requirements (OPR) so that they fail to be met if the OPR are not explicitly stated and tracked throughout the project.

The CA needs to provide input to the project schedule to ensure that it accommodates the steps necessary to achieve the owner's IAQ requirements. This input may include, for example, the timing of inspections that must be made while key assemblies are still open or the proper sequencing of work to avoid moisture damage.

Commissioning the Design

It is much easier and cheaper to correct deficiencies on paper during design than in the finished building after construction.

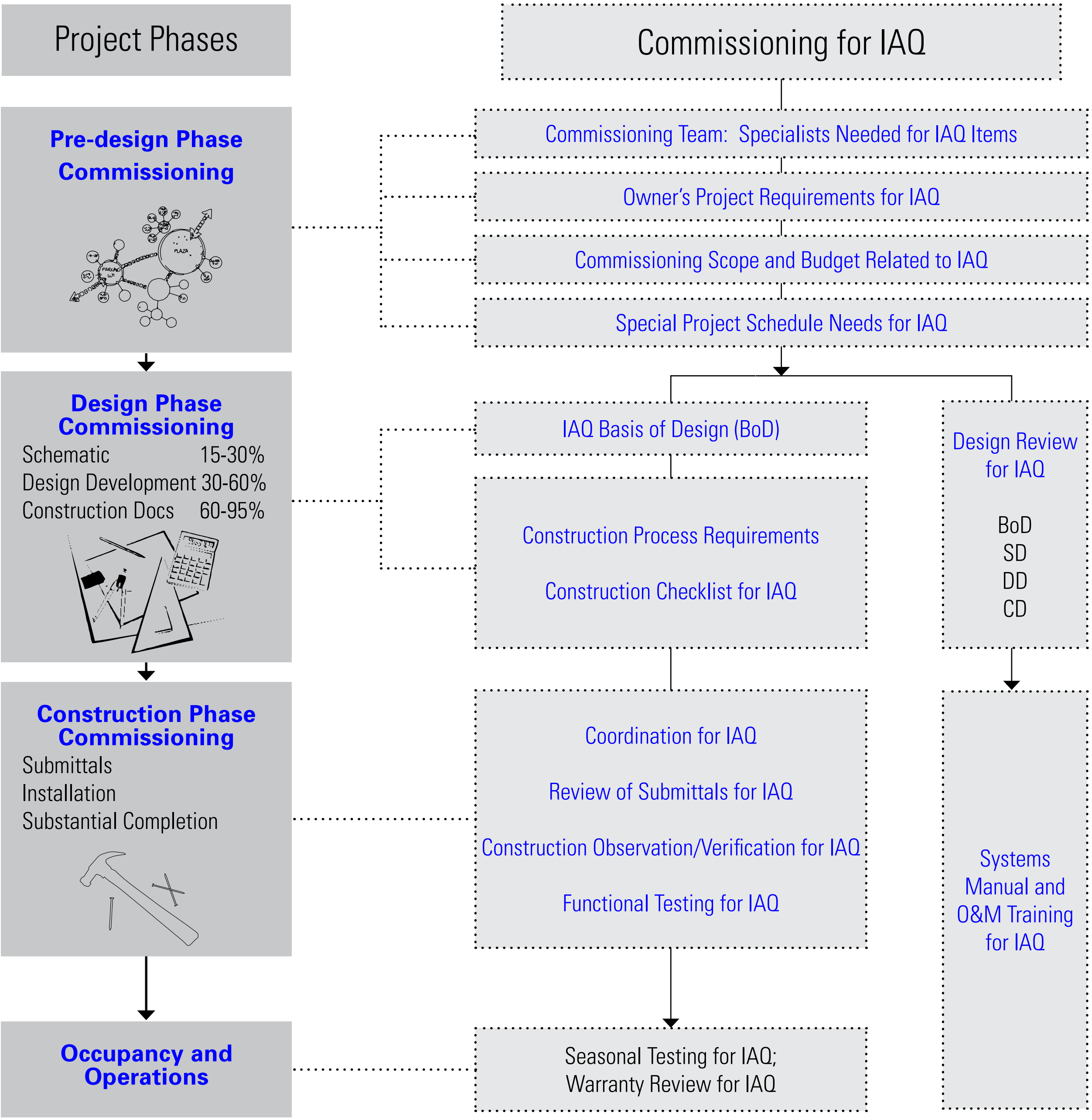
During conceptual design, Cx calls upon the design team to record the concepts, calculations, decisions, and product selections used to meet the OPR and applicable codes and standards in a Basis of Design (BoD) document. The CA plays an important role in reviewing this BoD document to determine whether it will meet the owner's requirements. The CA continues to review the design in the design development and construction documents phases to ensure that they will fulfill the owner's needs.

The CA assists the design team in incorporating into the specifications the Cx work that will be required of contractors so that the contractors can understand and budget their role in the Cx process.

Commissioning the Construction

During construction, the CA monitors work to ensure that it does not compromise the OPR. This includes reviewing submittals to ensure that they are consistent with the OPR and BoD and that they provide for Cx needs. It also includes early and ongoing observation of key aspects of construction to ensure that the owner's requirements are not compromised. This may include, for example, checking the continuity of drainage planes and air barriers while walls are under construction or checking that maintenance access is preserved as HVAC equipment and later services are installed.

Strategy 1.2



Project Phases

Pre-design Phase Commissioning

Design Phase Commissioning

Schematic 15-30%
Design Development 30-60%
Construction Docs 60-95%

Construction Phase Commissioning

Submittals
Installation
Substantial Completion

Occupancy and Operations

Commissioning for IAQ

Commissioning Team: Specialists Needed for IAQ Items

Owner's Project Requirements for IAQ

Commissioning Scope and Budget Related to IAQ

Special Project Schedule Needs for IAQ

IAQ Basis of Design (BoD)

Construction Process Requirements

Construction Checklist for IAQ

Design Review for IAQ

BoD
SD
DD
CD

Coordination for IAQ

Review of Submittals for IAQ

Construction Observation/Verification for IAQ

Functional Testing for IAQ

Systems Manual and O&M Training for IAQ

Seasonal Testing for IAQ;
Warranty Review for IAQ

The CA also provides the installation and start-up checklists that are executed and signed by the contractors and spot-checks them after completion. Often the CA verifies a statistical sample of the balancing report by observing the balancer as he or she conducts repeated measurements.

Testing for Acceptance
The CA designs, oversees, and documents functional tests that determine the ability of building assemblies and systems to meet the OPR. These may include testing of building assemblies for water penetration and air leakage or testing of control system sequences of operation for proper performance.

Systems Manual and O&M Training
O&M manuals are often massive and can lack key information while being laden with material that does not apply to the project. O&M training is often a cursory afterthought. In commissioned projects, however, the CA often defines requirements for a systems manual and O&M training to support ongoing achievement of the OPR and verifies their delivery to O&M staff.

Commissioning to Ensure that Design Ventilation Rates Are Met

Poor ventilation in an extensively renovated theater led to patron complaints of stuffiness. Investigation identified several factors contributing to low ventilation rates:

- The design called for demand-controlled ventilation (DCV) based on carbon dioxide (CO_2), with minimum outdoor air (OA) flow modulated between 2000 and 7200 cfm (940 and 3400 L/s) to maintain CO_2 at or below

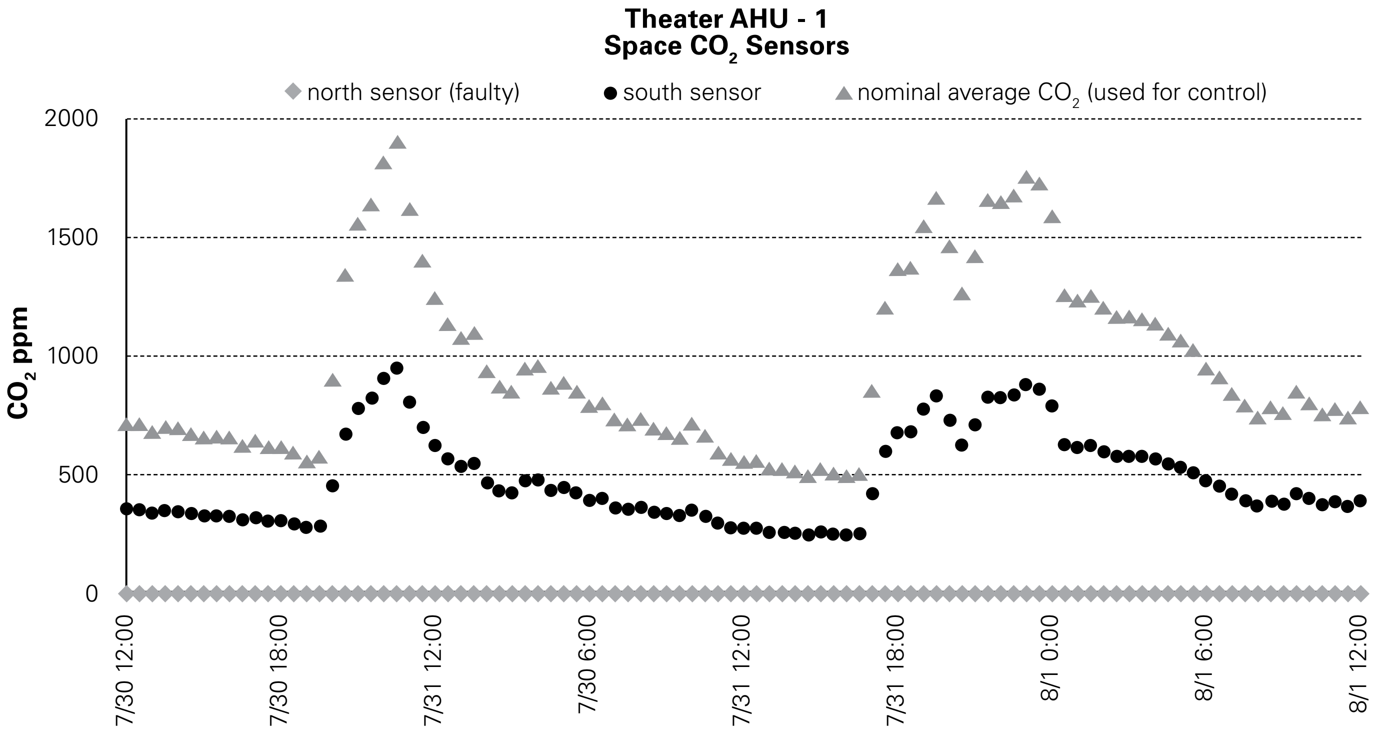


Figure 1.2-A Space CO_2 Sensor Graph

900 ppm (1600 mg/m^3). The programming as implemented actually reset the minimum OA between 2000 cfm (940 L/s) at 1000 ppm (1800 mg/m^3) CO_2 and 3000 cfm (1400 L/s) at 1500 ppm (2700 mg/m^3) CO_2.

- The north CO_2 sensor (diamonds near zero in Figure 1.2-A) was faulty and consistently read about 4 ppm (7 mg/m^3). The average CO_2 concentration used by the control system to adjust OA flow thus appeared to be about half its actual value. For example, if the actual CO_2 was 1900 ppm (3400 mg/m^3), the average value passed to the control loop was (1900 + 4)/2 = 952 ppm [(3400 + 7)/2 = 1703 mg/m^3], and the reset only called for the system to deliver 2000 cfm (940 L/s) of OA.
- The OA measuring station read about 1100 cfm (520 L/s) with the fan off, so it reached a reading of 2000 cfm (940 L/s) at an actual flow below 2000 cfm (940 L/s).

As a result of these problems, the actual minimum OA never went above about 2000 cfm (940 L/s) (Figure 1.2-B). Because the project was not commissioned, the cause of the stuffiness was not diagnosed until several years after the renovation when the building was retro-commissioned.

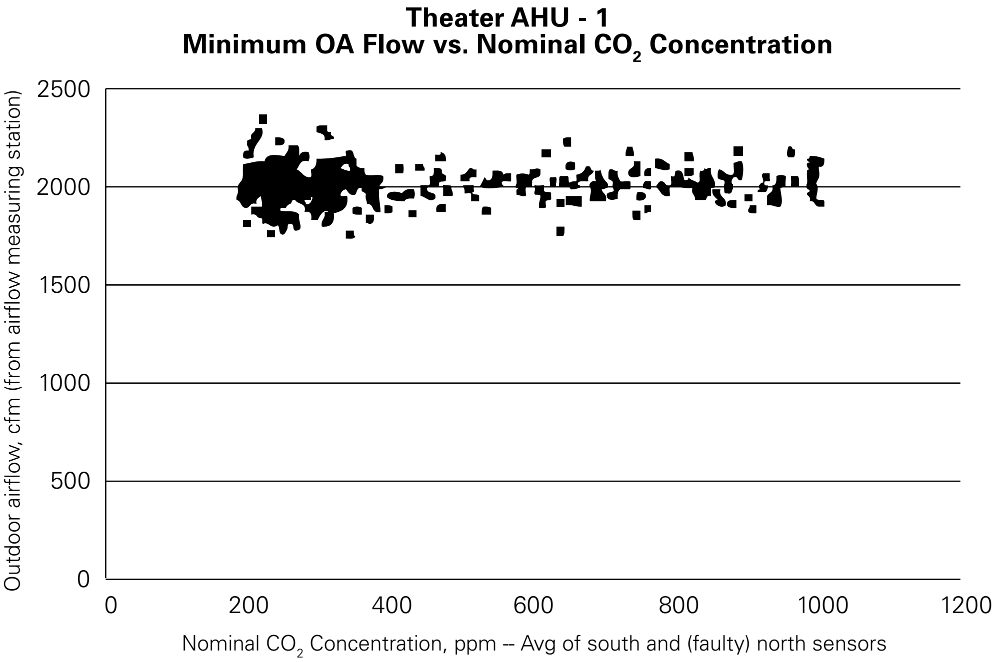


Figure 1.2-B Minimum OA Flow vs Nominal CO_2 Concentration

Control Moisture in Building Assemblies

Moisture is one of the most common causes of IAQ problems in buildings and has been responsible for some of the most costly IAQ litigation and remediation. Moisture enables growth of microorganisms, production of microbial VOCs and allergens, deterioration of materials, and other processes detrimental to IAQ. In addition, dampness has been shown to be strongly associated with adverse health outcomes. Control of moisture is thus critical to good IAQ.

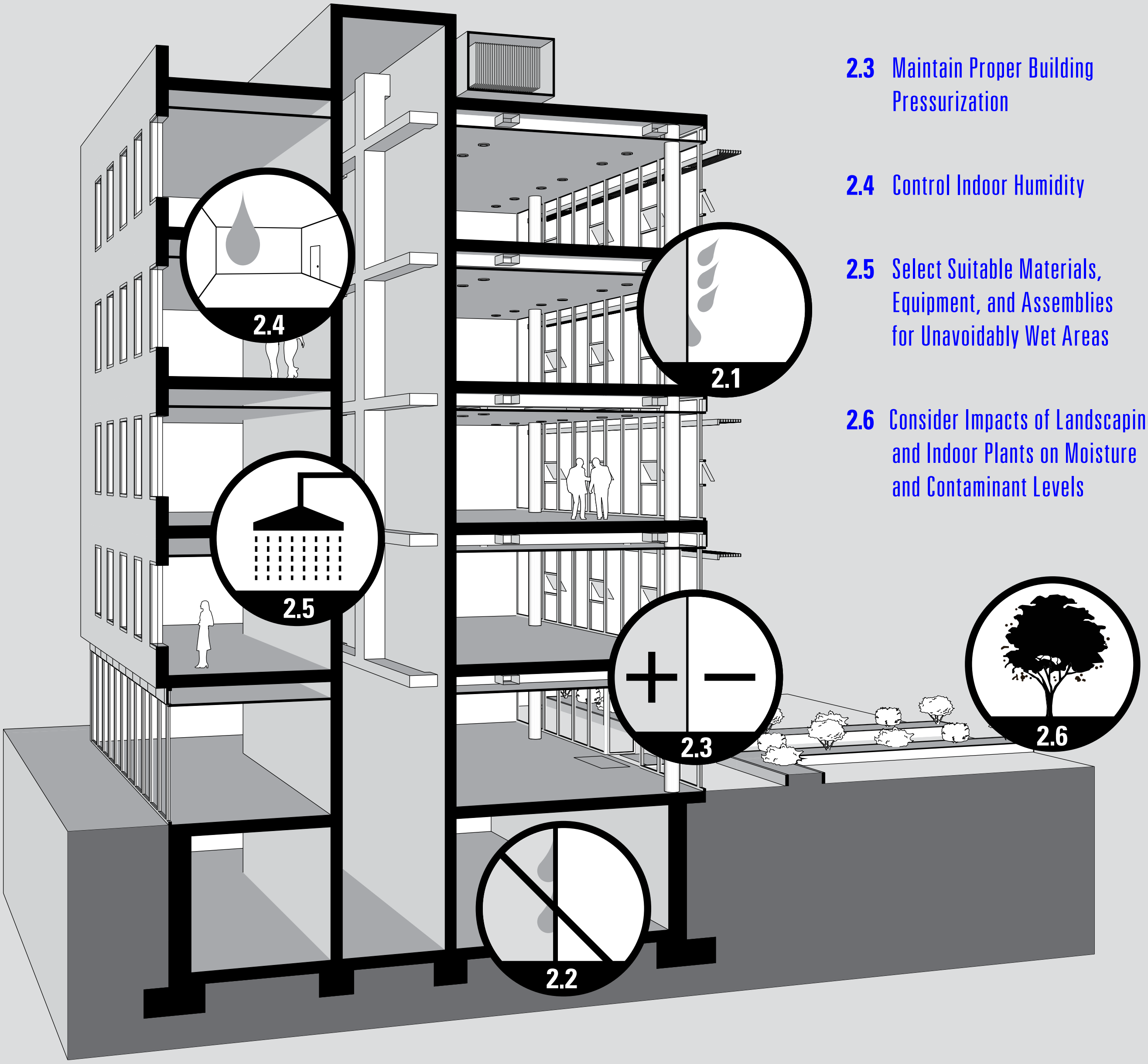
- Penetration of rainwater or snowmelt into the building envelope is a common cause of IAQ problems. Strategy 2.1 – Limit Penetration of Liquid Water into the Building Envelope describes design features and quality control processes that can limit water entry.
- Condensation is another common cause of IAQ problems. It most often occurs when moist air infiltrates into or exfiltrates out of the building enclosure and encounters a surface with a temperature below the air dew point. However, it can also occur due to vapor diffusion, capillary transport, or thermal bridging. Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces describes design and quality control to reduce the likelihood of condensation problems.
- Negative building pressure can draw moist outdoor air into the building envelope, potentially leading to condensation. It can also draw moist air into the conditioned space itself, potentially increasing the latent load beyond the cooling system design capacity and leading to elevated indoor humidity. Positive building pressure can push moist indoor air into the building enclosure, potentially leading to condensation under heating conditions. Strategy 2.3 – Maintain Proper Building Pressurization addresses pressurization control.
- High indoor humidity increases the risk of microbial growth and IAQ problems. Strategy 2.4 – Control Indoor Humidity addresses humidity control, especially in hot, humid climates where controlling indoor humidity can be particularly challenging.
- Some indoor areas, such as shower rooms, toilet rooms, janitorial closets, and kitchens, frequently are wetted with liquid water or experience condensation due to high humidity. Strategy 2.5 – Select Suitable Materials, Equipment, and Assemblies for Unavoidably Wet Areas describes strategies to preserve IAQ in wet areas.
- Strategy 2.6 – Consider Impacts of Landscaping and Indoor Plants on Moisture and Contaminant Levels provides information on the advantages and disadvantages of plants from an IAQ perspective.

Other important moisture control issues are discussed in the following sections:

- Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ
- Objective 4 – Control Moisture and Contaminants Related to Mechanical Systems

Objective 2

Objective 2



2.1 Limit Penetration of Liquid Water into the Building Envelope

2.2 Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces

2.3 Maintain Proper Building Pressurization

2.4 Control Indoor Humidity

2.5 Select Suitable Materials, Equipment, and Assemblies for Unavoidably Wet Areas

2.6 Consider Impacts of Landscaping and Indoor Plants on Moisture and Contaminant Levels

Limit Penetration of Liquid Water into the Building Envelope

Moisture in buildings is a major contributor to mold growth and the poor IAQ that can result. Wetting of building walls and rainwater leaks are major causes of water infiltration. Preventive and remedial measures include rainwater tight detail design, selection of building materials with appropriate water transmission characteristics, and proper field workmanship quality control.

Effective liquid water intrusion control requires both of the following:

- Barriers to water entry established and maintained using capillary and surface tension breaks in the building enclosure.
- Precipitation shed away from the building using continuous effective site drainage and a storm water runoff system.

Establish and Maintain Barriers to Water Entry

Leaking rainwater can cause great damage to a building and the materials inside. Rainwater that falls on the building is controlled by a combination of drainage and capillary breaks. A capillary break keeps rainwater from wicking through porous materials or through cracks between materials and thus entering the building. Creating a capillary break involves installing a material, such as rubber roofing, that does not absorb liquid water. Another way to create a capillary break is to provide an air gap between materials that get wet and materials that should stay dry. An example of an air gap is the space behind brick veneers in exterior walls. Wall systems must employ cladding and flashing systems that direct the water away from the building.

The moisture-resistant materials that form the exterior skin of a building intercept and drain rain from roofs and away from walls, down walls and over windows and doors, and away from foundations (above, at, and below grade).

Sometimes a single moisture-impermeable material, sealed at the seams, forms the entire rainwater barrier—drainage and capillary break all in one. Membrane roofing and some glass panel claddings work in this way. Usually, however, roofing and cladding systems are backed up by an inner layer of moisture-resistant material that forms the drainage plane. The drainage plane intercepts rainwater that seeps, wicks, or is blown past the outer layer and drains it out of the building. An air gap between the drainage plane and the roofing or cladding provides a channel for drainage. The air gap and the drainage plane form capillary breaks between the outer layer and the materials inboard of the drainage plane.

Directing Water Away from the Building

The first step in rainwater control is to effectively situate the building and use or change the landscape to divert rainwater away from the structure. These actions are known as *site drainage* and include sloping the grade away from the building to control surface water and diverting water from the foundation below grade.

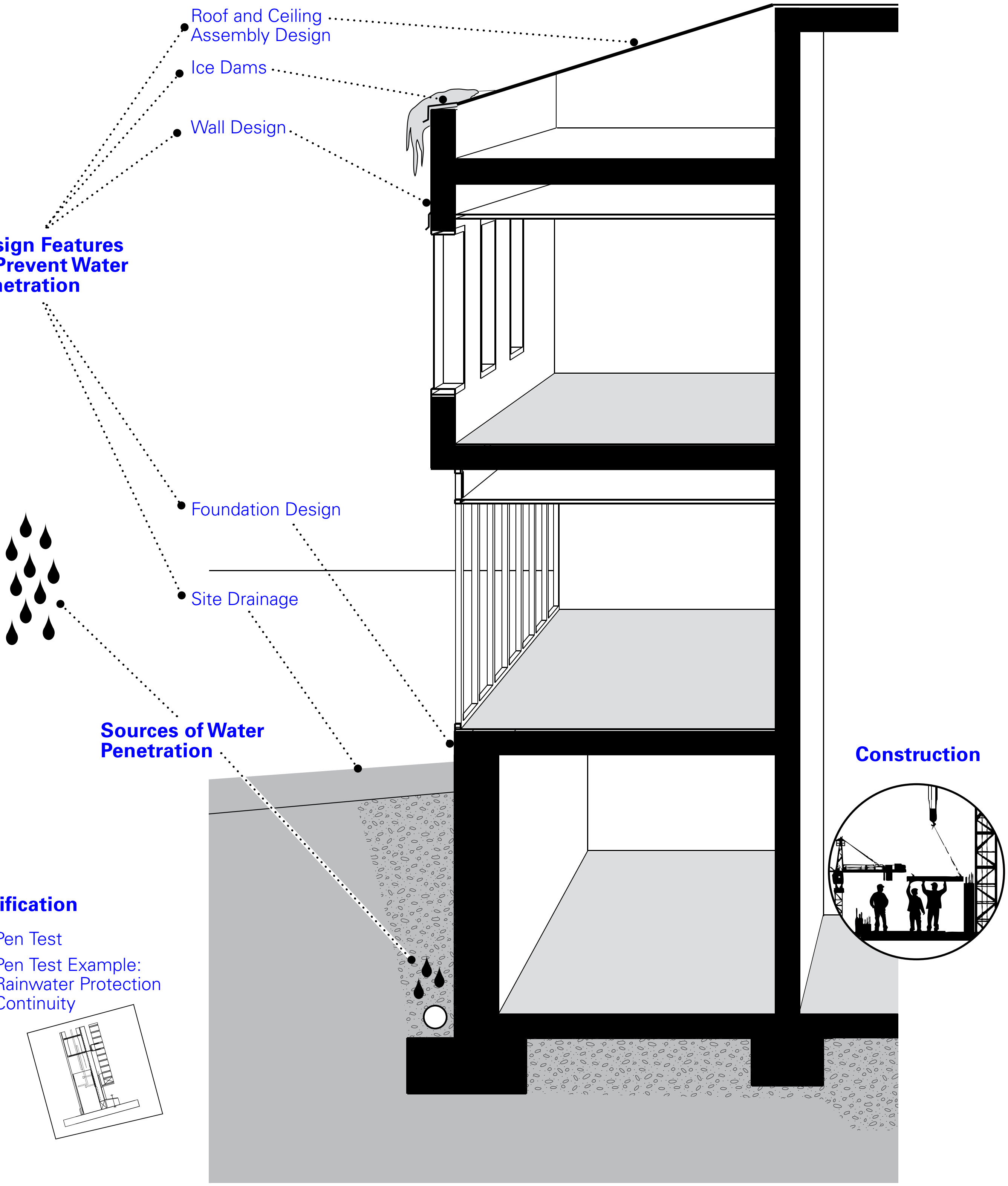
Once the site is designed properly to drain water away from the building, the building needs a storm water runoff system to divert precipitation from the roof into the site drainage system. This component of moisture control is called *storm water runoff management*.

The building foundation needs to be detailed to protect the building from rainwater. The above-grade portions of a foundation are often heavy masonry or concrete walls. A great deal of the rainwater that wets the above-grade wall simply drains off the surface to the soil below. Masonry and concrete walls are so massive, absorbed water is more likely to be stored in the wall—drying out between storms—than to wick through to the interior.

Landscape surfaces immediately surrounding the foundation perform the same function for the walls below grade as the roofing and cladding in the walls above grade: they intercept and drain rain away from

Strategy 2.1

Sources of Water Penetration



Design Features to Prevent Water Penetration

Roof and Ceiling Assembly Design

Ice Dams

Wall Design

Foundation Design

Site Drainage

Sources of Water Penetration

Construction

Verification

Pen Test

Pen Test Example: Rainwater Protection Continuity the building. The dampproof or waterproof coatings on below-grade walls serve the same purpose as the drainage plane in the above-grade walls, presenting a capillary break for rainwater that infiltrates the surrounding fill. Free-draining fill or geotechnic drainage mats placed against the below-grade walls serve the same function as the air gap in the above-grade walls; they provide a place for water to run down the drainage plane.

At the bottom of the below-grade wall, a footing drain system diverts rainwater or, in some cases, rising groundwater from the footing and the floor slab. Paint designed for use on concrete can be used on top of the footing to provide a capillary break between the damp footing and the foundation wall.

A layer of clean, coarse aggregate with no fines can provide a capillary break between the earth and the concrete floor slab. Plastic film beneath the floor slab provides a code-required vapor barrier and a capillary break beneath the slab.

Water Intrusion in a Multi-Family Complex

Figure 2.1-A Points of Water Entry into the Building Envelope

This multi-family complex (Figure 2.1-A) had several areas of water intrusion through the building envelope. These areas included the roof to vertical wall intersection, the window and window surround, the penetrations, and the elevated slabs. The water intrusion resulted in damage in these areas and the need to remove portions of the building envelope to repair the damage. The cost of the remediation was estimated to be over $2 million.

The areas of failure included penetrations that were not flashed or sealed as well as windows and other openings with improper flashing around them. Damage to these areas because of these failures required remediation of the building envelope to correct them:

- Penetrations through the waterproofing membrane resulted in a breach in the capillary plane and deterioration of the underlying structure (Figure 2.1-B).

Strategy 2.1

- Lack of flashing and sealant at vent penetrations through the veneer resulted in water intrusion (Figure 2.1-C).
- Lack of flashing at the windows for control of water drainage at the window openings resulted in intrusion (Figure 2.1-D).
- Lack of complete flashing at the low roof intersection and the adjacent vertical wall (rake wall condition) resulted in water intrusion into the wall (Figure 2.1-E).

Figure 2.1-B Structure Damage from Failures in the Building Envelope

Figure 2.1-C Damage from Failure at Vent Penetration

Figure 2.1-D Damage from Window Surround and Window Flashing Failures

Figure 2.1-E Damage from Failure of the Roof Flashing Termination

Photographs copyright Liberty Building Forensics Group®.

Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces

Preventing condensation or, more accurately, controlling the moisture content of building materials helps prevent the growth of microorganisms, especially molds, within the enclosure and on interior surfaces. The growth or amplification of microorganisms in buildings not only results in biodeterioration of susceptible construction materials but also leads to the production of allergens and microbial VOCs (which cause musty odors) that can affect occupant health and air quality. A complex microbial ecology can develop in or on construction materials that are chronically wet or damp (e.g., mites feed on mold; other organisms feed on mites). Allergens associated with molds and arthropods growing in chronically wet construction niches can enter the indoor environment and pose a risk to sensitive occupants.

The moisture content of building materials increases due to water vapor transport across enclosure assemblies either due to infiltrating, exfiltrating, or convecting air in contact with surfaces that have a temperature lower than the dew point of the air coming in contact with the surface and/or by diffusion due to a difference in water vapor pressure across the assembly or by capillary transport through the microscopic voids in building materials. Thermal bridges in the form of highly conductive materials that penetrate the insulated enclosure can drop temperatures of indoor surfaces to levels promoting condensation. Properly designed enclosure assemblies that have greater drying potential than wetting potential and that achieve a moisture balance over time are not always implemented, and many building designs do not get scrutinized for appropriate enclosure design.

Building enclosures are often designed without a proper understanding of the performance of the assembly when it is subjected to the exterior weather and interior boundary conditions. Code requirements may even impose solutions that are problematic, such as requiring vapor retarders prescriptively or requiring water-resistive barriers that may be too vapor permeable under certain conditions. Prescriptive criteria in codes are slowly being improved, but the substitution of a single material in an assembly can radically change how the assembly performs over time.

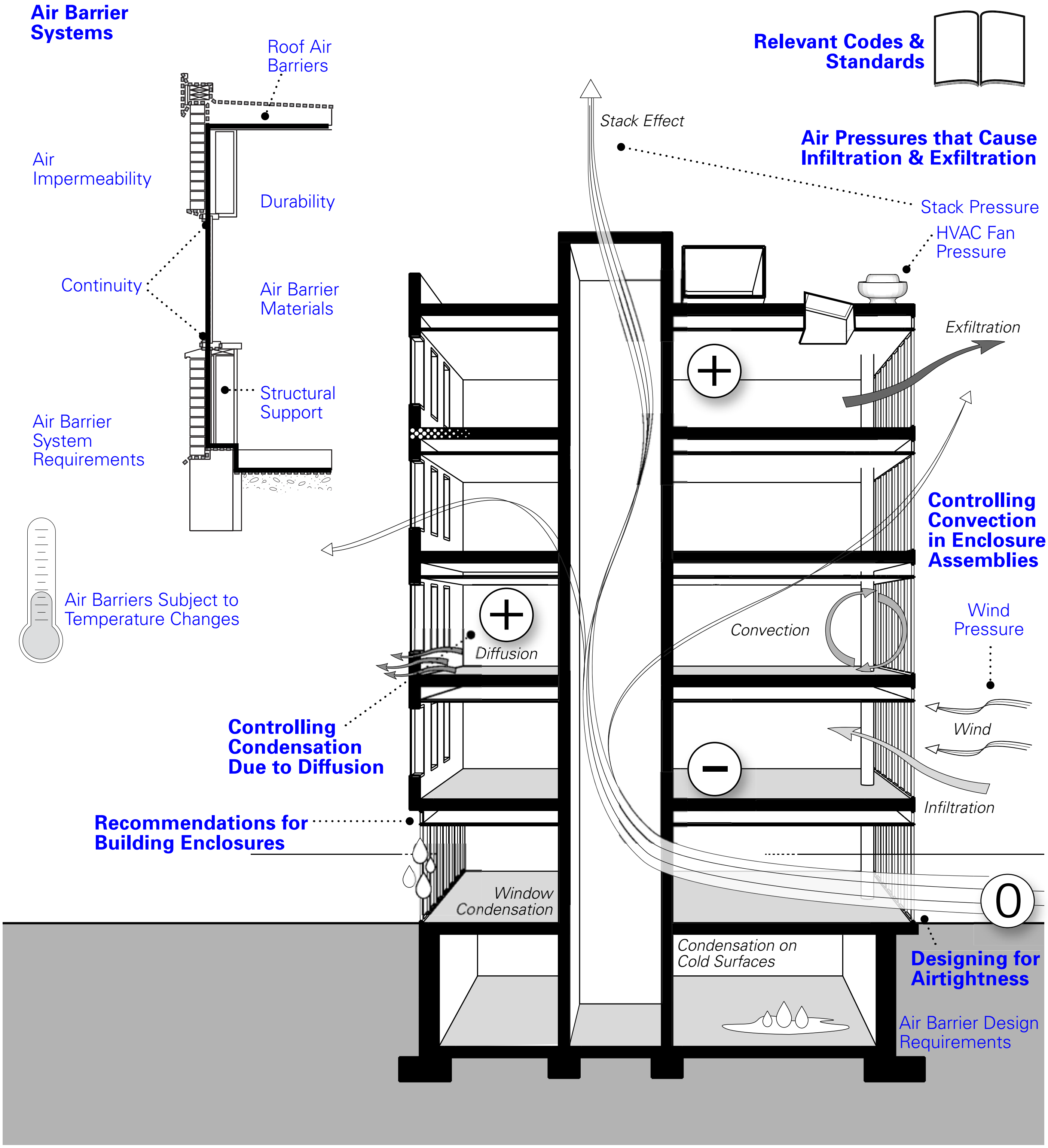
Building enclosures need to be designed by a knowledgeable design professional using design tools referenced in *ASHRAE Handbook—Fundamentals* (ASHRAE 2009) in order to avoid the likelihood of moisture-related problems.

Design for Airtightness of the Enclosure

A continuous air barrier system in the building enclosure needs to be included. A continuous air barrier system is created by adhering to the following steps.

- Select a material in each opaque wall, floor, and roof assembly that meets a maximum air permeance of 0.004 cfm/ft^2 at 0.3 in. w.g. (0.02 L/s·m^2 at 75 Pa) and join it together with tapes, sealants, etc., into an assembly.
- Join the air barrier layer of each assembly with the air barrier layer of adjacent ones and to all fenestration and doors until all enclosure assemblies (for the complete building as a six-sided box) are interconnected and sealed.
- Seal all penetrations of the air barrier layer. The airtight layer of each assembly will support the entire air pressure caused by wind, stack effect, and HVAC operation.

Strategy 2.2



Air Barrier Systems

Roof Air Barriers

Air Impermeability

Durability

Continuity

Air Barrier Materials

Structural Support

Air Barrier System Requirements

Air Barriers Subject to Temperature Changes

Controlling Condensation Due to Diffusion

Recommendations for Building Enclosures

Relevant Codes & Standards

Air Pressures that Cause Infiltration & Exfiltration

Stack Pressure

HVAC Fan Pressure

Controlling Convection in Enclosure Assemblies

Wind Pressure

Designing for Airtightness

Air Barrier Design Requirements

- Ensure that the airtight layer is structurally supported and can support the maximum positive and negative air pressures it will experience without rupture, displacement, or mechanical damage. Stresses must be safely transferred to the structure.

Design for Convection

Air gaps adjacent to cool or cold surfaces can promote convection within a wall assembly. Cold air is heavier and drops, pulling in warm humid air to replace it and deposit moisture on the cold surface. This is especially true in vertical or sloping assemblies. The colder side can be the sheathing in colder climates or the interior drywall in warmer climates. Eliminating the air space on one or the other side of the insulation can be effective in preventing these convective loops. Fibrous insulation, however, which is mostly air, can also promote these convective loops.

Design for Diffusion

A vapor retarder with appropriate permeance for the application should be placed on the predominantly high vapor pressure side of the assembly. To design assemblies for appropriate diffusion control, hygrothermal analysis is needed using either the steady-state dew point or the Glaser method, described in Chapter 25 of *ASHRAE Handbook—Fundamentals* (ASHRAE 2009) or by using a mathematical model that simulates transient hygrothermal conditions (such as WUFI, hygIRC, or Delphin). Users of such methods need to understand their limitations, and interpretation of the analysis results should be done by a trained person to reasonably extrapolate field performance approaching the design results. The International Energy Agency Annex 14 (IEA 1991) has established that a surface humidity of 80% represents a reasonable threshold for designers to achieve a successful building enclosure assembly for temperatures between 40°F and 120°F (5°C and 50°C).

Window and Skylight Selection

Fenestration should be selected carefully by designers to avoid condensation. Fenestration is selected taking into account the interior boundary conditions and exterior weather conditions, and, from a chart developed by American Architectural Manufacturers Association (AAMA; 1988), the appropriate condensation resistance factor (CRF) for the window or skylight is determined. Thermally broken units that minimize the amount of exterior metal exposed to cold usually perform best. The edge spacer of the insulating glass unit is usually the most conductive (and coldest) location in an assembly. A new generation of “warm-edge” spacers that include thermally broken aluminum spacers, stainless steel spacers, and non-metallic glass-fiber reinforced plastic spacers are increasingly being used and improve the thermal performance of fenestration. Window and skylight manufacturers generally can provide National Fenestration Rating Council (NFRC) simulations using the software THERM (LBNL 2008) that show how a specific selection of window, spacer, and glass with various gaseous fill will perform. It is also important to note that some non-metal windows that have improved U-factors may have worse CRFs than metallic thermally broken windows. Custom designs are often required to be verified using the THERM and WINDOW (LBNL 2009a) software and validated by physical laboratory testing.

Below-Grade Walls and Slabs on and Below Grade

Deep ground temperature in a locale is not unlike the average annual temperature, with local variations due to shading from vegetation, elevation, or proximity to the coast. Comparing the annual average temperature with the August dew-point temperature of the air is a good indication of whether mold will grow on slabs and walls of below-grade structures.

Concrete is highly conductive and its temperature will become very similar to ground temperature, making the concrete potentially become a condensation surface. Insulating outside the concrete is the best choice for keeping the concrete above the dew point of the air. In termite-infested areas, select rigid insulation that has termiticides included; this renders poisoning the soil unnecessary. Insulating under slabs with a vapor retarder on top in intimate contact with the slab is the best strategy for a dry slab. Insulating on the inside of below-grade walls is possible, but it is best to insulate using adhered rigid insulation so as to avoid convection through fibrous insulation.

Strategy 2.2

Comparing a location's average annual temperature (Figure 2.2-A) with the August dew point of the air (Figure 2.2-B) is a good indication of whether below-grade structures may cause condensation and mold.

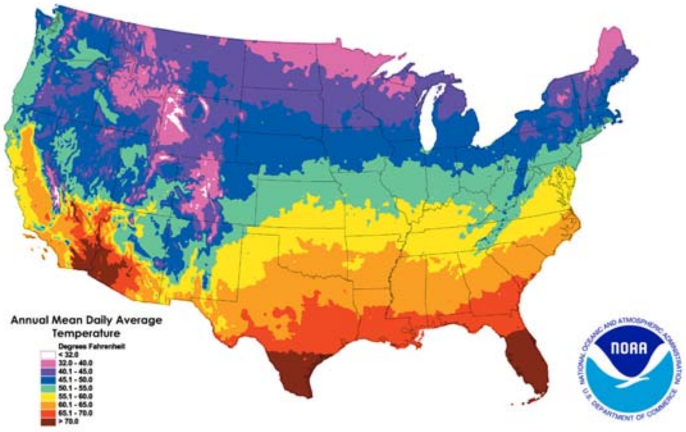


Figure 2.2-A Average Mean Daily Temperatures
Image courtesy of National Climatic Data Center.

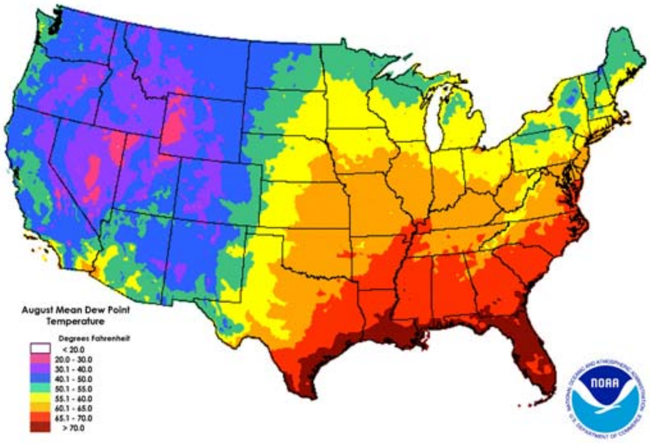


Figure 2.2-B Mean Dew-Point Temperatures for August
Image courtesy of National Climatic Data Center.

Thermal Bridging

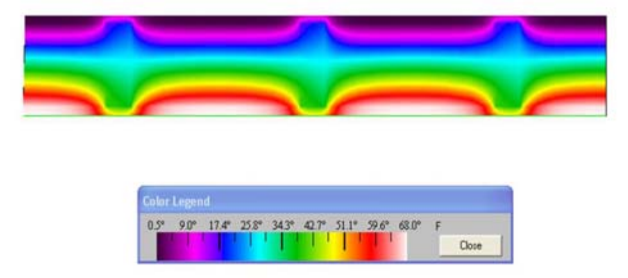


Figure 2.2-C THERM Study Showing Temperature of Studs

Figure 2.2-D Ghosting of Steel Studs on Walls
Photograph copyright Wiss, Janney, Elstner and Associates, Inc.

Thermal bridges, due to conductive materials that penetrate or interrupt the thermal insulation layer, cause a drop in temperature of the interior surface in cold climates (Figure 2.2-C). This can cause condensation and mold growth. It can also cause deposition of particulates onto the cold surfaces due to convective loops caused by the temperature differences, which is called "ghosting." In the building shown in Figure 2.2-D in a cold climate, interior humidity, candle smoke, and thermal bridging combined to cause ghosting of the steel studs.

Maintain Proper Building Pressurization

Proper building pressurization is required to limit moisture and contaminant transfer across the building envelope. Moisture transfer can result in mold damage within the envelope and, along with other contaminant transfers, can contaminate occupied spaces within the building.

Building pressurization is the static pressure difference between the interior pressure and the exterior (atmospheric) pressure of a building. This static pressure difference influences how much and where exfiltration and infiltration occur through the building envelope. The static pressure difference across the envelope is not the same at all points of the building envelope. Wind direction and speed; indoor-outdoor temperature differences; differing mechanical supply, return, and exhaust airflows to each space; and compartmentalization of spaces can create different static pressures at various points of the building envelope. While many HVAC systems are designed to achieve an overall building pressurization of 0.02 to 0.07 in. w.c. (5 to 17 Pa) differential (across the building envelope) in the lobby, this is not always advisable. The nature and extent of the pressure differential will depend on a variety of factors that will need to be assessed. The actual pressure differential can fluctuate due to changing weather conditions, wind load, and HVAC system operation.

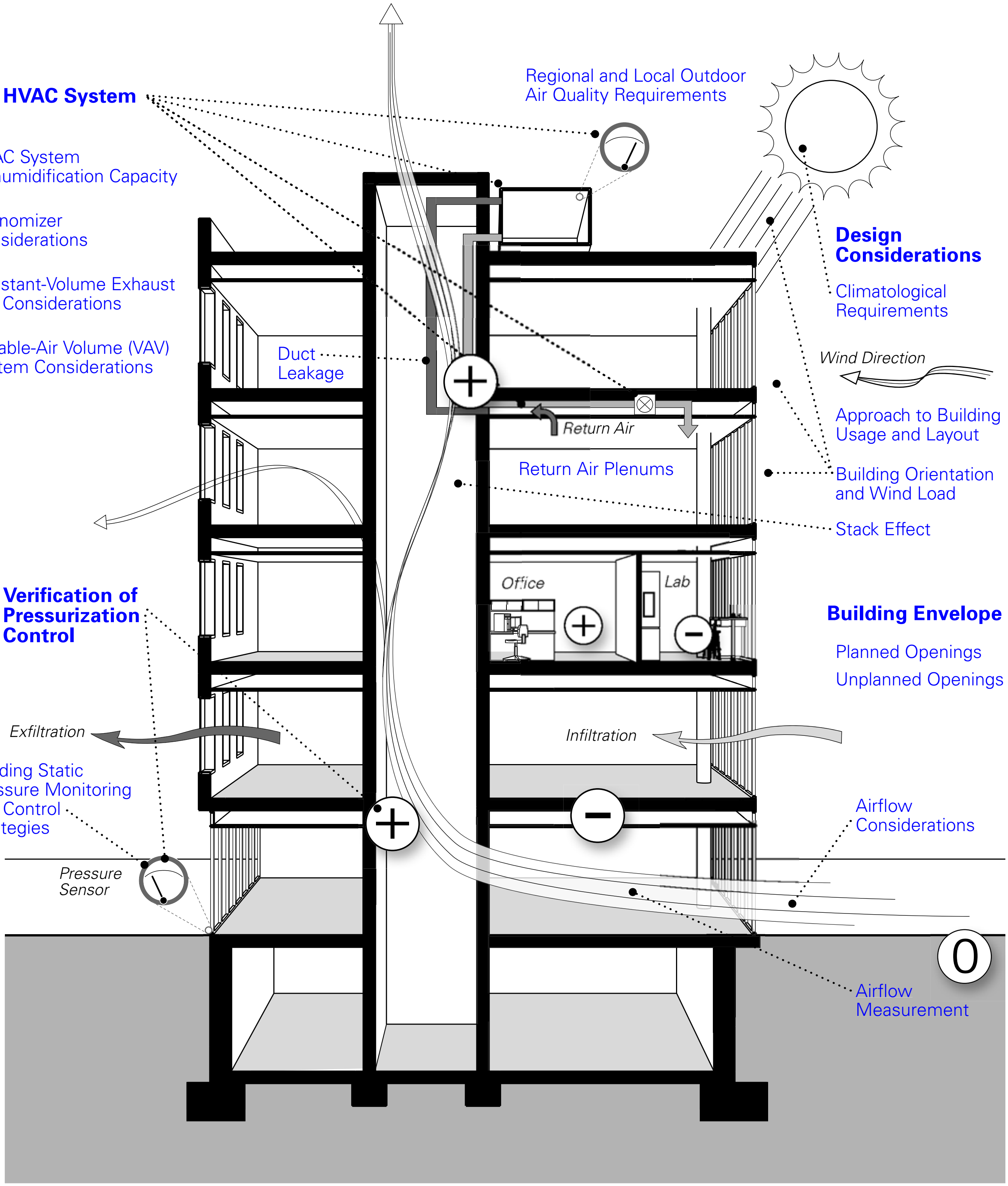
Positive building pressure is particularly important to maintain in the following situations: mechanically cooled buildings in hot and humid climates for reduced infiltration and control of condensation and mold growth, buildings maintained at low temperatures relative to outdoor temperatures (refrigerated warehouses, ice arenas, etc.) for reduced infiltration and control of condensation and mold growth, and buildings in areas with poor outdoor air quality to control the infiltration of the outdoor air contaminants.

Buildings in cold climates are typically designed for a neutral pressure to avoid exfiltration of relatively moist air during the heating season, which could cause condensation, mold in the building envelope, and deterioration of the building envelope. Similarly, humid spaces (e.g., natatoriums, shower rooms, spas, kitchens, indoor gardens, humidified buildings, or areas such as health-care facilities, museums, and musical instrument storage and performance areas) are of extra concern in cold climates and need to be slightly negative in pressure relative to the outdoors to reduce the risk of condensation and mold in the building envelope. A discussion on mixed climates can be found in the “Climatological Requirements” section in the Part II detailed guidance in the electronic version of this Guide.

Buildings are often treated as if they are one large compartment. In reality, buildings are typically composed of many smaller compartments or spaces. The static pressures differ from one space to another due to stack effect, changing wind direction, climate changes, HVAC system operation, etc. It is important that these factors be considered for proper compartmentalization and/or HVAC system control and system segregation. For example, maintaining positive building pressure in the lobby does not mean every space adjacent to the lobby is also positively pressurized. The top floors of a building in hot weather may be negatively pressured, and HVAC systems that employ return air plenum systems instead of return air ducts may have bands of negative pressure on each floor.

When designing for proper building pressurization, envelope leakage is often overlooked. The amount of envelope leakage can drastically change the required outdoor air (makeup air) quantity to maintain a positively pressured building.

Strategy 2.3


HVAC System
HVAC System Dehumidification Capacity
Economizer Considerations
Constant-Volume Exhaust Fan Considerations
Variable-Air Volume (VAV) System Considerations
Duct Leakage
Regional and Local Outdoor Air Quality Requirements
Design Considerations
Climatological Requirements
Wind Direction
Approach to Building Usage and Layout
Building Orientation and Wind Load
Return Air
Return Air Plenums
Stack Effect
Office
Lab
Building Envelope
Planned Openings
Unplanned Openings
Verification of Pressurization Control
Exfiltration
Infiltration
Building Static Pressure Monitoring and Control Strategies
Pressure Sensor
Airflow Considerations
Airflow Measurement
+
−
0

Strategy 2.3

The simple assumption that outdoor air intake exceeds exhaust airflow typically does not ensure that the building will be positively pressurized. Envelope leakage, wind load, building size and dimensions, building orientation, compartmentalization, and building usage all need to be assessed. The more complex the building, including layout, building height, architectural features, HVAC system type and usage, etc., the more difficult proper building pressurization attainment will be.

In addition to the proper volume of air being provided for proper building pressurization, the distribution of the air within the building spaces needs to be addressed. Makeup air needs to be provided in the correct areas or spaces to help overcome depressurization due to stack effect and/or wind effect. See Strategy 7.3 – Effectively Distribute Ventilation Air to the Breathing Zone and Strategy 7.4 – Effectively Distribute Ventilation Air to Multiple Spaces for guidance on how this can be accomplished.

Strategy 2.3

Results of a 300-Room Building Negatively Pressurized

A 300-room building was negatively pressurized to the outdoors (Figure 2.3-A). The warm moist outdoor air infiltrated the building and traveled through the walls and sought entry points into each room. One of those points was the electrical outlets. The surfaces were cool enough (the rooms were air conditioned) to result in condensation and widespread mold growth throughout the facility, including on the furniture and in the walls of the building (Figure 2.3-B). Each room had individual exhaust with outdoor air introduced into the common corridor. Verification of the building pressure and individual room pressure never occurred. The building required complete renovation at a cost of $9.9 million.

Figure 2.3-A "Smoke" Test Demonstrating the Building was Negatively Pressurized in Reference to the Exterior

Figure 2.3-B Mold Growth due to Negative Pressure

Photographs copyright Liberty Building Forensics Group®.

Control Indoor Humidity

Control of indoor humidity is important for occupant health and comfort and because high humidity can cause condensation, leading to potential material degradation and biological contamination such as mold. High humidity also supports dust mite populations, which contribute to allergies. On the other hand, low humidity affects health by drying out mucous membranes. Humidity conditions also affect people's perception of IAQ. Also see Strategy 7.6 – Provide Comfort Conditions that Enhance Occupant Satisfaction.

Situations where special consideration should be given to humidity control include:

- hot and humid climates, especially when building pressurization is difficult to achieve or there are long periods of no conditioning (such as school systems shut down for the weekend);
- conditioned spaces with large indoor moisture sources;
- conditioned spaces with unusually cold surfaces;
- spaces with continuous outdoor air ventilation and non-continuous air conditioning (for instance, when cooling coils cycle on/off or exhaust fans must continue to run when conditioning systems are off); and
- oversized systems with excessive airflow with modulation of the chilled-water flow rate as the only available control method.

These are situations that contribute to the risk of localized excessive humidity and condensation in the presence of surfaces with temperatures below the dew point. In addition, any building in a cold climate may experience extremely low humidity, but this situation does not always mean that installation of a humidifier is advisable due to concerns about other potential problems.

Principles of Condensation

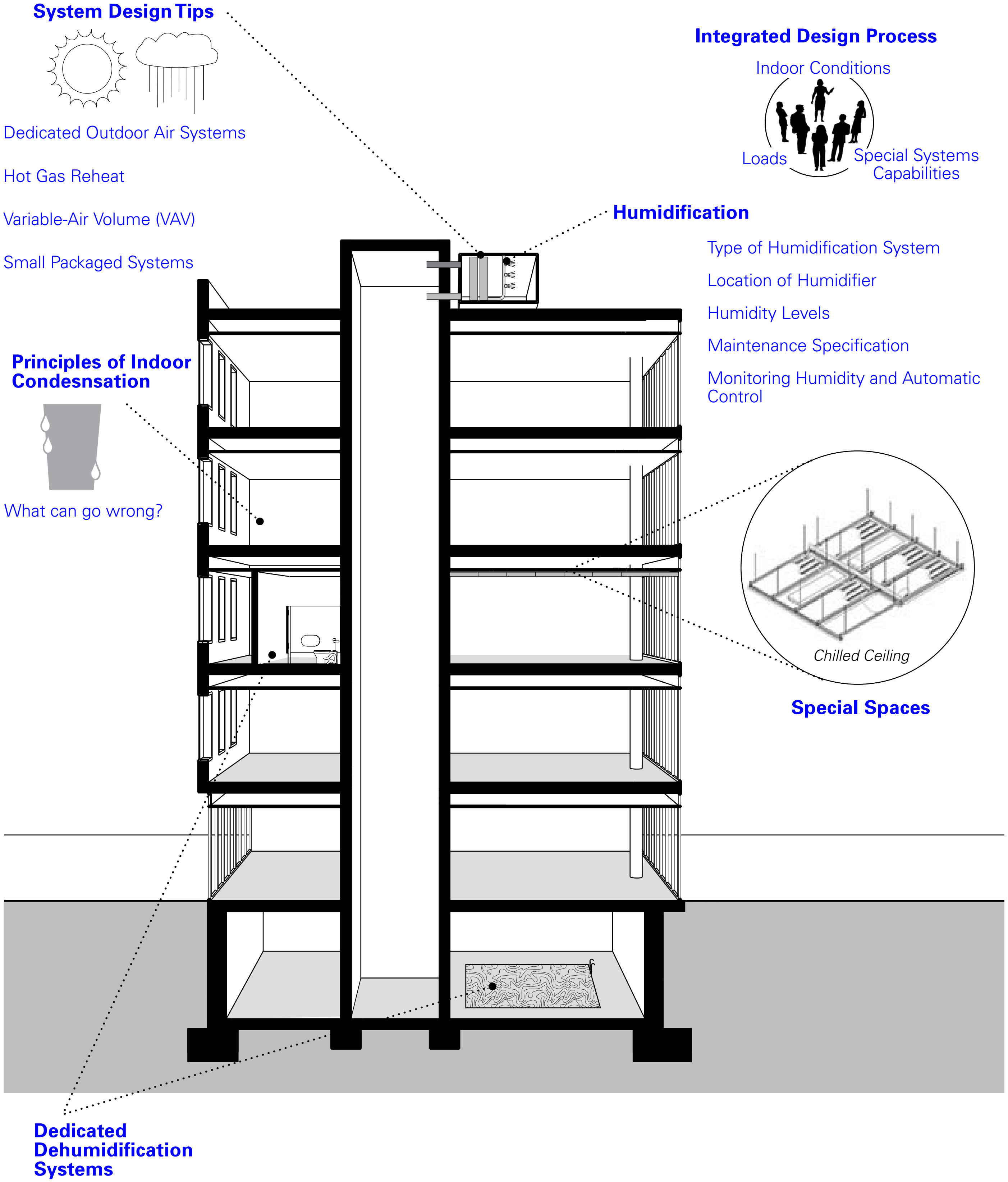
As air is cooled, its capacity to hold moisture diminishes. When air cools enough that it becomes saturated (100% RH) so it can no longer hold all its water vapor, the vapor turns back into a liquid (condenses). The temperature at which this happens is a called the *dew point* and typically occurs on surfaces that are cooler than the dew point of the surrounding air.

Integrated Design Process

Air-conditioning system designers often choose indoor conditions like 50% RH or 60% RH (ASHRAE Standard 62.1 requires 65% for systems that dehumidify [ASHRAE 2007a]) and design a system to handle the peak sensible load (i.e., peak dry-bulb temperature). However, most of the time systems operate at part load. Under these conditions, systems that control only space dry-bulb temperature may not provide enough dehumidification to keep space humidity within an acceptable range. For this reason, ASHRAE Standard 62.1 *now* requires that designers consider the dehumidification performance of the system at a "humidity challenge" condition intended to represent a part-load situation with high latent and low sensible load.

This change requires additional design effort for load calculations at more than one design condition, selection of automatic temperature control for humidity considerations, possibly a change of system type, and coordination with those selecting exterior walls and surfaces on the interior. Beyond these required

Strategy 2.4



System Design Tips

Dedicated Outdoor Air Systems

Hot Gas Reheat

Variable-Air Volume (VAV)

Small Packaged Systems

Integrated Design Process

Indoor Conditions

Loads

Special Systems Capabilities

Humidification

Type of Humidification System

Location of Humidifier

Humidity Levels

Maintenance Specification

Monitoring Humidity and Automatic Control

Principles of Indoor Condesnsation

What can go wrong?

Special Spaces

Dedicated Dehumidification Systems

design considerations, IAQ would benefit from actual measurement of humidity (relative humidity or dew point) and feedback to control system parameters.

System Design Tips

In hot, humid climates or other situations with high latent loads, constant-volume systems with on/off cycling control may not provide adequate humidity control at part-load conditions. Cycling a direct expansion (DX) cooling system on and off to satisfy space temperatures or resetting the discharge air temperature upward reduces the system's ability to remove moisture from the supply air. Other system designs can keep indoor humidity within an acceptable range without the need for dehumidifiers or humidity control systems. These may include selecting a lower discharge air temperature (lower cfm/ton [L/s per kW] ratio) VAV control (even for single-zone systems), use of hot gas reheat, dedicated outdoor air systems (DOASs) and demand control of outdoor air.

Some of these strategies may not be available with smaller packaged cooling units but may be available with an upgrade of the HVAC equipment or a change of the system type. Packaged units may not have published selection data at low discharge air temperature (lower cfm/ton [L/s per kW] ratio), and the designer may need to contact the manufacturer. It may be necessary to put multiple spaces on a single packaged unit or built-up system in order to get access to features available on the larger units, such as lower discharge air temperature, compressor unloading, VAV systems, energy recovery, hot gas reheat, or demand control of outdoor air (for instance, by control of CO_2).

Special Spaces

Spaces that have large latent loads and small sensible loads, either at full load or at part load, may require dedicated humidity control systems. Some designs call for intentionally cool surfaces, such as a chilled ceiling system and uninsulated ductwork in occupied spaces. It is especially important to analyze the resulting space humidity to avoid condensation in these systems. A space that requires high outdoor air ventilation rates in humid climates is a candidate for energy recovery ventilation, primarily for the purpose of using less energy to cool and dehumidify the outdoor air.

Dedicated Dehumidification Systems

Dedicated humidity control systems (dehumidifiers) may be required in spaces that are underground, in swimming and bathing areas, in kitchens, or where large volumes of unconditioned humid outdoor air enters the space, for instance, by door openings or other forms of infiltration. Dehumidifiers may be based on the refrigerant cycle or use a desiccant. The latter is a material that is hygroscopic (attracts water) and removes water vapor from an airstream; it must be regenerated by heating to drive off the water as part of the operation cycle.

In showers, natatoriums, and cooking areas, it is accepted that humidity will be high and condensation will occur, and consequently surfaces need to be inorganic and cleanable (see Strategy 2.5 – Select Materials, Equipment, and Assemblies for Unavoidably Wet Areas). Moisture can be kept out of less moisture-tolerant parts of the building by keeping spaces with high humidity at lower pressure than adjoining spaces.

Humidification

Humidification of buildings may solve some comfort and health problems but may create others. For this reason, ASHRAE Standard 62.1 no longer requires a minimum humidity level in buildings, and many designers prefer to err on the side of no humidifier. However, this view is not universally held. It is possible that humidifiers can have real benefits if properly applied and maintained (Schoen 2006).

When designing a system with humidification, be aware of the requirements of ASHRAE Standard 62.1 and several additional design issues delineated in the following.

The ASHRAE Standard 62.1 (Section 5.13) requirements are the following:

- Water must be from a potable or better source.
- Downstream air cleaners and duct obstructions such as turning vanes, volume dampers, and duct offsets should be kept greater than 15° away from the humidifier (as recommended by the manufacturer) or a drain pan should be provided to capture and remove water.

Additional design issues are the following:

- Consider preconditioning outdoor air using a total energy recovery wheel.
- Different types of humidifiers have different advantages and disadvantages. Avoid those using reservoirs of standing water and be aware of water treated with chemicals.
- Higher levels of indoor humidity concurrent with low outdoor temperatures increase the potential for condensation. Therefore, do not overhumidify. A setpoint of 20% RH or lower may be reasonable for many buildings during very cold weather.
- Locate the humidifier after the heating coil, where relative humidity is lowest, and provide water-tolerant, nonporous airstream surfaces downstream.
- Consult manufacturers and their representatives skilled in the application of systems in the climate and water conditions at the project location.
- Since the disadvantages of humidifiers are so driven by maintenance, it is especially important that building operators get additional assistance. Consider writing a maintenance specification for pricing with the installation.

Monitoring Humidity and Automatic Control

Whether the goal is to remove humidity from indoor air or to intentionally humidify, monitoring humidity is useful. Initially, monitoring can aid in verifying system performance during the test and balance/Cx process. During operation, monitoring can provide feedback and early warning of excursions.

Humidity is difficult to measure accurately, especially at very low or high relative humidity. Instruments to measure humidity cost significantly more than those for dry-bulb temperature and require more maintenance, and reliable standards against which to calibrate are more expensive. Inexpensive types of real-time monitoring that can prevent serious problems are the use of liquid moisture sensors in below-grade floors subject to flooding, secondary condensate pans, and water heater overflow pans.

Strategy 2.4

Assembly Room Humidity Control with VAV

An assembly room that is part of a large religious and educational facility has a single chilled-water air handler. The room is used for meetings, parties, and performances, and the chilled-water coil meets the full load, even at about 50% outdoor air. Conventional part-load controls would throttle the chilled-water valve at constant airflow, resulting in a warmer coil that would lose its ability to dehumidify unless reheat is applied. Figure 2.4-A and Table 2.4-A show how an upgrade of the air handler to VAV control accomplishes dehumidification without the use of reheat. The upgrade also includes DCV by sensing CO_2 and tracking the actual outdoor air supply using dedicated minimum outdoor air inlets with airflow sensing and dampers.

The psychrometric chart in Figure 2.4-A and the accompanying table (Table 2.4-A) represent the load conditions at the dehumidification design conditions and not the more common peak dry-bulb temperature. The system can meet the low room temperature and humidity design conditions. In order to do this, the coil discharge temperature is kept low (48.5°F [7.5°C]). The high latent load (54% of the total load) and the low airflow (about 180 cfm/ton [19 L/s per kW]) require a low entering chilled-water temperature (39°F [4°C]). In order to maintain humidity control, this particular design did not include upward reset of discharge air and chilled-water temperatures. Reset could be considered for efficiency but would require additional considerations for the control algorithm, such as possible measurement of room humidity as an input.

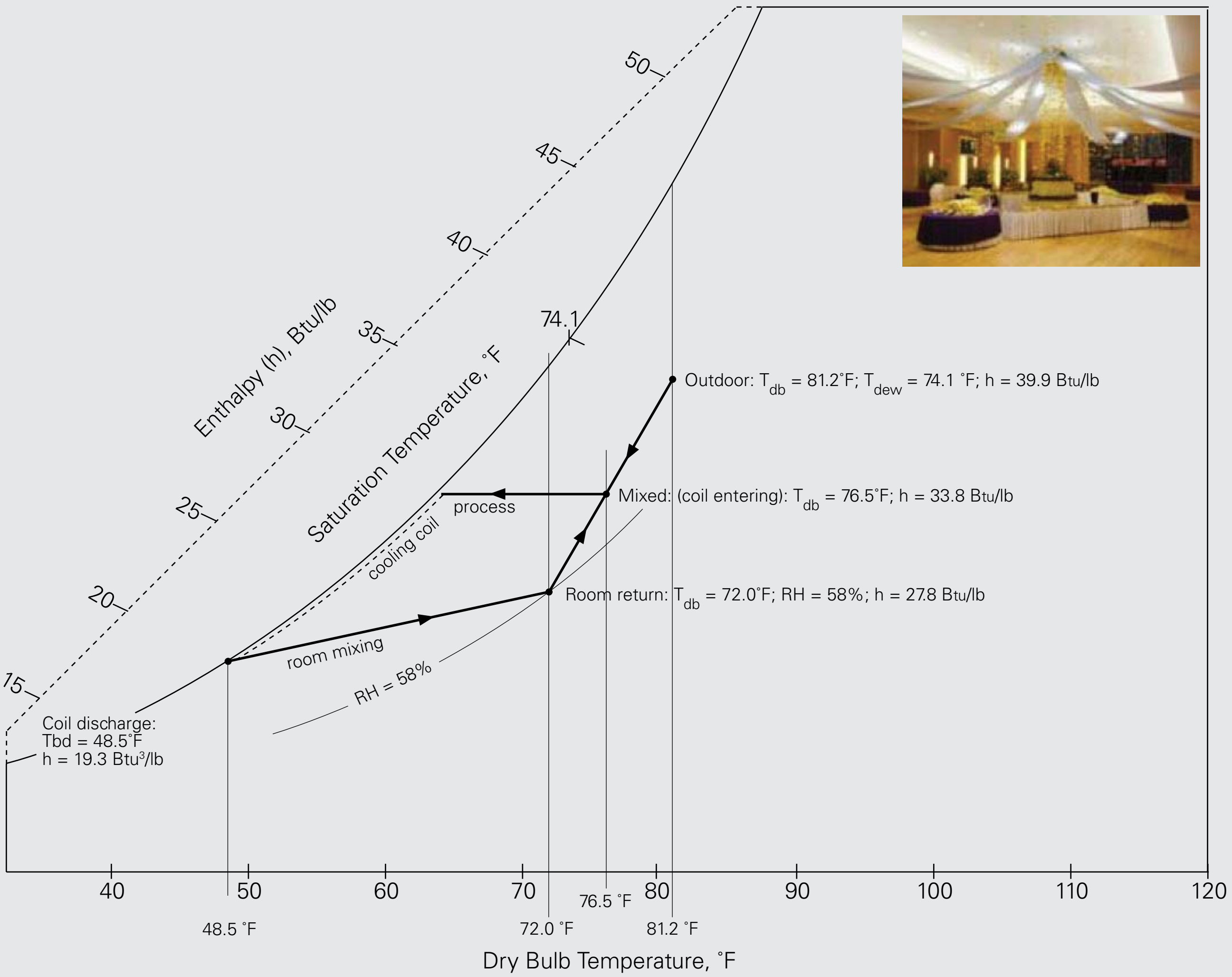


Figure 2.4-A Assembly Room Psychometric Chart

Inset photograph courtesy of Larry Schoen.

Design Conditions		
Room air temperature	72.0°F (22.2°C)	Low design temperature for comfort
Room humidity	58 % RH	Low design relative humidity for comfort
Outdoor air temperature at design dew point	81.2°F (27.3°C)	Coincident dry bulb, not peak dry bulb
Outdoor air design dew point	74.1°F (23.4°C)	This is the 1% design dew point
New Fan Conditions		
Total airflow	18345 cfm (8660 L/s)	Note the low airflow/ton (kW)
Outdoor air	9000 cfm (4250 L/s)	Note the high percentage outdoor air
New Cooling Coil Conditions		
Mixed/coil entering air temperature	76.5°F (27.7°C)	
Coil leaving air temperature	48.5°F (9.2°C)	Note the low temperature for dehumidification
Mixed/coil entering air enthalpy	33.8 Btu/lb (60.7 kJ/kg)	
Leaving coil air enthalpy	19.3 Btu/lb (27.0 kJ/kg)	
Total cooling	1197 MBh (350 kW)	Corresponds to 100 tons (350 kW) at design dew point
Sensible cooing	555 MBh (163 kW)	
Latent cooling	642 MBh (187 kW)	54% of the load is dehumidification
Coil sensible heat ratio (SHR)	0.46	Not the low coil SHR
Entering water temperature	39.0°F (3.9°C)	Note the low chilled-water temperature required
Leaving water temperature	49.0°F (9.4°C)	
Water flow	239 gpm (15 L/s)	

Table 2.4-A Assembly Room Dehumidification without Reheat

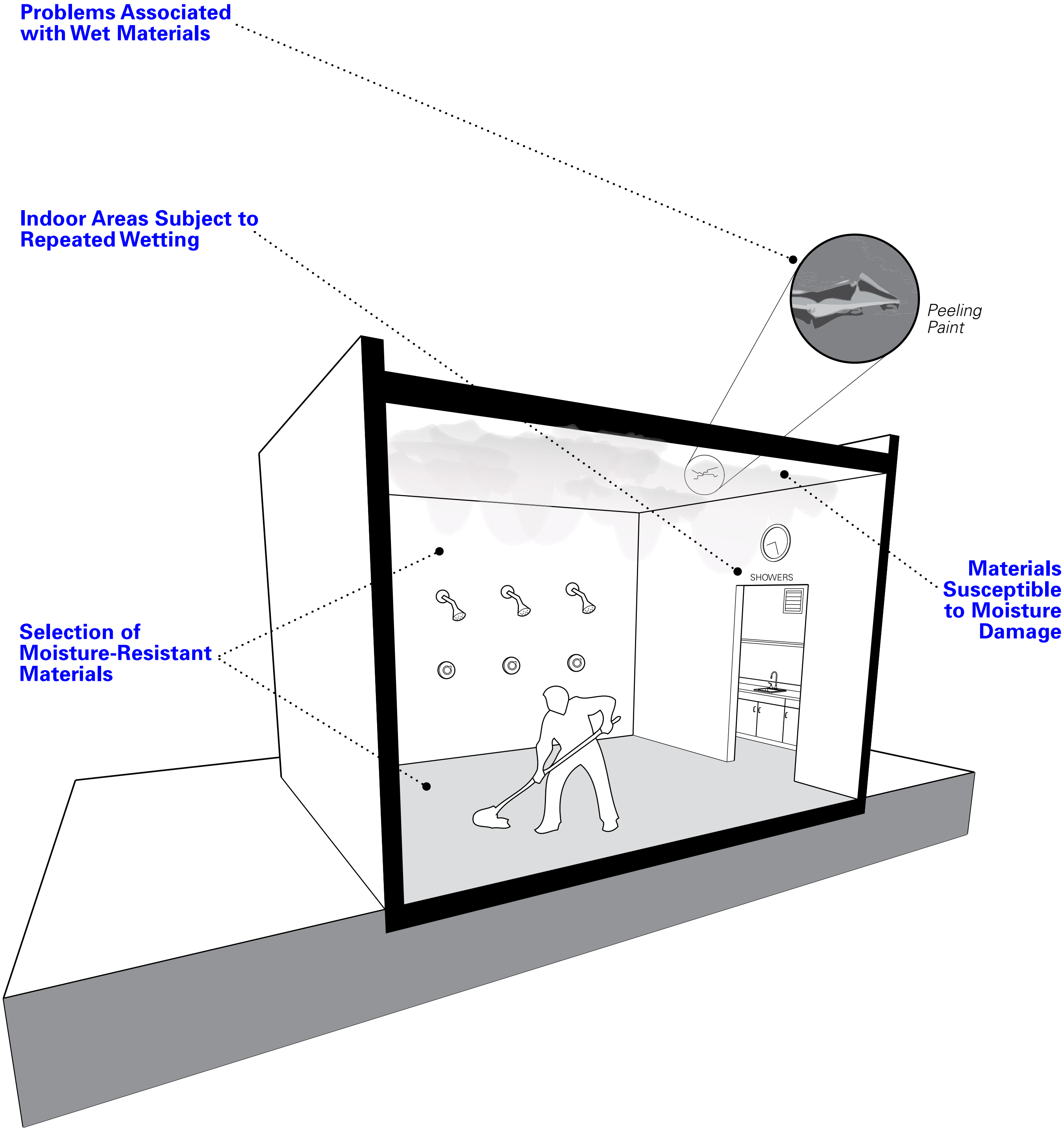
Select Suitable Materials, Equipment, and Assemblies for Unavoidably Wet Areas

Certain areas within buildings will have high local humidity and/or the frequent presence of liquid water. These include washrooms, kitchens, and janitorial closets. Special attention must be paid to the material surfaces employed in these zones such that they can withstand the impact of frequent wetting. As stated by Latta in 1962, the harmful effects of water on building materials cannot be overemphasized, and the construction of durable buildings would be greatly simplified without water's influence (Latta 1962). More recently, the concept of the "4 D's" of moisture control in buildings was advanced: *deflection* (don't let the moisture in), *drainage* (give moisture a means of escape), *drying* (facilitate air movement/breathing to remove moisture), and *durability* (mold and corrosion resistance of materials susceptible to wetting) (CMHC 1998). These aspects are well studied when it comes to building envelope design (see Strategy 2.1 – Limit Penetration of Liquid Water into the Building Envelope, Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces, and Strategy 2.3 – Maintain Proper Building Pressurization) but also apply to certain indoor spaces.

The best design efforts cannot prevent occasional wetting incidents, and certain indoor activities intentionally lead to damp conditions and materials. The main focus of this Strategy lies with the *durability* aspect of materials subjected to periodic wetting episodes within buildings. This Strategy identifies building areas that may be subject to repeated wetting, reviews the properties of materials that enable moisture resistance or tolerance, and finally describes those materials suitable for use in wet locations.

The growing concern regarding the impact of damp spaces on occupant health—specifically the involvement of damp materials in this regard—is highlighted in the recent report on Damp Indoor Spaces and Health (IOM 2004), which concludes that "studies should be conducted to evaluate the effect of the duration of moisture damage of materials and its possible influence on occupant health and to evaluate the effectiveness of various changes in building designs, construction methods, operation, and maintenance in reducing dampness problems" (p. 5). It is clear then that our knowledge in this area remains limited. Some practical advice can, however, be provided in terms of material selection. Materials that combine moisture-resistant and non-resistant layers (e.g., vinyl-coated wallboard) may be highly susceptible to mold growth when subjected to wetting. In zones with high humidity, the use of suspended ceilings can result in the creation of unconditioned spaces that may become susceptible to condensation.

Strategy 2.5


Problems Associated with Wet Materials
Indoor Areas Subject to Repeated Wetting
Peeling Paint
SHOWERS
Materials Susceptible to Moisture Damage
Selection of Moisture-Resistant Materials

Strategy 2.5

Building Entrance Design as Component in Control of Wet Surfaces and Materials

Figure 2.5-A Inadequate Track-Off Design for Local Conditions
Photograph courtesy of Hal Levin.

Depending on the local climate and season, building entrance areas may be exposed to wet conditions on a recurring basis. A social services building in a cold winter climate provides an example where inappropriate selection of flooring materials coupled with poor entranceway design created an IAQ problem that was further exacerbated by HVAC design and operation (Figure 2.5-A).

This building's inadequate track-off system could not cope with the snow and moisture introduced by visitors' footwear. Clients for the social services department waited in a large carpeted corridor immediately adjacent to the building entrance. Dirt and moisture accumulated on the corridor's carpeting such that it typically remained wet. A failure in the building's air-handling system resulted in reduced outdoor air delivery during cold winter days. As a result, inadequate air exchange limited the drying potential for the wet carpeting. The combined effect of these factors was an extremely moldy carpet and a strong odor throughout the social services section. Integrated design employing proper track-off systems, use of appropriate flooring materials, and effective HVAC system design and operation would have prevented these IAQ problems.

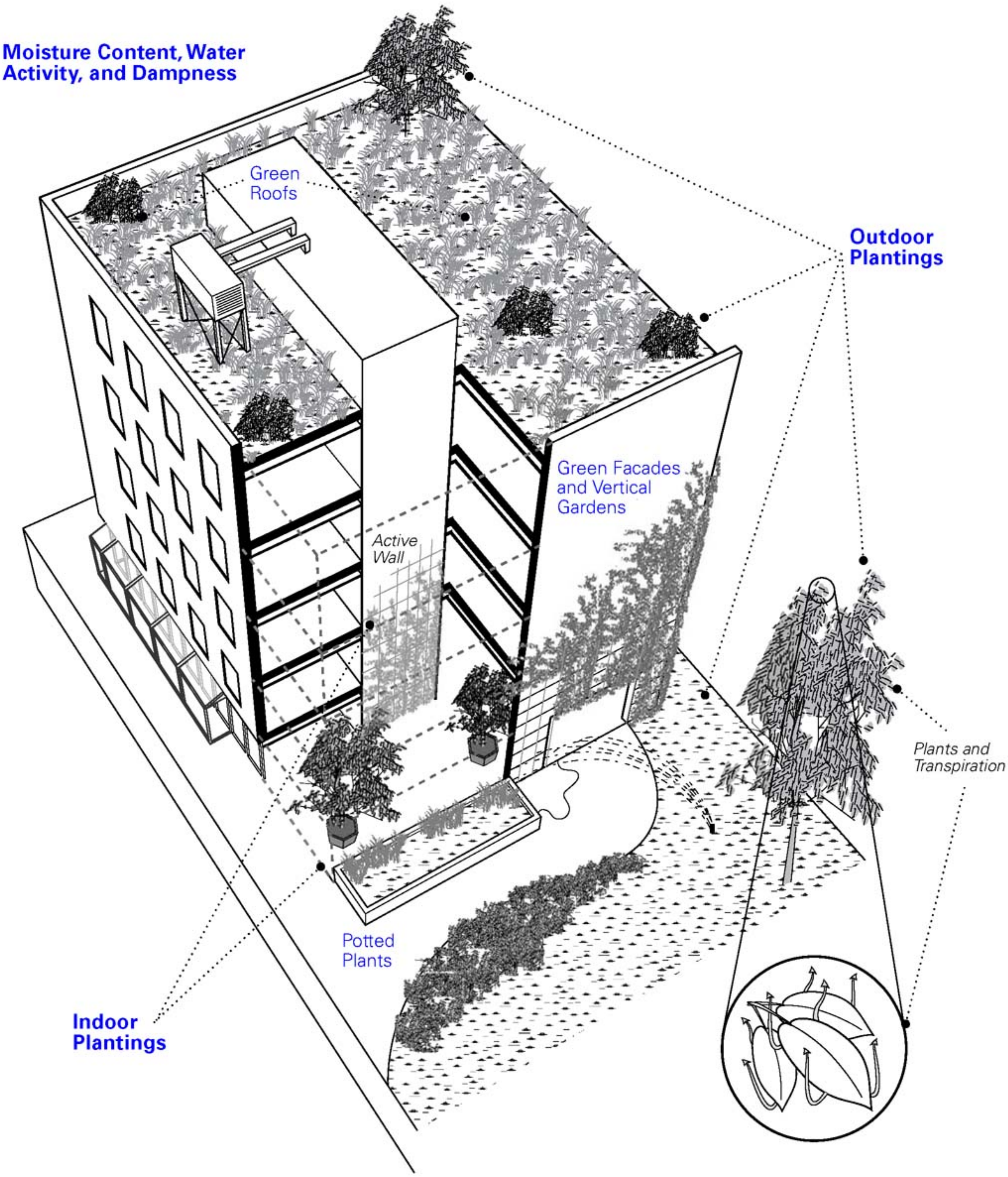
Consider Impacts of Landscaping and Indoor Plants on Moisture and Contaminant Levels

There are potential advantages and disadvantages associated with the presence of plants as a component of the building envelope (e.g., green roofs or roof gardens, living facades, or vertical gardens) or on walls or other locations in the interior space (e.g., atrium gardens, living walls, vertical gardens, biowalls). As part of their physiology, plants emit water molecules into the air through the process of transpiration. In an outdoor environment like a building roof, this provides evaporative cooling. Plants also provide shading to the microenvironment. Inside buildings, an average-sized houseplant emits up to 0.22 lb (100 g) of water per day into the indoor air. An increased amount of water vapor in the air will raise the relative humidity. In a building, this is an advantage during the dry season depending on the source of the water but can be a disadvantage in a warm, humid condition if not well managed.

Benefits of green roofs are thought to include reduction in stress (i.e., thermal stress) on the water proofing membrane, reduction in heat island effects in urban areas, and reduction in storm water runoff. It is widely recognized that both the integrity and protection of the waterproofing membrane beneath the roof garden need to be of very high quality if leakage into the building is to be avoided. In this regard, the building architect and the landscape (garden) architect need to work together to ensure that the waterproofing membrane is installed with excellent workmanship and that penetrations through the membrane are avoided.

The presence of indoor flora (potted plants, atrium gardens, etc.) is generally perceived as beneficial to occupants. However, this assumes that the water transpired does not exceed the capacity of the HVAC system to manage the increased water in the room, that the potted plants are not overwatered, and that atrium gardens are well maintained. Additionally, there is limited research that suggests that root-zone microbial communities of indoor plants reduce VOC contaminants in the indoor air. However, the presence of indoor plants needs to be decided with caution, because some literature also shows that potted plants can result in elevated levels of some fungi indoors, including some pathogenic species.

The illustration in Figure 2.6-A provides background for understanding the concept of water activity (a_w), which is a measure of how readily microorganisms or plant roots can extract moisture or free water for growth from the materials on which they are growing. Many fungi and bacteria can grow at an a_w of 0.97–0.98. This is equivalent to the moisture content in a building material in a closed system that has equilibrated with a 97%–98% RH atmosphere in that closed system. The roots of green plants require an a_w of 0.97–0.98 in order to extract water molecules from the materials on which they are growing. These conditions are similar to those that allow for microbial growth on construction materials. Thus, the concept that indoor plants may be beneficial needs to be tempered with the realization that moist building materials and the root-zone are also growth sites of various microbial communities.


Moisture Content, Water Activity, and Dampness
Green Roofs
Outdoor Plantings
Green Facades and Vertical Gardens
Active Wall
Plants and Transpiration
Potted Plants
Indoor Plantings

Strategy 2.6

Moisture in Envelope Infrastructure Facilitates Growth of Tree Sapling

Figure 2.6-A Tree Sapling Growing from Upper Portion of Window
Photograph courtesy of Phil Morey.

Figure 2.6-A shows a tree sapling growing from the upper portion of a window. The roots of this plant are obtaining moisture (see discussion on water activity in the overview) and nutrients from the envelope infrastructure. Microorganisms including fungi and bacteria also grow on plant roots in and on organic construction materials, from which the plant root systems are extracting water.

Limit Entry of Outdoor Contaminants

Contaminants from outdoor sources can have a major influence on IAQ. These contaminants include particles and gases in outdoor air, contaminants in the soil and groundwater, herbicides and pesticides applied around the building, and contaminants carried in by pests. The Strategies in this Objective are intended to limit entry of these contaminants.

Outdoor air pollutants entering a building through ventilation and infiltration can have significant health impacts. For example, airborne particles and ozone are both associated with respiratory and cardiovascular problems ranging from aggravation of asthma to premature death in people with heart or lung disease. In many areas of the U.S., levels of these and other pollutants exceed standards set by the EPA. Even in areas where regional outdoor air quality is good, pollution may be high at specific sites due to local sources.

- Strategy 3.1 – Investigate Regional and Local Outdoor Air Quality describes assessment of outdoor air pollution levels and control measures to limit the entry of these contaminants.
- Strategy 3.2 – Locate Outdoor Air Intakes to Minimize Introduction of Contaminants addresses separation of air intakes from such local and on-site sources as motor vehicle exhaust, building exhausts, and cooling towers.
- Strategy 3.3 – Control Entry of Radon describes mitigation techniques for radon, a naturally occurring radioactive soil gas that is the second leading cause of lung cancer in the U.S.
- An important but less widely recognized source of contaminants is intrusion of vapors from contaminated soil or groundwater. Strategy 3.4 – Control Intrusion of Vapors from Subsurface Contaminants describes processes to screen sites for such sources and techniques to limit vapor intrusion.
- People entering buildings can track in contaminants such as pesticides as well as dirt and water that can foster microbial growth. Strategy 3.5 – Provide Effective Track-Off Systems at Entrances describes strategies to reduce tracked-in pollutants.
- Rodents, birds, insects, and other pests can be sources of infectious agents and allergens. Strategy 3.6 – Design and Build to Exclude Pests describes techniques to limit infestation by pests.

Other Strategies that are important in limiting entry of outdoor contaminants are the following:

- Strategy 1.1 – Integrate Design Approach and Solutions
- Strategy 2.3 – Maintain Proper Building Pressurization
- Strategy 2.6 – Consider Impacts of Landscaping and Indoor Plants on Moisture and Contaminant Levels
- Strategy 4.4 – Control Legionella in Water Systems
- Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives

Objective 3

Objective 3

3.1 Investigate Regional and Local Outdoor Air Quality

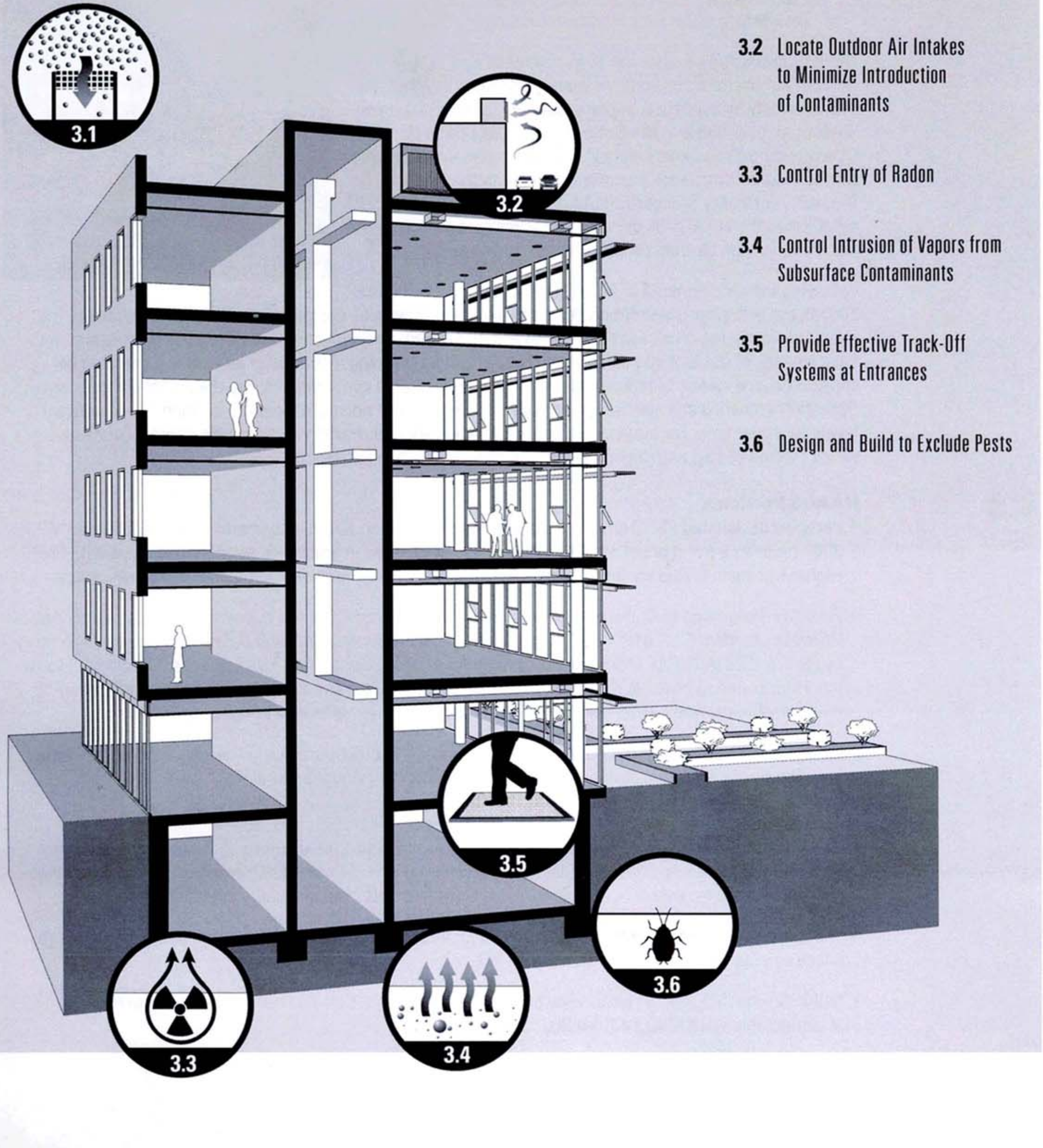
3.2 Locate Outdoor Air Intakes to Minimize Introduction of Contaminants

3.3 Control Entry of Radon

3.4 Control Intrusion of Vapors from Subsurface Contaminants

3.5 Provide Effective Track-Off Systems at Entrances

3.6 Design and Build to Exclude Pests



Investigate Regional and Local Outdoor Air Quality

Assessment

> *"The control of air quality is one of the functions of complete air conditioning, and some knowledge of the composition, concentration and properties of air contaminants under various circumstances is therefore essential… the engineer will find, at times, that odors originating outside buildings in industrial of business districts may have an even greater bearing than indoor contamination on the kind and capacity of equipment he must provide for a high quality air supply installation." (ASHVE 1946)*

More than sixty years after the 1946 reference above, the outdoor atmosphere still contains many particles and gases that can adversely affect IAQ. A primary resource for information on outdoor air pollution is in the Green Book on the EPA Web site (www.epa.gov/air/oaqps/greenbk). EPA illustrates on maps areas that are not in compliance (nonattainment) with the National Ambient Air Quality Standards (NAAQS) (EPA 2008b, 2008c). EPA established the NAAQS as directed by Congress in the Clean Air Act. Pollution can be from particles, gases, or both.

Following the requirements in ASHRAE Standard 62.1 (ASHRAE 2007a), the first step in ventilation design for IAQ is to determine compliance with outdoor air quality standards in the region where the building will be located. The next step is to determine if there are any local sources of outdoor air pollution that may affect the building. Filtration or air cleaning can then be considered as a means of reducing the entry of these outdoor contaminants into the indoor environment. Operating scenarios can also be developed to reduce entry of pollutants into the building if the pollutant levels vary over time. For instance, CO from cars will vary with traffic volumes and patterns. Ozone also varies by time of day, with higher concentrations usually in the afternoon.

NAAQS Particles

- Particles designated PM10 are particles that are smaller than 10 μm in diameter. ASHRAE Standard 62.1-2007 requires a minimum of MERV 6 filters at the outdoor air in areas that are nonattainment with PM10. Higher Minimum Efficiency Reporting Value (MERV) filters will provide additional filtration efficiency.

- Particles designated PM2.5 are particles that are smaller than 2.5 μm in diameter. Filters tested by *ANSI/ASHRAE Standard 52.2, Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size* (ASHRAE 2007c), are measured for efficiency at particle size fractions including 0.3 to 10 μm. Filters need to have MERV values greater than MERV 8 to have any effective removal efficiency on these smaller particles. Filters with MERV ≥ 11 are much more effective at reducing PM2.5.

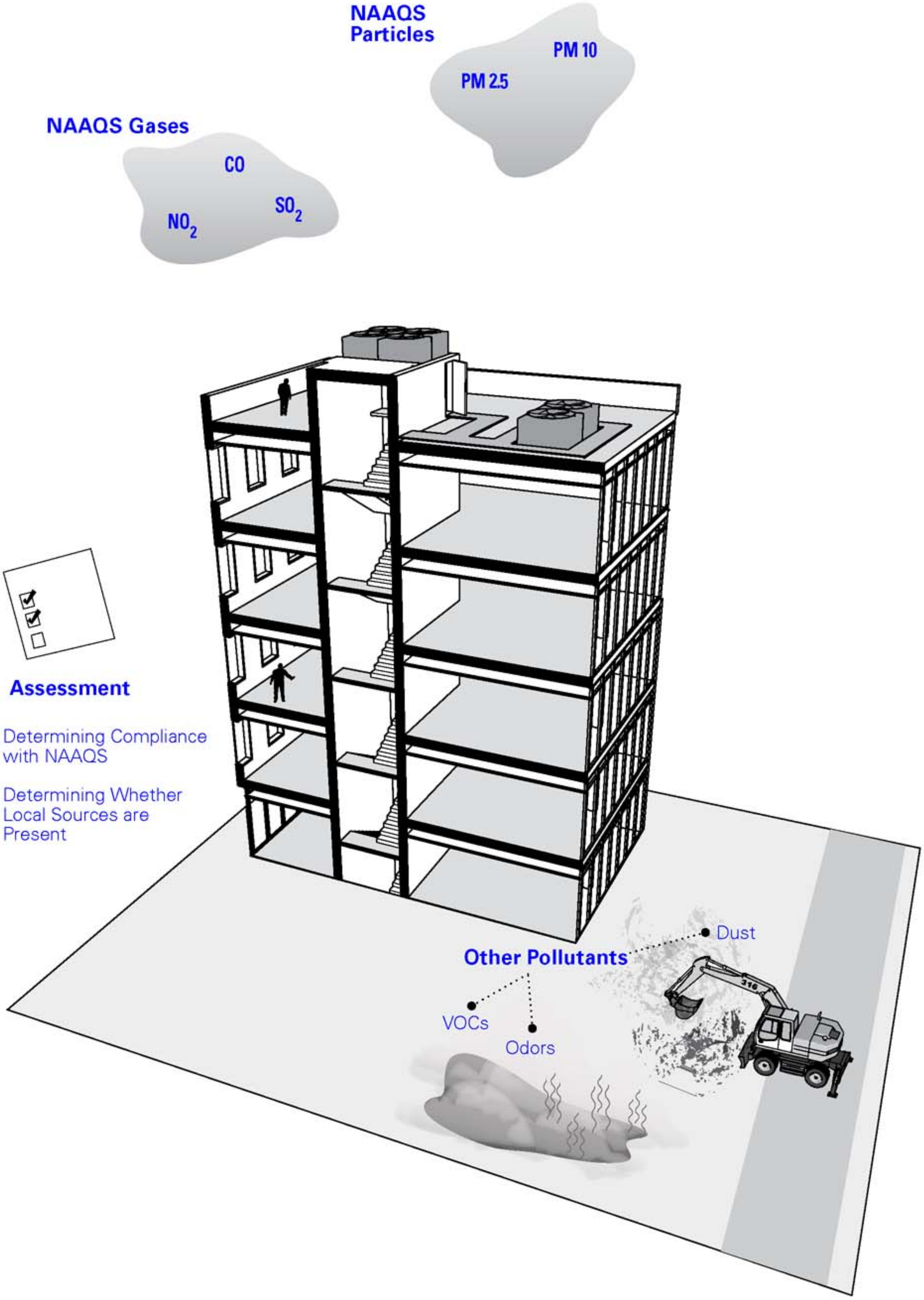
- Lead is a solid and will be a particle or may be attached to other particles in the atmosphere. Filters that are effective on small particles will also be effective at removing lead from the outdoor airstream.

NAAQS Gases

- Ozone is formed in the atmosphere by a photochemical reaction under sunlight. Therefore, ozone is not generated on cloudy or cold days. Ozone air treatment is provided by carbon or other sorbent filters that cause the ozone to react on the surface. Table 3.1-A illustrates the air quality index for ozone.

- There are no areas in the U.S. that are currently nonattainment for nitrogen dioxide (NO_2). There are gas-phase air cleaners that can be effective on NO_2.

- Sulfur dioxide (SO_2) can be cleaned by gas-phase air cleaners. Certain filter materials (for example, activated alumina/$KMnO_4$) adsorb SO_2.


NAAQS Particles
PM 10
PM 2.5
NAAQS Gases
CO
SO$_2$
NO$_2$
Assessment
Determining Compliance with NAAQS
Determining Whether Local Sources are Present
Other Pollutants
Dust
VOCs
Odors

- There is no commercially available air cleaner for CO that operates at room temperature. Scheduling of activities and the ventilation system operation, as well as outdoor air intake location, are strategies to reduce the impact of CO on the indoor environment.

Other Pollutants

- Airborne dust is no longer regulated as a NAAQS pollutant but can be a problem in areas with agriculture, high pollen, certain industries, or desert climates. Filtration of airborne dust needs to focus on the dust-holding capacity of the filtration system.

- Outdoor sources of VOCs include industrial emissions, traffic, mobile equipment, area sources such as wastewater lagoons, and some natural sources. If there are local (nearby) sources of VOCs, filtration or air cleaning needs to be considered.

- Odors in the atmosphere are often (but not always) regulated in response to citizen complaints in urban environments. Odors can be removed from outdoor air with air-cleaning technology that is tailored to the specific compounds that cause the odor. Occupants tend to be highly sensitive to odors.

Strategy 3.1

Controlling Outdoor Air Pollutants Indoors

Figure 3.1-A Building in a Polluted City
Photograph courtesy of H.E. Burroughs.

Outdoor ozone pollution results in several adverse effects, some of which are lung irritation and respiratory illness. Ozone can also damage paper documents and books, which is of great concern when they are valuable. Ozone and acid gases (e.g., gases from sulfur) are detrimental to the chemistry of paper, and prolonged exposure to trace concentrations can cause fading and embrittlement. When the state archive facility shown in Figure 3.1-A was designed, special consideration was given to controlling outdoor air pollutants. In separate filtration systems, both the outdoor air and the recirculated air are treated with deep-bed gas-phase air-cleaning equipment as well as high-efficiency MERV 16 particulate filters. MERV 6 pleated particulate filters are used to prefilter the final filters. A special dehumidification system is also employed to remove the excess humidity from the outdoor air. The archives building is located near major expressways and is beneath a primary landing pathway for the Atlanta international airport. When evaluated in 2007, the ozone concentration of the outdoor air was tested at peaks of 88 ppb (172 μg/m^3), which is sufficient to cause deterioration of paper. Yet concentrations of ozone in the supply to the storage chambers were below detection. Further, there were no sulfur compounds found in the conditioned space.

Air Quality Index	Protect Your Health
Good (0-50)	No health impacts are expected when air quality is in this range.
Moderate (51-100)	Unusually sensitive people should consider limiting prolonged outdoor exertion.
Unhealthy for Sensitive Groups (101-150)	The following groups should limit prolonged outdoor exertion: • People with lung disease, such as asthma • Children and older adults • People who are active outdoors
Unhealthy (151-200)	The following groups should avoid prolonged outdoor exertion: • People with lung disease, such as asthma • Children and older adults • People who are active outdoors Everyone else should limit prolonged outdoor exertion.
Very Unhealthy (201-300)	The following groups should avoid all outdoor exertion: • People with lung disease, such as asthma • Children and older adults • People who are active outdoors Everyone else should limit outdoor exertion.

Table 3.1-A Air Quality Index for Ozone
Source: OAQPS (2009).

Locate Outdoor Air Intakes to Minimize Introduction of Contaminants

Outdoor air enters a building through its air intakes. In mechanically ventilated buildings, the air intakes are part of the HVAC system. In naturally ventilated buildings, the air intakes can be operable windows or other openings in the building's envelope.

As outdoor air enters a building through its air intakes, it brings with it any contaminants that exist outside the building near the intake. That is why the quality of the outdoor air delivered to a building greatly affects the quality of the indoor air. Therefore, it is important to evaluate the ambient air quality in the area where a building is located as well as the presence of local contaminant sources. Outdoor air intakes need to be designed and located in such a way as to reduce the entrainment of airborne pollutants emitted by these sources.

Applicable Codes, Standards, and Other Guidance

Mechanical codes—such as *International Mechanical Code* (*IMC*; ICC 2006a), *International Plumbing Code* (*IPC*; ICC 2006b), *Uniform Mechanical Code* (*UMC*; IAPMO 2006a), and *Uniform Plumbing Code* (*UPC*; IAPMO 2006b)—have some requirements for the locations of building intakes. However, in most cases these requirements are very limited and there may be value in considering going beyond these requirements.

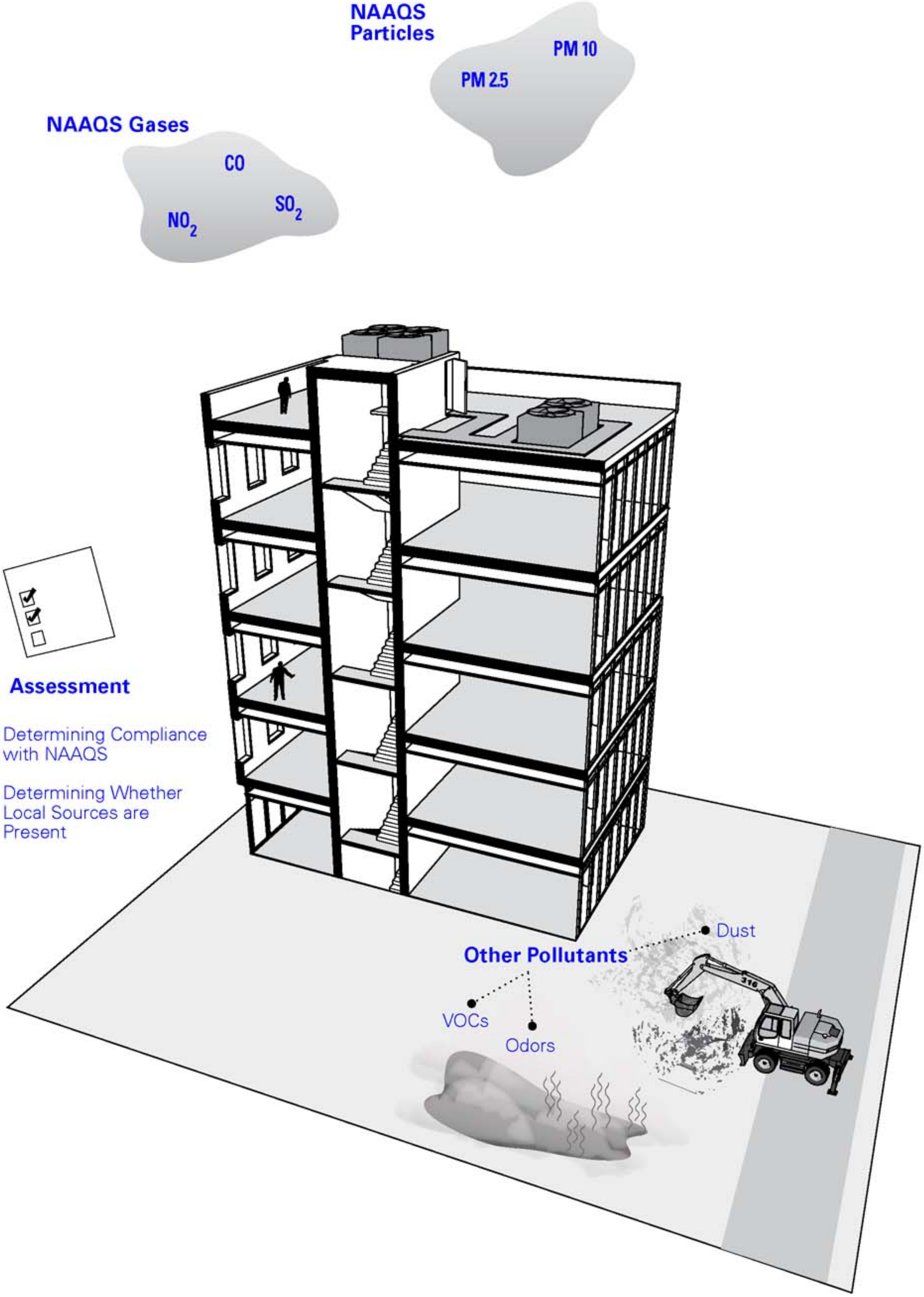
Table 5.1 of ASHRAE Standard 62.1 (ASHRAE 2007a) lists minimum separation distances between air intakes and specific contamination sources. Although ASHRAE Standard 62.1 does not cover all possible sources, it does give the designer a guiding tool. Appendix F of the same standard allows the designer to calculate distances from sources other than the ones listed in Table 5.1. The distances listed in ASHRAE Standard 62.1 should be considered design minimums; greater distances may provide better protection against these contaminants entering the building.

Cooling Towers, Evaporative Condensers, and Fluid Coolers

According to Table 5.1 of ASHRAE Standard 62.1, outdoor air intakes need to be located at least 25 ft (7.6 m) from plume discharges and upwind (prevailing wind) of cooling towers, evaporative condensers, and fluid coolers. In addition, outdoor air intakes need to be located at least 15 ft (4.6 m) away from intakes or basins of cooling towers, evaporative condensers, and fluid coolers. Buildings designed with smaller separation distances can increase the risk of occupant exposure to *Legionella* and other contaminants, such as the chemicals used to treat the cooling tower water. See Strategy 4.4 - Control Legionella in Water Systems for more information.

Other Sources of Contamination

All nearby potential odor or contaminant sources (such as restaurant exhausts, emergency generators, etc.) and prevailing wind conditions need to be evaluated. Locations of plumbing vents in relationship to outdoor air intakes in high-rise buildings may require additional analysis. Model codes such as *IMC* and *UMC* require a 3–10 ft (0.9–3.0 m) separation distance between building air intakes and terminations of vents carrying non-explosive or flammable vapors, fumes, or dusts. In the case of plumbing vents, *IPC* and *UPC* require a 2–10 ft (0.6–3.0 m) separation distance. For the health-care industry, *Guidelines for Design and Construction of Health Care Facilities* (AIA 2006) requires separation distances of 25 ft (7.6 m) between building intakes and plumbing vents, exhaust outlets of ventilating systems, combustion equipment stacks, and areas that may collect vehicular exhaust or other noxious fumes. However, these guidelines allow the 25 ft (7.6 m) separation distance to be reduced to 10 ft (3 m) if plumbing vents are terminated at a level above the top of the air intake.


NAAQS Particles
PM 10
PM 2.5
NAAQS Gases
CO
SO_2
NO_2
Assessment
Determining Compliance with NAAQS
Determining Whether Local Sources are Present
Other Pollutants
Dust
VOCs
Odors

Next Page

Strategy 3.2

Modeling

It is clear that due to wind effects around buildings and multiple other local variables, establishing separation distances that will result in no entrainment for each source is extremely difficult if not impossible. Each design case must be evaluated based on local conditions and variables, and the designer ultimately needs to exercise professional judgment. In some cases, advanced calculations and/or modeling may be required, such as wind tunnel analyses with scale models, computer simulations, or computational fluid dynamics (CFD) analyses.

Packaged HVAC Systems

In packaged HVAC systems, an exhaust stack elevated 10 in. (0.25 m) or more can reduce re-entrainment of combustion products. In HVAC systems where the intakes and exhausts are in close proximity, dilution of building exhaust air in the economizer mode is significantly less than the dilution of flue gas in the heating mode. Packaged HVAC units need to be located so that their air intakes and exhausts are directed away from large obstructions.

Intake/Exhaust Separation at a New Office Building

The HVAC unit shown in Figure 3.2-A is one of several units on the roof of a large five-story office building. Indirect evaporative cooling was installed in all HVAC units before the building was occupied. Although the reason for the relocation of all the intakes was the installation of the indirect evaporative coolers, it created an opportunity for the designers to increase the separation distance between intakes and exhausts.

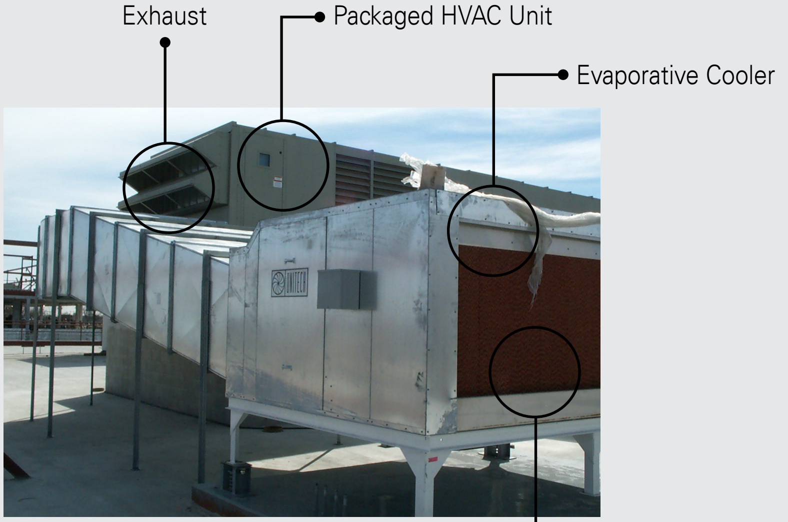


Figure 3.2-A Large Packaged HVAC Unit with Relocated Outdoor Air Intake to Reduce Exhaust Air Re-entrainment (Shown is a Closeup of the Indirect Evaporative Cooler at the Outdoor Air Intake)

Photograph courtesy of Leon Alevantis.

Control Moisture and Contaminants Related to Mechanical Systems

Mechanical systems play an important role in providing good IAQ through ventilation, air cleaning, and comfort conditioning. However, since many mechanical systems carry water or become wet in operation, they can also amplify and distribute microbial contaminants. In occupants this can cause building-related symptoms such as nasal and throat irritation and, more rarely, building-related illnesses (BRIs) such as Legionnaires' Disease or humidifier fever. The Strategies in this Objective can help reduce the likelihood of IAQ problems related to mechanical systems.

- Moisture and dirt in air-handling systems provide an environment for microbial growth. Strategy 4.1 – Control Moisture and Dirt in Air-Handling Systems provides techniques to limit rain and snow entry, manage condensate from cooling coils and humidifiers, and keep airstream surfaces clean and dry.
- Condensation on cold piping or ductwork and leaks from piping and fixtures can lead to microbial growth. Strategy 4.2 – Control Moisture Associated with Piping, Plumbing Fixtures, and Ductwork addresses insulation and vapor retarders, including design assumptions and damage protection as well as reduction of piping leaks.
- Periodic inspection, cleaning, and repair of mechanical systems is critical to IAQ but is often hindered by poor access. Strategy 4.3 – Facilitate Access to HVAC Systems for Inspection, Cleaning, and Maintenance addresses equipment location, clearances, and other access issues.
- Legionella can multiply in building water systems such as cooling towers, humidifiers, potable water systems, spas, and fountains. Inhalation of *Legionella* from these sources causes about 18,000 cases of Legionnaires' Disease and 4500 deaths per year in the U.S. Strategy 4.4 – Control *Legionella* in Water Systems addresses the control of *Legionella*.
- One approach that can be used to limit the growth of microorganisms in air-handling systems is ultraviolet germicidal irradiation (UVGI). Strategy 4.5 – Consider Ultraviolet Germicidal Irradiation discusses the state of knowledge regarding UVGI.

Strategies discussed under other Objectives that also help to limit IAQ problems related to mechanical systems include the following:

- Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ
- Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ
- Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces
- Strategy 2.3 – Maintain Proper Building Pressurization
- Strategy 2.5 – Select Suitable Materials, Equipment, and Assemblies for Unavoidably Wet Areas
- Strategy 3.2 – Locate Outdoor Air Intakes to Minimize Introduction of Contaminants
- Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives

Objective 4

Objective 4

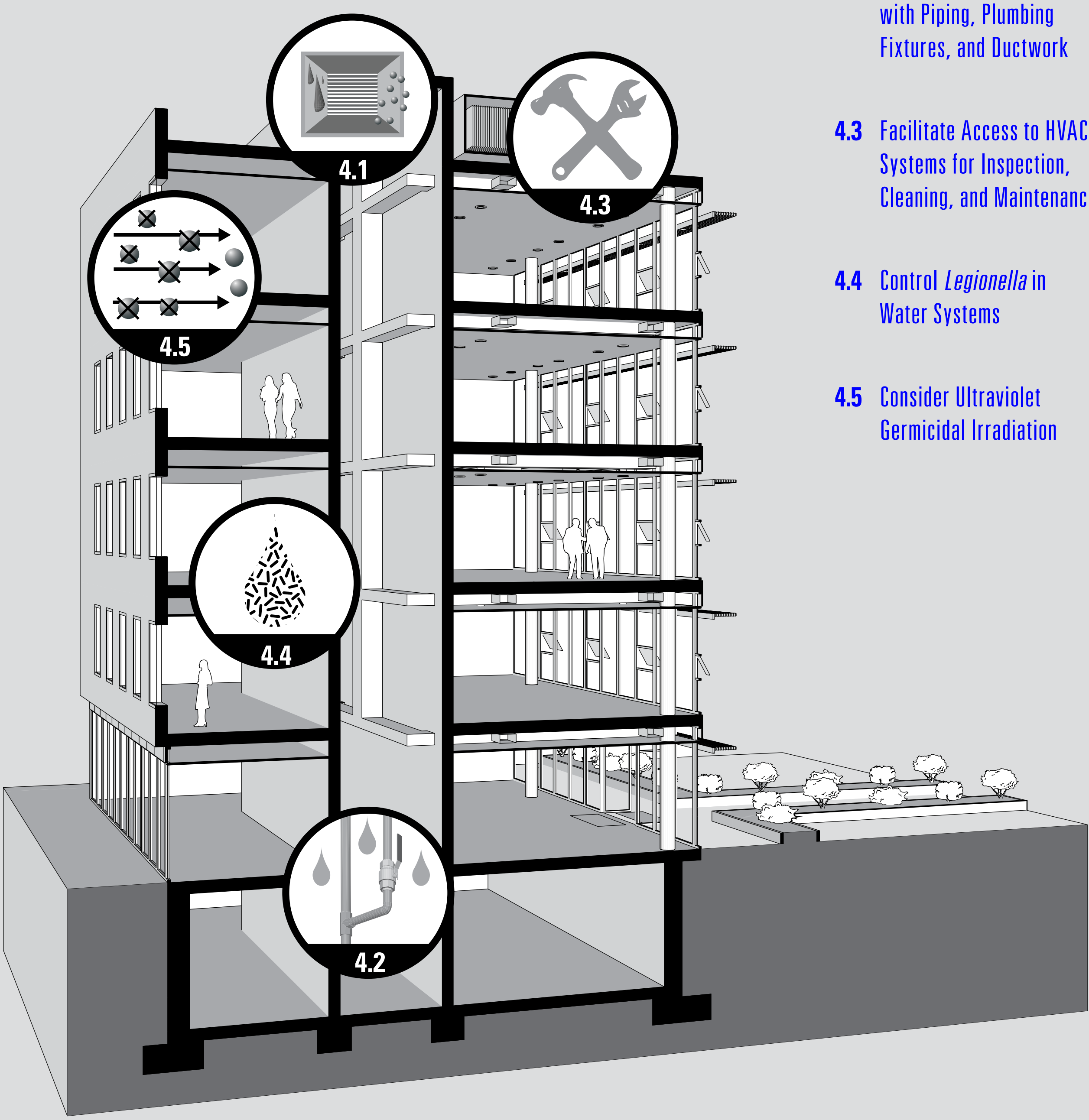
4.1 Control Moisture and Dirt in Air-Handling Systems

4.2 Control Moisture Associated with Piping, Plumbing Fixtures, and Ductwork

4.3 Facilitate Access to HVAC Systems for Inspection, Cleaning, and Maintenance

4.4 Control *Legionella* in Water Systems

4.5 Consider Ultraviolet Germicidal Irradiation



Control Moisture and Dirt in Air-Handling Systems

Fungi and bacteria are normally present on most interior surfaces in buildings, including on surfaces in HVAC system components. These microorganisms become problematic to IAQ when they amplify or grow on surfaces, sometimes to the point where the growth is visibly obvious. The growth of microorganisms in HVAC systems can result in malodors, building-related symptoms in occupants (e.g., nasal and throat irritation), and in rare cases, building-related illnesses such as humidifier fever and hypersensitivity pneumonitis. Implementation of design strategies that limit moisture and dirt accumulation in HVAC components lessens the risk of microbial growth on HVAC component surfaces.

- *Outdoor Air Intakes and Outdoor Air Inlet Areaways.* Protection against rain and snow intrusion is important. In addition, below-grade outdoor intakes can become accumulation sites for dirt and debris and landscaping pesticides and fertilizers, plus leaves, which are also growth sites for fungi.

- *Filters and Microbial Growth in HVAC Equipment*. Highly efficient filters provide an important tool for reducing the amount of dirt and dust on airstream surfaces that are nutrients for microbial growth under damp-wet conditions.

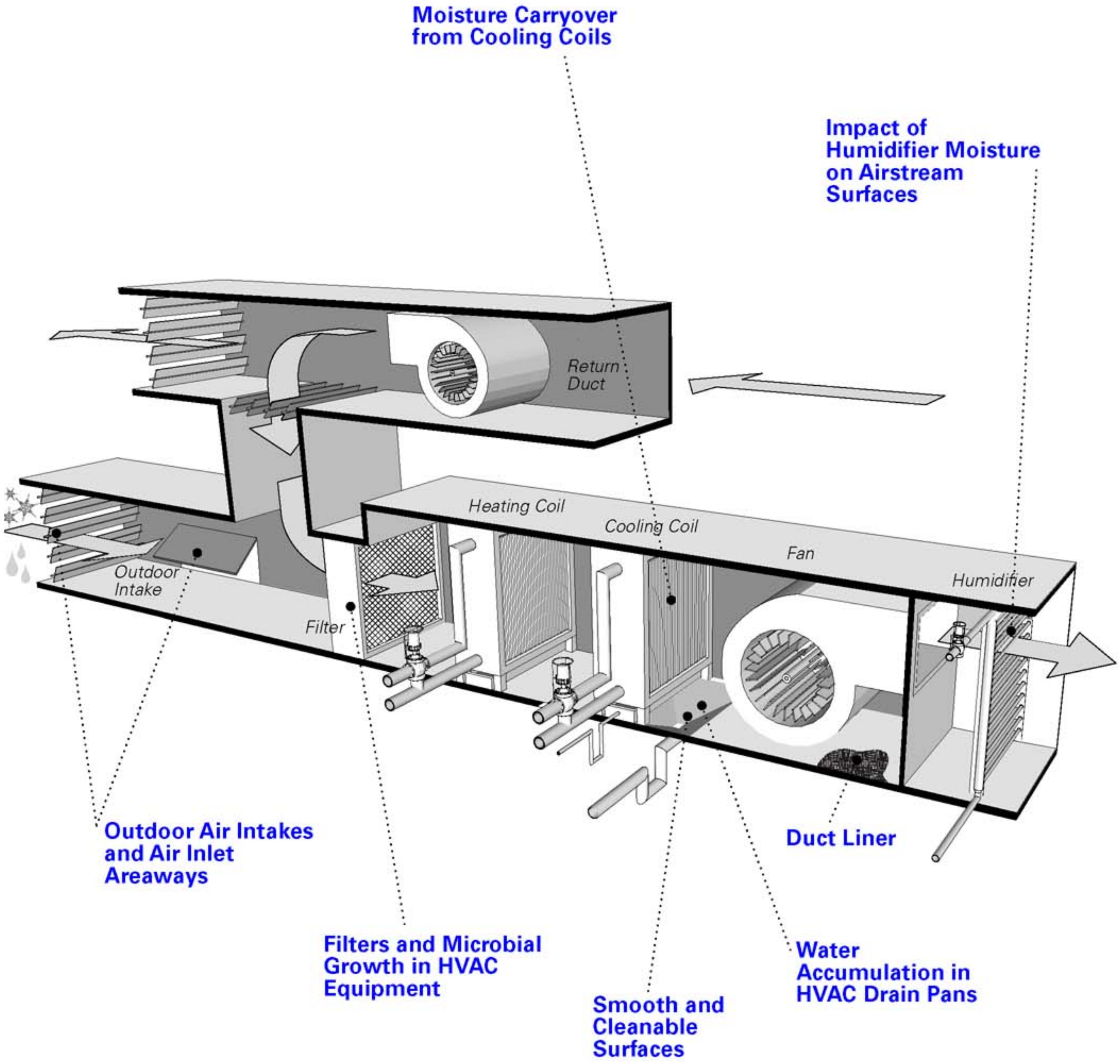
- *Water Accumulation in HVAC Drain Pans*. Adequate drainage design is critical to limiting microbial contamination. The drain hole for the pan needs to be flush with the bottom of the pan. When the air-handling unit (AHU) is mounted in a mechanical room, it is important to make certain that allowance is made for mounting the drain line at the very bottom of the pan.

- *Moisture Carryover from Cooling Coils*. If the air velocity is too high over part of the coil section (e.g., due to localized accumulation of dirt or poor design), water droplets can and will wet downstream surfaces.

- *Smooth and Cleanable Surfaces*. While microorganisms can grow on smooth but dirty surfaces in HVAC equipment, growth will usually be greatest on porous or irregular airstream surfaces where dust and dirt (nutrient) accumulation is highest. In addition, removal of microbial growth, dirt, and dust from porous or fibrous airstream surfaces can be more difficult.

- *Duct Liners*. It is difficult to achieve a completely clean and dry duct liner that has a fibrous or rough surface over the life of the building with typical, or even above average, airstream filtration. Duct liners with fibrous or rough surfaces present the potential for mold growth since the dirt that accumulates on the surface promotes the retention of moisture and the organic material in the accumulated dirt provides nutrients for mold growth. In addition, it is difficult to remove mold structures, such as hyphae that have grown into fibrous materials.

- *Impact of Humidifier Moisture on Airstream Surfaces*. Water droplets aerosolized from sumps containing recirculated water are heavily colonized by various microorganisms, including actinomycetes, gram-negative bacteria such as *flavobacterium*, and yeasts. It is desirable to use humidifiers that work on the principle of aerosolization of water molecules (absence of carryover of microbes) instead of water droplets (where microbial components may be carried over). Boiler water is not an appropriate source if it contains corrosion inhibitors.


Moisture Carryover from Cooling Coils
Impact of Humidifier Moisture on Airstream Surfaces
Return Duct
Heating Coil
Cooling Coil
Fan
Humidifier
Outdoor Intake
Filter
Outdoor Air Intakes and Air Inlet Areaways
Duct Liner
Filters and Microbial Growth in HVAC Equipment
Water Accumulation in HVAC Drain Pans
Smooth and Cleanable Surfaces

Strategy 4.1

Poorly Designed and Maintained Drain Pan

Figure 4.1-A Drain Pan that was Poorly Designed and Maintained

Photograph courtesy of Phil Morey.

The AHU shown in Figure 4.1-A was poorly designed and maintained. Access to the pan was achieved only after removal of more than ten fasteners, and the drain pan outlet was not flush with the bottom of the pan. The tan-yellow mass in the pan is a biofilm consisting of a gelatinous mass of fungi, bacteria, and protozoa. This plenum was opened for inspection because of concerns about building-related symptoms and building-related illnesses in the occupied space served by the AHU.

Control Moisture Associated with Piping, Plumbing Fixtures, and Ductwork

Mold growth can occur on cold water pipes or cold air supply ducts with inadequate thermal insulation or a failed vapor retarder and result in material damage or significant IAQ problems leading to potential adverse health impacts on occupants. Liquid water from condensation can damage materials nearby such as ceiling tiles, wood materials, and paper-faced wallboard located below or adjacent to the piping or ducts. Leaks from poorly designed plumbing within walls or risers may go unnoticed until damage, including mold growth, becomes evident in occupied spaces. Implementation of design strategies that limit condensation on cold water piping and ducts and that reduce the likelihood of piping leaks hidden in building infrastructure will lessen the likelihood of these potential problems.

Condensation Associated with High Dew-Point Temperature around Chilled-Water Pipes

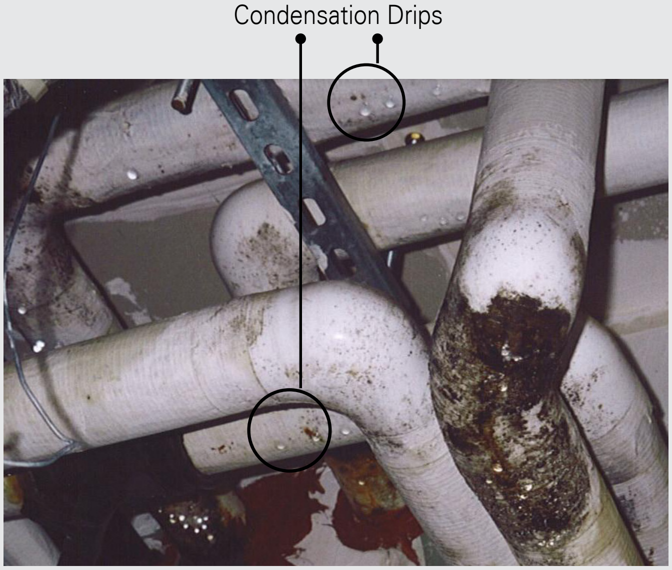
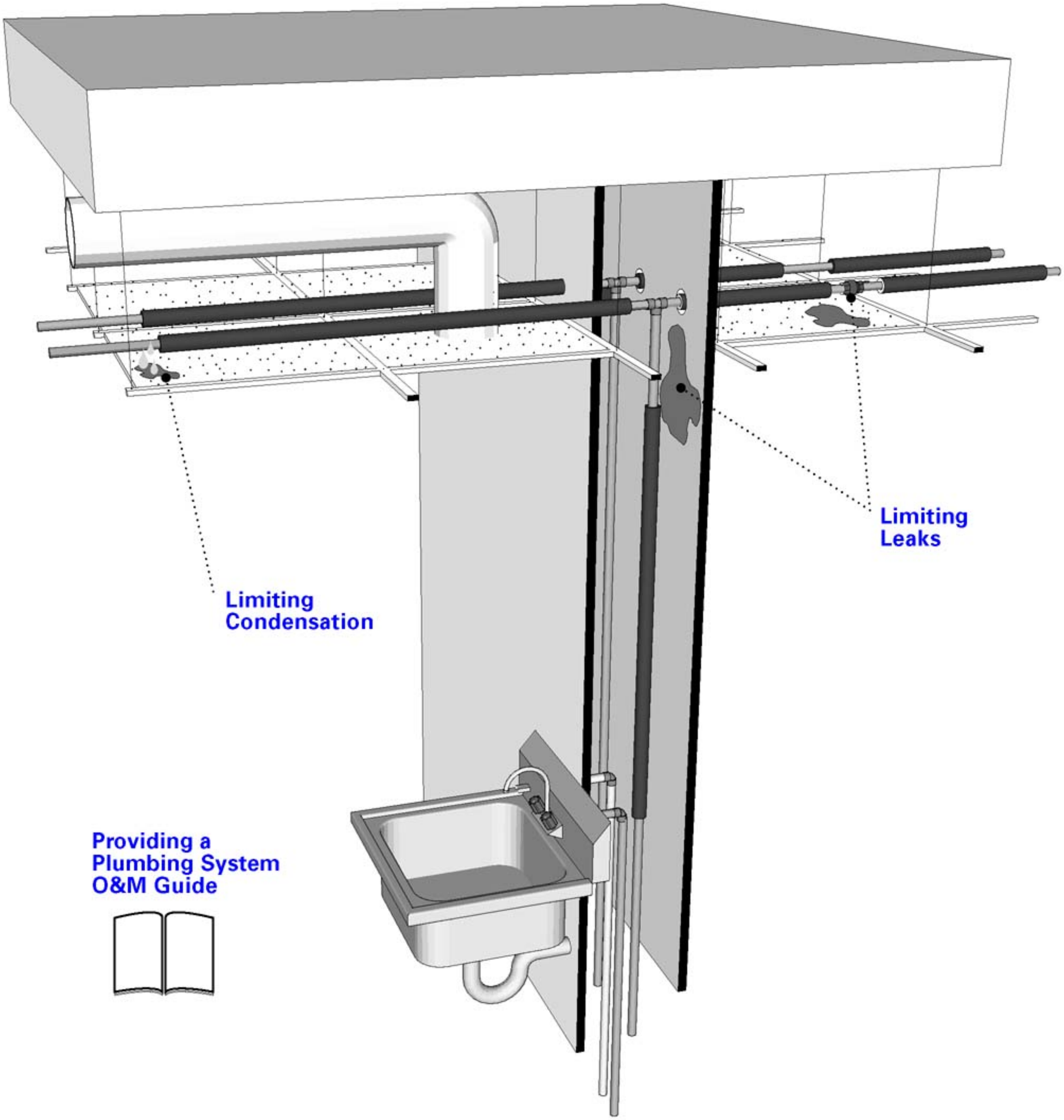


Figure 4.2-A Condensation Drips and Mold on Pipe Insulation
Photograph courtesy of Phil Morey.

Condensation drips are visible on pipe insulation surfaces in an above-ceiling location, as shown in Figure 4.2-A. Mold growth is present on pipe jacketing. Condensation was associated with the infiltration of warm humid air into the above-ceiling spaces and unexpectedly high dew points in this unconditioned space.

Next Page

Strategy 4.2



Limit Contaminants from Indoor Sources

Many building materials, finishes, and furnishings emit compounds that can cause discomfort, irritation, or other more serious health impacts. These include organic compounds that can cause health effects ranging from eye, nose, and throat irritation to headaches and allergic reactions to organ damage and cancer. The occupant complaints, lost productivity, and absences that can result can lead to additional costs for IAQ investigations, material replacement, and litigation. Some emissions may be relatively benign themselves but react with other compounds in the air, such as ozone, to form secondary products that are more irritating or harmful. Materials, finishes, and furnishings that are difficult to clean may contribute to IAQ problems by necessitating use of strong cleaning agents. While scientific understanding of these issues is still evolving, the Strategies presented here provide practical means to limit their IAQ impacts based on current knowledge.

- Selecting appropriate materials, finishes, and furnishings reduces the likelihood of emissions-related IAQ problems. Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection provides background information, describes strengths and weaknesses of emission data sources and rating systems, and contains succinct information and recommendations for a dozen priority product categories.
- Sometimes it is difficult to avoid use of certain materials and products. Strategy 5.2 – Employ Strategies to Limit the Impact of Emissions outlines steps that can be taken to limit the impact of unavoidable emissions, including the use of emission barriers, material conditioning, in-place curing, delayed occupancy, building flush-out, and short-term use of gas-phase air cleaning.
- Cleaning agents and processes can have detrimental effects on indoor air. While this Guide does not address O&M, it does address design to facilitate O&M. Strategy 5.3 – Minimize IAQ Impacts Associated with Cleaning and Maintenance addresses selection of easily cleaned materials and finishes, provision for proper storage and handling of cleaning materials, inclusion of cleaning protocols in O&M documentation and training, and other steps to reduce the IAQ impacts of cleaning.

This Objective focuses on Strategies to reduce indoor contaminant sources. Additional Strategies to deal with contaminants generated indoors include capture and exhaust, filtration and air cleaning, and dilution ventilation. These are discussed under the following:

- Objective 6 – Capture and Exhaust Contaminants from Building Equipment and Activities
- Objective 7 – Reduce Contaminant Concentrations through Ventilation, Filtration, and Air Cleaning

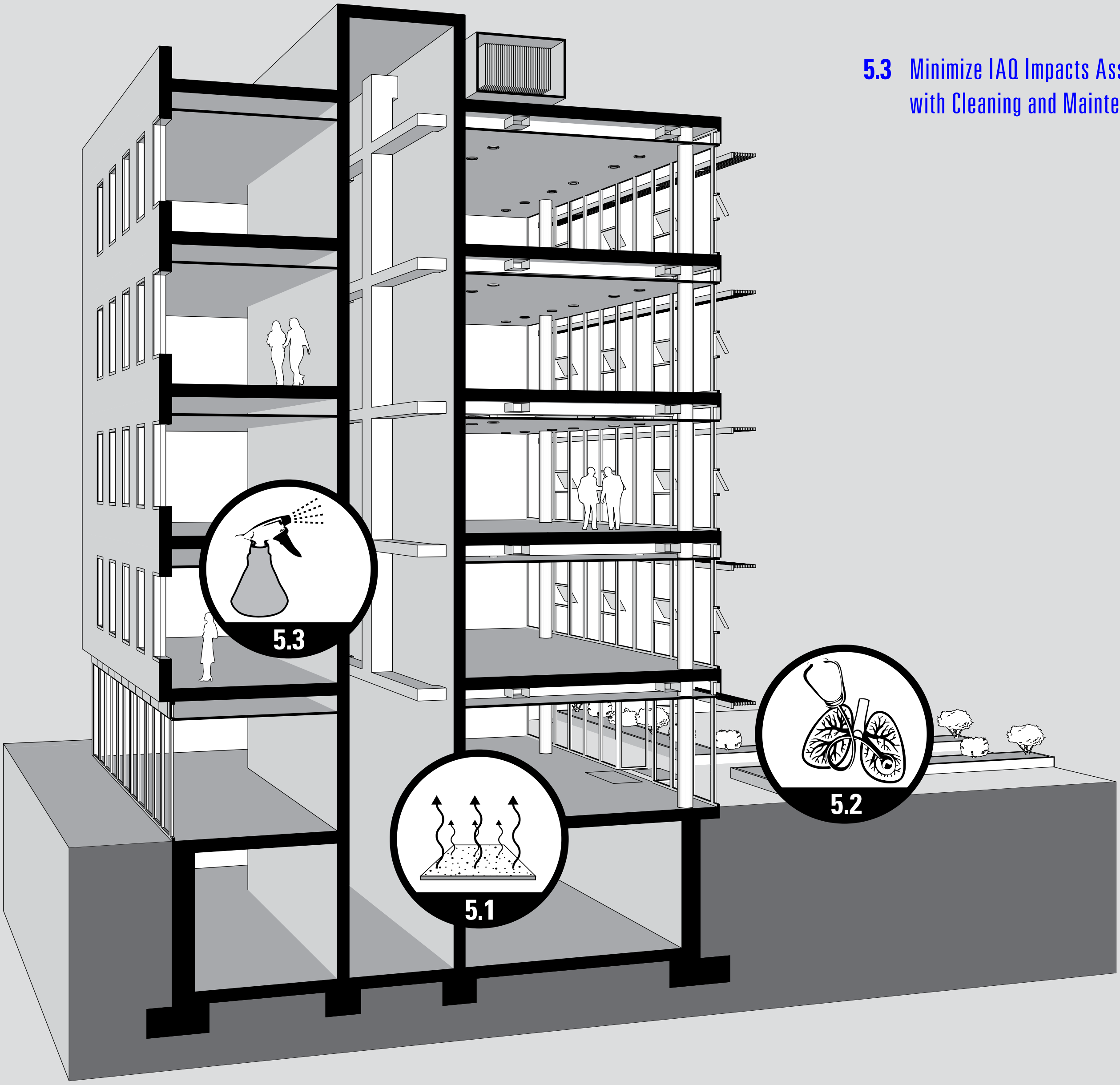
Objective 5

Objective 5

5.1 Control Indoor Contaminant Sources through Appropriate Material Selection

5.2 Employ Strategies to Limit the Impact of Emissions

5.3 Minimize IAQ Impacts Associated with Cleaning and Maintenance



Control Indoor Contaminant Sources through Appropriate Material Selection

Recent advances in the sampling and analysis of indoor contaminants and in toxicology and indoor chemistry have contributed to a greater understanding of the nature and impacts of the pollutants that affect building occupants. In parallel, advancements in the techniques used to determine the emissions (or *off-gassing*) properties of materials and products used in building construction, finishing, and furnishing have enabled us to more clearly see their chemical "fingerprints" on indoor environments and thus their impact on IAQ.

Provision of good IAQ requires coordination of many aspects of building design, and a practical first step is problem avoidance through careful selection of materials with minimal emission of irritating or harmful compounds. This form of source control is an effective means of preventing IAQ problems while reducing the need to dilute avoidable contaminants through costly ventilation. Thus, building designers, in addition to specifying material structural, fire, and moisture (and mold) resistance properties, need to also carefully consider the chemical emission characteristics of materials. Long-term durability, maintenance, and cleaning requirements also have significant impacts on IAQ and need to therefore be included in material specifications. These aspects of material selection need to be considered in the midst of pressure to adopt "green" products that may or may not adequately consider IAQ impact as a component of environmental sustainability.

Rating systems for assessing the chemical emissions of products are still evolving. Product labels describing emission properties provide far more information than that given by content-based product labels, which merely report the percent by weight of VOCs. Within emissions-based systems, the total volatile organic compound (TVOC) emission rate, while still widely reported, is increasingly recognized as a poor indicator of the true impact of any given material. This is largely due to the great range in irritant, odor, and toxicological impact of individual VOCs: some have significant impacts at relatively low levels, while others may be relatively harmless at high concentrations. Long-term emissions of SVOCs such as phthalates, pesticides, and flame retardants are now recognized as important factors in IAQ problems and need to be considered in the evaluation of material properties.

Actual emission rates vary significantly over time: for a given product, emissions of some chemicals decay rapidly (within hours or days), while others may release contaminants at nearly constant rates for many months. The acute or long-term impacts of materials can thus be dramatically different and need to be factored into product assessment. Formation of secondary products through indoor chemistry reactions may have real impact on IAQ; thus, elimination or reduction of the primary reactants (such as terpenoids) could be considered by advanced labeling systems on which designers can base material selection decisions.

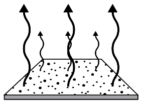
In evaluating emissions impacts, materials need to be considered as parts of systems whenever possible. For example, carpeting is not independent of cushions, adhesives, or subfloors. Wallboard requires primer and paint. Emissions from a system may be markedly different than those from its individual constituents.

Strategy 5.1

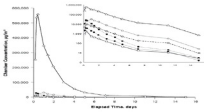
Contaminant Emissions: Basic Concepts

- VOCs—Total vs. Target: Irritancy, Odor, and Health Impact
- Semi-Volatile Organic Compounds (SVOCs)
- Indoor Chemistry - Secondary Emissions
- IAQ Guidelines, Standards and Specifications
- Shades of Green - Environmentally Preferred Products
- Product Information - Composition vs. Emissions
- Emissions Behavior

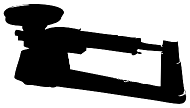
Emissions Data: Available Information



Emissions Testing



Emissions Databases

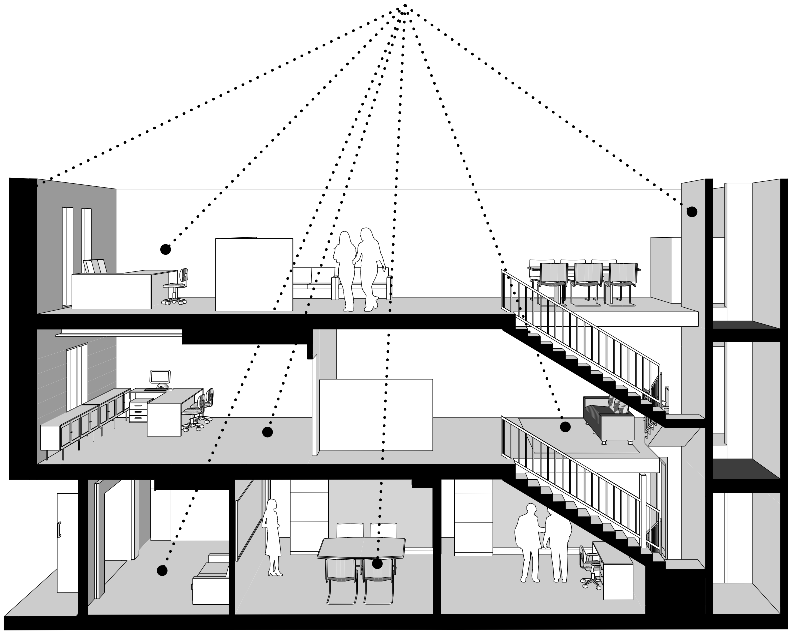


Manufacturer Supplied Information: MSDSs

Labels: Emissions-Based

Labels: Content-Based

Priority Materials/ Finishes/Furnishings



- Architectural Coatings
- Flooring Materials
- Ceiling Tiles
- PVC Materials
- Insulation Materials
- HVAC Components
- Caulks, Sealants & Adhesives
- Porous of Fleecy Materials
- Flame-Retardant Materials
- Structural Materials
- Office Furniture Systems
- Office Equipment
- Composite Wood / Agrifiber Materials

Local environmental conditions may influence contaminant release. For example, materials subjected to relatively high temperatures (possibly through solar gains) or high humidity may have increased emissions.

IAQ guidelines and standards for specific contaminants are currently sparse. Occupational regulations for air quality do not directly apply to nonindustrial buildings due to differences in the levels and compositions of the contaminant species as well as the nature of the building occupants. In the absence of legislated limit values, emission labels need to rely on guidance-level information. Building designers need a basic understanding of the key issues related to emissions labeling in order to effectively specify building materials, finishes, and furnishings. In the absence of detailed guidance, several basic recommendations can be made concerning material selection for the diverse range of products that go into building design (Schoen et al. 2008).

In general, the following recommended strategies will assist in selecting low-emitting materials for building design:

- Require submission and review of material composition (VOC contents or, preferably, detailed emissions properties) as condition of acceptance for project (ensure supplier receives detailed information from manufacturer) prior to material selection.
- Where product-specific emissions data are not available, limit usage of products/materials generally known to have higher contaminant emissions, including unfinished composite or engineered wood products; oil-based architectural coatings and paints; and caulks, sealants, and adhesives. Specify use of low-emission resins if required during product manufacture.
- Specify and use products with low-formaldehyde emissions.
- Limit use of porous/fleecy materials including carpeting, fabrics, and upholstery to reduce sink effects and facilitate cleaning.
- Select materials that are durable and low maintenance and have easily cleanable surfaces. Require detailed installation, maintenance, and cleaning instructions as part of the material specification process. Verify that product installation practice conforms to project specification. Ensure that detailed maintenance and cleaning instructions are delivered to building owner/operators (refer to Strategy 5.3 – Minimize IAQ Impacts Associated with Cleaning and Maintenance for additional guidance on cleaning and maintenance that will reduce the IAQ impact of these activities).
- Avoid use of polyvinyl chloride (PVC) based flooring materials in contact with damp concrete that may, through hydrolysis, result in the release of undesirable (secondary) emissions.
- Limit the use of lining materials on interior surfaces of ventilation ducts (see Strategy 4.1 – Control Moisture and Dirt in Air-Handling Systems for guidance on HVAC ducting design to control noise). Use low-emission cleaning agents to remove any residual oils on the interior surfaces of ductwork prior to installation. Immediately following manufacture, seal all duct openings and store in a dry location. Remove seals only just prior to installation to prevent contamination during construction.
- Fully identify each material or product in the project specifications. Prepare a Schedule of Materials, identifying each material by a unique name and symbol that need to appear on project plans.
- Review available emissions information for all substitutions prior to approval; confirm delivered products meet specifications.

Despite best efforts to avoid materials with high contaminant emissions, the use of certain materials and products with moderate to high emissions may still be necessary, depending on building use and function. Additional techniques will therefore be required to limit the effects of material emissions on indoor air. Refer to Strategy 5.2 – Employ Strategies to Limit the Impact of Emissions for further details.

Strategy 5.1

Selection of Low-Chemical-Emission Materials Leads to Reduced Contaminant Levels in Office Environment

During construction of a new office building, the specification of building materials and furnishings for eight floors to be occupied by one client was made with particular regard for IAQ impact. Construction materials employed on these floors that were carefully screened included insulation, particle boards, wall coverings, paints (latex), stains and varnishes, cabinets, sealing and spackling compounds, glues and adhesives (water-based), tile grout, and plasters and cements. Furnishing specifications included the use of low-formaldehyde fabrics and continuous filament carpeting (to reduce particle shed). Systems furniture and work stations, draperies, and ornamental fabrics were also selected based on IAQ impact considerations.

The contractor employed to construct these eight office floors also simultaneously constructed adjacent floors that did not require similar IAQ specifications for materials and furnishings. These "typical" floors were indistinguishable from the other eight floors in terms of appearance, furnishings, and space usage. Post-occupancy air sampling conducted in the building (Figure 5.1-A) revealed that VOC levels on the low-emission floors were approximately 50%–75% below those found on the conventionally constructed floors.

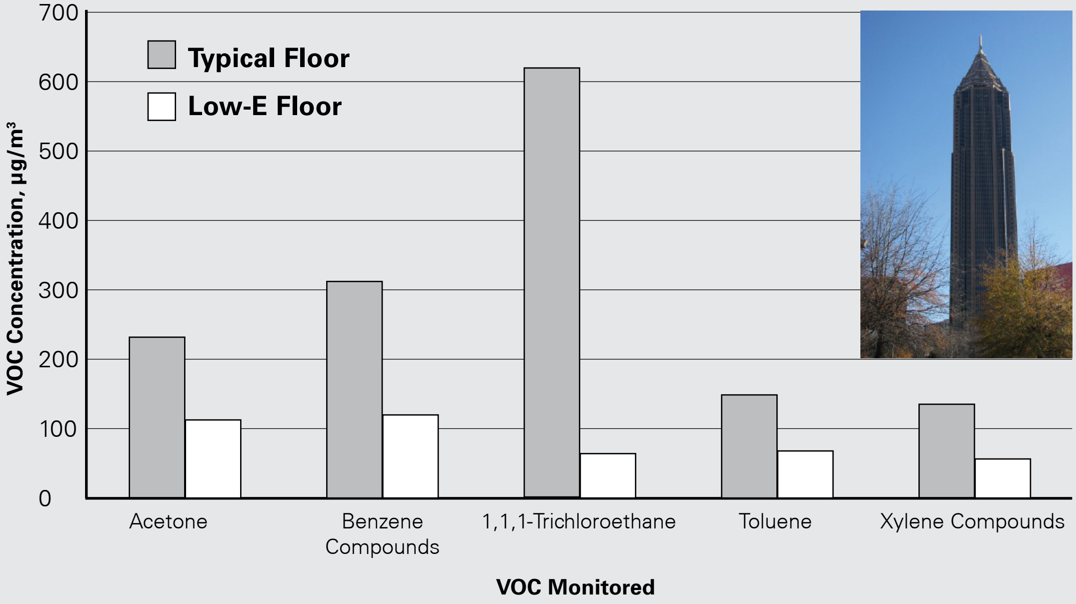


Figure 5.1-A Monitored VOC Levels

Data source: Milam (1994). Inset photograph courtesy of H.E. Burroughs.

Next Page

Strategy 5.1

Capital Area East End Complex—Sacramento, California

Figure 5.1-B Capitol Area East End Complex
Photograph courtesy of Leon Alevantis.

The Capitol Area East End Complex (CAEEC) in Sacramento, California, is a five-building sustainable office complex built in 2002–2003 with a total area of 1,500,000 ft^2 (140,000 m^2) (Figure 5.1-B). Emissions testing of the majority of the interior finishing materials was required per *Section 01350, Special Environmental Requirements Specification* (CIWMB 2000). Details of the project are available at www.eastend.dgs.ca.gov/AboutTheProject/default.htm.

Overall, concentrations of the common chemicals measured at the CAEEC shortly after initial occupancy and for several months thereafter were comparable to those reported in the EPA Building Assessment Survey and Evaluation (BASE) study (EPA 2008d) with only few chemicals at the CAEEC being higher. The BASE study measured contaminant concentrations in buildings that were at least seven years old. In contrast, the CAECC results were collected from a newly constructed building (at the time when emissions from building materials and furnishings are expected to be at their peak). The finding of comparable levels of contaminants in the two studies indicates that careful selection of materials leads to reduced exposures to indoor contaminants, especially during early occupancy of buildings.

The CAECC study shows that requiring emissions testing from manufacturers helped achieve better-than-average IAQ. The concentration targets established for this project were not exceeded in the majority of the locations. Therefore, as expected, careful selection of building materials during a building's design appears to result in lower concentrations of VOCs during the initial months of a newly constructed building (Alevantis et al. 2006).

EPA Waterside Mall—Washington, DC

This case study shows the costs that can occur when emissions are not considered during material selection.

The first phase of the EPA Waterside Mall, a mixed-use building, was completed in 1970, and the building was occupied by EPA in 1971. Additions were made in the 1980s, including a major renovation in 1987 that included the installation of 243,000 ft^2 (22,600 m^2) of new carpeting.

Of 3700 employees who responded to a 1989 survey, 880 reported health effects. Although the problem was likely due to a number of factors (including HVAC system inadequacies, occupant crowding, and the density of the office equipment), employees attributed many of the health effects to the new carpeting, which was eventually replaced with a low-odor alternative.

The estimated cost of the replacement was approximately $4 million, including carpet replacement, HVAC renovations, IAQ investigations, sick leave, labor to address IAQ issues, compensation claims, etc., plus litigation costs.

Capture and Exhaust Contaminants from Building Equipment and Activities

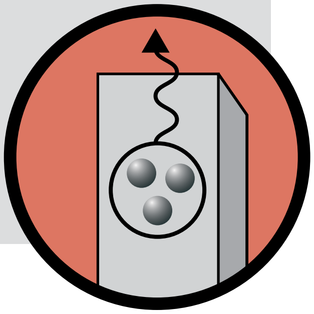
Building equipment and activities can be significant sources of indoor air contaminants. Among these are combustion products from fuel-burning equipment; exhaust from vehicles in enclosed parking garages; hazardous air pollutants from dry cleaners and nail and hair salons; particles and fumes from school laboratories, shops, and art classrooms; VOCs and ozone from office equipment; infectious agents from medical and dental procedure rooms; and odors from various sources. The Strategies discussed in this Objective can reduce the likelihood that these emissions will degrade IAQ.

- Combustion produces moisture, CO_2, oxides of nitrogen and sulfur, soot, and potentially CO. Strategy 6.1 – Properly Vent Combustion Equipment describes venting and combustion air requirements to limit occupant exposure to combustion products.
- Point sources such as large copiers and printers; nail care stations; certain workstations in laboratory, shop, and art classrooms; and commercial cooking equipment can produce contaminants that may cause irritation or illness. Strategy 6.2 – Provide Local Capture and Exhaust for Point Sources of Contaminants describes techniques to reduce users' and other occupants' exposure through well-designed exhaust and depressurization of the source area.
- Contaminants in exhaust air can re-enter the occupied space if exhaust ductwork is not well sealed, especially if the exhaust duct static pressure is higher than that in the surrounding area. Exhaust discharge can also be re-entrained into outdoor air intakes or windows. Strategy 6.3 – Design Exhaust Systems to Prevent Leakage of Exhaust Air into Occupied Spaces or Air Distribution Systems addresses duct sealing, fan location, and discharge design to reduce the risk of re-introducing exhaust to the occupied space.
- Many contaminant sources are too diffuse to be exhausted at the point of generation. Strategy 6.4 – Maintain Proper Pressure Relationships Between Spaces describes methods to control contaminant transfer from such spaces as enclosed parking garages, natatoriums, dry cleaning shops, hair salons, and bars through space layout and compartmentalization and control of space-to-space pressures.

Other Strategies that can affect or be affected by exhaust and space depressurization include the following:

- Strategy 1.3 – Select HVAC Systems to Improve IAQ and Reduce the Energy Impacts of Ventilation
- Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces
- Strategy 2.3 – Maintain Proper Building Pressurization
- Strategy 3.2 – Locate Outdoor Air Intakes to Minimize Introduction of Contaminants
- Strategy 3.3 – Control Entry of Radon
- Strategy 3.4 – Control Intrusion of Vapors from Subsurface Contaminants

Objective 6



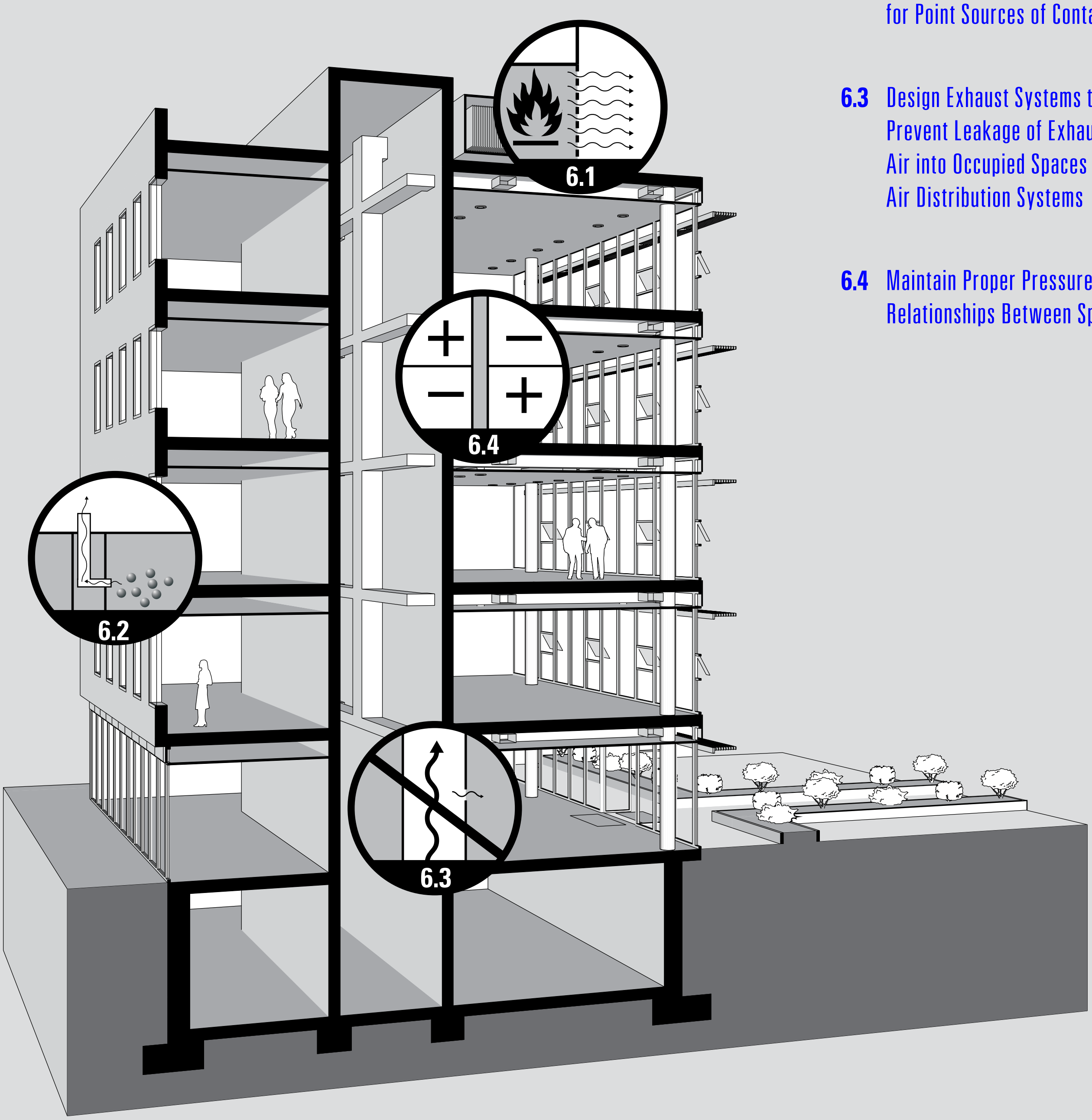
Objective 6

6.1 Properly Vent Combustion Equipment

6.2 Provide Local Capture and Exhaust for Point Sources of Contaminants

6.3 Design Exhaust Systems to Prevent Leakage of Exhaust Air into Occupied Spaces or Air Distribution Systems

6.4 Maintain Proper Pressure Relationships Between Spaces



Properly Vent Combustion Equipment

Many types of combustion equipment and appliances are used in buildings. Since combustion produces harmful byproducts (e.g., CO, NO_2, and fine particles), it is important to control the flow of these byproducts through carefully designed venting and exhaust systems and through provisions for supplying outdoor air for combustion.

Capture and Exhaust of Combustion Byproducts

The type of exhaust capture system used will depend on the fuel, process, and type of equipment being vented.

- Chimney (natural draft) systems rely on the buoyancy of the warm combustion products in the chimney or stack (relative to the cooler and denser surrounding air) to produce a natural draft that exhausts the combustion products from the building.
- Induced draft systems use a fan on the downstream side of the combustion chamber to pull combustion products through the combustion chamber and exhaust them from the building.
- Forced draft systems use a fan on the upstream side of the combustion chamber to push air through the combustion chamber and exhaust combustion products from the building.

Regardless of the type of system used, all components of any capture and exhaust system must be selected to properly function under the expected operating conditions, including the temperature and other properties of the exhaust air. The system must then be designed and installed to effectively remove the products of combustion.

As important as the size and operation of the exhaust system to remove combustion products is the availability of an adequate supply of makeup air for combustion. An inadequate amount of makeup air may lead to incomplete combustion, resulting in an increase of the harmful combustion byproducts, particularly CO. The inadequate supply of makeup air can also result in negative pressures at the equipment burner, which can cause back-drafting, where the exhaust gasses are pulled back down through the exhaust vents.

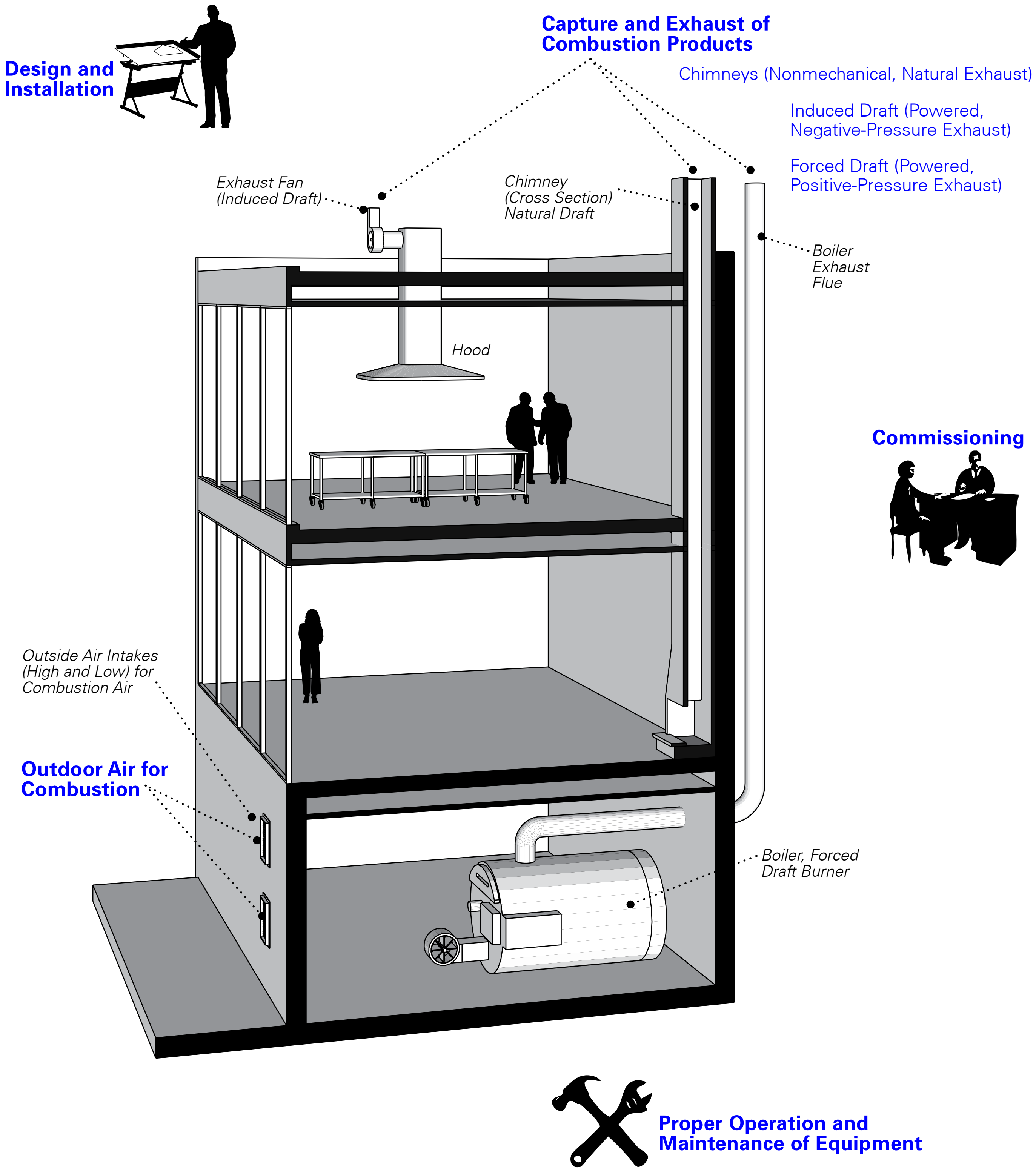
Operation and Maintenance

There is a greater potential for exposure to harmful combustion products if the combustion equipment itself is not well maintained. Installation of combustion equipment must therefore provide adequate access for proper maintenance according to the manufacturer’s instructions. It is also recommended that monitoring of the design and installation of combustion equipment and exhaust and supply duct systems be included as part of the building Cx process. The O&M manual should provide information on the recommended frequency of inspections to ensure that combustion equipment is operating properly.

Commissioning

Given the potential hazards from combustion equipment, the design and installation of combustion equipment, along with the exhaust and supply duct systems, should be included as a part of the building Cx process.

Strategy 6.1


Design and Installation
Capture and Exhaust of Combustion Products
Chimneys (Nonmechanical, Natural Exhaust)
Induced Draft (Powered, Negative-Pressure Exhaust)
Forced Draft (Powered, Positive-Pressure Exhaust)
Exhaust Fan (Induced Draft)
Chimney (Cross Section) Natural Draft
Boiler Exhaust Flue
Hood
Commissioning
Outside Air Intakes (High and Low) for Combustion Air
Outdoor Air for Combustion
Boiler, Forced Draft Burner
Proper Operation and Maintenance of Equipment

Provide Local Capture and Exhaust for Point Sources of Contaminants

In ASHRAE Standard 62.1, a contaminant is defined as “an unwanted airborne constituent that may reduce acceptability of the air” (ASHRAE 2007a, p. 4). By this definition, in the indoor environment today, contaminants are generated as a part of such processes as cooking, commercial laundries, scientific procedures and experimentation, generation and reproduction of paper materials, personal nail treatments, and woodworking and metal shop procedures as well as in areas where chemicals may be utilized extensively (such as natatoriums, photographic material facilities, and hair salons). The potential impacts on the occupants in these spaces and the surrounding areas include skin irritations, nose/sinus irritations, objectionable odors, and damage to interior building construction materials and/or finishes. The effective local capture and exhaust for point sources of contaminants can significantly reduce the impact of these contaminants on the occupants in the area in which the contaminant is generated and surrounding occupied spaces.

To be effective, the exhaust system design needs to achieve the following:

- Capture the exhaust as close to the source as possible, and exhaust directly to the outdoors.
- Maintain the area in which these contaminants are generated at a negative pressure relative to the surrounding spaces to reduce the potential impact on occupants in adjacent spaces.
- Enclose and exhaust the areas where contaminants are generated.

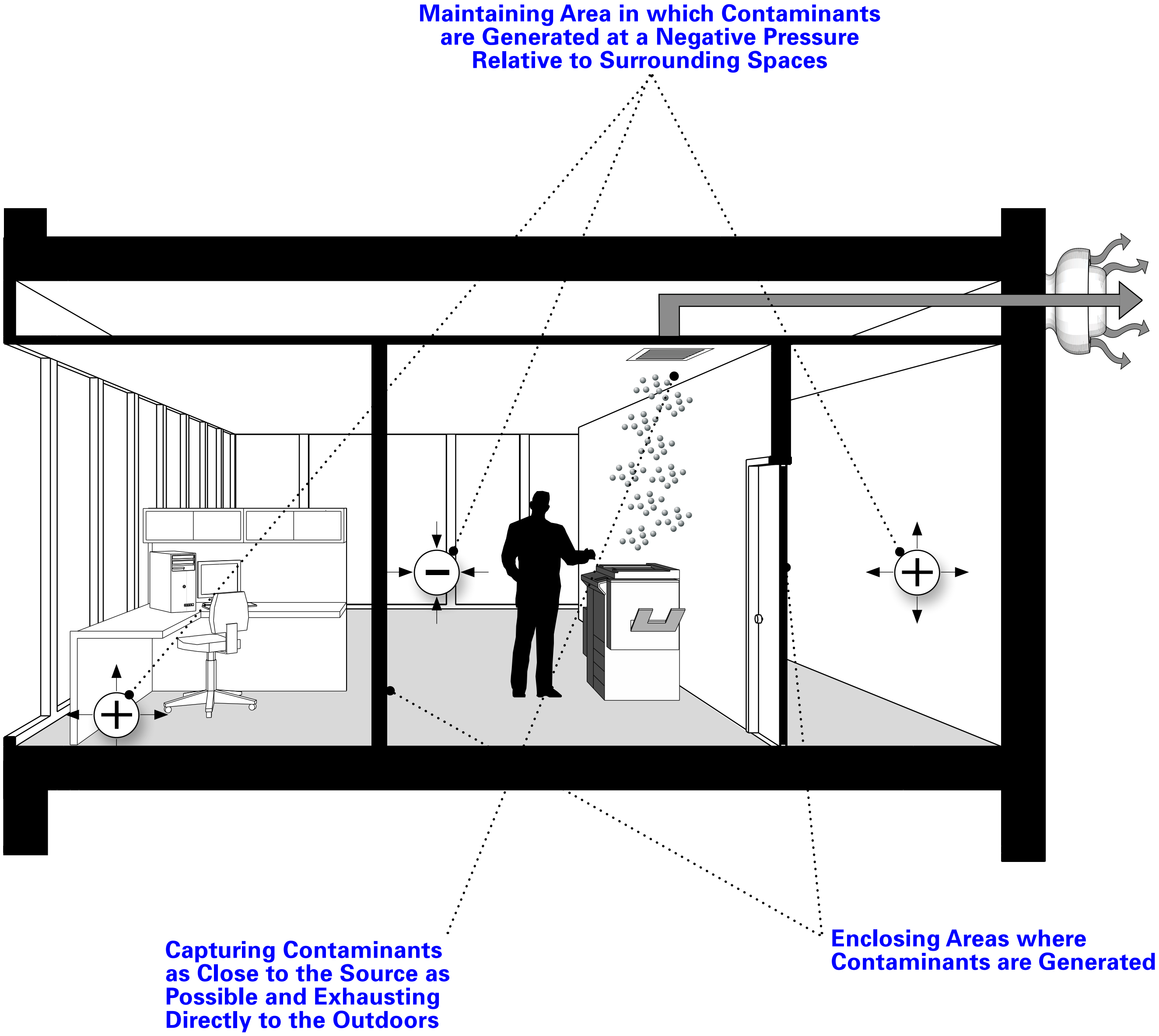
Capturing contaminants as close to the source as possible, as with an exhaust hood, significantly increases the capture rate of contaminants and reduces the exposure of occupants to these contaminants.

Exhausting directly to the outdoors removes the contaminants from the building. The location and height of the exhaust discharge outside the building is important to prevent re-entrainment of the contaminants into the building or surrounding buildings.

Maintaining the area in which these contaminants are generated at a negative pressure relative to the surrounding space reduces the potential migration of contaminated air into adjacent occupied spaces.

Enclosing the area where the contaminants are being exhausted assists in maintaining the space under negative pressure and also adds a physical barrier to the potential migration of contaminants to adjacent spaces.

The principles of capturing contaminants close to the source and exhausting to the outdoors, maintaining the area under negative pressure, and enclosing the area are part of a contaminant control system and are meant to be used in concert with one another and not as substitutes for each other.


Maintaining Area in which Contaminants are Generated at a Negative Pressure Relative to Surrounding Spaces
Capturing Contaminants as Close to the Source as Possible and Exhausting Directly to the Outdoors
Enclosing Areas where Contaminants are Generated

Next Page

Strategy 6.2

Lack of Exhaust—Indoor Swimming Pool

Figure 6.2-A Corridor to Indoor Swimming Pool

Photograph courtesy of H.E. Burroughs.

Figure 6.2-A shows a hotel facility in the southeastern United States. The photograph was taken from a corridor connecting the main hotel building to the remote pod where the indoor swimming pool is located. The swimming pool area is not provided with an exhaust fan, which results in several IAQ issues:

1. chemicals utilized for the pool treatment are not exhausted from the space,
2. the lack of exhaust in the space contributes to condensation on the fenestration in the space, and
3. the adjacent space (main hotel building) is impacted by the chemical contaminants and odors from the pool area, which are evident a substantial distance into the hotel building wing. Moisture from the pool is also likely to migrate into the hotel building. The migration of odors and/or moisture in this case study is encouraged by the main hotel building, and not the indoor swimming pool pod, operating under a negative pressure relative to surrounding spaces and the outdoor environment.

Reduce Contaminant Concentrations through Ventilation, Filtration, and Air Cleaning

Design for IAQ should focus first on reducing contaminant sources and then on capturing and exhausting contaminants close to their source. Remaining contaminants should be diluted with ventilation air or reduced by filtration and gas-phase air cleaning (FAC). Inadequate ventilation increases the likelihood of adverse health effects and IAQ complaints. Insufficient FAC allows outdoor contaminants to be brought into the building, indoor contaminants to be recirculated, and dirt to accumulate in air-handling systems.

- Minimum ventilation requirements are described in Strategy 7.1 – Provide Appropriate Outdoor Air Quantities for Each Room or Zone.
- Poor control of minimum outdoor air delivery can waste energy if the flow is too high and degrade IAQ if the flow is too low. Strategy 7.2 – Continuously Monitor and Control Outdoor Air Delivery describes options to ensure that design airflows are actually delivered.
- To dilute contaminants effectively, ventilation air must be delivered to the breathing zone. The effectiveness of different systems in achieving this varies considerably, and failure to account for this can result in significant underventilation. Strategy 7.3 – Effectively Distribute Ventilation Air to the Breathing Zone describes procedures to calculate air distribution effectiveness and the impact of differences in effectiveness on energy use and costs.
- The percentage of outdoor air required by a system that serves multiple spaces can be difficult to determine and, for VAV systems, varies over time. Failure to properly account for these factors can result in poor ventilation. Strategy 7.4 – Effectively Distribute Ventilation Air to Multiple Spaces describes proper design of such systems.
- FAC can remove a substantial fraction of contaminants from incoming outdoor air, reduce recirculation of indoor contaminants, and reduce accumulation of dirt in air-handling systems. Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives provides guidance on FAC selection.
- Occupant perception of IAQ is closely correlated to thermal comfort. Strategy 7.6 – Provide Comfort Conditions that Enhance Occupant Satisfaction addresses design for thermal comfort and integration of comfort and ventilation design.

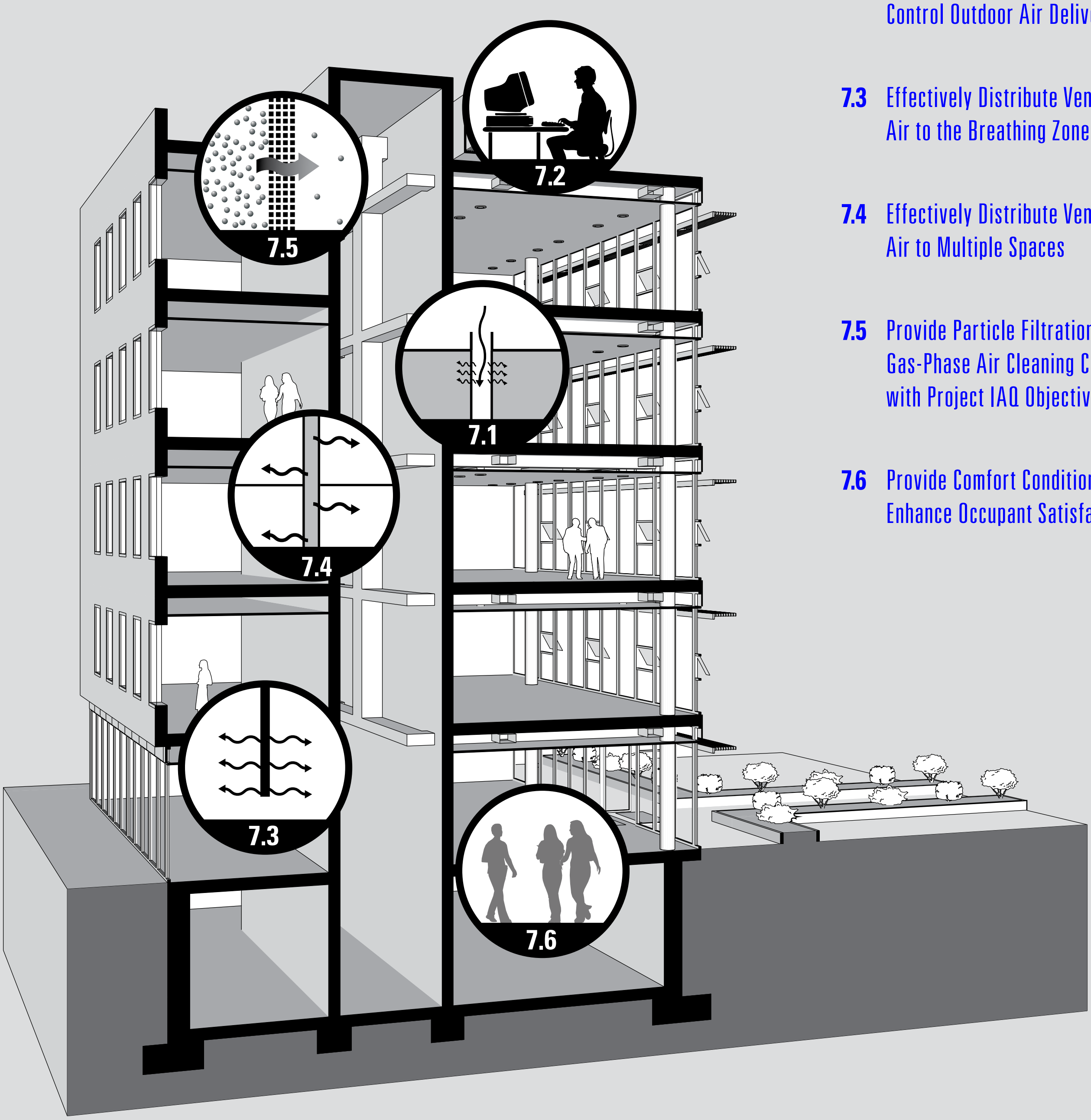
Decisions made very early in the design phase may limit the project team's ability to provide good ventilation and FAC. These issues are discussed in the following Strategies:

- Strategy 1.1 – Integrate Design Approach and Solutions
- Strategy 1.3 – Select HVAC Systems to Improve IAQ and Reduce the Energy Impacts of Ventilation
- Strategy 3.2 – Locate Outdoor Air Intakes to Minimize Introduction of Contaminants

Strategies to reduce ventilation energy use are discussed in Objective 8 – Apply More Advanced Ventilation Approaches.

Objective 7

Objective 7



7.1 Provide Appropriate Outdoor Air Quantities for Each Room or Zone

7.2 Continuously Monitor and Control Outdoor Air Delivery

7.3 Effectively Distribute Ventilation Air to the Breathing Zone

7.4 Effectively Distribute Ventilation Air to Multiple Spaces

7.5 Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives

7.6 Provide Comfort Conditions that Enhance Occupant Satisfaction

Provide Appropriate Outdoor Air Quantities for Each Room or Zone

Outdoor air has been provided to indoor spaces for centuries, but the nature of building ventilation changed with the advent of electricity and the ability to provide ventilation to buildings mechanically, without relying on natural drafts. Ventilation with outdoor air is required for all occupied spaces. Inadequate outdoor air ventilation rates can result in poor IAQ and the potential for adverse health effects and reduced productivity for occupants, along with increased occupant complaints.

The Ventilation Rate Procedure in ASHRAE Standard 62.1-2007 (ASHRAE 2007a), specifies minimum ventilation rates for the U.S. Local building codes usually reference or include these rates but may differ in various ways from the standard. If local codes require more ventilation than specified in the standard, the local code requirements must be met. After the designer determines the outdoor air required for each zone, the quantity of air for the ventilation system must be adjusted to account for air distribution effectiveness and air-handling system ventilation efficiency.

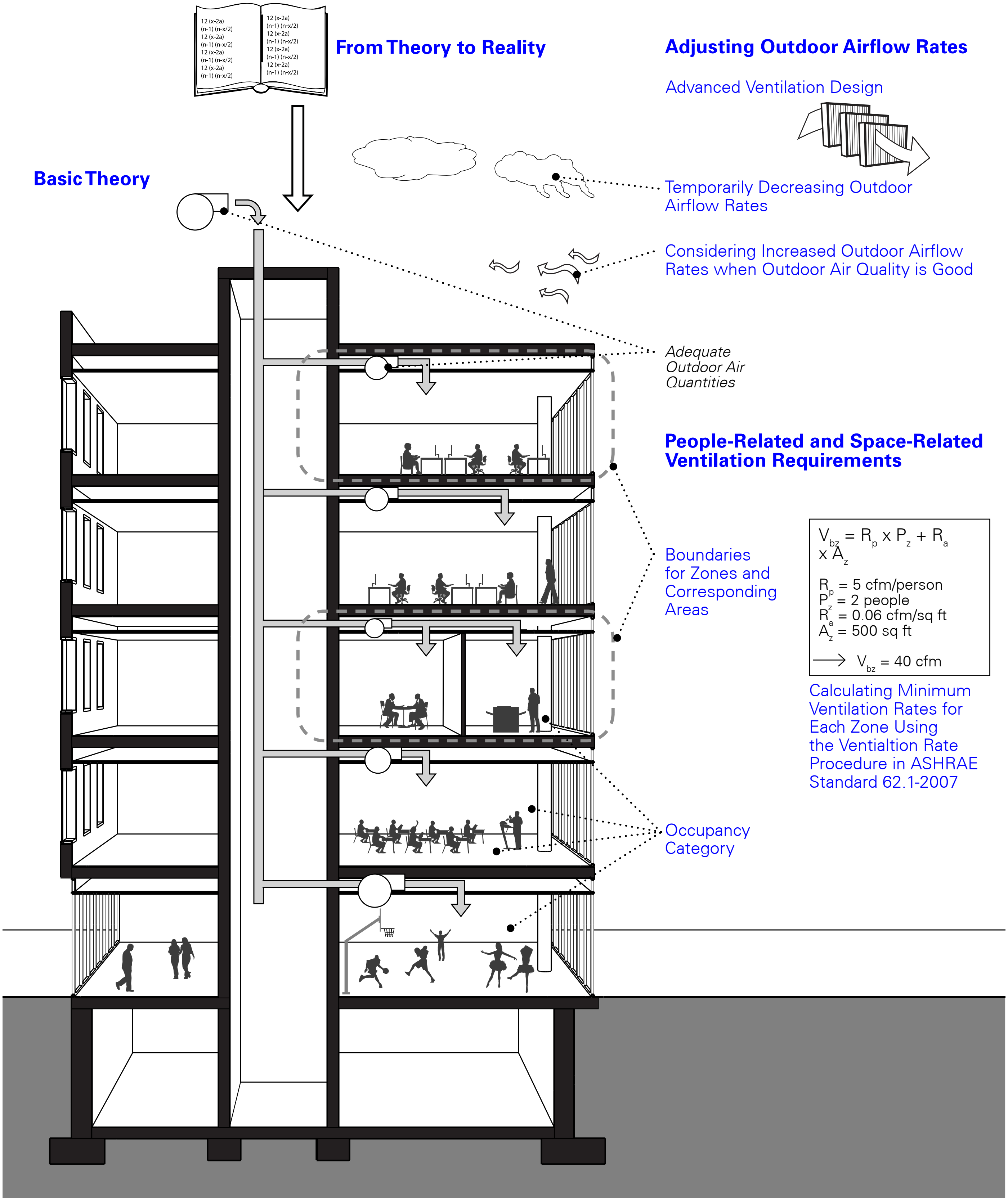
ASHRAE Standard 62.1-2007 specifies two distinct ventilation rate requirements. The first is a per-person requirement to dilute pollutant sources associated with human activity that are considered to be proportional to the number of occupants. The second is a per-unit-area requirement designed to dilute pollutants generated by building materials, furnishings, and other sources not associated with the number of occupants.

The ventilation rates are specific to the type of occupant activity. For example, the outdoor air ventilation rates for different parts of an office building may vary depending on the occupant activity in the zones. Differences in occupant activity requiring different ventilation rates are evident in the graphical guide to the detailed information in Part II.

During short-term episodes of poor outdoor air quality, ventilation can be temporarily decreased using a short-term conditions procedure from ASHRAE Standard 62.1-2007. Similarly, consideration may be given to increasing outdoor air ventilation rates beyond those required in the standard where the quality of the outdoor air is high and the energy consumed in conditioning it is not excessive.

Information related to providing adequate outdoor air ventilation is also discussed in Strategy 7.3 – Effectively Distribute Ventilation Air to the Breathing Zone, Strategy 7.4 – Effectively Distribute Ventilation Air to Multiple Spaces, and Strategy 8.5 – Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate.

Strategy 7.1



Basic Theory

From Theory to Reality

Adjusting Outdoor Airflow Rates

Advanced Ventilation Design

Temporarily Decreasing Outdoor Airflow Rates

Considering Increased Outdoor Airflow Rates when Outdoor Air Quality is Good

Adequate Outdoor Air Quantities

People-Related and Space-Related Ventilation Requirements

Boundaries for Zones and Corresponding Areas

$$V_{bz} = R_p \times P_z + R_a \times A_z$$

R_p = 5 cfm/person
P_z = 2 people
R_a = 0.06 cfm/sq ft
A_z = 500 sq ft

$\longrightarrow$ V_{bz} = 40 cfm

Calculating Minimum Ventilation Rates for Each Zone Using the Ventialtion Rate Procedure in ASHRAE Standard 62.1-2007

Occupancy Category

Strategy 7.1

Ventilation and Performance

Two recent studies have documented the associations between ventilation and student attendance and classroom performance. The first study (Shendell et al. 2004) documented the associations between classroom attendance in Washington and Idaho and CO_2 concentrations, which were used as a surrogate for ventilation rates. For classrooms where the difference between indoor and outdoor CO_2 concentrations exceeded 1000 ppm (1800 mg/m^3), student absences were 10%–20% higher than for classrooms where the difference in CO_2 was below 1000 ppm (1800 mg/m^3).

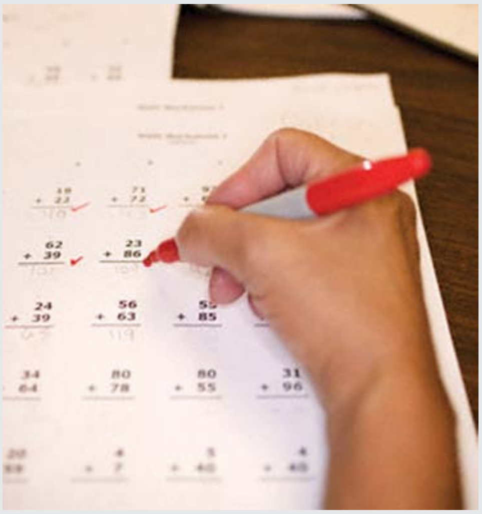


Figure 7.1-A Measuring Student Performance

A second study (Wargocki and Wyon 2006) examined academic performance in a controlled classroom situation in Denmark where ventilation and temperature were varied. The authors reported that "increasing the outdoor air supply rate and reducing moderately elevated classroom temperatures significantly improved the performance of many tasks (Figure 7.1-A), mainly in terms of how quickly each pupil worked (speed) but also for some tasks in terms of how many errors were committed (% errors, the percentage of responses that were errors). The improvement was statistically significant at the level of $P \leq 0.05$" (p. 26).

These and other studies, including those conducted in office environments, are summarized in the IAQ Scientific Findings Resource Bank (IAQ-SFRB) (http://eetd.lbl.gov/ied/sfrb/sfrb.html).

Continuously Monitor and Control Outdoor Air Delivery

Accurate monitoring and control of outdoor air intake at the air handler is important for providing the correct amount of outdoor airflow to a building. In particular, it has been a common practice for designers to use fixed minimum outdoor air dampers. However, this approach does not necessarily provide good control of outdoor air intake rates, particularly in VAV systems.

In most systems, it is difficult to accurately measure outdoor airflows at the outdoor air dampers during balancing, Cx, or operation. As a result, both overventilation and underventilation can commonly occur. Furthermore, in occupied buildings, overventilation is common since occupancy rates per floor area in most buildings are less than design values. It is estimated that the current amount of energy for ventilating U.S. buildings could be reduced by as much as 30% (first order estimate of savings potential) if the average minimum outdoor rate is reduced to meet the current standards (Fisk et al. 2005).

Accurate measurement of airflows in ducts also requires careful design, proper Cx, and ongoing verification. Under carefully controlled laboratory conditions, commercially available airflow sensors are very accurate. However, in most cases, laboratory conditions and accuracies cannot be replicated in the field; therefore, appropriate correction factors in the programming of the controls may be required.

Continuous monitoring of the outdoor rates at the air handler does not guarantee that the proper amount of ventilation is delivered locally within the building. Poor air mixing both in the ductwork and in the occupied space, especially in larger and more complex air distribution systems, can result in parts of a building receiving less than the design minimum amount of ventilation.

Measuring Outdoor Airflow

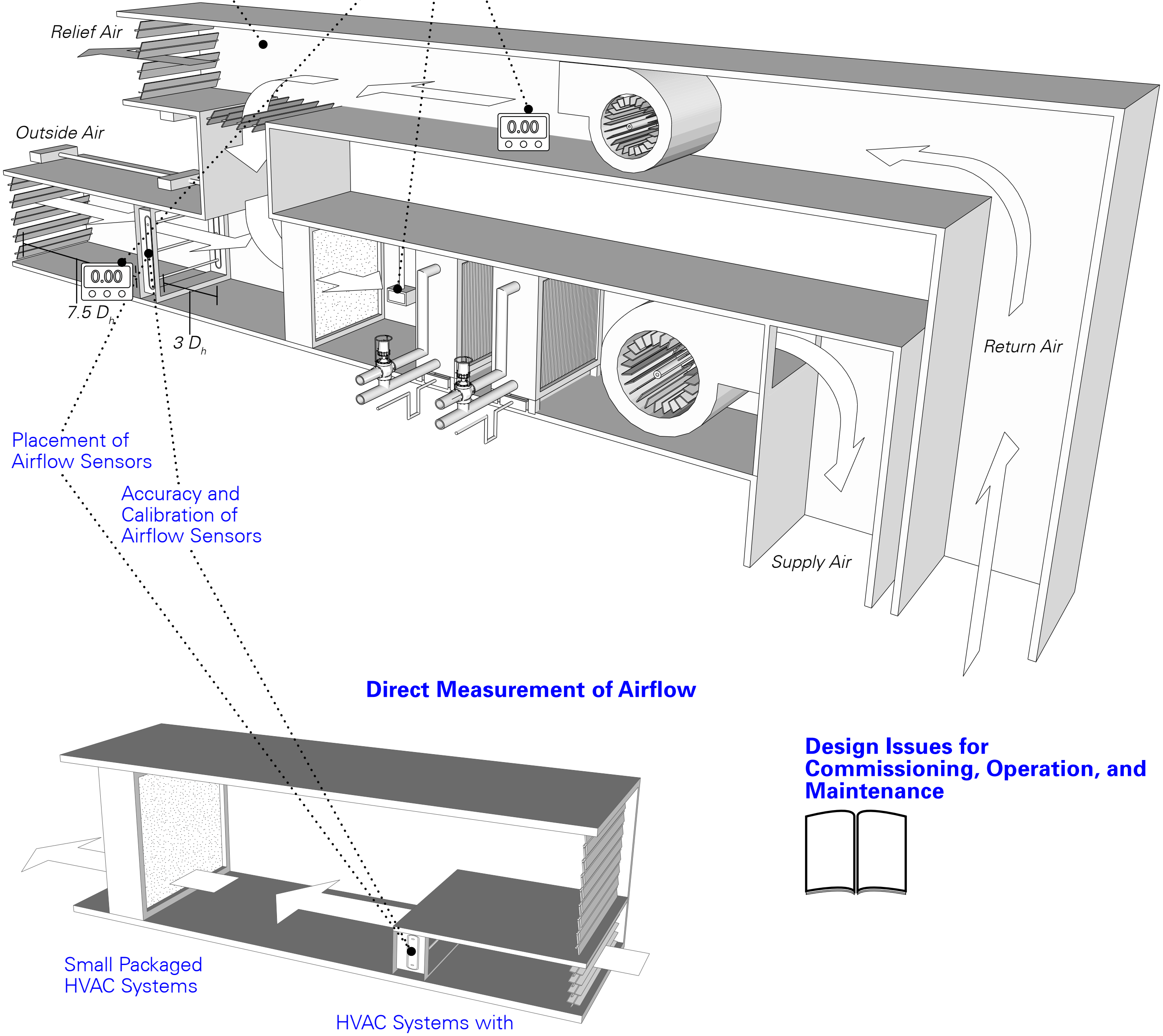
- *Straight Ducts.* Accurate airflow measurements require long, straight duct runs. This presents a challenge to the designer because space and architectural constraints often limit achieving sufficient straight duct lengths.

- *VAV Systems.* VAV systems with single outdoor air intakes need to be designed with modulating dampers and with airflow sensors appropriate for the expected airflow range. In VAV systems with airside economizers, a separate minimum outdoor air intake duct with airflow sensors and a dedicated outdoor air fan with speed control can help ensure accurate control and measurement of the outdoor airflow.

- *Small Packaged Systems*. Small packaged HVAC systems typically do not have continuous measurement of outdoor airflows. This suggests the need for even greater attention to confirmation of the delivery of design airflow rates through balancing, Cx, and periodic recommissioning. For small packaged HVAC systems, straight runs of ductwork in both the supply and return airstreams provide more accurate airflow measurements. Assuming that there is no exhaust (or relief) in the HVAC system, outdoor airflows can then be estimated by subtracting the return airflow rate from the supply airflow rate. Caution needs to be exercised when taking the difference between supply and return airflow measurements in small packaged HVAC systems without sufficient straight ductwork for the supply and return airstreams; such measurements may not meet reasonable accuracy requirements due to cumulative errors in airflow measurement, especially when the outdoor airflow rate is small relative to supply and return airflow rates. If practical, adding ductwork onto the unit's outdoor air intake allows for a traverse of outdoor air.

- *Placement of Sensors.* In general, the best accuracies can be expected when sensors are placed within the manufacturer's guidelines and field-verified for optimum performance. Some research has shown that accuracies of certain measurement technologies may be improved when installed in the following

Strategy 7.2



Indirect Methods of Measuring Minimum OA

Straight Ducts

Plenum Pressure Control

The CO_2 or Temperature Method

Placement of Airflow Sensors

Accuracy and Calibration of Airflow Sensors

Direct Measurement of Airflow

Design Issues for Commissioning, Operation, and Maintenance

Small Packaged HVAC Systems

HVAC Systems with Economizers

locations: a) between the fixed louver blades where the air speeds are more uniform compared to air speeds downstream of the louvers or b) at the outlet face of the louvers (Fisk et al. 2008). Limited research has shown that in some applications, installation of airflow or pressure sensors downstream of the louvers and upstream of the dampers in combination with an airflow straightening device between the louvers and the airflow or pressure sensors may result in inaccurate airflow measurements (Fisk et al. 2008). Regardless of whether or not airflow sensors are factory or field installed, accuracies of these sensors need to be verified with appropriately calibrated equipment at start-up and during occupancy on regular time intervals.

Indirect Measurement Methods

Direct measurement methods for measuring outdoor airflow rates are considered to be substantially more accurate than indirect methods. Indirect methods for measuring outdoor airflow rates include plenum pressure control, CO_2 concentration balance, CO_2 mass balance, supply/return differential calculation, variable-frequency-drive-controlled fan slaving, adiabatic proration formulae, and fixed minimum position intake dampers.

Design Issues for Commissioning and O&M

The designer needs to make provisions for measurement and verification of the minimum outdoor airflows during the initial Cx as well during the ongoing Cx of a building. Such provisions include easy access to the airflow sensors, hardware and software that can detect sensor (e.g., airflow) and equipment (damper motor) malfunctions, etc. In addition, the design criteria and occupancy assumptions need to be listed in a clear format in the O&M manual so that one can evaluate the continued relevance of design outdoor airflow rates. The building maintenance staff needs to be informed of the need to adjust the minimum amount of outdoor air as space use and occupancy change.

Next Page

Strategy 7.2

Minimum Injection Fan in One of Several Large HVAC Built-Up Systems Serving a New Office Building

In order to ensure that the minimum outdoor airflow is provided when the economizer (i.e., 100% outdoor air) is not on, the minimum outdoor air fan in this system is designed to operate when the main outdoor air dampers are closed (Figure 7.2-A). The economizer does not operate when the outdoor air temperature exceeds the return air temperature. A number of identical systems are serving this five-story office building with underfloor air supply in four of the five floors.

Figure 7.2-A Minimum Outdoor Air Fan and Main Outdoor Air Dampers of a Build-Up HVAC System

Photograph courtesy of Leon Alevantis.

Apply More Advanced Ventilation Approaches

Conditioning and transporting ventilation air accounts for a significant fraction of building energy use. The Strategies presented in this Objective can help reduce the energy required to deliver good IAQ.

- Strategy 8.1 – Use Dedicated Outdoor Air Systems Where Appropriate covers systems that condition 100% outdoor air and deliver it directly to occupied spaces or to other heating/cooling units that serve those spaces. DOASs can make it easier to verify that the required amount of outdoor air is delivered and can reduce the total outdoor air required relative to other systems. DOASs can easily be combined with energy recovery or DCV to further reduce energy use.
- Energy recovery ventilation reduces energy use by transferring energy from the exhaust airstream to the outdoor airstream. Strategy 8.2 – Use Energy Recovery Ventilation Where Appropriate explains when energy recovery ventilation is required by energy standards and when it can have favorable economics even though not required as well as how it can improve humidity control and reduce the risk of mold growth.
- DCV varies ventilation airflow based on measures of the number of occupants present. It can be particularly cost-effective for spaces with intermittent or highly variable occupancy. Strategy 8.3 – Use Demand-Controlled Ventilation Where Appropriate describes DCV design concepts and considerations.
- Natural ventilation can be a low-energy strategy that provides a pleasant environment in mild climates with good outdoor air quality. Mixed-mode ventilation can provide similar benefits in additional climates through the limited use of mechanical equipment. Meeting ventilation requirements with natural or mixed-mode ventilation is a new challenge that requires careful design, as described in Strategy 8.4 – Use Natural or Mixed-Mode Ventilation Where Appropriate.
- Strategy 8.5 – Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate describes an alternative to the Ventilation Rate Procedure that can be used to comply with ASHRAE Standard 62.1 (ASHRAE 2007a), using lower outdoor airflow rates or to provide enhanced IAQ with the same rates. The IAQ Procedure can be cost-effective in applications requiring large volumes of ventilation air in climates where the cost to condition outdoor air is high.

Before considering these approaches, it is important to understand the basic issues described in Objective 7 – Reduce Contaminant Concentrations through Ventilation, Filtration, and Air Cleaning.

Objective 8

Objective 8

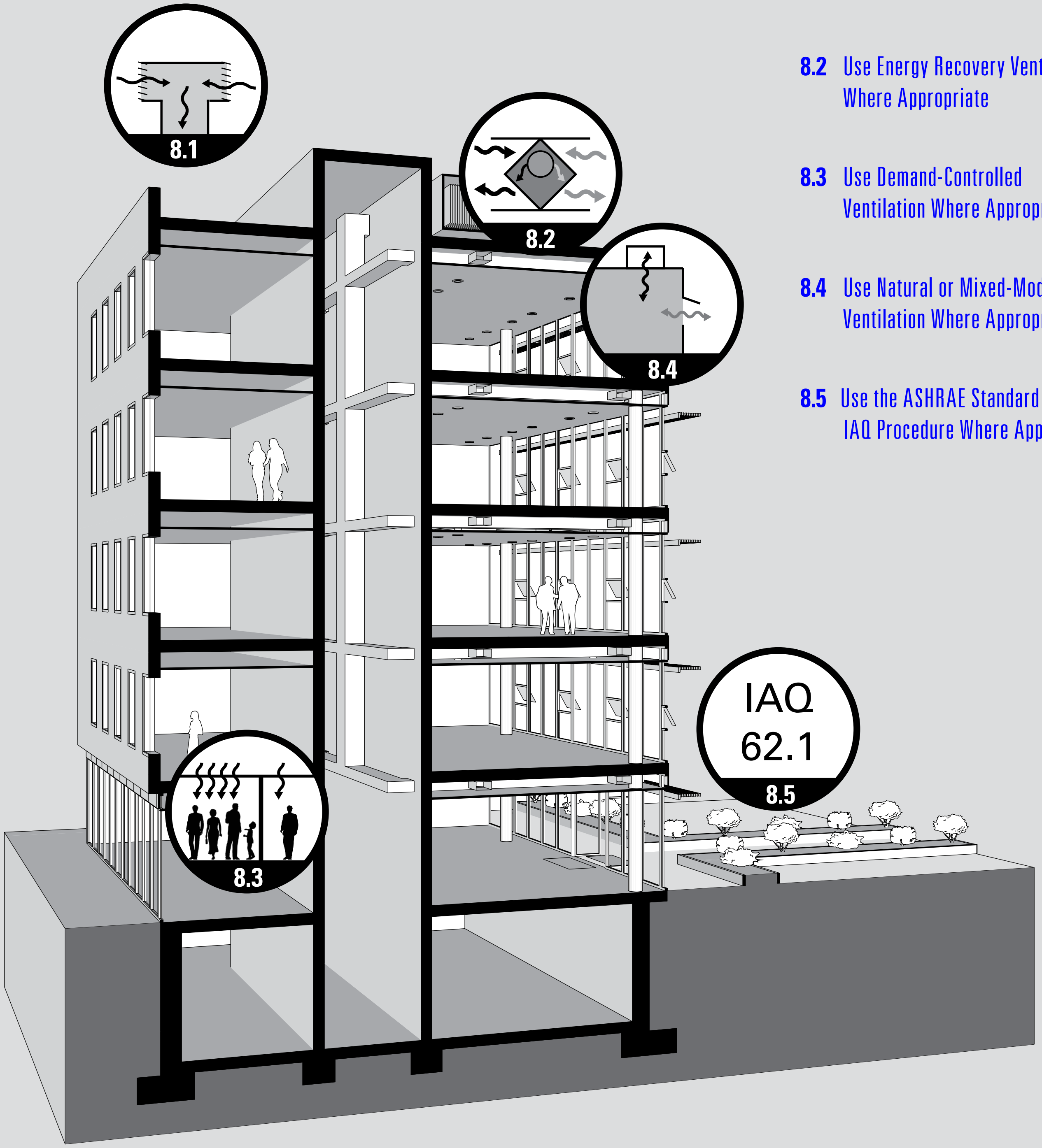
8.1 Use Dedicated Outdoor Air Systems Where Appropriate

8.2 Use Energy Recovery Ventilation Where Appropriate

8.3 Use Demand-Controlled Ventilation Where Appropriate

8.4 Use Natural or Mixed-Mode Ventilation Where Appropriate

8.5 Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate



Use Dedicated Outdoor Air Systems Where Appropriate

All DOASs are 100% outdoor air systems. The DOAS approach makes calculating the required outdoor ventilation airflow more straightforward than for multiple-space systems. Having the ventilation system decoupled from the heating and air-conditioning system can provide many advantages for HVAC system design. A disadvantage may be that there is an additional item of equipment, the DOAS unit itself.

DOASs must address latent loads, the largest being the latent load from the outdoor air in some cases. The DOAS may also be designed to remove the latent load from both the outdoor air and the building (total latent load), in which case there are multiple advantages.

If the exhaust airstream is located close to the ventilation airstream, both sensible and latent energy can be recovered in the DOAS. This feature makes DOASs much more energy efficient. It is not necessary that the exhaust and supply airflows be exactly the same rate, but if they differ the difference must be accounted for in the equipment sizing calculations.

DOAS Component Combinations

A DOAS is made up of a site-appropriate selection of components and can be built-up or manufactured. In most areas of the country, cooling coils (CCs) are required to cool and dehumidify the air. In some areas, heating coils may be required.

Integration of energy recovery technology can reduce the load on the heating and cooling coils. Energy recovery components can be either total (enthalpy) energy recovery or sensible energy recovery. See Strategy 8.2 – Use Energy Recovery Ventilation Where Appropriate.

Because of the latent load of outdoor air, in many areas use of an active desiccant wheel (AdesW) or a passive dehumidification component (PDHC) may be cost justified. These devices assist in managing humidity within the building. The rationale for humidity control is presented in Strategy 2.4 – Control Indoor Humidity.

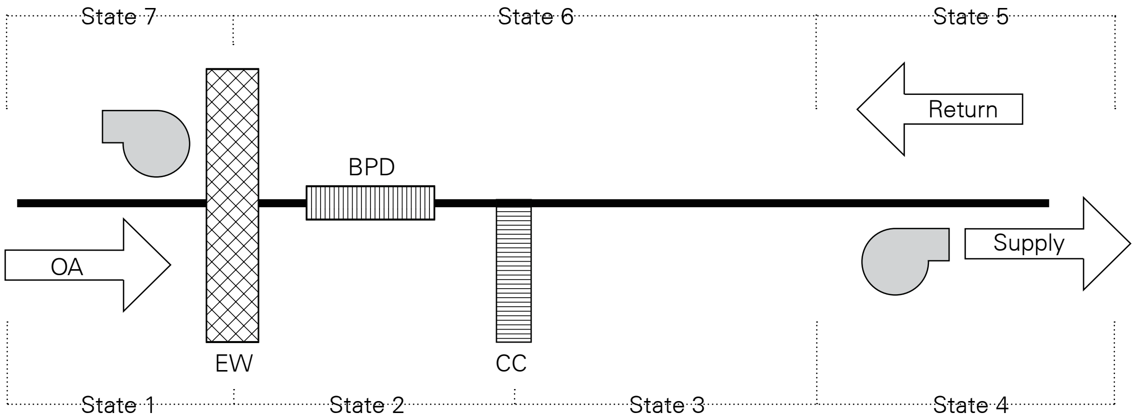
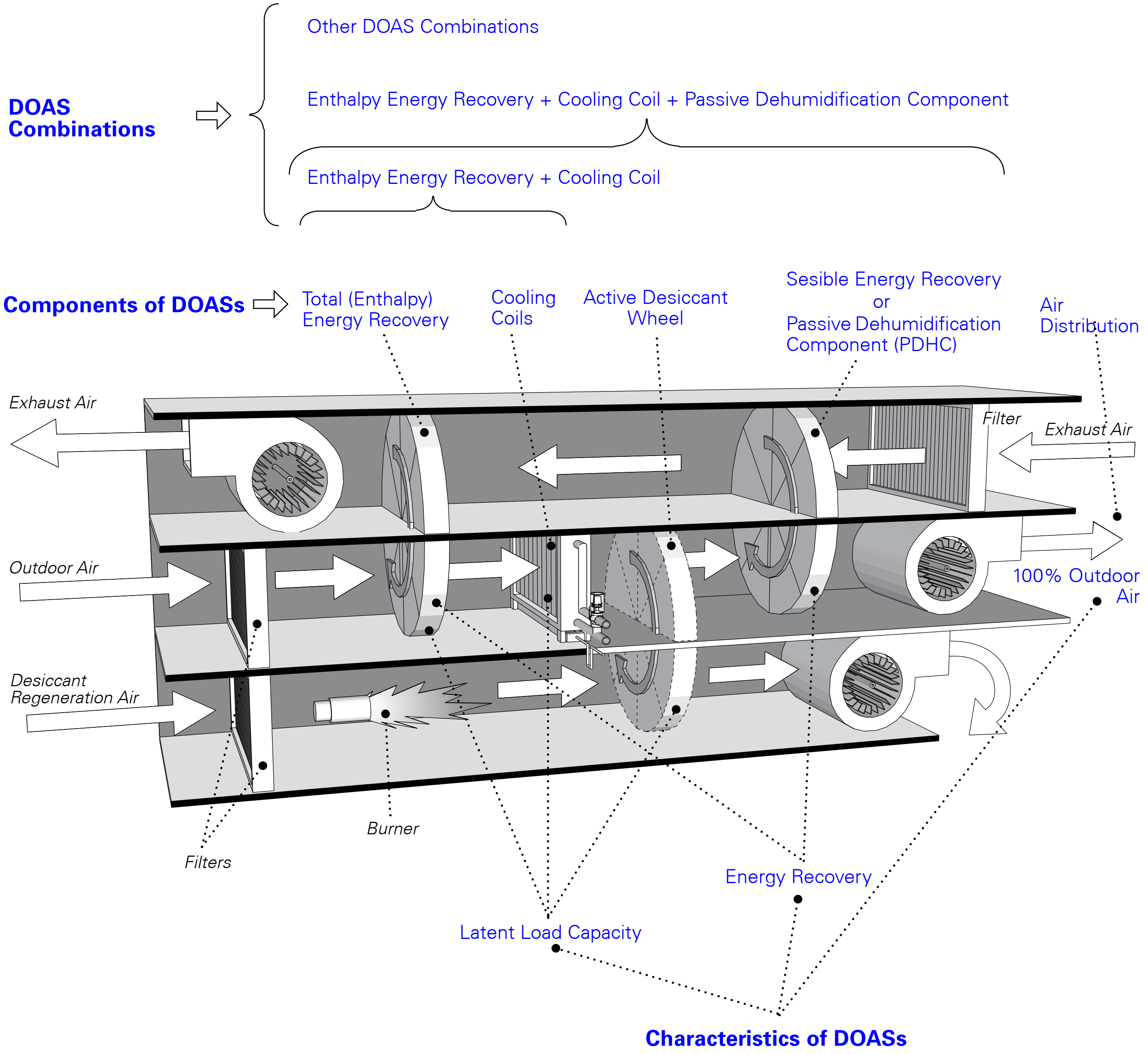


Figure 8.1-A Example of DOAS with enthalpy wheel (EW) and CC


DOAS Combinations
Other DOAS Combinations
Enthalpy Energy Recovery + Cooling Coil + Passive Dehumidification Component
Enthalpy Energy Recovery + Cooling Coil
Components of DOASs
Total (Enthalpy) Energy Recovery
Cooling Coils
Active Desiccant Wheel
Sesible Energy Recovery or Passive Dehumidification Component (PDHC)
Air Distribution
Exhaust Air
Filter
Exhaust Air
Outdoor Air
100% Outdoor Air
Desiccant Regeneration Air
Burner
Filters
Energy Recovery
Latent Load Capacity
Characteristics of DOASs

Strategy 8.1

After the air is conditioned by the DOAS, it must still to be delivered to the space. The design must specify how the air is to be delivered and how it is to interact with other heating and cooling equipment located in the spaces.

- *Enthalpy Energy Recovery + Cooling Coil.* A straightforward and efficient DOAS can be constructed with a CC and an enthalpy air-to-air energy recovery device when the exhaust airstream is available for energy recovery (see Figure 8.1-A).
- *Enthalpy Energy Recovery + Cooling Coil + Passive Dehumidification Component.* Another efficient DOAS can be constructed using a CC, passive dehumidification, and enthalpy energy recovery. This system also requires that an exhaust airstream be available (see Figure 8.1-B).
- *Other DOAS Combinations.* There are many other combinations of components that are appropriate for differing applications. What is site appropriate depends on local climate, availability of waste heat to regenerate desiccants, and many other factors.

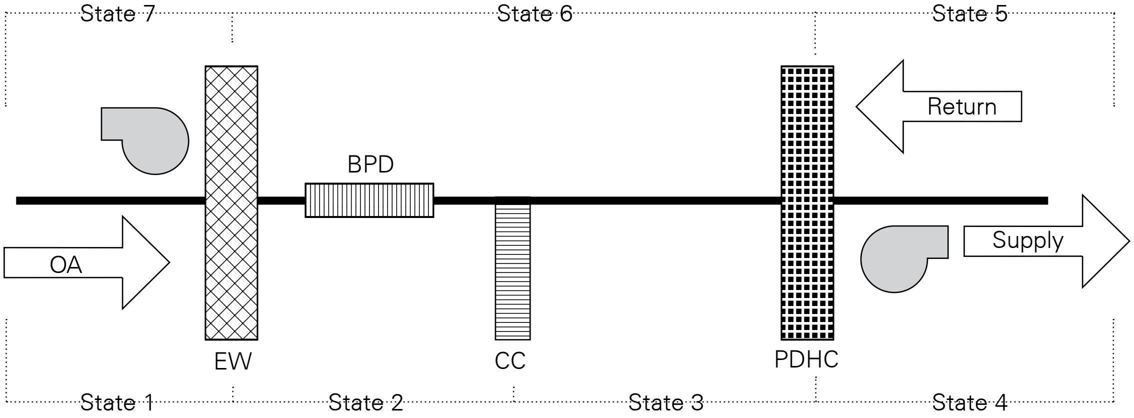


Figure 8.1-B Example of DOAS with EW, CC, and PDHC

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Strategy 8.1

Junior High School in Pennsylvania with DOAS

Figure 8.1-C Junior High School in Pennsylvania (Roof-Mounted DX DOAS Visible)

Photograph copyright McClure Company.

The Halifax Elementary School (Figure 8.1-C) is a 53,450 ft^2 (4,946 m^3) building in Central Pennsylvania. The original facility contained a traditional two-pipe unit ventilator heating and air-conditioning system. Due to storm water control problems and the inability of the HVAC systems to properly dehumidify the facility, the school experienced excessively high relative humidity conditions.

In 2006 the building HVAC and electrical systems were upgraded. Packaged gas-electric rooftop units with enthalpy heat recovery wheels were installed to provide dedicated outdoor ventilation air to the classrooms. The unit ventilators were removed and replaced with two-pipe fan-coil units, which are decoupled from the outdoor ventilation air. The unit ventilator outdoor air intakes were tightly covered with insulated panels. The fan-coil units satisfy individual room heating and sensible cooling requirements. Decoupling the DX DOAS from the two-pipe fan-coil system greatly simplified the semi-annual changeover between hot and chilled water distribution.

The HVAC upgrades were implemented at a cost of \$15.50/ft^2 (\$164/m^2). Facility energy use was reduced from 105 kBtu/ft^2 (1190 MJ/m^2) before the project to 97 kBtu/ft^2 (1100 MJ/m^2) after the project was completed. Sixty-five percent of these energy savings are associated with the HVAC portion of the project, while the remainder is due to lighting system upgrades. The facility no longer experiences excessive relative humidity.

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PART II—Detailed Guidance

Detailed Information for Design, Construction, and Commissioning for IAQ

Part II provides detailed guidance for use in design, construction management, and commissioning. The Part II detailed guidance is included along with the Part I summary guidance in the electronic version of this Guide.

For information on how to use the interactive links in this Guide, see the section “How this Guide is Organized” in the Introduction in Part I.

Strategy 1.1

Integrate Design Approach and Solutions

Introduction

Building design professionals understand that the design of virtually every building element affects the performance of others, so it makes sense to integrate various design elements of a building. Unfortunately, the prevailing design process of our time is such that we tend to create design elements in a compartmentalized and linear process rather than jointly designing these elements in an interactive process. Figure 1.1-D depicts this traditional design process.

In the traditional process, design elements are compartmentalized such that different design professionals work in relative isolation from one another. During conceptual design, assumptions may be made about how certain design elements will be handled without fully exploring other possibilities. The assumptions may be implicit in the sense that early decisions are made based on programmatic requirements for space allocation resulting in the basic shape, orientation, massing, and location on site; these decisions are also strongly based on considerations of aesthetics and presentation without fully exploring the implications for ventilation, illumination, noise, thermal control, energy, or IAQ. Many options for handling these issues are inadvertently eliminated in this process, thus requiring in some cases that involved design professionals "force fit" (or one could even say "retrofit") their design solutions onto a suboptimal design structure.

Traditional

Hierarchical Organization
Owner - Architect - Engineer
Transactional Design Process
Boundaries / Boxes
Percentage Based Fees

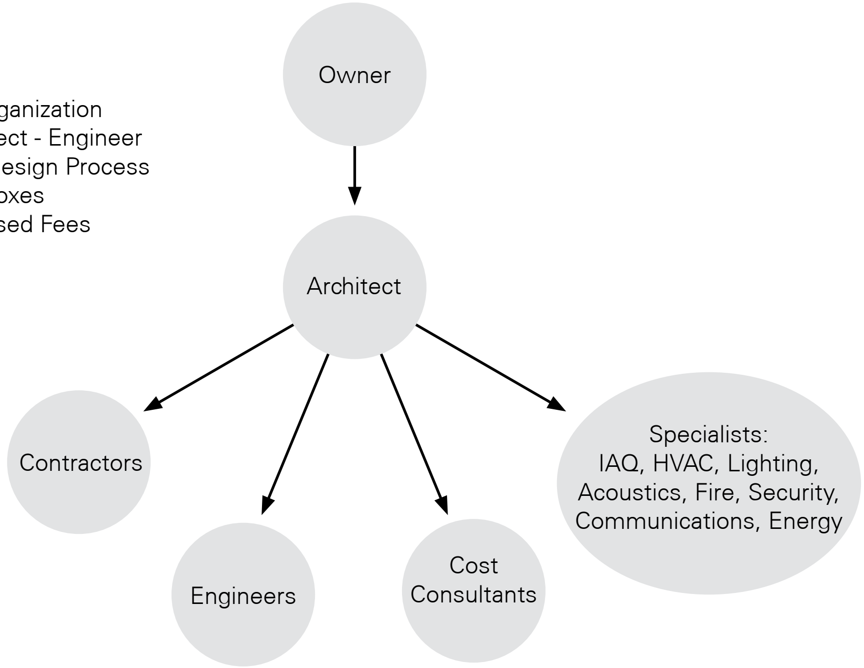

Figure 1.1-D Traditional Design Team

An alternative to this is the "integrated design process" represented by Figure 1.1-E. Such a process is intended to take full advantage of the symbiotic nature of design so that the design elements work to reinforce each other and thereby maximize the ability of the overall building design to fulfill its design objectives effectively and with greater efficiency and also lower capital and operating costs. Conceptually, it does this by matching, as much as possible, the design process (interactive, mutual consideration of design

Strategy 1.1

Integrated

Holistic Thinking
Team Based
Organic design Process
Larger Inclusive Team
Users, Operators, Code
Innovations Encouraged by Client

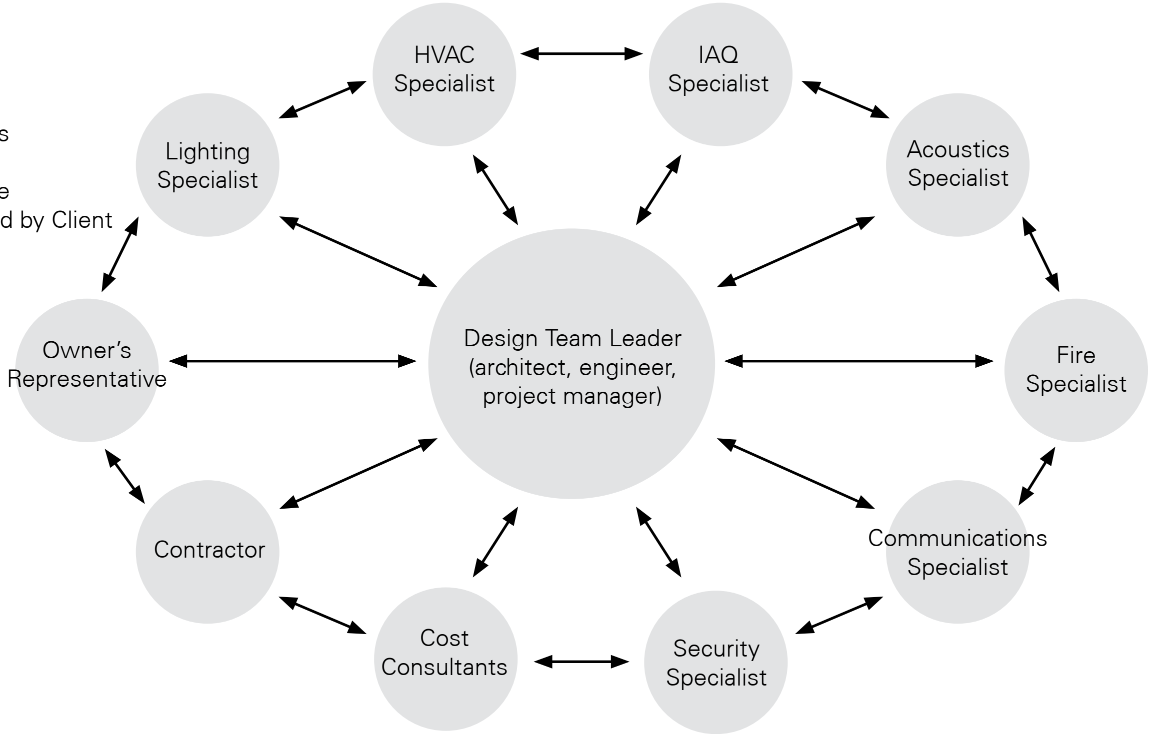

Figure 1.1-B Integrated Design Team

elements during each design phase) to the physical reality of design (the design of virtually every building element affects the performance of other building elements).

Current Trends call for Integrated Design
Up to the 1900s (prior to the advent of building specialists), architects and master builders were trained engineers and their designs incorporated both architectural notions as well as engineering fundamentals—e.g., Roman baths with in-floor heating, St. Paul Cathedral with its thermal mass/volume assisting the building's natural/forced ventilation systems[1]

After World War II and the advent of central air conditioning and sealed buildings, using natural forces such as thermal mass, daylighting, and natural ventilation was often seen by designers and owners as an archaic design solution. Today, with the worldwide movement toward buildings that employ "green" strategies, architects and engineers, mostly in Europe, are using advanced techniques, including computer simulation and modeling, to assist in developing optimal and often simpler designs in which each element is designed with full consideration of other elements so that the elements are mutually reinforcing. The designs are therefore often less complex, more energy efficient, easier to maintain, and more accommodating to occupants. The primary difference between present-day conventional design and this emerging approach is in the design process. All members of the design team are required to work within an integrated framework, thinking about all design decisions within the context of occupant and building safety, thermal comfort, IAQ, and the impact of the design decision upon the environment. This team should include all of the specialists: those in IAQ, lighting, acoustics, fire, security, communications, and energy, among others. Indeed, the more

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[1] Reyner Banham documented this evolution nicely in his book, *The Architecture of the Well-tempered Environment* (1984), and Richard Rush, former senior editor of the now defunct journal *Progressive Architecture*, edited a book on integrated design in early 1990s titled *The Building Systems Integration Handbook* (1991).

efficient design solutions require such a process. A key example is the use of natural and/or displacement ventilation where thermal solar gains and thermal losses have to be minimized.

Indoor Environmental Quality is Best Served by Integrated Design
As suggested by the Table of Contents of this Guide, the forces that combine to produce good or poor IAQ touch on almost all of the design elements of a building that fall within the purview of a wide range of design team members. Integration of the design is therefore particularly important for achieving good IAQ. For example, it is impossible to separate the design solutions that address ventilation and those that address climate, weather, and outdoor air quality. They are too closely connected. For example:

- Thermal conditions indoors affect the quality of the indoor air, and ventilation with outdoor air almost always impacts indoor thermal conditions.
- The building envelope will strongly affect the thermal performance of the building and local thermal comfort for those who are near exterior walls, windows, or doors.
- Cold exterior wall surfaces not only affect occupants but also affect the potential for condensation and problems related to moisture and mold on or in the walls.
- Warm or hot exterior walls can result in significantly elevated emission rates for chemicals such as formaldehyde that might be components of insulation or composite wood products in the walls.
- Illumination through exterior windows can provide lighting and higher perceived occupant comfort and well being at no cost but can also be accompanied by thermal gains or losses that need to be addressed by thermal conditioning or by passive or active control, such as glass coatings, or by manual or automatic shading devices.
- Electrical lighting is always accompanied by some heat gain, which is usually not the best way to provide thermal conditioning of the occupied space in the winter; in a cooling dominated or mixed climate, the heat gain from electrical illumination sources creates an added and often unnecessary cooling load and accompanying energy penalty.

Many more examples can be cited regarding the interactions between ventilation, indoor and outdoor air quality, thermal conditions, climate, weather, illumination, and acoustics. They demonstrate that it is simply impossible to achieve an energy-efficient, comfortable, and healthy building without addressing all these issues in concert. Addressing them separately is often fraught with conflicting or counter-productive solutions. Addressing them as an integrated design team is the most effective way to optimize the economic and environmental performance of the completed building.

Capturing the Synergy of Integrated Design Solutions

The researchers who prepared the section on buildings' potential role in the mitigation of greenhouse gas emissions for the Nobel-Prize-winning 2007 Intergovernmental Panel on Climate Change (IPCC) report on global climate change identified the potential for large reductions in greenhouse gas emissions through the synergy of implementing various energy-use reduction measures in concert rather than in isolation.

Nearly 80% of the potential reductions identified by the researchers can be made at a cost saving (or negative cost) to the owner. Many of the potential savings are related to ventilation, thermal conditioning, and illumination of buildings, thus demonstrating the cost-saving potential for integrated design solutions.

Adapted from Levine and Ürge-Vorsatz (2007).

Examples of Integrated Design Solutions
The following three examples of integrated design solutions serve to highlight the concepts and benefits of integrated design for indoor environmental quality.

Integration of Envelope, Illumination, and Mechanical Design
By controlling heat gain through the building envelope while also using windows to increase the use of daylight for illumination, the equipment and energy required for electrical illumination and mechanical cooling can be reduced. This produces direct energy savings by reducing the amount of energy used for

illumination and also by reducing the amount of energy needed for the additional cooling load created by the waste heat emitted by electrical illumination sources. In locations where cooling loads dominate, the savings can be significant.

Use of shading to prevent unwanted insolation and the associated heat gain and glare will increase the potential for the effective use of daylight illumination without heat gain. Thus, the amount of HVAC system capacity can be reduced and the resulting operating costs will also be less.

On south facades, horizontal exterior shading will prevent the entry of daylight when the sun is relatively high in the sky. The horizontal projection of the shading can be determined by the latitude and the desirability of direct insolation during certain parts of the year.

On east and west facades, the use of vertical shading can allow reflected light to penetrate and enhance daylight illumination while preventing direct solar penetration that generally results in glare, thermal discomfort, and unwanted heat gain. Ideally, the vertical shading should be adjustable since the angle of the sun changes quite significantly over the course of the year. In the weeks around the summer solstice, it is at its northern-most latitudes, and in the winter it is at its southern-most latitudes. The difference in the angle of incidence on east and west facades can be 45° or more, depending on the latitude.

The use of "light shelves" results in deeper penetration and more effective distribution of daylight while providing shading to prevent direct insolation and unwanted heat gain, especially through south-facing glass.

Thus, by coordinating the selection of glazing, exterior shading, illumination, and mechanical heating and cooling, considerable benefits can be obtained. Analysis of the trade-offs by lighting and mechanical design team members can indicate the most cost-effective and environmentally beneficial strategy.

Integration of Interior Architecture with Illumination, Air Quality, and Thermal Control Strategies

Ceiling height and type, air quality, thermal control, and daylighting are mutually connected. As ceilings get higher from the floor, daylight penetrates deeper into a space. By raising the top of the window along with the height of the ceiling, daylighting strategies can be optimized. Properly shaded windows admit light but control unwanted solar heat gain. Further, the properly shaded daylight reduces unwanted heat gains as well as energy use from electric illumination sources.

Higher ceilings increase the potential for thermal and air pollutant stratification; the higher the ceiling, the greater the potential benefit. Warm air naturally rises, and emissions from human metabolism can be carried up into the upper portion of the space while they are replaced by cooler, cleaner air in the occupant breathing zone. Occupants will be more comfortable and typically experience cleaner air as a result.

While the additional ceiling height may increase the overall height of the building and the associated costs, use of exposed ductwork and elimination of the suspended ceilings can offset much or all of those costs. The longer lag time associated with a higher ceiling and thermal stratification permits the use of smaller equipment to respond to rapid increases in demand for thermal conditioning or ventilation air.

Use of Hybrid Ventilation, Occupant Control, and Daylight

There is scientific evidence of the benefits of giving occupants control over the indoor environment (Wyon 1996; Zweers 1992). These benefits include improved perception of the quality of the indoor environment, lower building-related symptom prevalence, and improved task performance. Among the means for occupant control are operable windows, personal fans, control of lighting, and control of thermal conditions.

But provisions for occupant control require coordination among design team members. Integration of the process by assessing the total environmental impacts yields the maximum benefits at the lowest costs.

- Operable windows can provide ventilation and thermal conditioning in many climates over much of the year, thus reducing the demands for mechanical ventilation or thermal conditioning—air conditioning or heating. Systems can be sized smaller and used less often, saving both first costs and operating costs.
- However, natural ventilation through operable windows must be planned carefully and provide for some path for exhaust air to relieve the air entering through windows or to actually draw the air into the building by creating a negative pressure in the occupied areas relative to the outdoors. This is often accomplished by taking advantage of the stack effect (the natural tendency of warm air to rise) through multifloor atria, towers, or chimneys.
- Small, simple buildings and very tall, sophisticated buildings have been successfully ventilated using the stack effect to drive natural ventilation. Very high air exchange rates can be achieved without the use of mechanical fans. But careful and integrated planning is essential.
- Ventilation aimed at supplying only what is needed when and where it is needed is much like a lighting system that only operates when people are present and require the illumination and where daylight is not sufficient for the activities being conducted. Sensors that detect the presence of occupants are effective in controlling electrical illumination or in modulating daylight entry and also in controlling ventilation and thermal conditioning systems. Thus, when the ventilation and illumination design team members collaborate, there are even larger savings than when they work in isolation.
- Occupants of naturally ventilated buildings have been shown to tolerate or accept a wider range of thermal conditions. Enhancing the cooling effect of air movement by the addition of personal fans (e.g., 4 or 6 in. [100 or 150 mm] diameter desktop fans with two or three speeds) can allow for warmer operating temperatures, thus reducing the demand on mechanical system capacity for cooling in warmer weather conditions.
- In most parts of the U.S. and Europe, during a very large number of hours in the course of the year, outdoor air is cooler than indoor air and can be used beneficially to provide a more comfortable indoor environment.
- The use of natural ventilation must be coordinated with IAQ and acoustic considerations. Noisy outdoor conditions or poor outdoor air quality present problems for natural ventilation and must be addressed in a comprehensive way. An integrated approach involving hybrid ventilation design can respond to the temporal variations in weather and outdoor air quality as well as noise.

Leadership and Communication with Integrated Design

The integrated design concept calls for integration of design elements. This cannot be done successfully in a compartmentalized design process. An integrated design process requires a substantial commitment to the interactive process, with periodic meetings among relevant design team members to jointly design symbiotic design elements.

The lead designer (architect or other manager of the design and construction processes) needs to orchestrate the direct interactions of the various design team members, which will include, for example, general architecture, HVAC, lighting, electrical, interior design, and landscape design. While it may not always be obvious how these diverse professional disciplines affect each other or how their collective considerations and decisions impact IAQ, the integrated design process needs to ensure good communications and coordination. It is a process with a fundamental expectation that design team members will interact and coordinate their designs. In addition, the commissioning authority (CxA) and those writing specifications and leading value engineering analyses and decision making all impact the building design and operational features and also need to be interactively integrated.

Strategy 1.1

The Importance of the Conceptual Design Phase

Laying the Groundwork for an Interactive Process

An effective way to accomplish a well-integrated design is to start the project design with a gathering of all the important design team members to discuss potential solutions and the advantages and disadvantages of each from the perspective of each professional's design specialty. Brainstorming design solutions from the beginning as a team will allow each team member to better understand the concerns of the others, will allow the members of the team to get to know each other personally, and will lay the groundwork for communication and collaboration throughout the process. At this time, the project architect and the team members can establish the formal process for periodic collaboration and create the expectation that each member will interact as necessary with other team members when problems or solutions arise that require resolution of competing interests and specialties.

Design is an iterative process; sequential refinement and increased specificity occur at each stage until the completed building is turned over to the owner/user/occupant. Modifications outside the control and direct influence of the designers begin to dominate the process at later stages. Therefore, it is imperative that the designers inform the owner of the IAQ design considerations and constraints at the very beginning. Thus, the conceptual design provides the design team with an opportunity to obtain agreement and acceptance by the owner.

IAQ Considerations During Conceptual Design

Many of the most important decisions are made during the conceptual design stage of a building. Decisions made at the beginning can have the greatest influence on the building's IAQ with the lowest cost impact. This influence decreases as design and construction proceed, mainly due to the cost impacts of changes made later in the process. Good IAQ can be far more difficult to achieve by decisions and actions later in the process—essentially retrofitting the overall concept—if not considered at the initial, conceptual level.

The following issues should be addressed during conceptual design.

Overall Architectural Design. During the conceptual design phase, as initial concepts of a building such as siting, massing, orientation, and openings are addressed, the design team should consider related consequences to ventilation, heating, cooling, illumination, and control of noise. For instance, a schematic diagram of airflow on site and in and out of the building ought to be made along with the initial building concept diagram. Related functions including heating, cooling, and ventilation as well as illumination and noise control are best diagramed at this point so that the major elements of the design scheme are developed with these functions in mind.

How air will be brought into, distributed through, and removed from the occupied spaces needs to be a central consideration while generating schematic design diagrams, models, and related analyses. Whether ventilation is to be mechanical, natural, or hybrid, the assumptions made during the early formulation of building schematic design will drive the design and be reflected in the subsequent process of detailing the building in plans and specifications.

Heating and cooling needs and solutions are also important design assumptions that need to be reflected in the basic formal scheme, especially if ventilation and thermal conditioning are to be provided by integrated solutions or systems. Failure to consider these aspects of design early can limit the flexibility to provide for good IAQ at a later stage in the design process.

Building Location on Site. The location of air, soil, or groundwater pollution sources on site can greatly impact the environment indoors. Attempts to locate the building as far as possible from and upwind of these sources will alleviate future problems. These sources include vehicle roads and parking areas/structures and surrounding industrial, agricultural, and commercial activities. If natural (passive) ventilation is to be considered, it is also important to locate the building—and especially its operable openings—as far as possible from sources of noise.

Building Massing, Shape, and Orientation. The effects of massing and orientation on IAQ and thermal conditions are important considerations. A larger surface-to-volume ratio will enable the use of illumination with daylight and potentially reduce unwanted heat gains from electrical illumination. In cooler climates, sources of heat loss through the envelope (or by exhausting conditioned air) are of considerable concern.

A narrow building profile (cross section) can provide opportunities for cross ventilation or local ventilation through windows. A wide profile will reduce envelope-dominated heat losses.

Passive solar gain and passive ventilation, which are affected by compass and wind direction, ought to be considered in the overall massing and orientation. Solar gain can be an asset in heating-load-dominated climates if glare and overheating are controlled by proper consideration of shading. Fixed or operable shading devices can be used, but orientation and time of year will be important considerations.

More heat gain will result in the need for more cooling and, therefore, more risk of elevated sick building syndrome symptoms if air-conditioning systems are used (Seppänen and Fisk 2002).

Location and Type of Envelope Openings Relative to Pollutant Sources. Considerations of where clean outdoor air can be brought into the building are of critical importance for IAQ. Whether by mechanical or passive ventilation, locating operable windows, doors, or outdoor air intakes away from and upwind of known or potential pollutant sources is an important consideration. The locations of these sources and the locations of building openings need to be considered jointly. Sources include parking or loading areas for vehicles, storage of waste or chemical supplies, outlets from exhausts for combustion appliances or laboratory or cooking equipment, and cooling towers. The building ventilation conceptual flow diagram ought to include avoidance of obvious contamination pathways.

Daylight Illumination. Where light will enter the building and how much daylight is being sought to compliment or replace electrical lighting needs to be considered, along with the impact of windows on thermal conditions, especially for those seated close to them.

Envelope Design. In addition to pollutant pathways and daylighting, basic strategies and assumptions about air leakage, air barriers, and strategies to limit moisture penetration and condensation in the building envelope need to be considered.

Ventilation and Climate Control. During schematic design, questions of how the building will be ventilated and thermally conditioned and how noise will be controlled should be addressed. Once these questions are answered with preliminary design concept drawings or models, the following details should be identified on the design concept documentation (drawings or models):

- Outdoor air intake locations
- Local exhaust and building exhaust locations
- Air cleaning and filtration
- Space air distribution
- Building pressure control
- Internal pressure control
- Microbial control
- Moisture and humidity control

Strategy 1.1

Some IAQ problems, especially those caused by unusual occupancy, cannot be anticipated adequately by designers. However, if a building is designed and constructed with the capacity to control contaminants in indoor air, trained operators can then use that capacity when it is needed. It is, therefore, important to design and construct the ventilation system with a level of flexibility that allows either a simple controls adjustment or installation of additional equipment to obtain additional ventilation as needed.

Materials Selection and Specification. During schematic design, questions of what the major envelope materials and interior surface materials will be and how they will affect thermal conditions, illumination, and IAQ need to be addressed. Once these questions are answered, some consideration needs to be given to the following:

- Materials emissions (chemicals or particles; emission rates)
- Resistance to microbial growth and effects of accumulated moisture
- Preventive installation procedures
- In-place curing
- Flush-out

While some of these issues will be detailed at later stages in the process (design development and construction documents phases), early consideration will enable a wider range of options and ensure adequate consideration throughout the design process.

Construction Process and Initial Occupancy. Early in the design process, it is important to discuss issues about how IAQ will be protected and advanced during construction and initial occupancy and how IAQ performance will be determined and reported. Raising these issues early in the design process helps ensure that plans for IAQ protection and enhancement during construction will be developed and become part of the commissioning process.

IAQ Throughout the Design and Construction Phases

Important IAQ processes throughout the design and construction phases are detailed in the following Strategies:

- Strategy 1.2 – Commission to Ensure that the Owner’s IAQ Requirements are Met
- Strategy 1.3 – Select HVAC Systems to Improve IAQ and Reduce the Energy Impacts of Ventilation
- Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ
- Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ
- Strategy 8.4 – Use Natural or Mixed-Mode Ventilation Where Appropriate

In addition, summary guidance for considering IAQ throughout the design and construction process is available from the EPA at their website about the IAQ Building Education and Assessment Model (I-BEAM) (EPA 2009).

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Strategy 1.2

Commission to Ensure that the Owner's IAQ Requirements are Met

Introduction

Few manufacturers today would consider producing a product without a formal quality assurance and quality control process. Yet the majority of buildings are built without the use of systematic quality control procedures. This is especially problematic since most commercial and institutional buildings are in essence prototypes—the first (and only) full-scale version of the design—so quality is not improved over time through refinement of the design in later models. Further, some of the members of the design and construction team often are working together for the first time so, like a sports team that has never played together, their work may not be fully coordinated.

A variety of other factors can also contribute to quality problems, such as the following:

- Budget pressures can lead to less time spent on design, undesirable changes during value engineering, awarding of contracts to contractors who are able to lower their bids by substituting poorer-quality materials and equipment or cutting corners in the execution of the work, and elimination of all or most of the site visits by the design professionals.
- Time pressures can lead to incomplete design work, improper sequencing of work, and unspoken agreements to turn a blind eye on known problems that would delay completion.
- On the architectural side, fear of litigation has led some designers to write performance specifications and cease providing construction details (Aldous and Lemieux 2007). Yet on the contractor side the responsibilities for construction of the building enclosure are typically very diffuse, with a multitude of subcontractors contracted directly to the general contractor, who may not have the time, desire, or ability to coordinate envelope construction and quality control (Parzych and MacPhaul 2005, MeLampy 2006).
- On the mechanical side, the development of complex, proprietary digital control systems has led most design engineers to write a performance specification for the controls, typically in quite general terms, leaving the actual engineering up to the controls contractor, who may not understand the mechanical systems well enough to optimize their control (Wheeler 2006).
- On all sides, use of innovative systems that are not standard practice for manufacturers, designers, or installers can lead to problems that would not arise with more conventional products or systems (Wheeler 2006).

As a result of these factors, buildings are frequently turned over to the owner with deficiencies, and key assemblies or systems may fail to function as intended. IAQ may suffer due to problems in design or material and equipment selection or construction. To address these problems, a growing number of building owners are incorporating commissioning (Cx), a quality-oriented process used to achieve successful construction projects that meet the owner's requirements (ASHRAE 2005), into their building projects.

The information presented here focuses on the application of Cx to achieve IAQ objectives. It is not a comprehensive guide to Cx. For further information on the Cx process in general, see *ASHRAE Guideline 0-2005, The Commissioning Process* (ASHRAE 2005). For further information on Cx of the building exterior enclosure and HVAC&R systems, see *NIBS Guideline 3-2006, Exterior Enclosure Technical Requirements for the Commissioning Process* (NIBS 2006), and *ASHRAE Guideline 1.1-2007, HVAC&R Technical Requirements for The Commissioning Process* (ASHRAE 2007), respectively.

Effect of Budget and Time Pressures on Quality

A general contractor who had a contract that provided a bonus for early completion allowed the air handlers to be installed before the building was dried in. After a rainstorma, one of the contractors discovered that water poured out when he opened the air handler access doors. The general contractor warned the contractor to say nothing about this to the owner.

Pre-Design Phase Commissioning

It is a common misconception that Cx is a post-construction process. In fact, Cx is most effective and most cost-effective if it starts at project inception.

During pre-design, the commissioning authority (CxA) can help the owner identify and make explicit all functional requirements for the project. Explicit documentation of the Owner's Project Requirements (OPR) reduces the potential for problems arising from different implicit assumptions about project requirements or failure to maintain focus on requirements as the project progresses. When measurable performance criteria are negotiated on the front end, the owner knows what he or she can expect and the design and construction teams know how success will be measured, providing clear accountability. If Cx starts later in the project, it can be costly or even impossible to reconcile decisions already made by various team members operating under their own assumptions to the owner's belatedly defined requirements.

Starting Cx at project inception is also more cost-effective because it is much less expensive to correct problems in the design phase while they are still on paper than after submittals have been approved, materials and equipment have been received, and construction is under way (or even complete) (see Figure 1.2-C).

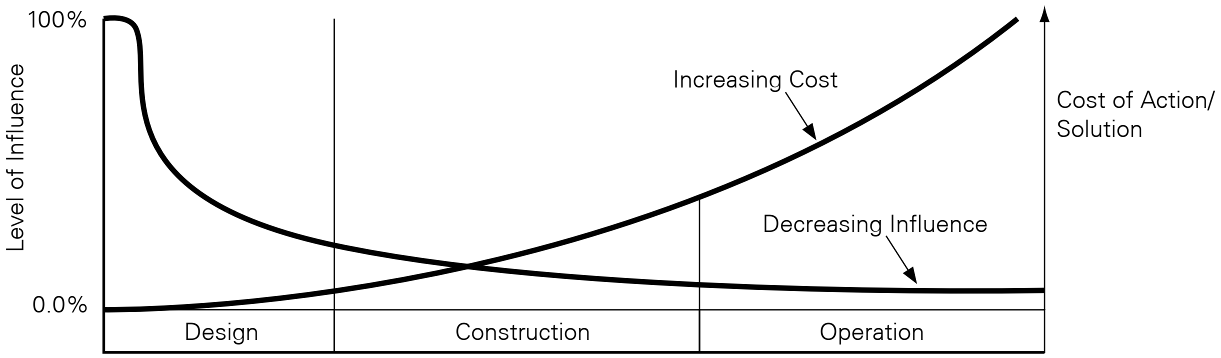

Figure 1.2-C Decreasing Ability to Influence Outcomes and Increasing Cost of Action as Project Proceeds
Adapted from a figure copyright CH2M HILL.

With this approach, the owner selects a CxA and establishes the Cx scope and budget in the pre-design phase. If possible, the design team's responsibilities related to Cx are defined in their initial agreements with the owner. If the CxA is involved early, he or she can provide input to the project schedule to ensure that it accommodates the steps necessary to achieve the owner's IAQ requirements. This input may include, for example, the timing of inspections that must be made while key assemblies are still open or proper sequencing of work to avoid moisture damage.

These issues are discussed in this section. Other pre-design Cx tasks are identified in ASHRAE Guideline 0 (ASHRAE 2005).

Commissioning Team: Specialists Needed for IAQ Items

To be effective, the CxA must represent the interests of the owner. Many people recommend that the CxA be a third party hired directly by the owner who is not affiliated with any of the firms involved in the design or construction. This ensures that the CxA does not have a conflict of interest in pointing out problems with design or construction work or advocating for their correction.

Strategy 1.2

The owner needs to determine whether the CxA has technical knowledge and experience in Cx the building elements important for a particular project, check references, and review sample reports for recently completed comparable projects. Informative Annex E of ASHRAE Guideline 0 (ASHRAE 2005) provides an example of a Request for Qualifications for a Cx provider. A number of different organizations certify Cx providers (see CCC [2009] for further information), but criteria vary considerably.

Cx of mechanical systems developed considerably earlier than Cx of building enclosure systems, and there are more experienced providers for the former than for the latter. However, the performance of the building enclosure can be critical to IAQ because of the potential for microbial growth due to incursion of liquid water or water vapor. A Cx firm that focuses on commissioning mechanical systems may have little or no experience in commissioning the building enclosure, and vice versa. While the Cx processes are the same in broad terms, the technical expertise required is different. Where moisture control for IAQ is a key concern, the owner needs to ensure that both the envelope and mechanical systems can be properly commissioned.

Building envelope specialists can be well suited to commissioning building enclosures. These consultants are retained by owners to bridge the gap between the architect as generalist and the envelope contractor/subcontractors as specialists in order to reduce the risk of envelope failure. They may assist the architect of record in defining relevant performance criteria; identifying suitable products; detailing interfaces; reviewing proposed subcontractors, material substitutions, shop drawings, and submittals; reviewing and testing mock-ups; monitoring on-site construction; and functional performance testing for water penetration, air infiltration, etc. Some of these activities are outside the typical role of a CxA and fall more in the category of consulting to the architect, who may not have the technical expertise in-house to design all of the technical aspects of the building enclosure for more complex or critical designs (Aldous and Lemieux 2007).

Other specialists may be needed in specific situations. For example, when a vapor intrusion mitigation system is used, Cx and ongoing performance monitoring are likely to be required by the regulatory agency.

Indoor Air Quality Monitoring

Monitoring indoor contaminant levels is not necessary to design and construct a building with good IAQ. The extremely large number of contaminants found in buildings, many of which do not have specific authoritative guidance or regulatory limits related to occupant health and comfort, make the collection and interpretation of monitoring results problematic. (See Appendix A – Environmental Monitoring for a more detailed explanation of monitoring issues.) Further, the monitoring results only provide a snapshot characterization of the indoor environment and do not necessarily reflect the conditions that will exist during future years of operation. Rather, an examination of the design and construction features in relation to the principles of good IAQ as covered in this Guide offers a more realistic, reliable, and useful method of evaluation.

Note that contaminant monitoring may well be appropriate when an IAQ problem is being investigated in an existing building (see EPA [1991] for guidance on diagnosing IAQ problems) or where there is a need or desire to understand the IAQ performance of a building for another reason.

In the context of this Guide, there are two circumstances where contaminant monitoring might be relevant. The first is where the building will contain a monitoring system as part of a demonstration project, to provide detailed performance data showing the impacts of certain design or operational features on IAQ. The second circumstance is one in which contaminant monitoring is part of the building Cx process based on concerns about specific contaminants or contaminant sources. Because these circumstances do not occur in many buildings, they are not discussed in this document. Guidance on monitoring is available and is discussed in Appendix A – Environmental Monitoring.

Owner's Project Requirements for IAQ

The purpose of Cx is to enhance the project delivery process in order to achieve the Owner's Project Requirements (OPR). An essential first step in Cx is to clearly define and document these requirements, since they "form the basis from which all design, construction, acceptance and operational decisions are made" and become "the primary tool for benchmarking success and quality at all phases of the project delivery and throughout the life of the facility" (ASHRAE 2005).

Often the owner is focused on the project cost and schedule and basic program requirements and may not have given much thought to other project goals that will in the end be critical to his or her satisfaction with the completed project (Corbett 2002). Making the OPR explicit reduces the potential for costly misunderstandings. Defining the OPR in the pre-design phase gives the entire team a shared understanding of the owner's expectations and establishes unambiguous criteria for acceptance of the completed work.

Examples: Benefits of Written OPR for IAQ

OPR Example 1: Consider a school located in an area with high outdoor ambient levels of fine particulate matter (PM2.5). The design team might assume that the level of filtration provided should be the minimum required by codes and standards (MERV 6) because the school is a project driven by first cost. The owner might not realize that the area has high ambient PM2.5 or that this is associated with increased asthma symptoms. Raising the issue of control of outdoor contaminants as a possible part of the OPR, the CxA might discover that the district has had numerous parental complaints related to perceived aggravation of children's asthma at school. Once the school district realizes that high ambient PM2.5 contributes to asthma symptoms, it may want a higher level of filtration. If the CxA were not engaged and this issue not discussed until after the HVAC systems had been selected, it might not be possible to meet this (previously unrecognized) OPR if the type of system selected were unable to accommodate a deeper filter. On the other hand, with the CxA engaged at project inception and assisting in developing the OPR, one requirement might be identified to "minimize aggravation of student asthma." The performance criteria might be to provide MERV 13 filters and to seal around the filtration and air-cleaning system, around filter frames and retainer systems, and at access doors to reduce air bypass (see Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives).

OPR Example 2: Discussion with the developer of a motel in a humid climate might cause one of the OPRs to be "limit the risk of condensation and mold growth." The CxA, working with the design team, might establish measurable performance criteria that include the following:

1) A continuous plane of airtightness must be established throughout the building envelope with all moving joints made flexible and sealed.

2) Air permeance compliance alternatives might be that the air barrier material in an assembly of the opaque envelope must have an air permeance not to exceed 0.004 cfm/ft2 at 0.3 in. w.g. (1.57 lb/ft2 [0.02 L/s·m2 at 75 Pa]) when tested in accordance with ASTM E2178 (ASTM 2003) or an air barrier assembly must have an air permeance not to exceed 0.04cfm/ft2 at 0.3 in. w.g. (1.57 lb/ft2 [0.2 L/s·m2 at 75 Pa]) when tested according to ASTM E 2357 (ASTM 2005a) or ASTM E 1677 (ASTM 2005b).

3) The air barrier system must be able to withstand the maximum design positive and negative air pressures and must transfer the load to the structure.

4) The air barrier must not displace under load or displace adjacent materials.

5) The air barrier material used must be durable for the life of the assembly.

6) Connections between the roof air barrier, the wall air barrier, window frames, door frames, foundations, floors over crawlspaces, and across building joints must be flexible to withstand building movements due to thermal, seismic, and moisture content changes and creep; the joint must support the same air pressures as the air barrier material without displacement.

7) Penetrations through the air barrier must be sealed.

See Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces for more information.

This tends to compel explicit recognition of trade-offs between performance and cost and clarify the level of quality and risk management that are consistent with the project budget.

A fundamental role of the CxA is to ensure that all important requirements are identified and included in the OPR. IAQ may not be the first thing that comes to the owner's mind as a requirement. Unless the owner has had a problem with IAQ in the past, he or she may assume that the project team's default practices will automatically result in acceptable IAQ. To ensure that the OPR includes all of the important functional requirements related to IAQ, the CxA should obtain the owner's input and establish acceptance criteria related to each of the eight IAQ Objectives set forth in this Guide:

Objective 1 – Manage the Design and Construction Process to Achieve Good IAQ
Objective 2 – Control Moisture in Building Assemblies
Objective 3 – Limit Entry of Outdoor Contaminants
Objective 4 – Control Moisture and Contaminants Related to Mechanical Systems
Objective 5 – Limit Contaminants from Indoor Sources
Objective 6 – Capture and Exhaust Contaminants from Building Equipment and Activities
Objective 7 – Reduce Contaminant Concentrations through Ventilation, Filtration, and Air Cleaning
Objective 8 – Apply More Advanced Ventilation Approaches

ASHRAE Guideline 0 defines the OPR as "A written document that details the functional requirements of a project… [including] project goals, measurable performance criteria, cost considerations, benchmarks, success criteria, and supporting information" (ASHRAE 2005, p. 4).

Usually the owner is only able to articulate IAQ requirements in general terms such as "meet code," "consistent with a Class A office building," "no mold problems," "pleasant environment," "no odors," "not aggravating students' asthma," etc. A key CxA responsibility is to translate these comments into measureable (and contractually enforceable) performance criteria, using input from the design team, contractors, codes and standards, and his or her own knowledge. ASHRAE Guideline 0 states that "Each item of the Owner's Project Requirements shall have defined performance and acceptance criteria. Those that can be benchmarked should have the benchmark defined in specific terms and the means of measurement defined" (p. 6)

Informative Annex J of ASHRAE Guideline 0 (ASHRAE 2005) provides a suggested format for the OPR document. Informative Annexes J of *NIBS Guideline 3, Exterior Enclosure Technical Requirements for the Commissioning Process* (NIBS 2006) and ASHRAE Guideline 1.1 (ASHRAE 2007) provide examples of OPR documents for the building enclosure and HVAC&R systems, respectively.

NIBS Guideline 3 lists numerous objectives and functional requirements to be addressed in the OPR for the building exterior enclosure. Among those particularly relevant to IAQ are the following:

- Exterior enclosure system performance requirements for
  - airflow control
  - water vapor flow control
  - rain penetration control
  - durability
  - maintainability
- System integration requirements for integration of building enclosure systems with mechanical ventilation, natural ventilation, and heating and cooling systems
- Site constraints, including depth to water table, groundwater contaminants, outdoor air contaminants, brownfield mitigation methods, and outdoor air treatment methods

- Quality requirements of systems, materials, and construction
- Warranty requirements
- Occupant requirements for thermal comfort, IAQ, and level of occupant control
- Training requirements to enable owner to operate and maintain the exterior enclosure
- Operation and maintenance (O&M) approach (fix on failure, interval-based preventive maintenance, condition-based maintenance), source (in-house or contracted), and staffing levels
- Maintenance and access requirements
- Project documentation requirements

The draft OPR is reviewed, revised, and approved by the owner and then used by the design team to provide direction for their design. The OPR document needs to be updated continually as the project proceeds to reflect adjustments made during design and construction. The CxA typically facilitates development of the OPR, but it is important that the owner be engaged and take final responsibility for the OPR content (Barber 2008). The owner needs to be prepared to back up the CxA if the design, submittals, delivered products, or installation do not meet the OPR and, conversely, needs to be prepared to accept work that meets the OPR.

Further information on development of the OPR document (formerly referred to in the industry as *the design intent*) is given by Dorgan et al. (2002), Stum (2002), Castelvecchi (2002), and Wilkinson (1999).

Commissioning Scope and Budget Related to IAQ

Cx efforts must be prioritized, since it is not economically justifiable to commission every aspect of every building system. For IAQ, it makes sense to prioritize on the basis of risk management.

Berner et al. (2006) suggest an analytical process for defining the Cx scope based on risk tolerance (see Table 1.2-A). First, potential risks or failure modes are identified. These fall into two categories: *catastrophic failures*, in which a major portion of a system fails, taking it offline or crippling it to levels below minimum performance requirements, and *partial failures*, in which the system is still operational but performance is reduced. The qualitative level of criticality of each potential risk and the associated potential for loss of human health or life and for occurrence of financial costs are then estimated. The criticality and cost levels are summed to create a risk factor that roughly quantifies the owner's aversion to the risk and desire to mitigate it through Cx. The CxA can then group the risk factors into categories in order to help the owner select the risks to be mitigated, which in turn drives the development of the Cx scope. The CxA uses this owner guidance to develop a matrix relating equipment and systems to the previously identified risks, assigns a sampling rate to each type of equipment or system based on the associated risk factor, and calculates the estimated Cx costs. These are compared to the estimated cost of the failures, and the process is iterated until the owner is satisfied with the ratio of Cx costs to failure costs.

Although the CxA and owner may not explicitly conduct such an analysis, the Cx scope for IAQ ought to be based on similar considerations, for example:

- Excessive moisture due to penetration of liquid water, condensation of water vapor, or inadequate control of humidity by the HVAC equipment is the most important cause of building-related symptom complaints, based on the experience of IAQ investigators (Mendell et al. [2006]; see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ for additional information on important causes of IAQ complaints). These problems have led to catastrophic failures that have rendered buildings unusable and required massive repairs as well as to partial failures that have led to loss of tenants, occupant symptoms, etc. This strongly suggests that Cx of the building enclosure should be a high priority in Cx for IAQ. However, Tseng (2004) reports that most Leadership in Energy and Environmental Design (LEED) projects have not included the building envelope in their Cx scope, although LEED requires Cx on any building element or system that has an impact on energy efficiency, water use, or indoor environmental quality. This may reflect the longer history of Cx of mechanical systems and the greater availability of mechanical system Cx providers.

Table 1.2-A Using Risk Tolerance to Develop the Commissioning Scope
Adapted from Berner et al. (2006).

Impact/Cost components by failure type	
Catastrophic Failures	**Partial Failures**

• Loss of human health or life
• Repair and replacement costs
  • Materials
  • Equipment
  • Labor
• System cleanup costs
• Reduced productivity (processes or human performance)
	• Higher life-cycle costs
	  • Lower efficiency—increased operation costs
	  • Higher maintenance costs
	  • Premature replacement costs
	  • Reduced salvage value
	• System cleanup costs
	• Reduced productivity (processes or human performance)

Criticality level and cost level	
Criticality	
Level 3—Failure results in severe bodily harm or loss of life or in loss of service to critical areas. (5 points) Level 2—Failure results in system damage and loss of service to non-critical areas. (2 points) Level 1—Failure results in loss of service or reduced performance to non-critical areas. (1 point)	
Cost (Dollar categories are examples only. See potential cost components above.)	
Level 3—Failure results in severe bodily harm or loss of life or in cost to the owner over $200,000. (5 points) Level 2—Failure results in cost to the owner between $25,000 and $200,000. (2 points) Level 1—Failure results in cost to the owner between $0 and $25,000. (1 point)	
Risk categories and recommended commissioning strategy (Used to assist owner in selecting risks to be mitigated through commissioning)	
Critical: Risk Factor 6–10 points	Full verification for static checkout and dynamic testing.
Essential: Risk Factor 3–5 points	Sampling for static checkout and full verification for dynamic testing.
Desirable: Risk Factor 1–2 points	Sampling for both static checkout and dynamic testing.

- *Legionella* can cause life-threatening illness, which strongly suggests that location of cooling towers, provision for treatment of towers, design of humidification systems, and design of potable water systems and the like should be included in Cx for IAQ.
- Other common causes of IAQ problems that suggest potential areas of focus for Cx include insufficient outdoor air, poor quality of outdoor air, inadequate exhaust of contaminant sources, poor supply air distribution or balance, and poor HVAC maintenance (relating in the design phase to system access). (See information from Mendell et al. [2006] and Angell and Daisey [1997] presented in Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ).
- Wheeler (2006) suggests that Cx is particularly important for "innovative" systems that are unfamiliar to designers, installers, operators, and, at least in a relative sense, manufacturers and therefore have an increased risk of problems. Specific examples he identifies that relate to IAQ include energy recovery ventilation and underfloor air distribution. He notes that Cx of innovative systems warrants additional rigor and suggests that this might include additional rigor in design review to ensure proper selection and application, factory witness testing even when a conventional system would not be witness-tested, enhanced submittal review, samples, mock-ups, efforts to raise the awareness of the construction team regarding the intent and characteristics of innovative systems, O&M training regarding the design intent and operational theory, etc. The advanced ventilation approaches covered in Objective 8 – Apply More Advanced Ventilation Approaches may fall in the category of innovative systems needing greater attention in Cx.

Strategy 1.2

Little if any published information is available on costs of Cx for IAQ. D'Antonio (2007) reported Cx costs of \$0.19 to \$1.50/ft^2 (\$2 to \$16/m^2) with an average cost of \$0.55/ft^2 (\$6/m^2) for 10 LEED buildings in Colorado, all but one of which incorporated LEED's "enhanced" Cx. It was not reported whether any of these included Cx of the building enclosure, nor was the extent of Cx for IAQ reported. Mills et al. (2004) reported median costs of \$1.00/ft^2 (\$11/m^2) (2003 dollars) for 69 new construction projects with varying scopes. The middle 50% of projects had costs between \$0.49 and \$1.66/ft^2 (\$5 and \$18/m^2). Of 30 projects for which the reasons for Cx were given, 83% included ensuring adequate IAQ. Wilkinson (2000) provides an older source of cost data.

Many factors influence Cx costs, including which systems are commissioned (e.g., HVAC, envelope, other), the complexity of the systems, the size of the building, the sampling strategy (e.g., 100% vs. 50% vs. 25% of units) and other factors.

Special Project Schedule Needs for IAQ

In the pre-design phase the CxA should identify Cx activities that need to be integrated into (and in some cases may affect) the project schedule. These may include, among others, the following:

- Design phase Cx workshop
- Cx of the design review and issue resolution
- Cx of the review of value engineering
- Preparation of Cx specifications for inclusion in the project manual
- Submittal review
- Pre-construction meeting
- Construction and testing of mock-ups
- Construction observation/on-site inspections while assemblies are open
- Testing, adjusting, and balancing (TAB) verification
- Functional testing

Over the course of the project, the CxA needs to monitor how project schedule changes affect scheduling of Cx activities and ensure that Cx activities are accommodated in schedule revisions.

Design Phase Commissioning

During the design phase the CxA verifies the Basis of Design (BoD) prepared by the design team against the OPR, performs Cx-focused design review, develops Cx process requirements for inclusion in the specifications, develops draft construction checklists, defines training requirements, and updates various Cx documents drafted earlier (ASHRAE 2005).

IAQ Basis of Design (BoD)

The BoD is developed by the designer to record the "concepts, calculations, decisions, and product selections used to meet the Owners Project Requirements and to satisfy the applicable regulatory requirements, standards, and guidelines" (ASHRAE 2005, p. 4). The CxA reviews a sample of the BoD to verify that it fulfills the OPR. The BoD is updated throughout the project to reflect the evolution of the design.

Per ASHRAE Guideline 0 (ASHRAE 2005), the BoD should include the following:

- System and assembly options
- System and assembly selection reasoning
- Facility, system, and assembly performance assumptions

  - Assumptions for calculations/sizing
  - Analytical procedures and tools
  - Environmental conditions
  - Limiting conditions
  - Reference make and model
  - Operational assumptions
- Narrative system and assembly descriptions
- Codes, standards, guidelines, regulations, and other references
- Owner guidelines and directives
- Specific descriptions of systems and assemblies
- Consultant, engineering, and architectural guidelines for design developed by the design team or others

Some of the ventilation system design criteria and assumptions that would be part of a BoD for IAQ are already required by *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007a). The designer must provide to the building owner

- an outdoor air quality investigation (Section 4.3),
- assumptions made in the design with respect to ventilation rates and air distribution (Section 5.2.3),
- justification for classes of air (for recirculation or transfer) from any location not listed in certain tables of the standard (Section 5.17.4), and
- design criteria used in conjunction with the IAQP (Section 6.3.2).

Informative Appendix H of ASHRAE Standard 62.1 contains templates that can be used to document these design criteria and assumptions. These templates are shown in Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ in the context of system documentation for O&M needs.

Other elements of the BoD for air-handling systems also need to be documented to facilitate O&M for IAQ. These could include, for example:

- Specific ventilation codes followed
- Outdoor design conditions
- Indoor design conditions and rationales
- Rationales for type(s) of HVAC systems selected (in this context, IAQ-related considerations)
- Rationales for type(s) of air distribution systems selected (ducting, type and sizing of ducts, terminal equipment, diffuser type and location)
- Methods used to control indoor humidity and rationales
- Methods used to monitor and control minimum outdoor airflow rates and rationales
- Outdoor airflow to be provided before and after normal hours of occupancy for morning flush-out of contaminants and after-hours cleaning crews and rationales
- Rationales and methods used to achieve building pressurization and relative space pressurization
- Other relevant control strategies and rationales
- Rationales for the level of filtration and air cleaning selected (which may be related to outdoor air quality or to other factors) and for its location(s) in the HVAC system
- Rationales for exhaust systems provided and for exhaust flow rates

Design criteria and assumptions also need to be documented for other building systems that affect IAQ. These include the following:

- Mechanical systems other than air handlers
  - Criteria for location and design of cooling towers to limit growth and distribution of *Legionella*
  - Criteria for design of potable water systems to limit growth and distribution of *Legionella*
  - Criteria for piping and duct insulation to limit condensation
  - Criteria for venting of combustion equipment
- Building enclosure systems intended to control liquid water and condensation
- Radon mitigation systems
- Vapor intrusion systems
- Track-off systems
- Building materials, finishes, and furnishing systems

For an example of the BoD documentation for HVAC issues not covered by ASHRAE Standard 62.1, see Informative Annex K of ASHRAE Guideline 1.1 (ASHRAE 2007b).

Annex K of NIBS Guideline 3 (NIBS 2006) provides a checklist illustrating the structure and contents of the BoD for the building exterior enclosure. Some of the IAQ-related criteria include the following:

- Air leakage criteria for walls, windows, curtain walls, storefronts, skylights, and doors
- Water leakage criteria for walls, windows, curtain walls, storefronts, skylights, doors, below-grade systems, and slabs-on-grade
- Water vapor and condensation control requirements for walls, windows, curtain walls, storefronts, skylights, and slabs-on-grade
- Thermal performance criteria for all enclosure assemblies
- Site circulation/access
- Exhausts that may damage built-up and rubber membrane roofs (e.g., kitchen grease exhaust)
- Roof drain sizing

Design Review for IAQ

Design reviews are typically completed at several points throughout design and construction, such as at completion of the BoD (see the previous section), 100% design development, 65% construction documents, and 95% construction documents. ASHRAE Guideline 0 (ASHRAE 2005) contemplates targeted, sample-based reviews consisting of four tasks:

- General quality review
- Review for coordination between disciplines (constructability, interfaces)—10% to 20% of total building area
- Discipline-specific review for achieving the OPR—10% to 20% of the drawings
- Review of specifications for applicability to the project, inclusion of Cx requirements, submittal requirements, consistency with the OPR and BoD, and coordination with other sections

The ASHRAE and NIBS guidelines stress that the intent of these reviews is to determine whether there are systematic errors and that the responsibility for complete checks of the design remains with the design team.

A design review checklist is a helpful tool for the CxA. Checklist items for IAQ can be developed based on the owner's OPR for IAQ and the information provided in this Guide. A checklist developed for the Energy Design Resources (EDR) *Cx Assistant* software tool (EDR 2005) can serve as a model and starting point (PECI 2007; Gillespie et al. 2007). Examples of design review IAQ benefits are given in the sidebar titled "Examples: IAQ Benefits of Design Review."

Construction Process Requirements

During the design phase, the CxA needs to ensure that the contractors' Cx process requirements are included in the construction documents. These include requirements related to the following:

- Participation in the Cx team
- Specific information required as part of submittals
- Laboratory testing
- Mock-ups of exterior assemblies
- Periodic inspections during construction
- Documentation of equipment and component performance using construction checklists provided
- Schedule for witnessing testing activities
- Field testing of enclosures
- TAB verification
- Functional testing of HVAC&R systems
- Training development and implementation (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ)
- Systems manual development and submittal (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ)

Note that, for enclosure systems, the level of Cx activity during construction (testing of mock-ups, periodic inspections to ensure construction consistent with the approved mock-ups) may be more intensive than it is for HVAC&R systems. Construction phase Cx activities for HVAC&R systems tend to be more intensive during functional testing near the completion of construction.

Further information and sample specifications are given in ASHRAE Guidelines 0 and 1.1 (ASHRAE 2005, 2007b) and NIBS Guideline 3 (NIBS 2006).

Construction Checklists for IAQ

Construction checklists are forms developed by the CxA and used by the contractors to verify that the correct components are on site, ready for installation, correctly installed, and functional. The checklists are supplements to the drawings and specifications and are intended to convey requirements in simple language, help contractors understand quality expectations and do their work correctly the first time (Martin 2007), and reduce punch-list items, rework, and callbacks. Draft construction checklists are developed during the design phase but generally cannot be finalized until the contract is awarded and the actual components, equipment, assemblies, and systems to be used are known. The CxA field-verifies samples of the completed construction checklists throughout construction to verify that the items are in fact complete and meet the OPR.

For equipment and components, construction checklists include the following elements:

- Model verification—completed on delivery to the job site or storage location
- Pre-installation checks—completed just prior to installation
- Installation checks—completed as installation progresses
- Reasons for any negative responses (deficiencies)

For systems and assemblies, such as duct systems, the checklists include pre-installation and installation checks completed daily and conflicts recorded as they arise.

Examples: IAQ Benefits of Design Review

Figure 1.2-D Humid Climate Buildings
Photograph copyright H. Jay Enck.

Design Review Example 1: Two buildings located in a humid climate and totaling 900,000 ft2 (84,000 m2) were commissioned for IAQ (Figure 1.2-D). Peer review of the structural systems during design review determined that during storm events the drift of the buildings under wind loads would exceed the movement tolerances of the building enclosures and would have resulted in failure to prevent rainwater intrusion. Identification of this problem during design avoided significant IAQ problems and repair costs (Enck 2004).

Design Review Example 2: Renovation of a school included replacement of all of the HVAC systems. Because of previous mold problems related to cooling coils, one of the owner's requirements was to have no wet cooling coils. Dehumidification was accomplished with desiccant units controlled to a return air dew-point temperature of 50°F (10°C). The chilled-water supply temperature setpoint was to be maintained at 2°F (1°C) above setpoint to ensure that the chilled-water coils would remain dry. Unfortunately, other parts of the design were not modified to take into account this high chilled-water supply temperature. The air handler cooling coils and variable-air-volume (VAV) box cooling coils were specified for more typical entering chilled water temperatures of 46°F (7.8°C) and 45°F (7.2°C), respectively. The approved submittals matched these design criteria. The installed systems were therefore undersized to meet the space cooling loads with a 52°F (11°C) entering water temperature. Drain pans had to be added to all of the VAV boxes to allow a lower entering water temperature to be used. Thus, a project that had started with a goal of no wet coils in HVAC systems serving the building ended with a wet coil in every classroom. Design review by a CxA would have focused on the unusual aspects of this design and the CxA very likely would have caught the mis-specification of the chilled-water temperature entering the VAV boxes, preventing this problem and enabling the realization of this key aspect of the OPR.

Construction checklists should be as short as practicable and the questions should be clear, specific, and wherever possible worded such that a "yes" response indicates compliance with requirements and a "no" response indicates a deficiency (ASHRAE 2005). Martin (2007) provides a simple example for a slab vapor barrier that illustrates these principles (Table 1.2-B).

Table 1.2-B Simple Construction Checklist for a Slab Vapor Barrier
Source: Martin (2007).

Checklist Item	YES	NO
Is the vapor barrier polyethylene with a minimum thickness of 10 mil (0.25 mm)?		
Are vapor barrier layers installed with 6 in. (152.4 mm) of overlap?		
Are edges sealed with tape along entire length of lap?		
Are edges turned up to within 0.5 in. (12.7) of top of slab?		

Examples of construction checklists and citations for other checklist sources are provided in Informative Annex M of ASHRAE Guideline 0 (generic structure), Annex M of NIBS Guideline 3 (building enclosure), and Informative Annex M of ASHRAE Guideline 1.1 (HVAC&R). The sample checklists in these guidelines do not cover all equipment/assembly/system types, and those that are covered may need expansion to address all OPR for IAQ. For example, the three-page sample construction checklist for an air-handling unit (AHU) with chilled and hot water coils provided in Informative Annex M of ASHRAE Guideline 1.1 includes some items closely related to IAQ (Part 1 of Table 1.2-C) but does not include many others. Some of these IAQ items are included in an optional IAQ section of the sample specification in Informative Annex L of the guideline (Part 2 of Table 1.2-C).

Table 1.2-C IAQ-Related Construction Checklist Items for AHU with Chilled and Hot Water Coils (ASHRAE 2007)

Part 1. Items Included in ASHRAE Guideline 1.1 Sample Construction Checklist

1. Model Verification
   - None
2. Physical Checks
   - Air openings are sealed with plastic
3. Installation
   - Adequate clearance around unit for service
   - All components accessible for maintenance
   - Cooling coil drain pan slopes correctly
   - Adequate (ductwork) locations available for testing and balancing of unit
   - All dampers and sensors are accessible (access panels)
   - All dampers close tightly and stroke fully and easily
   - Ductwork is clean and free of debris
   - Temperature, humidity, pressure and carbon dioxide (CO_2) sensors (as applicable) are installed and calibrated
   - Damper actuators installed and calibration verified
   - Unit is clean
   - Filters installed properly (no bypass) and are clean
   - Filters and coils are clean

Part 2. Additional Items Not Included in Guideline 1.1 Sample Construction Checklist*

1. Model Verification
   - None
2. Physical Checks
   - Area where AHU is to be installed is dried-in to protect AHU from weather (Strategy 1.4)
   - Liners on airstream surfaces free of damage (Strategy 4.1)
   - Filters meet specified Minimum Efficiency Reporting Value (MERV) rating of ______ (Strategy 7.5)
   - Gas-phase air cleaners installed and clean (Strategy 7.5)
3. Installation
   - As-installed outdoor air intake meets specified distances from contaminant sources as follows (Strategy 3.2):
     - 25 ft (~7.6 m) or more from cooling tower discharge and upwind (prevailing wind)
     - 15 ft (~4.6 m) or more from cooling tower basin and upwind (prevailing wind)
     - ___ ft (m) or more from plumbing vents
     - ___ ft (m) or more from areas that may collect vehicular exhaust
   - AHU kept off at all times during construction (not used for temporary heating/cooling) (Strategy 1.4)
   - Drain pan outlet at lowest point of drain pan as installed (Strategy 4.1)
   - Condensate drainage trap meets required depth of ____ in. (mm) (Strategy 4.1)
   - Condensate drain pan drains completely with AHU off and with supply fan at maximum speed (Strategy 4.1)
   - Cooling coil face velocity below condensate carryover velocity of ____ ft/min (m/s) at all points (Strategy 4.1)
   - No visible condensate carryover beyond drain pan (Strategy 4.1)
   - Building pressurization sensor installed and calibrated? (Strategy 2.3)
   - Outdoor airflow measuring station installed and calibrated? (Strategy 7.2)
   - Building pressurization sequence of control verified? (Strategy 2.3)
   - Exhaust fan lockout sequence of control verified? (Strategy 2.3)
   - Minimum outdoor air sequence of control verified? (Strategy 7.2)

*Relevant Strategies in this Guide are indicated in parentheses after the applicable item.

Construction Phase Commissioning

Key construction phase Cx objectives related to IAQ are to:

- coordinate the work of the various contractors to facilitate achievement of the OPR;
- verify that the submittals meet the OPR;
- observe construction to verify that the work being completed will support delivery of the OPR;
- verify construction checklists and TAB report;
- develop detailed test procedures and documentation forms;
- conduct functional testing to verify that systems and assemblies meet the OPR; and
- ensure that the specified systems manual and training are delivered (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ).

Verification is conducted using quality-based sampling. Verification conducted as part of Cx does not relieve the contractors of responsibility to conduct their own quality control activities, nor does it affect the responsibility of the designers and contractors to achieve the OPR.

The timing and emphasis of construction phase Cx activities tend to be different for the enclosure than for the HVAC&R systems.

- For the building enclosure, Cx activities during the early stages of construction may be extensive. Various trades working on the enclosure are less likely to be familiar with Cx, so early contractor training and coordination can be critical. Delaying functional testing of the enclosure until it is complete is ill-advised, since at that point the cost of modifications to correct problems is very often prohibitive. Thus, Cx of the building enclosure may involve factory visits, laboratory or field testing of mock-ups of typical wall assemblies, small mock-ups of other details, sample constructions, and field observation and inspection early in the construction phase. Meetings, observation and inspection, testing, and other Cx activities continue through construction and especially during installation of complex portions of the enclosure and at milestone events (MeLampy 2006, Parzych and MacPhaul 2005, Taylor 2007, Aldous et al. 2008).
- For HVAC&R systems, Cx activities during the early stages of construction (after submittal review) may be fairly limited—consisting of periodic site visits to observe construction, verify that construction checklists are being completed regularly, and verify samples of checklist information—with much more effort occurring toward the end of construction in verification of the TAB report and functional testing of complete HVAC&R systems.

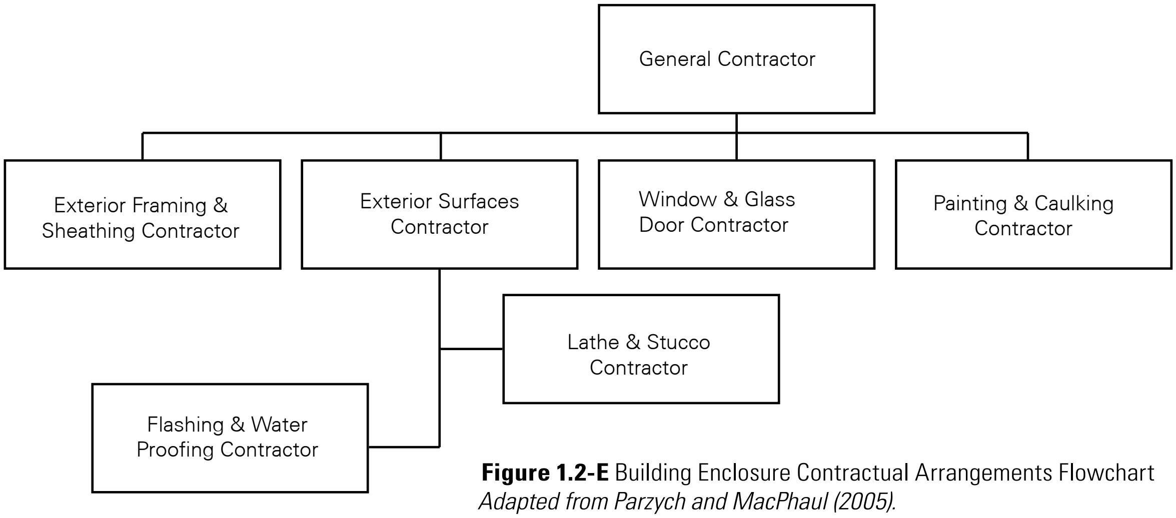

Figure 1.2-E Building Enclosure Contractual Arrangements Flowchart
Adapted from Parzych and MacPhaul (2005).

Coordination for IAQ

Coordination and communication is critical to successful construction phase Cx. Many contractors are still not familiar with Cx and many employees do not read the specifications.

For the building enclosure, a pre-construction meeting may be very important. Building envelope Cx is newer to the market, and building envelope contractors are even less familiar with it than are HVAC&R contractors. Moreover, it is common for many envelope contractors to be contracted directly to the general contractor, who typically does not have the time or focus and may not have the expertise to ensure that the final building enclosure meets the OPR (Figure 1.2-E). The pre-construction meeting ought to include review of the accepted shop drawings and the construction sequence.

Figure 1.2-E shows the contractual arrangements for building envelope work on a hotel expansion (Parzych and MacPhaul 2005). See the sidebar in this Strategy titled "Example: Benefits of Functional Tests of the Building Enclosure" for information on Cx of the building enclosure for this hotel.

For HVAC&R, a pre-construction meeting can address timing and content of submittals, checklist procedures, functional testing procedures and contractor roles, retainage related to functional completion, and specific issues that may affect IAQ such as protection of equipment and components during storage, temporary use of HVAC equipment, and preservation of access for maintenance when installing other equipment (see Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ).

Coordination of building enclosure and HVAC&R work with each other and with other trades can also be important for IAQ. For example:

- Plenum-type underfloor air distribution (UFAD) systems are part of the HVAC&R system, but their performance depends critically on the integrity of building enclosure construction, so they require close coordination and intensive Cx work during enclosure construction (Beaty 2005; Ring and Ingwaldson 2005; Nelson and Stum 2006; Hughes and English 2007; Anis 2007).
- Coordination of HVAC&R with electrical and other work can affect access to HVAC systems for maintenance (see Strategy 4.3 – Facilitate Access to HVAC Systems for Inspection, Cleaning, and Maintenance).
- Installation of HVAC systems before the building is enclosed may result in wetting and mold growth in these systems (see Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ).

Review of Submittals for IAQ

During the construction phase, the CxA reviews coordination drawings, qualifications data, shop drawings, product data, pre-construction test reports, field quality control reports, the preliminary systems manual, and the training program to evaluate whether they will achieve the OPR, including any IAQ-related elements. This submittal review typically occurs concurrently with the design team review and owner review to minimize the impact on the project schedule. Typically, a quality-based sample of the submittal is reviewed, perhaps 10%, and if significant deviations from project requirements are found, an additional percentage is reviewed. The impact of substitutions or other proposed changes from the contract documents on achievement of the OPR needs to be carefully evaluated. As with other CxA activities, the submittal review does not relieve the designer or contractor of their contractual obligations.

The CxA for building enclosures may review submittals to evaluate whether the components are coordinated in a way that will achieve the OPR for airtightness, moisture control, and thermal performance. The CxA's comments are provided to the architect for consideration in his or her response to the submittal (Aldous et al. 2008).

Construction Observation/Verification for IAQ

Site visits are conducted by the CxA to monitor compliance of the work with the contract documents, approved shop drawings, and OPR. They fall into two categories. One category is milestone-driven. These visits may include inspection of initial work on a critical detail, assembly, etc. to verify that it is being implemented in accordance with the OPR before a large volume of work has been completed, inspection of work that will later be covered and inaccessible, or observation of construction quality control tests. Examples relevant to IAQ could include inspection of initial work on the roof-wall interface, inspection of the sub-slab vapor retarder or of elements of the radon mitigation system before the slab is poured, inspection of overhead ductwork before ceilings are installed, observation of duct leakage testing, etc.

The other category of site visits is verification-based. These are conducted to verify construction checklists, as-built drawings, etc. These ought to be conducted using statistical sampling techniques to avoid bias in selection of areas or units checked. The CxA compares the installation against the construction checklist to verify the accuracy of checklisting by the contractor and reviews any items indicated by the contractor as deviating from the OPR (i.e., "no" responses on the checklist). The CxA can also verify that the checklists are being used on an ongoing and timely basis by the contractors to check their own work and are being signed off by responsible parties as required. Many IAQ-related aspects of air-handling systems can be included in the construction checklists (as shown in Table 1.2-C) and verified by the CxA as part of construction verification.

A key task for IAQ is verification of the TAB report. Balancing is critical to the delivery of proper outdoor and exhaust airflow and building and space pressurization. TAB verification typically requires the balancer to repeat a certain percentage of the measurements in the balancing report under observation by the CxA and using the same instruments used in balancing. This could be used to verify such IAQ-related items as

- zone airflow,
- outdoor airflow measuring station calibration,
- building pressure mapping,
- exhaust airflows,
- energy recovery unit enthalpy wheel cross leakage, and
- UFAD system pressurization and leakage.

The CxA's observations and verifications do not take the place of the contractor's own quality assurance/quality control program and do not relieve the contractor of responsibility to complete his work and deliver a fully functional final project.

Functional Testing for IAQ

Functional testing evaluates the performance of assemblies, systems, and interactions between systems under a full range of conditions to verify that they meet the OPR. Design and submittal review and completion and verification of construction checklists are really only preparatory steps that increase the likelihood that various building elements will ultimately pass the functional tests. The CxA develops the functional test procedures and witnesses or verifies the tests.

Field functional tests for HVAC&R systems may include either active testing or passive monitoring.

- Active functional performance tests put a system (or system interface) through each of its modes of operation manually and observe/record its behavior and performance to determine whether it is consistent with the control submittals and OPR. The key advantage of active functional performance tests is that they can be used to simulate a wide range of operating conditions within a short period of time, almost regardless of actual conditions. The primary disadvantage is that the steps taken to simulate these conditions (e.g., overriding setpoints) may not precisely simulate performance under normal operation.

- System performance monitoring passively observes/records system behavior and performance under normal operation. The primary advantage of system performance monitoring is that it provides information on true normal operation. The primary disadvantages are that it must be conducted over an extended period of time to capture a wide range of operating conditions and it may never capture some conditions (e.g., certain alarm conditions).

System performance monitoring is almost always conducted using automated data collection, either with the building automation system (BAS) and/or portable data loggers. Active functional testing is often conducted using automated data collection but can also be conducted simply by observing system performance (usually at the head-end computer for the BAS). Any sensors used for data collection need to have been recently calibrated for the monitored data to be reliable. Most commercial and institutional buildings of any size today have BASs, and most of these can store at least some trend data. However, the amount of data that can be stored, the file format used, and the ease with which this data can be manipulated, displayed, or downloaded varies considerably.

An HVAC&R system functional testing guide with general guidance, sample tests, and other resources is available from PECI (2008). An example of system performance monitoring to test the function of an outdoor air monitoring and control system is shown in Figures 1.1-A and 1.1-B in Part I of this Strategy.

Some of the IAQ-related HVAC system functions that could be evaluated as part of functional performance tests under a wide range of HVAC system operating conditions include, for example:

- Building pressurization control
- Minimum outdoor airflow control (e.g., for VAV or demand-controlled ventilation systems)
- Space humidity control
- Space temperature control
- Air handler and exhaust fan interlocks (to limit building depressurization when the air handler is off)
- Proper operation of energy recovery ventilation system control sequences
- Proper operation of automated natural ventilation system sequences

Building enclosure functional testing includes both laboratory and field testing of enclosure components, subassemblies, assemblies, and systems. Field testing may be performed on a mock-up or on part of the actual building enclosure. Functional tests related to IAQ include tests for water penetration, air leakage, and vapor permeance, among other things. Other tests such as adhesion or wind-induced drift tests affect long-term IAQ performance. Building enclosure functional testing is discussed in Strategy 2.1 – Limit Penetration of Liquid Water into the Building Envelope and Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces. Annex U of NIBS Guideline 3 (NIBS 2006) provides extensive information on testing methods and procedures. Some examples of building enclosure Cx are given by Aldous et al. (2008), Dalgleish (2008), Totten and Hodge (2008), Stroik (2008), Taylor (2007), MeLampy (2006), Parzych and MacPhaul (2005), Turner et al. (2005), Tseng (2005), and Enck (2004).

Systems Manual and O&M Training for IAQ

Enhanced O&M training is an important element of Cx and is discussed in Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ.

Occupancy and Operations

In the occupancy and operations phase, the CxA can provide ongoing guidance to O&M staff to achieve the OPR. Seasonal testing that could not be completed prior to substantial completion can be conducted. The CxA can work with facilities staff to ensure that all warranty issues are identified and resolved before the end of the warranty period.

Example: IAQ Benefits of Completing Construction Checklists

Figure 1.2-F Drain Pan with Standing Condensate
Photograph courtesy of Martha Hewett.

Construction Checklist Example. Condensate stands in the drain pan on the suction side of the fan in this two-year-old air handler even with the fan off (Figure 1.2-F). The unit has a double-sloped drain pan that is permanently fixed in position within the air handler. The air handler itself was not installed level, so the drain pan did not drain properly. Had the building been commissioned for IAQ, this problem would probably have been detected during construction checklisting. Without Cx, the problem was not recognized and addressed until two years later. Because all the hot and chilled water piping and ductwork were attached, the air handler could not practically be re-leveled. Instead, the drain pan outlet had to be relocated to properly drain the pan.

Example: IAQ Benefits of TAB Verification

TAB Verification Example. A middle school in the Midwest was heated and cooled by several constant-volume air handlers. Balancing dampers had been specified for each zone but in the finished project were missing on 38 of 75 zones. The TAB report had been completed with no mention of missing balancing dampers and showing all airflows within 10% of design. It is highly unlikely that all the zone flows were this close to design flows in the absence of balancing dampers. If TAB verification had been conducted, the poorly balanced flows would have been detected and could have been corrected.

Example: Benefits of Functional Tests of the Building Enclosure

Enclosure Functional Testing Example (Parzych and MacPhaul 2005). A 229-room expansion was added to a hotel in Florida (Figure 1.2-G). The owner, the U.S. Army Community and Family Support Center, wanted to maintain a moisture-free hotel. Building enclosure Cx was implemented, including

- peer reviews of the design drawings focusing on the enclosure's ability to resist moisture intrusion and act as an air barrier;
- CxA review of value management concepts;

Figure 1.2-G Completed Project
Photograph courtesy of Dave MacPhaul; copyright CH2M HILL.

- a Cx workshop for the building enclosure contractors, who were not familiar with Cx;
- review of submittals and substitutions;
- mock-up and model construction;
- photographic documentation of all details of the mock-up wall to provide a means to refer back to the successful installation to determine if deviations were occurring;
- functional performance testing of the mock-up;
- on-site inspections; and
- post-occupancy functional performance testing.

It was found that the sliding glass door unit (not the connection between the door frame and the wall) failed during the initial water spray testing (Figure 1.2-H). After modifications were worked out by the CxA, design team, and contractor, 7 of 12 sliding glass door units failed the second round of testing (Figures 1.2-I and 1.2-J). Modifications were made by the manufacturer and a construction checklist procedure was instituted; after this, random water spray testing of ten doors found no failures.

The expansion was designed for positive pressurization to limit infiltration of humid outdoor air. Blower door testing of the guest rooms showed that the enclosure construction was tight, and follow-up testing found the HVAC systems had no problem maintaining the design positive pressurization of ~0.02 in. w.g. (5 Pa).

Six months after the hotel expansion opened, Hurricanes Charley, Frances, and Jeanne struck, with top wind speeds over 90 mph (~40 m/s) and rain totaling over 14 in (~356 mm). While the older portions of the hotel and other facilities in the area suffered severe water and wind damage, the new hotel expansion did not experience any identified water intrusion. The expansion had hundreds of sliding glass doors, so failure of this component could have been catastrophic for the property.

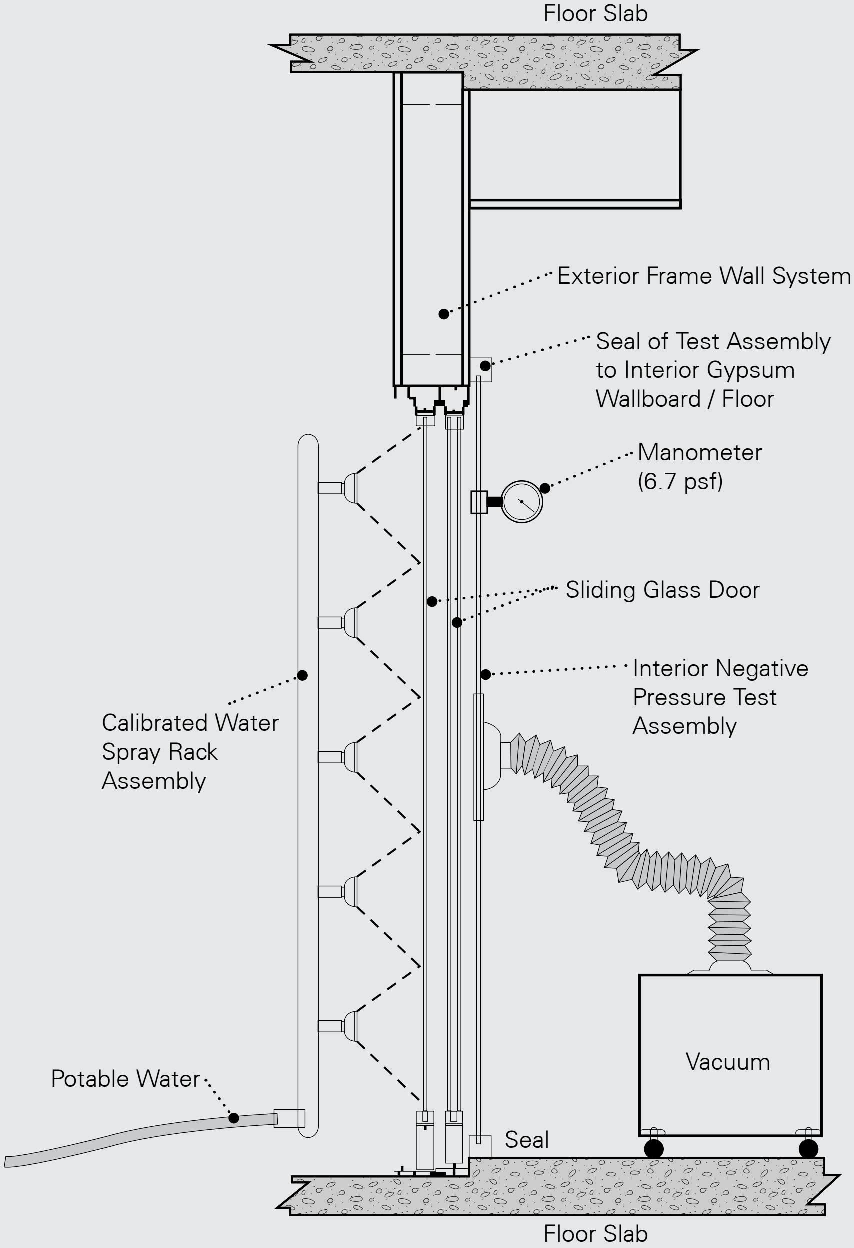

Figure 1.2-H Water Spray Test Assembly for Sliding Glass Doors
Adapted from Parzych and MacPhaul (2005).

Figure 1.2-I Water Spray Test Assembly in Use
Photograph courtesy of Dave MacPhaul; copyright CH2M HILL.

Figure 1.2-J Water Leakage Failure—Early Test Unit
Photograph courtesy of Dave MacPhaul; copyright CH2M HILL.

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Strategy 2.1

Limit Penetration of Liquid Water into the Building Envelope

Introduction

Moisture in buildings is a major contributor to mold growth and poor IAQ. Wetting of building walls and rainwater leaks are major causes of water infiltration. Preventive and remedial measures include rainwater tight detail design, selection of building materials with appropriate water transmission characteristics (see Strategy 2.5 – Select Suitable Materials, Equipment, and Assemblies for Unavoidably Wet Areas), and proper field workmanship quality control. Good design is a prerequisite for a building that resists moisture problems; however, good design alone is not enough. To prevent water intrusion problems, design details need to be reflected in design documents, building drawings, and specifications, and they need to be implemented correctly during construction.

This Strategy provides guidance on design and construction to protect buildings from penetration of liquid water—such as rain, snow and ice melt, surface runoff, and below-grade groundwater. This Strategy does not address flood waters from rivers, lakes, or the sea.

The following forces account for water penetration into and/or through the building envelope (see NCARB [2005]).

- *Gravity.* The force of water entering by gravity is greatest on improperly sloped horizontal surfaces and vertical surfaces with penetrations. These areas must remove water from envelope surfaces through adequate sloping, correct drainage, and proper flashing.
- *Capillary Action.* This is the natural upward wicking force that can draw water into the envelope. This occurs primarily at the base of exterior walls but can easily occur at any gaps in the building envelope.
- *Surface Tension.* This allows water to adhere to and travel along the underside of building components such as joints and window heads. This water can then be drawn into the building by gravity, unequal air pressures, or capillary action.
- *Mechanically Induced Air Pressure Differentials.* A positive pressure differential between the outside and inside of the envelope can force water into the envelope through microscopic holes in the building materials.
- *Wind Loading Induced Air Pressure Differentials.* Wind loading during heavy storm events can force water inside the building if the envelope is not resistant to these forces. For example, window sealants and gaskets that are not properly designed to flex with the window may create gaps that allow water into the building.

Sources of Water Penetration

There are two primary sources of liquid water entry into the building, as follows:

- *Water Entry due to Site Drainage Problems.* In order to avoid these problems, the building site must be designed to collect and divert water away from the building.
- *Water Entry because the Building Envelope does not Shed Water.* In order to avoid these problems, the building envelope must be designed to provide proper shedding or drainage of water and needs to have capillary and surface tension breaks (See Figure 2.1-F).

Design Features to Prevent Water Penetration

Site Drainage

A good site drainage design creates a controlled condition that moves water away from the building. Figure 2.1-G demonstrates good drainage design principles. Items that should be included in the plans are maximum rainfall or snow melt assumptions; drainage surface areas, including shapes, slopes, superstructures, or other obstructions; estimated water flows; and the locations of all conduits. Water flow rates are typically determined by the civil engineer who designs the storm water retention and control system. Water that does not infiltrate into the soil (runoff) must be managed by other drainage methods.

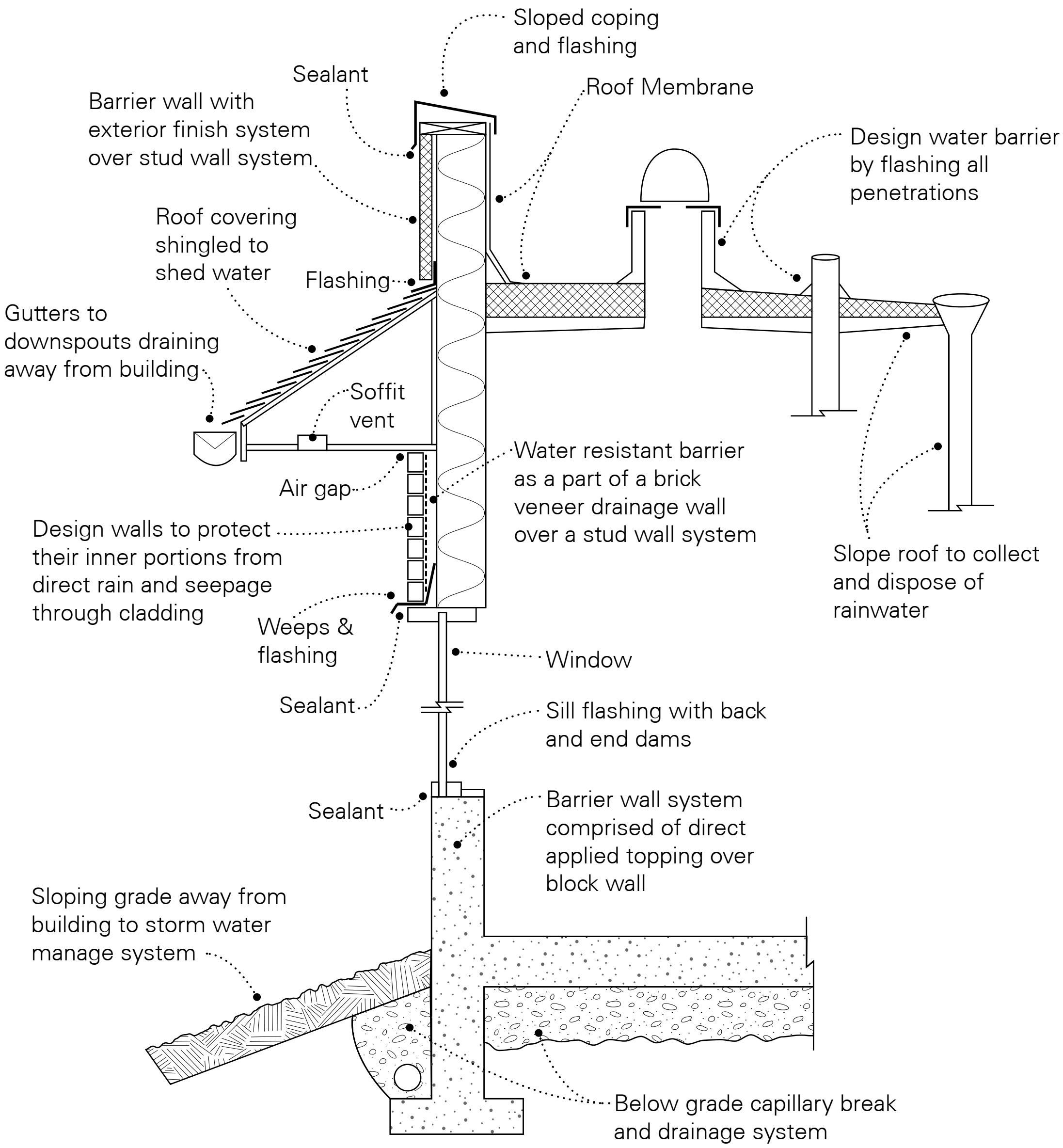


Figure 2.1-F Areas of Waterproofing for a Typical Foundation, Wall, and Roofing System

Based on the topography of the site, water runoff management approaches appropriate for the site's characteristics can be identified. Topography helps to determine the amount, direction, and rate of runoff. Potential approaches include infiltration control methods such as swales or infiltration trenches and retention or detention control methods such as wet or dry ponds. As demonstrated in Figure 2.1-G, any site design needs to ensure that positive drainage principles are met. These include

- making certain water is moved away from the building,
- ensuring water is not allowed to accidentally pond in low areas, and
- making sure that the finished floor is elevated enough so that water will not back up into the building if the drainage systems are blocked.

Grading can be used to direct water runoff away from the building and to slow down the rate of runoff. The recommended grades for a good site design depending upon the proximity to the building are depicted in Figure 2.1-G.

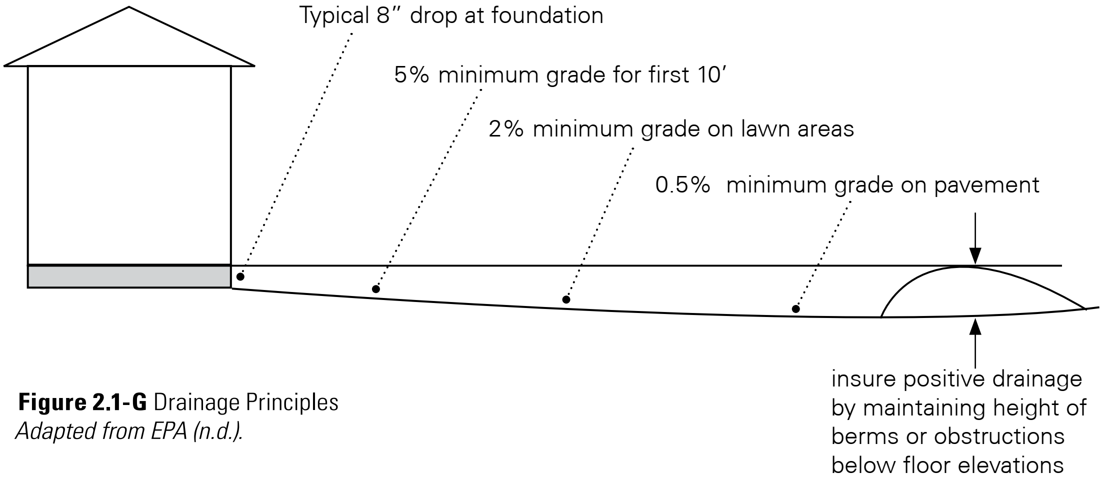


Figure 2.1-G Drainage Principles
Adapted from EPA (n.d.).

The use of relatively permeable paving materials rather than impervious surfaces will allow more water to infiltrate into the ground, thus reducing the size and cost of systems to manage runoff. Specifically, the following are alternative paving materials that can be used to reduce runoff:

- Porous pavement is a permeable surface often built with an underlying stone reservoir that temporarily stores surface runoff before it infiltrates into the subsoil.
- Modular porous pavers are permeable surfaces that can replace asphalt and concrete and can be used for driveways, parking lots, and walkways.
- The two broad categories of alternative pavers are paving blocks and other surfaces that include gravel, cobbles, wood, mulch, brick, and natural stone.

When runoff must be controlled and redirected away from the building, water runoff management approaches for the site's characteristics need to be identified and designed. Potential approaches include the following:

- *Infiltration Control Methods such as Swales or Infiltration Trenches.* A swale is a vegetated open-channel management practice designed to treat and slow runoff for a specified water quality volume. An infiltration trench is a rock-filled trench with no outlet that receives runoff and then treats the runoff as the runoff infiltrates through the rock and through a bottom layer of soil.
- *Retention or Detention Control Methods such as Wet or Dry Ponds.* Wet ponds are constructed basins that contain a permanent pool of water throughout the year and treat particles and associated pollutants in the runoff through settling. Dry retention ponds are designed to detain runoff for some minimum time to allow particles and associated pollutants to settle without holding water in the pond year round.

For detailed information including applicability, design criteria, limitations, and maintenance requirements on these and many other site drainage methods, visit EPA's storm water management Web site, www.epa.gov/greeningepa/stormwater/index.htm (EPA 2009).

Landscaping irrigation systems need to be designed so that they do not spray the building or soak the soil next to the foundation. This can be accomplished by

- avoiding wind impacts on spray heads and rotor heads that spray water into the air so that there is no back spray onto the building or foundation;
- utilizing drip irrigation systems that provide slow and even application of water through plastic tubing buried in the soil, thus avoiding inadvertent spray problems; and
- controlling and monitoring all irrigation systems for proper water flow and time of operation (use timers).

The amount of water needed to irrigate landscaping can be reduced by capturing and storing rainwater to use as irrigation and/or selecting trees, shrubs, and ground cover that have the ability to grow with little or no water.

Final grading design needs to include allowances for the installation of landscaping. Figures 2.1-H and 2.1-I show a poorly installed grade against a building. The grade was impacted by the landscaping that was installed after construction and ended up higher than the elevation of the building slab. This resulted in water backflow into the building. The grade nearest the building had to be trenched to avoid water flow into the base of the exterior wall.

Figure 2.1-H Grade Example 1
Photograph copyright Liberty Building Forensics Group®.

Figure 2.1-I Grade Example 2
Photograph copyright Liberty Building Forensics Group®.

Foundation Design

Moisture problems associated with improperly designed foundations can be difficult and expensive to identify and fix, can facilitate growth of mold that create the potential for health problems, and can be a liability for building owners. Foundations are vulnerable to penetration of liquid water for a number of reasons, such as the following:

- Water from rain and plumbing leaks is drawn by gravity to building foundations.

- Basements are often finished and use details that put materials vulnerable to mold in contact with concrete (or sometimes wood) that is likely to get wet.
- Crawl spaces and basements have more problems because they have more extensive contact with soil (they are essentially holes in the ground) than do slab-on-grade foundations.

Whether the building has a slab-on-grade foundation, a crawlspace, or a basement, the surrounding slope above grade needs to divert water away from the building. In addition, for basements or crawlspaces, below-grade drainage systems also need to divert water away from the foundation and include capillary breaks to keep water from wicking through the foundation to moisture-sensitive materials (e.g., wooden framing and paper-covered gypsum board). Figures 2.1-J and 2.1-K demonstrate basic principles of groundwater control for slab foundations by showing improper foundation waterproofing at the foundation of the building, including the improper installation and incorrect component for the connection to the below-grade foundation.

Water penetration into a foundation can be prevented by planning the surrounding slope to divert water away from the building. Specifically, this can be accomplished by the following:

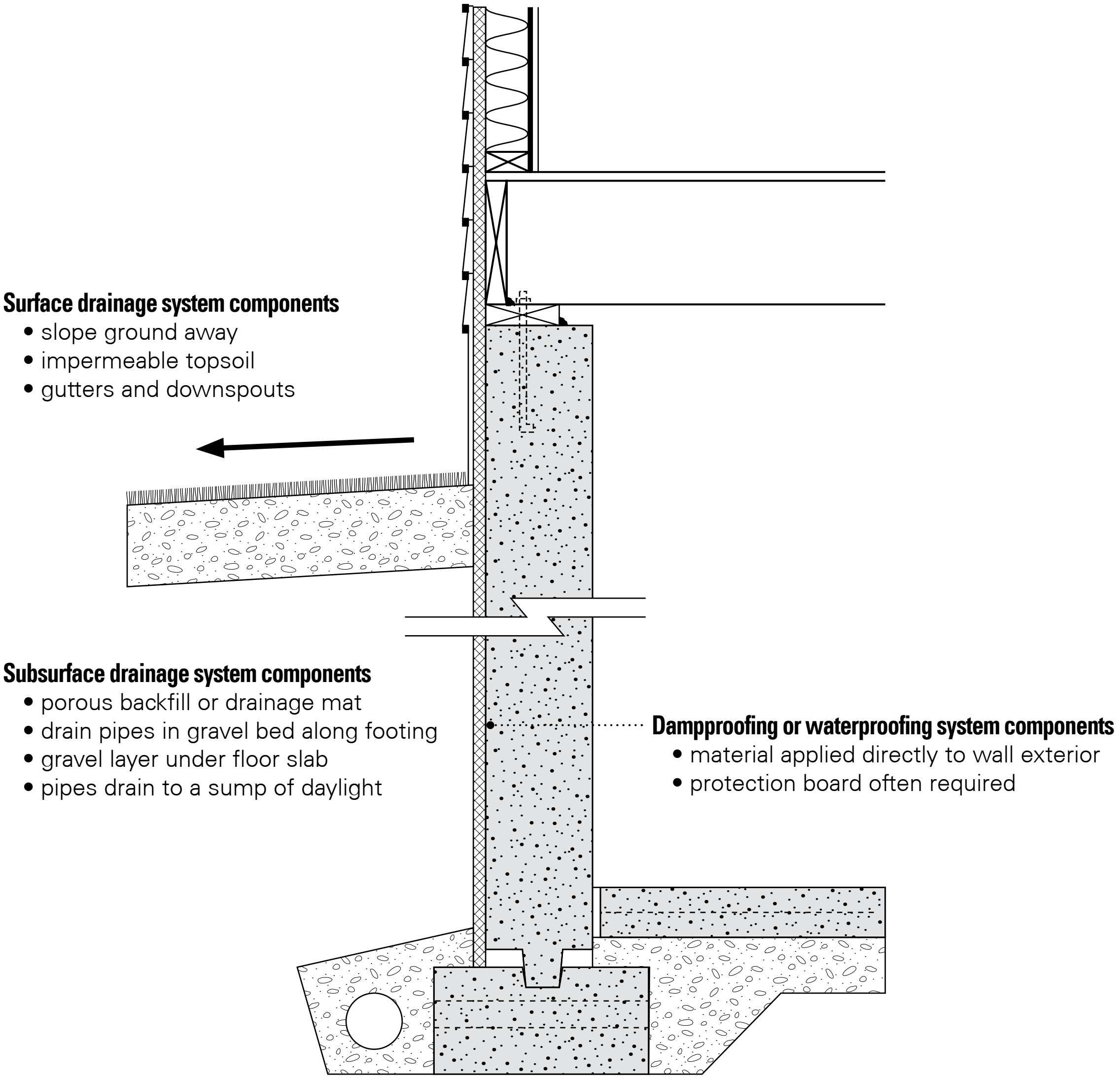
- Specifying a 5% slope to the finish grade away from the foundation to control surface flow of water (in some areas of the country there may be more stringent building code requirements for the finish grade).
- Reduce water infiltration into the soil surrounding the building using a barrier at or slightly beneath the surface, for example, a subsurface drainage landscape membrane as shown in Figure 2.1-L. However, Figures 2.1-J and 2.1-K show the improper lapping of the membrane, which would eventually allow water to penetrate at the building foundation.

It is important to design below-grade drainage systems to divert water away from the foundation and to specify capillary breaks to keep water from penetrating through the foundation. This can be accomplished in the following manner (refer to Figure 2.1-L):

- Below-grade perimeter drainage is not required for concrete slab-on-grade foundations when the surrounding finish grade is sloped.
- A capillary break needs to be incorporated at the following locations:
  - Between the foundation and the above-grade wall assembly
  - Between the earth and the floor slab
  - Between the earth and the below-grade portion of the perimeter stem wall or thickened edge slab
- If there is a joint between the slab's perimeter edge and the stem wall, a capillary break may be required.
- If the roof slopes to eaves without gutters, the bottom of the above-grade portion of the wall needs to be protected against rain splash as well as directed, concentrated flows of rainwater runoff from the roof.

Figure 2.1-J Slab Foundation Example 1
Photograph copyright Liberty Building Forensics Group®.

Figure 2.1-K Slab Foundation Example 2
Photograph copyright Liberty Building Forensics Group®.



Surface drainage system components
- slope ground away
- impermeable topsoil
- gutters and downspouts

Subsurface drainage system components
- porous backfill or drainage mat
- drain pipes in gravel bed along footing
- gravel layer under floor slab
- pipes drain to a sump of daylight

Dampproofing or waterproofing system components
- material applied directly to wall exterior
- protection board often required

Figure 2.1-L Components of Basement Drainage and Waterproofing Systems
Adapted with permission from ORNL (1991), John Carmody, Jeffery Christian, Kenneth Labs.

For crawlspaces and basements, the below-grade drainage system needs to be designed in the following manner (refer to Figure 2.1-M):

- Design the basement or crawlspace so that the interior floor grade is elevated above the 100-year flood level and local water table.
- Specify a curtain of free-draining material (e.g., sand and gravel, coarse aggregate, or a synthetic drainage mat) around the outside of the foundation between the unexcavated earth and the basement wall.
- Waterproofing on the foundation wall is strongly recommended, especially in areas of high water table and/or impervious soils.
- Specify a drainage collection and disposal system to be located below the top of the footer of the bottom of the slab floor.
- Locate footing drain piping at least 6 in. (150 mm) below the top of the slab.

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Strategy 2.1

- Specify filter fabric to prevent fine soils from clogging the curtain drain and the footer drain system.
- Incorporate capillary breaks at the top of the foundation wall and the first floor framing system, at the earth and the basement floor slab, and at the free-draining perimeter fill and the below-grade portion of the basement wall.
- Floor slab should always be installed, even in crawlspaces, as opposed to dirt floor. Crawlspace slabs, often referred to as "rat slabs"—thin concrete slabs with the primary purpose of keeping vermin from tunneling up—minimize dampness from earth.
- Design a capillary break between the top of the footer and the foundation wall (e.g., fluid applied system).
- Specify a drain in the foundation floor.

Note: if the water table is within 2 feet of the bottom of the basement floor slab, special engineering and detailing beyond the scope of this book are required.

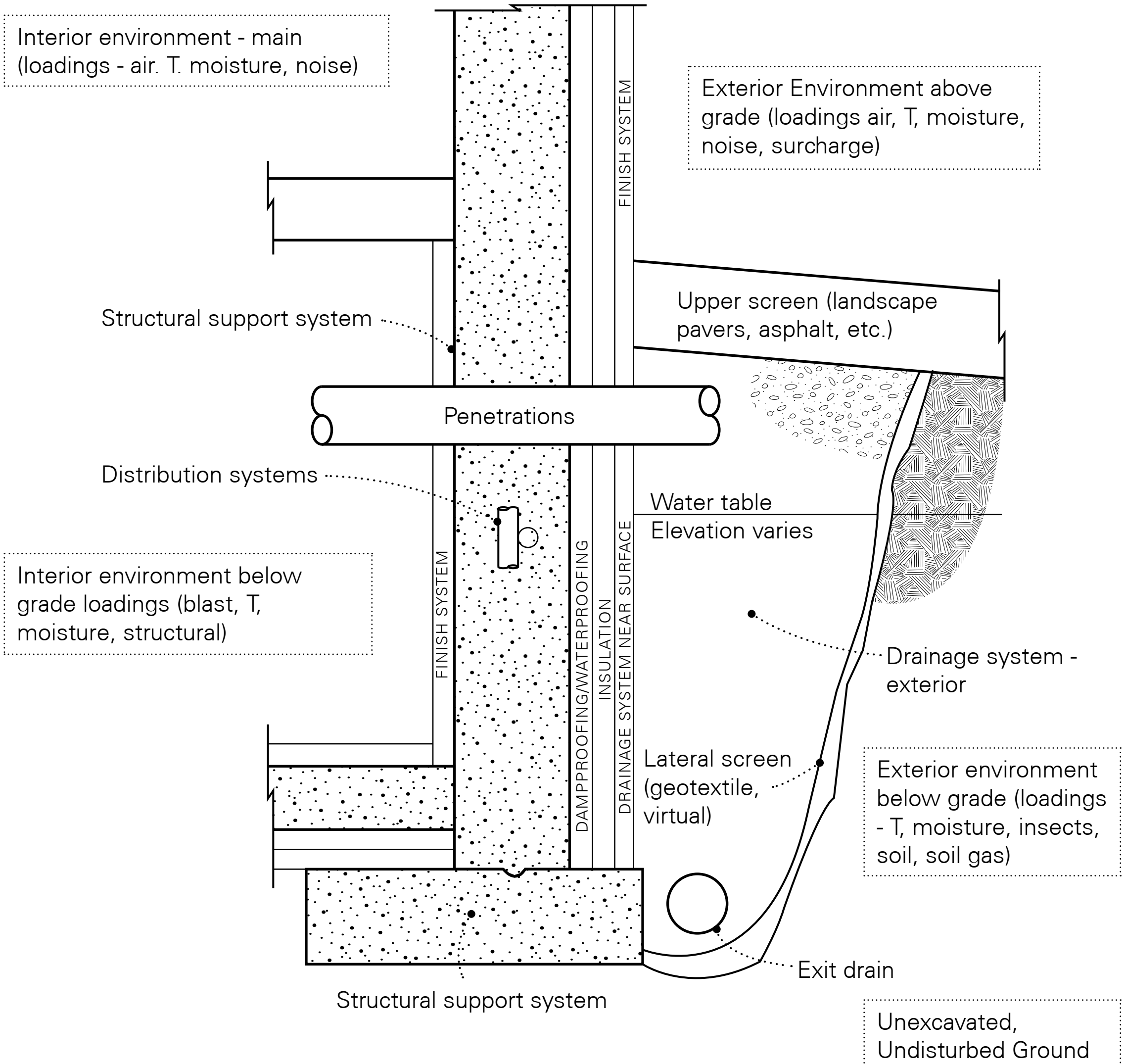

Figure 2.1-M Below-Grade Systems for Foundation Walls
Adapted from Postma (2009); used with permission from the National Institute of Building Sciences.

Strategy 3.1

Investigate Regional and Local Outdoor Air Quality

Introduction

Under the Clean Air Act, the U.S. Environmental Protection Agency (EPA) develops National Ambient Air Quality Standards (NAAQS) to which jurisdictions throughout the country need to comply (EPA 2008). The standards limit the ambient concentrations of particles and gases. EPA monitors compliance and publishes information on compliance and non-compliance areas. This information is useful when developing strategies to protect indoor air from outdoor contamination. It is important, however, to be familiar with the NAAQS in order to best interpret this information. In addition, it is important to inventory the site and surrounding area for sources of contaminants and to thereby characterize the site with respect to outdoor air quality.

To protect indoor occupants from outdoor contaminants, the first step is to assess the ambient and local air quality at points where outdoor air will enter the building, after which provisions for filtration of gas-phase air cleaning can be addressed. For information on filtration and air-cleaning technology, see Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives.

Assessment

Determining Compliance with NAAQS

A beginning step in assessment is to determine the attainment status of the area. The primary outdoor air quality information resource is the Green Book Nonattainment Areas for Criteria Pollutants Web page, www.epa.gov/air/oaqps/greenbk (EPA 2009a). Here, EPA illustrates with maps and lists areas with air quality problems that are not in compliance (nonattainment) with NAAQS. Attainment status and the corresponding maps change annually. From the Web site provided, one can download the latest information on attainment at the site of interest. Figures 3.1-B through 3.1-G show various nonattainment areas, with snapshots of the nonattainment status as of March 13, 2009. The highlighted areas are counties in the lower 48 states that contain nonattainment areas (the entire county may not be nonattainment).

Determining Whether Local Sources Are Present

Often, even if the regional air quality is good, there are local sources of pollutants that can affect IAQ. These can include airborne sources of volatile organic compounds (VOCs), airborne dust, and airborne odors. A site survey can usually determine if sources are nearby. In some cases a site can be affected by a particularly strong source more than a mile away.

NAAQS Particles

In addition to the information on particle removal efficiency of filters provided in the subsections that follow, see Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives for more detailed information.

Particulate Matter—PM10

PM10 are particles that are smaller than 10 μm in diameter. *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007a), requires a minimum of MERV 6 filters at the outdoor air intakes in areas that are nonattainment with PM10. Higher Minimum Efficiency Reporting (MERV) ratings will provide additional filtration efficiency. (See Figure 3.1-B.)

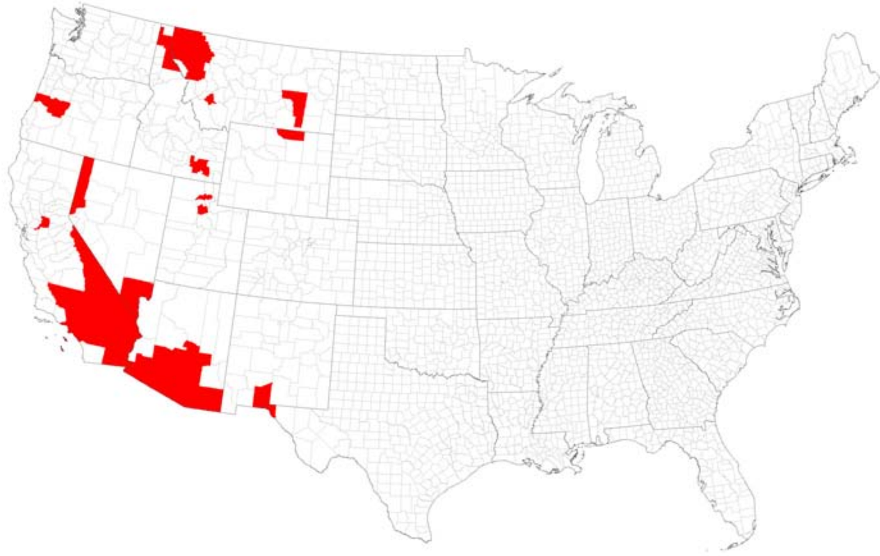

Figure 3.1-B U.S. Counties with PM10 Nonattainment Areas
Graph courtesy of EPA.

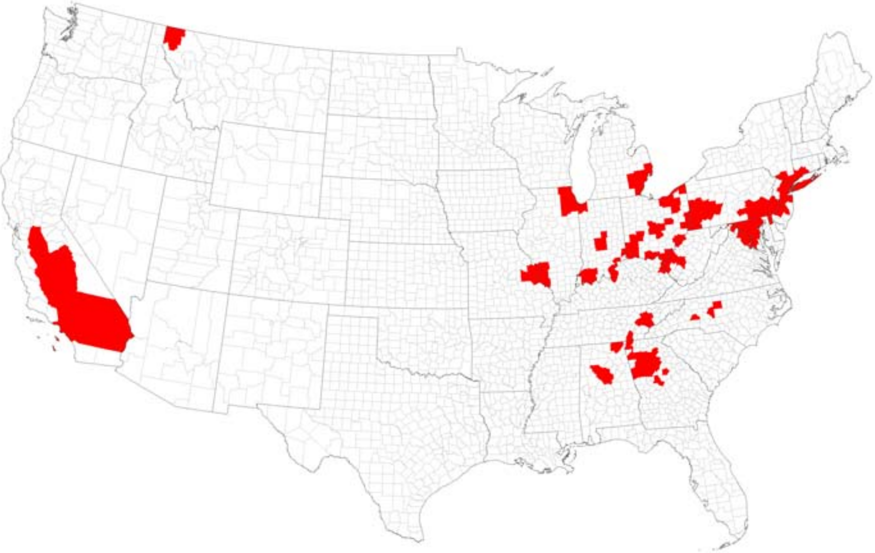

Figure 3.1-C U.S. Counties with PM2.5 Nonattainment Areas
Graph courtesy of EPA.

Particulate Matter—PM2.5

PM2.5 are particles that are smaller than 2.5 µm in diameter. Filters tested by *ANSI/ASHRAE Standard 52.2, Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size* (ASHRAE 2007b), are measured for efficiency at particle size fractions including 0.3 to 10 µm. Filters need to have MERV ratings greater than MERV 8 to have any effective removal efficiency on these smaller particles. Filters with MERV ≥ 11 are much more effective at reducing PM2.5. (See Figure 3.1-C.)

Lead

Lead is a solid and will be an airborne particle or may be attached to other particles in the atmosphere. Filters that are effective on small particles will also be effective at removing lead from the outdoor airstream. (See Figure 3.1-D.)

NAAQS Gases

In addition to the information on gas-phase air cleaning provided in the subsections that follow, see Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives for more detailed information.

Ozone

Ozone is an unstable O_3 molecule of oxygen formed in the atmosphere by a photochemical reaction. The reaction requires sunlight, warm temperatures, nitrogen oxides (NO_x), and photochemically reactive VOCs. If any of these four components are missing, ground-level ozone will not form. Therefore, ozone is not generated on cloudy or cold days. Ozone air treatment is provided by carbon or other sorbent filters that cause the ozone to react on the surface of the active medium. This mechanism is different from how other gases are cleaned from the air. (See Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives).

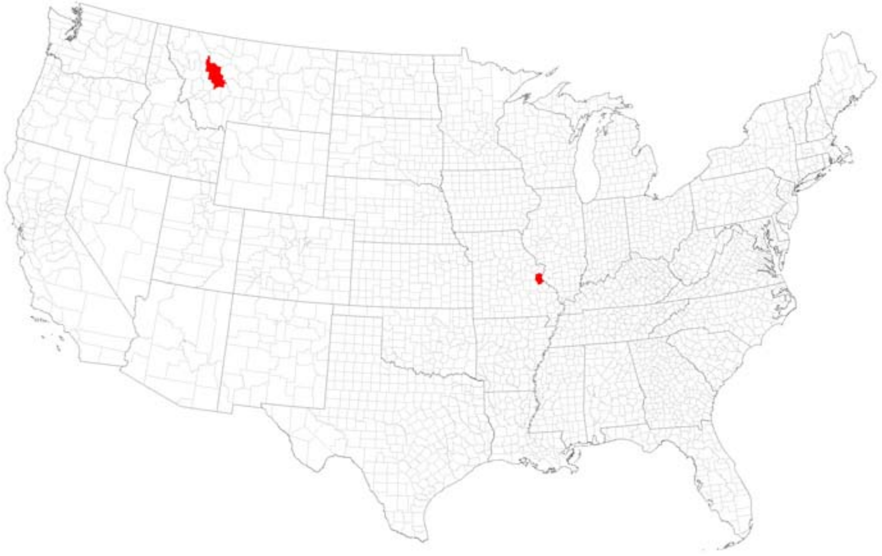

Figure 3.1-D U.S. Counties with Lead Nonattainment Areas
Graph courtesy of EPA.

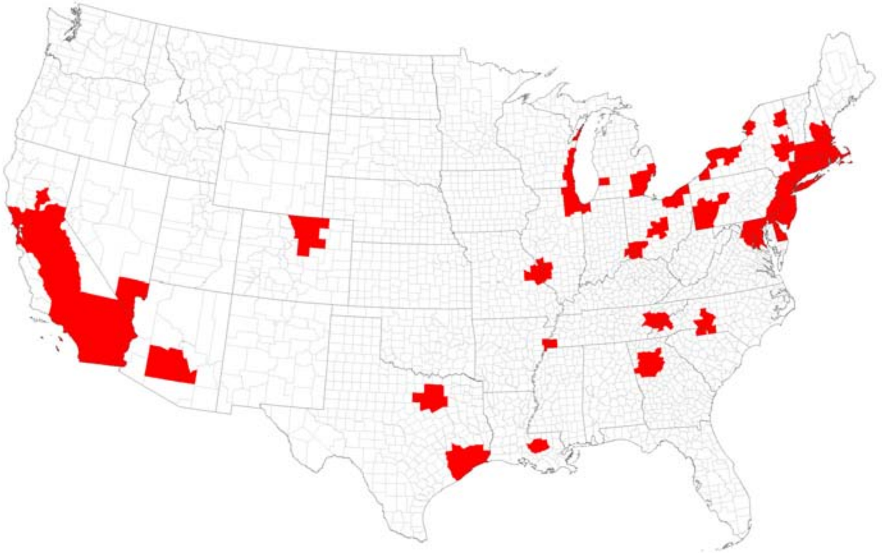

Figure 3.1-E U.S. Counties with 8-Hour Ozone Nonattainment Areas
Graph courtesy of EPA.

Figure 3.1-E shows the status of geographic areas based on nonattainment of the EPA ozone standard for 8 hours. A maintenance area is an area that formerly was nonattainment but is now attainment and is following special procedures to maintain attainment status. However, the designer needs to be cognizant that ozone can attain problem peaks of shorter duration that can have a severely deleterious effect on the indoor environment.

A good-quality carbon filter or air cleaner can provide control for an entire ozone season or longer in many locations. The elimination of ozone in the conditioned space is important for two reasons. First, the ozone molecule is irritating to humans, as it negatively affects the delicate mucous membrane of the eyes and upper respiratory system. It is particularly harmful to occupants that have heightened sensitivity or are prone to allergic reactions to airborne chemicals. Second, ozone is a highly reactive oxidant that has been shown to react with trace VOCs in the indoor environment to create by-products that are often more toxic than the original constituent (Weschler 2004). The sorbent filter chosen to clean ozone from the indoor air needs to be protected by a high-quality particle filter so that it is not blinded by dirt that would prevent the filter from working. (See Figure 3.1-E.)

Nitrogen Dioxide (NO_2)

There are no areas in the U.S. that are currently in nonattainment status for nitrogen dioxide (NO_2). There are gas-phase air cleaners that can be effective on NO_2.

Sulfur Dioxide (SO_2)

Sulfur dioxide (SO_2), as well as other sulfur-bearing compounds, can be cleaned by gas-phase air cleaners. Certain filter materials (for example, activated alumina/$KMnO_4$) adsorb SO_2 at available receptor sites

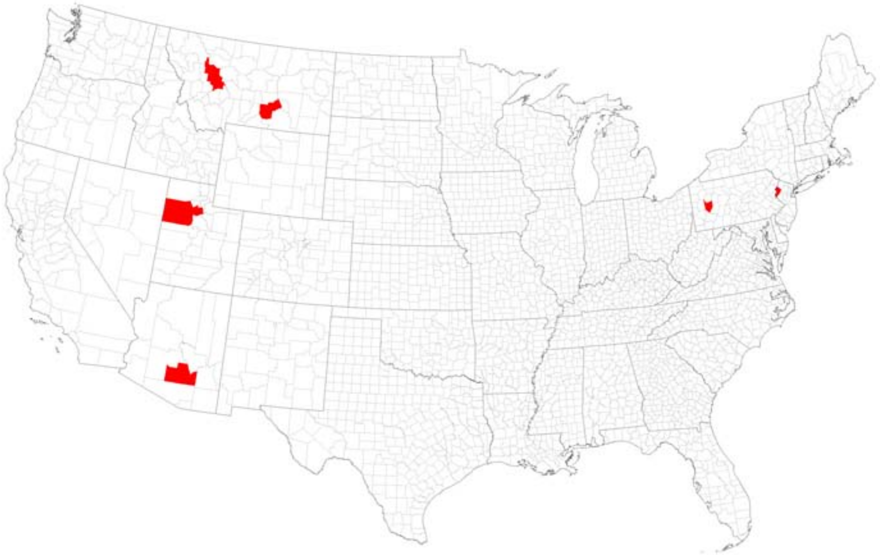

Figure 3.1-F U.S. Counties with SO_2 Nonattainment Areas
Graph courtesy of EPA.

Figure 3.1-G U.S. Counties with CO Nonattainment Areas
Graph courtesy of EPA.

and provide control through chemical reaction, referred to as *chemisorption*. Noxious and malodorous to occupants at higher concentrations, this compound is also a significant concern for processes and materials stored within the conditioned space even at trace concentrations. When combined with airborne moisture it becomes acidic, leading to chemical degradation of paper products, delicate electronics, and valuable metallic assets such as silver and gold. The activated filter chosen to remove SO_2 needs to also be protected from particles and its hours of life will depend on the concentration of SO_2 and other compounds that are carried in the same airstream.

The EPA tracks both primary and secondary attainment statuses. Primary standards are established to protect human health; secondary standards are established to protect the environment. All areas shown are nonattainment with the primary standard for SO_2. (See Figure 3.1-F.)

Carbon Monoxide (CO)

Carbon monoxide (CO) is a colorless, odorless gas that is produced by incomplete combustion. According to EPA (2009b), "[a]cute [health] effects are due to the formation of carboxyhemoglobin in the blood, which inhibits oxygen intake. At moderate concentrations, angina, impaired vision, and reduced brain function may result. At higher concentrations, CO exposure can be fatal." There is no commercially available air cleaner for CO that operates at room temperature. Scheduling of activities and the ventilation system operation are the most practical strategies to reduce the impact of CO on the indoor environment. (See Figure 3.1-G.)

Other Pollutants

Dust

Airborne dust is no longer regulated as a NAAQS pollutant but can be a problem in areas with agriculture, high pollen, or certain industries or in desert climates. Filtration of airborne dust needs to focus on the dust-holding capacity of the filtration system. This is usually attained by the selection of the filtration configuration having the appropriate MERV level, depending on particle mix, that provides the greatest surface area. This also will extend the loading life cycle because of lowered operating pressure drop.

Volatile Organic Compounds (VOCs)

Most industrial emissions of VOCs are regulated and controlled at the source, either as a part of ozone reduction or as a hazardous air pollutant. Other sources of VOCs include traffic, mobile equipment, area sources such as wastewater lagoons, and some natural sources. If there are local (nearby) sources of VOCs, filtration or air cleaning needs to be considered. In a recent study reported by *USA Today* in 2008 (Heath et al. 2008), it was reported that 435 schools across the country had been identified as being potentially exposed to dangerous levels of toxic industrial chemicals. It was also reported that over half of the nation's schools are located "in what the government calls 'vulnerable zones'—areas close enough to industrial sites that they could be affected by an accident" (Heath et al. 2008, p. 1A). This widespread awareness of the role of toxic industrial sources provides a powerful incentive for design teams to be more fully aware of the surrounding potential sources of toxic chemicals, as well as all contaminants of concern, when evaluating the cleanliness and dependability of the ambient air surrounding new construction sites.

Odors

Odors in the atmosphere are often (but not always) regulated in response to citizen complaints in urban environments. Odors can be removed from the outdoor air with air-cleaning technology that can be tailored to the specific compounds that cause the odor. Odor can play an important role in both the prevention and the recognition of airborne chemical exposures. Odor thresholds are often much lower than irritation or adverse health risks; thus, they provide an early warning of impending trauma or risk from more acute exposure. It is also important for the design team to recognize that odors are much more than just "complaints"—they represent a threat to the occupant and bring on stress followed by distress. This is because the sense of smell that detects the malodor is part of the limbic or primitive response portion of the brain. It is the animal response mechanism for recognizing edible food, mate, mother, home, turf, sex, or enemy. As such, it is the trigger for 'fight or flight,' which brings on adrenalin and stress. This explains why occupants tend to react emotionally and irrationally when exposed to unknown chemical odors (Burroughs and Hansen 2008).

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Strategy 3.2

Locate Outdoor Air Intakes to Minimize Introduction of Contaminants

Introduction

Outdoor air enters a building through its air intakes. In mechanically ventilated buildings, these air intakes are part of the HVAC system. In naturally ventilated buildings, the air intakes can be operable windows or other openings in the building's envelope.

As outdoor air enters a building through its air intakes, it brings with it any contaminants that exist outside the building near the intake. That is why the quality of the outdoor air delivered to a building greatly affects the quality of the indoor air. Therefore, it is important to evaluate the ambient air quality in the area where a building is located as well as the presence of local contaminant sources. Outdoor air intakes can be located to reduce the entrainment or re-entrainment of airborne pollutants emitted by these sources.

Due to wind effects around buildings and multiple other local variables, establishing minimum separation distances that will result in no entrainment for each source is extremely difficult if not impossible. Each design case needs to be evaluated based on local conditions and variables, and the designer ultimately needs to exercise professional judgment. In some cases, advanced calculations and/or modeling may be needed.

Applicable Codes, Standards, and Other Guidance

Mechanical codes—such as *International Mechanical Code* (*IMC*; ICC 2006a), *International Plumbing Code* (*IPC*; ICC 2006b), *Uniform Mechanical Code* (*UMC*; IAPMO 2006a), and *Uniform Plumbing Code* (*UPC*; IAPMO 2006b)—have some basic requirements for locating building intakes (see Tables 3.2-A and 3.2-B for a list of ASHRAE and model code requirements). In most cases these requirements are minimums, are not always up to date relative to published standards and research, and may not adequately minimize exhaust re-entrainment into a building's intake. For example, on separation distance between cooling tower exhaust and building intakes, the 2006 *IMC* (ICC 2006a) and *UMC* (IAPMO 2006a) allow a vertical separation of only 5 ft (1.5 m) between a cooling tower and a building intake, whereas *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007a), requires a 25 ft (7.6 m) separation. The 5 ft (1.5 m) separation could allow contaminated cooling tower mist into the air intake. The 2009 *UMC* will increase this distance consistent with Table 5.1 of ASHRAE Standard 62.1 as a result of a change proposal.

For vents carrying non-explosive or flammable vapors, fumes, or dust, most model codes require a 3–10 ft (0.9–3 m) separation distance between the vent termination and the building air intakes (other than health-care facilities). In the case of plumbing vents, most codes require a 10 ft (3 m) separation distance. The American Institute of Architect's *Guidelines for Design and Construction of Health Care Facilities* (AIA 2006) requires a separation distance of 25 ft (7.6 m) between building intakes and plumbing vents, exhaust outlets of ventilating systems, combustion equipment stacks, and areas that may collect vehicular exhaust or other noxious fumes.[1] However, these guidelines allow the 25 ft (7.6 m) separation distance to be reduced to 10 ft (3 m) if plumbing vents are terminated at a level above the top of the air intake. For hospitals, Section 407.2.1 of the 2007 *California Mechanical Code* requires that "outdoor air intakes shall be located at least 25 ft (7.62 m) from exhaust outlets of ventilating systems, combustion equipment stacks,… cooling towers and areas that may collect vehicular exhaust or other noxious fumes. The bottom of outdoor air intakes shall be located as high as practical, but not less than 10 ft (3048 mm), above ground level. If installed through the roof, they shall be located 18 in. (457 mm) above roof level or 3 ft (914 mm) above a flat roof where heavy snowfall is anticipated" (CBSC 2007a, p. 46).

Table 5.1 of ASHRAE Standard 62.1 (2007a) lists minimum separation distances between air intakes and specific contamination sources (see Table 3.2-A for a copy of this table). These distances are the shortest "stretched-string" distances measured from the closest point of the outlet opening to the closest point of

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[1] Health-care facilities are not specifically covered in this Guide, but some discussion is being provided for informational purposes.

the outdoor air intake or building opening. Although the list does not cover all possible sources, it does give the designer a guiding tool. Appendix D – Separation of Exhaust Outlets and Outdoor Air Intakes allows the designer to calculate distances from sources other than the ones listed in Table 3.2-A. The distances listed in Table 3.2-A should be considered design minimums and not necessarily recommendations applicable to all designs. In general, it is wise to locate building intakes upwind and as far as practically possible from strong contaminant sources. For example, while the ASHRAE Standard 62.1 (ASHRAE 2007a) minimum distance for cooling towers is 25 ft (7.6 m), a 40 ft (12 m) distance was recently specified and implemented in a 1 million square foot building office complex without any additional costs to the owner (Alevantis et al. 2002).

Table 3.2-A ASHRAE Standard 62.1 Air Intake Minimum Separation Distance

Source: ASHRAE (2007), Table 5-1.

Object	Minimum Distance, ft (m)
Significantly contaminated exhaust (Note 1)	15 (5)
Noxious or dangerous exhaust (Notes 2 and 3)	30 (10)
Vents, chimneys, and flues from combustion appliances and equipment (Note 4)	15 (5)
Garage entry, automobile loading area, or drive-in queue (Note 5)	15 (5)
Truck loading area or dock, bus parking/idling area (Note 5)	25 (7.5)
Driveway, street, or parking place (Note 5)	5 (1.5)
Thoroughfare with high traffic volume	25 (7.5)
Roof, landscaped grade, or other surface directly below intake (Notes 6 and 7)	1 (0.3)
Garbage storage/pick-up area, dumpsters	15 (5)
Cooling tower intake or basin	15 (5)
Cooling tower exhaust	25 (7.5)

Note 1: Significantly contaminated exhaust is exhaust air with significant contaminant concentration, significant sensory-irritation intensity, or offensive odor.

Note 2: Laboratory fume hood exhaust air outlets shall be in compliance with NFPA 45 (NFPA 1991) and AIHA Z9.5 (AIHA 1992).

Note 3: Noxious or dangerous exhaust is exhaust air with highly objectionable fumes or gases and/or exhaust air with potentially dangerous particles, bioaerosols, or gases at concentrations high enough to be considered harmful. Information on separation criteria for industrial environments can be found in *ACGIH Industrial Ventilation Manual* (ACGIH 1988) and in *ASHRAE Handbook—HVAC Applications* (ASHRAE 2003).

Note 4: Shorter separation distances are permitted when determined to be in accordance with a) Chapter 7 of ANSI Z223.1/NFPA 54 (ANSI/NFPA 2002)for fuel gas-burning appliances and equipment, b) Chapter 6 of NFPA 31 (NFPA 2001) for oil-burning appliances and equipment, or c) Chapter 7 of NFPA 211 (NFPA 2003) for other combustion appliances and equipment.

Note 5: Distance measured to closest place that vehicle exhaust is likely to be located.

Note 6: No minimum separation distance applies to surfaces that are sloped more than 45° from horizontal or that are less than 1 in. (3 cm) wide.

Note 7: Where snow accumulation is expected, distance listed shall be increased by the expected average snow depth.

At this time, model codes have not adopted Table 5-1 of ASHRAE Standard 62.1. As mentioned previously, although Table 5-1 of ASHRAE Standard 62.1 does not cover all possible sources, it does cover more sources and provides for greater separation distances than can be found, for example, in the *2001 California Mechanical Code* (CBSC 2001). See Table 3.2-B for a comparison of Table 5-1 of ASHRAE Standard 62.1 to model codes.

Table 3.2-B Comparison of Table 5-1 of ASHRAE Standard 62.1 to Model Codes

Object	Minimum Distance, ft (m)								
	ASHRAE Standard 62.1, Table 5-1 (ASHRAE 2007a)	*2007 California Mechanical Code* (CBSC 2007a) and *Uniform Mechanical Code* (IAMPO 2006a)		*2007 California Plumbing Code* (2007b) and *Uniform Plumbing Code* (IAMPO 2006b)		*International Mechanical Code* (ICC 2006a)		*International Plumbing Code* (ICC 2006b)	
		Separation Distance, ft (m)	Section	Separation Distance, ft (m)	Section	Separation Distance, ft (m)	Section	Separation Distance, ft (m)	Section
Significantly contaminated exhaust (Note 1)	15 (5)	For commercial kitchen exhausts: 10 (3.1) horizontal or 3 (0.9) vertical separation	510.8.2.1	For vent terminations: 10 (3.1) from or 3 (0.9) above any operable window, door, air intake, or vent shaft	906.2	For commercial kitchen exhausts: 10 (3.1) horizontally or 5 (1.5) if air from exhaust is away from air intake openings	506.3.12.3	For vent terminations: 10 (3.1) from or 2 (0.6) above any operable window, door, or other intake opening	904.5
Noxious or dangerous exhaust (Notes 2 and 3)	30 (10)	(a) For mechanical refrigeration rooms: 20 (6.1), exceptions allowed (b) For product-conveying ducts: 10 (3.1); 30 (9.1) from openings into the building that are in the direction of the exhaust	1117.8 506.9.2			(a) For ducts with explosive/flammable vapors: 10 (3.1) (b) For other product-conveying ducts: 30 (9.1)	501.2.1		
		Discharge of air from refrigeration machinery rooms: 20 (6.1) from property line or building openings; if discharge exceeds 25% of lower flammable limit or 50% of Immediately dangerous to life and health" limit, then approved treatment systems are required	1108.7			Discharge of air from refrigeration machinery rooms: 20 (6.1) from property line or building openings	1105.6.1		

Object	Minimum Distance, ft (m)								
	ASHRAE Standard 62.1, Table 5-1 (ASHRAE 2007a)	*2007 California Mechanical Code* (CBSC 2007a) and *Uniform Mechanical Code* (IAMPO 2006a)		*2007 California Plumbing Code* (2007b) and *Uniform Plumbing Code* (IAMPO 2006b)		*International Mechanical Code* (ICC 2006a)		*International Plumbing Code* (ICC 2006b)	
		Separation Distance, ft (m)	Section	Separation Distance, ft (m)	Section	Separation Distance, ft (m)	Section	Separation Distance, ft (m)	Section
Vents, chimneys, and flues from combustion appliances and equipment (Note 4)	15 (5)	(a) For environmental air ducts (domestic range and clothes dryer vents): 3 (0.9) (b) Mechanical draft venting: 4 (1.2) below or horizontally from and 1 (0.3) above any building opening. (b) Gas vent: 3 (0.9) above a forced air inlet if located within 10 (3.1)	504.5 802.8.2 802.6.2.6			(a) For environmental air ducts: 3 (0.9) (b) Intakes: 10 (3.1) horizontally from or 2 (.6) below hazardous or noxious contaminant source (vents, chimneys, plumbing vents, streets, alleys, parking lots, loading docks) c) Direct-vent, integral vent, and mechanical draft systems: 3 (0.9) above any forced air inlet located within 10 (3.1); at least 4 (1.2) horizontally from or 1 (0.3) above any door/window	401.4 and 501.2.1 401.4.1 804.3.4		
Garage entry, automobile loading area, or drive-in queue (Note 5)	15 (5)	Not covered							
Truck loading area or dock, bus parking/idling area (Note 5)	25 (7.5)	Not covered							
Driveway, street, or parking place (Note 5)	5 (1.5)	Public way or driveway: 10 (3) above							

Object	Minimum Distance, ft (m)								
	ASHRAE Standard 62.1, Table 5-1 (ASHRAE 2007a)	*2007 California Mechanical Code* (CBSC 2007a) and *Uniform Mechanical Code* (IAMPO 2006a)		*2007 California Plumbing Code* (2007b) and *Uniform Plumbing Code* (IAMPO 2006b)		*International Mechanical Code* (ICC 2006a)		*International Plumbing Code* (ICC 2006b)	
		Separation Distance, ft (m)	Section	Separation Distance, ft (m)	Section	Separation Distance, ft (m)	Section	Separation Distance, ft (m)	Section
Thoroughfare with high traffic volume	25 (7.5)	Not covered							
Roof, landscaped grade, or other surface directly below intake (Notes 6 and 7)	1 (0.30)	Not covered							
Garbage storage/pick-up area, dumpsters	15 (5)	Not covered specifically							
Cooling tower intake or basin	15 (5)	Not covered							
Cooling tower exhaust	25 (7.5)	5 (1.5) above or 20 (6.1) away	1131.0			5 (1.5) above or 20 (6.1) away	908.3		
		25 (7.6) for hospitals (OSHPD*)	1131.1						

Note 1: Significantly contaminated exhaust is exhaust air with significant contaminant concentration, significant sensory-irritation intensity, or offensive odor.

Note 2: Laboratory fume hood exhaust air outlets shall be in compliance with NFPA 45 (NFPA 1991) and AIHA Z9.5 (AIHA 1992).

Note 3: Noxious or dangerous exhaust is exhaust air with highly objectionable fumes or gases and/or exhaust air with potentially dangerous particles, bioaerosols, or gases at concentrations high enough to be considered harmful. Information on separation criteria for industrial environments can be found in *ACGIH Industrial Ventilation Manual* (ACGIH 1988) and in *ASHRAE Handbook—HVAC Applications* (ASHRAE 2007b).

Note 4: Shorter separation distances are permitted when determined to be in accordance with a) Chapter 7 of ANSI Z223.1/NFPA 54 (ANSI/NFPA 2002) for fuel gas-burning appliances and equipment, b) Chapter 6 of NFPA 31 (NFPA 2001) for oil-burning appliances and equipment, or c) Chapter 7 of NFPA 211 (NFPA 2003) for other combustion appliances and equipment.

Note 5: Distance measured to closest place that vehicle exhaust is likely to be located.

Note 6: No minimum separation distance applies to surfaces that are sloped more than 45° from horizontal or that are less than 1 in. (3 cm) wide.

Note 7: Where snow accumulation is expected, distance listed shall be increased by the expected average snow depth.

*OSHPD = Office of Statewide Health Planning and Development, California Health and Human Services Agency

A sidebar in this Strategy features an excerpt showing the separation distances and other requirements for outdoor air intakes and exhaust discharges for health-care facilities as published in *ANSI/ASHRAE/ASHE Standard 170, Ventilation of Health Care Facilities* (ASHRAE 2008). A 25 ft (7.6 m) separation distance is required between outdoor air intakes and cooling towers and all exhaust and vent discharges.

Exhaust Vents

For exhausts, other parameters such as velocities and orientations of exhausts (or exhaust stacks) are additional considerations for the designer. Chapter 44 of the *ASHRAE Handbook—HVAC Applications* has a detailed discussion of the subject, with expanded guidance in the section titled "Exhaust-to-Intake Dilution

Calculations" (ASHRAE 2007b). In addition, Chapter 16 of the *ASHRAE Handbook—HVAC Applications* provides basic information for evaluating wind airflow patterns and identifying problems caused by the effects of wind on intakes and exhausts. Figure 3.2-B provides a good example of improperly locating an HVAC outdoor air intake downwind and in close proximity to a bathroom exhaust of a five-story building. The HVAC system shown is the largest of the building's 13 air handlers.

Cooling Towers, Evaporative Condensers, and Fluid Coolers

Outdoor air intakes are best located at least 25 ft (7.6 m) away and upwind (prevailing wind) from plume discharges of cooling towers, evaporative condensers, and fluid coolers. In addition, outdoor air intakes need to be located at least 15 ft (4.6 m) away from intakes or basins of cooling towers, evaporative condensers, and fluid coolers (ASHRAE 2007a).

Buildings designed with insufficient separation distances between cooling towers and building intakes or with outdoor air intakes downwind of cooling towers could increase the risk of re-entrainment of cooling tower exhaust, which could include *Legionnella* bacteria (which could result in Legionnaires' Disease) as well as pollutants emitted by the chemicals used to treat the cooling tower water (which could affect health when inhaled). See Strategy 4.4 – Control *Legionella* in Water Systems for more information on Legionnaires' Disease.

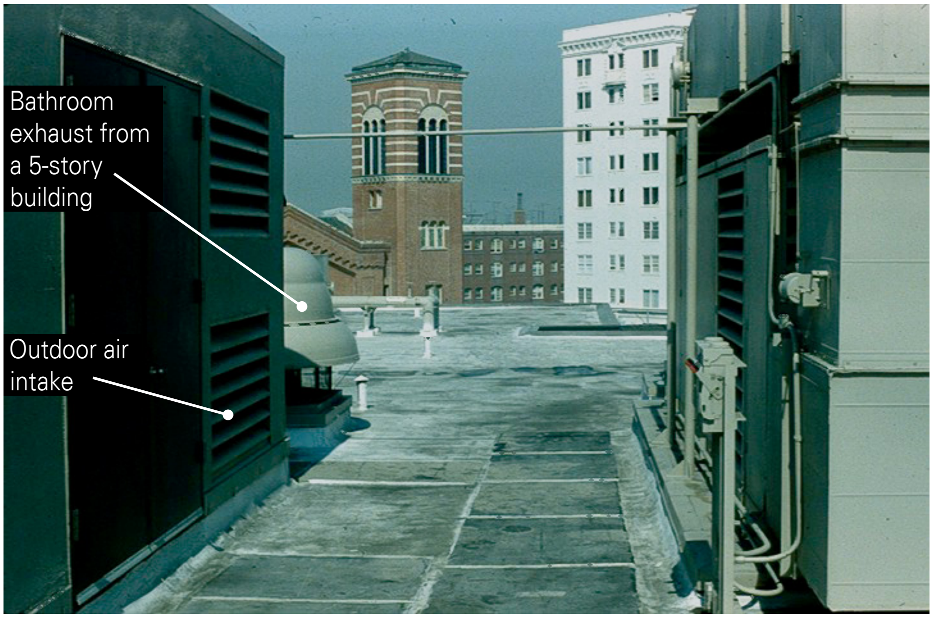

Figure 3.2-B HVAC Outdoor Air Intake Located Downwind of and in Close Proximity to Main Bathroom Exhaust of a Five-Story Office Building
Photograph courtesy of Hal Levin.

The ASHRAE Standard 62.1 (ASHRAE 2007a) recommendation on separation distances of cooling towers is paralleled by that of the California

ASHRAE/ASHE Standard 170

Section 6.3, Outdoor Air Intakes and Exhaust Discharges

6.3.1 Outdoor Air Intakes. Outdoor air intakes for air-handling units shall be located a minimum of 25 ft (8 m) from cooling towers and all exhaust and vent discharges. Outdoor air intakes shall be located such that the bottom of the air intake is at least 6 ft (2 m) above grade. Intakes on top of buildings shall be located a minimum of 3 ft (1 m) above roof level. New facilities with moderate-to-high risk of natural or man-made extraordinary incidents shall locate air intakes away from public access. All intakes shall be designed to prevent the entrainment of wind-driven rain, shall contain features for draining away precipitation, and shall be equipped with a bird screen of mesh no smaller than 0.5 in. (13 mm).

6.3.2 Exhaust Discharges. Exhaust discharge outlets that discharge air from AII rooms, bronchoscopy rooms, emergency department waiting rooms, nuclear medicine laboratories, radiology waiting, and laboratory chemical fume hoods shall

1. be designed so that all ductwork in occupied spaces is under negative pressure;
2. discharge in a vertical direction at least 10 ft (3 m) above roof level and shall be located not less than 10 ft (3 m) horizontally from air intakes, openable windows/doors, or areas that are normally accessible to the public or maintenance personnel and that are higher in elevation than the exhaust discharge; and
3. be located such that they minimize the recirculation of exhausted air back into the building.

Source: ASHRAE (2008).

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Department of Health Services (CDHS) in a publication titled *Minimizing the Risk of Legionnaires' Disease in Public Buildings*, which also recommends a 25 ft (7.6 m) separation distance between cooling towers and building air intakes (CDHS 1995). This recommendation is not limited to any specific building type. Similarly, ASHRAE Standard 170 also requires a 25 ft (7.6 m) separation (ASHRAE 2008).

In existing buildings where these recommended distances are not met, there are a variety of engineering alternatives such as extending the HVAC outdoor air intakes (see the case study titled "Cooling Tower Exhaust Locations") or adding extension cylinders or cowls at the exhaust plumes of the cooling towers. Such engineering solutions ought to be avoided in new construction in lieu of the recommended minimum distances.

Figure 3.2-C shows a cooling tower with extension cylinders (cowls) added to the exhaust plume. Extension cylinders need to be level with and preferably higher than any adjacent walls or buildings. In this instance, more extensions could have been added; however, the number of extensions is limited by the manufacturer's design of the exhaust plume.

In contrast, Figure 3.2-D shows a cooling tower with extension cylinders added to the exhaust plume where the extension cylinders are higher than the adjacent wall, helping to ensure better dispersion of the exhaust plume mist and contaminants.

Laboratory Fume Hoods and Exhaust Stacks

The National Fire Protection Association (NFPA) and the American Industrial Hygiene Association (AIHA) each provide guidance for separation distances between building air intakes and laboratory fume hood exhausts (NFPA 2004; AIHA 2003). A minimum separation distance of 30 ft (9 m) is recommended by McIntosh et al. (2001), but the maximum possible separation is a good practice (McIntosh 2001; DiBernardinis 1993). Computational fluid dynamics (CFD) and/or wind tunnel analyses may be needed in these or similar applications, depending on the constituents in the exhaust airstream.

Other Sources of Contamination

All nearby potential odor or contaminant sources (e.g., restaurant exhausts, emergency generators) and prevailing wind conditions need to be evaluated. Figure 3.2-E is a good example of a unit ventilator outdoor air intake located too close to ground level. This unit ventilator outdoor air intake at a school resulted in debris being drawn into the intake.

Figure 3.2-C Cooling Tower with Too Few Extension Cylinders (Cowls) Added to the Exhaust Plume
Photograph copyright Evapco, Inc.

Plumbing Vents

In certain applications, sewage systems may be under slightly positive pressure, resulting in excessive odor at the plumbing vent outlet. If the designer determines that the resulting required separation distances are excessive and impractical, such as in the case of an existing installation, alternatives are available as listed below. It is important that the designer a) does not use these alternatives in lieu of plumbing vents to the outdoors, b) ensures that all code requirements are met, and c) confirms with the local building authorities that these alternatives are acceptable. In addition, attention needs to be paid to ensuring that build-up of potentially explosive sewer gases (e.g., methane) in the building's plumbing

Strategy 4.1

Control Moisture and Dirt in Air-Handling Systems

Introduction

Fungi and bacteria are normally present on most interior surfaces in buildings, including surfaces in HVAC system components.[1] These microorganisms become problematic to IAQ when they amplify or grow on surfaces, with growth sometimes manifest to the point where it is visibly obvious. The cost from asthma resulting from dampness and mold in U.S. homes has been estimated to be $3.5 billion annually, and current evidence suggests that schools and commercial buildings have similar dampness and mold problems (Mudarri and Fisk 2007). The growth of microorganisms in HVAC systems can result in malodors, building-related symptoms such as nasal and throat irritation, and in rare cases building-related illnesses (BRIs) such as humidifier fever and hypersensitivity pneumonitis.

Studies in air-conditioned buildings in both North America and Europe have found that building-related symptoms can be associated with moisture and dirt in HVAC systems. Early studies in the United Kingdom (Burge et al. 1987; Harrison et al. 1987) as well as more recent investigations (Seppanen and Fisk 2002) have consistently hypothesized that microbial contaminants in moist HVAC components may be responsible for increased-building related symptoms in air-conditioned buildings. Studies by the National Institute of Occupational Safety and Health (NIOSH) in 104 problem buildings (buildings with IAQ complaints) have shown that defects such as flooded drain pans and inadequately maintained and dirty HVAC systems were found in at least 50% of the evaluated buildings (Crandall and Sieber 1996; Sieber et al. 1996). Thus, control of both moisture and dirt (nutrient) in HVAC systems is important in reducing microbial contamination associated with building-related symptoms in air-conditioned buildings. Implementation of design strategies that limit moisture and dirt accumulation in HVAC components will lessen the risk of microbial growth on HVAC component surfaces.

Moisture can enter HVAC systems from snow and rain intrusion through outdoor air intakes and from water leaks into ducts. In some HVAC systems, moisture is intentionally added to the airstream by humidifiers in the air-handling units (AHUs) or in the air supply ductwork. In addition, low temperatures in HVAC equipment associated with the air-conditioning process result in the production of liquid water in the coil section along with moisture-saturated air and damp surfaces in supply air ducts downstream of cooling coils. Microorganisms including fungi and bacteria can grow in liquid water and damp/moist niches along airstream surfaces in HVAC systems. Reviews on microbial problems in buildings discuss requirements for growth including moisture, temperature, and nutrients (ACGIH 1999; Flannigan and Miller 2001; AIHA 2005). As noted, wet/damp niches can and do occur in HVAC equipment and while moisture, especially in air-conditioning equipment, can be reduced by good design, elimination of wet/damp airstream surfaces is seldom possible. Temperature is generally not limiting for microbial growth in HVAC equipment, as a wide variety of fungi and bacteria can grow on wet/damp surfaces even at temperatures in refrigerators (e.g., growth of the common mold *Cladosporium cladosporioides* on refrigerator gaskets [AIHA 2005]).

The HVAC designer is encouraged wherever possible to use nonbiodegradable materials in wet or damp HVAC equipment niches. However, dust and dirt accumulation on all wet/damp surfaces can readily support microbial growth, even on surfaces such as steel that are nonbiodegradable. Thus, limiting the amount of liquid water, damp niches, and dust and dirt accumulation are all important HVAC design considerations.

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[1] Molds such as *Cladosporium cladosporioides* grow on vegetation (botanical materials such as leaves and twigs) in the outdoor terrestrial environment. Spores of these molds are thus universally present in the outdoor air under most circumstances (one exception being winter snow cover). Other molds such as *Aspergillus* and *Penicillium* species grow on decaying botanical debris in the soil and consequently occur in small amounts in the outdoor air. It is therefore normal to find airborne molds in buildings (entry is by infiltration through openings in the envelope and via HVAC outdoor air inlets) as well as in settled dust on interior surfaces. The presence of a few mold spores on interior surfaces is considered "normal deposition." A problem occurs when viable spores on a surface encounter a moisture condition adequate to initiate the growth process, leading to the presence of visible mold on that surface.

Outdoor Air Intakes and Air Intake Plenums

Sections 5.6.2, 5.6.3, and 5.6.4 of *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007a), offer considerable discussion on rain and snow intrusion into HVAC equipment. Section 5.6.4 requires suitable access doors to permit cleaning and presumably to remove snow (meltwater) that may penetrate into the intake. In addition to what is covered in these sections, note that below-grade outdoor air intakes in practice are accumulation sites for dirt and debris, including rotting botanical materials like leaves, which are growth sites for fungi such as *Aspergillus fumigatus*. Outdoor air entering below-grade and grade-level inlets is often contaminated by various pollutants such as mold spores from decaying leaves, pesticides, and fertilizers.

Practical actions to protect outdoor air intakes from contamination and to remove water that may enter the inlet include the following:

- Recognize during the design process that below-grade and grade-level outdoor air intakes are most susceptible to the entry of landscape pollutants such as leaves, pesticides, and fertilizers. Consider provision during design for removal of leaves, dirt, and debris that accumulate near inlets, within wells associated with below-grade intakes, or downstream of the intake bird screens. Adequate access is needed so that maintenance persons can enter these spaces with vacuum cleaners to remove accumulated dust and debris.
- Materials that are used to construct the airstream surfaces of outdoor air intake plenums should be as smooth as possible, resistant to corrosion, and readily cleanable.
- Outdoor air intakes constructed above grade should be located as far as possible from external pollutant sources, including moisture and particulate matter (dirt). (See minimal separation distances in Table 5.1 of ASHRAE Standard 62.1 [ASHRAE 2007a]).
- Information on design of outdoor air intakes to reduce rain and snow entry is found on pages 5-16 to 5-18 of the *62.1 User's Manual* (ASHRAE 2007b).

Filters and Microbial Growth in HVAC Equipment

Highly efficient filters provide an important design tool for reducing the amount of dirt and dust that might otherwise settle on airstream surfaces. Fine dust that can settle out in HVAC equipment contains an abundance of carbonaceous-rich components such as lint and textile fragments, soil and silt particles, skin scales, and outdoor botanical (e.g., pollen) and microbial (e.g., phylloplane-leaf sourced fungi) particles that are nutrients for microbial growth under damp/wet conditions.

The dust cake of a wet filter provides a nutrient-rich site for microbial growth. A wet filter thus becomes a microbial growth site. Design considerations for filters that potentially affect HVAC microbial contamination include the following:

- Keep filters dry regardless of filter location. Provide for an operation and maintenance (O&M) inspection program to verify that filters are periodically checked to verify a dry condition (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ.)
- Use the most highly efficient filters possible (see Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives) to keep fine dust out of damp or wet HVAC niches such as drain pans and cooling coil sections. A MERV 11 filter provides good protection for reducing fine dust on HVAC surfaces; a MERV 13 filter provides better protection.
- Discard wet filters.

Water Accumulation in HVAC Drain Pans

The purpose of the drain pan beneath the cooling coil section is to collect water that condenses on the coils and to quickly remove this water from the AHU. Figure 4.1-A in Part I of this Strategy provides an example of poor design and subsequent poor maintenance of an AHU drain pan. Water stagnated in the pan, fine dust accumulated over time in the pan, and a thick biofilm (a gelatin-like mass containing bacteria, fungi, and protozoa) grew on the inside metal pan surfaces, eventually filling up much of the pan. Section 5.11.1 of ASHRAE Standard 62.1 (ASHRAE 2007a) and Section 10.4.4.3 of the American Conference of Governmental Industrial Hygienists (ACGIH) *Bioaerosols Assessment and Control* (ACGIH 1999) contain guidance on making drain pans self-draining. It is important that the drain hole for the pan be flush with the bottom of the pan. When the AHU is mounted in a mechanical room, it is important to make certain that allowance is made for mounting the drain line at the very bottom of the pan. Figure 4.1-B from *Managing Building Moisture* (Stanke et al. 1998) illustrates a double-sloped drain pan design intended to maximize water drainage.

Just as the location and slope of the drain pan are important, it is equally important to make certain that the trap on the drain line is properly sealed (see Section 5.11.3 of ASHRAE Standard 62.1 and Section 10.4.4.3 of *Bioaerosols Assessment and Control*) to allow water from the pan to drain even under maximum negative pressure created by the fan. Pages 5-27 to 5-28 of the *62.1 User's Manual* (ASHRAE 2007b) contain additional design information for drain pans and trap seals. *Managing Building Moisture* (Stanke et al. 1998) provides drain pan trap seal design information for both draw-thru and blow-thru AHUs.

It is important during design of the AHU to provide the owner/operator with a maintenance/inspection plan for the drain pan assembly. Key elements of this plan include periodic inspection of the pan for self-drainage and for biofilm development. If the wet surfaces of the pan feel gelatin-like or slimy to the touch, this is a certain sign of biofilm development. Physical cleaning of the pan is required for biofilm removal; biocide treatment is not a substitute for physical cleaning (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ).

Moisture Carryover from Cooling Coils

Moisture carryover from cooling coils can result in wetting of downstream surfaces and microbial growth on these surfaces. It can be reduced by guidance in Section 5.11.4 of ASHRAE Standard 62.1 (ASHRAE 2007a) and Section 10.4.4.2 of *Bioaerosols Assessment and Control* (ACGIH 1999). If the air velocity is too high over a part of the coil section (e.g., possibly due to localized accumulation of dirt), water droplets may wet downstream surfaces.

Ultraviolet germicidal irradiation (UVGI) of cooling coils and drain pans is also useful for microbial control. The designer is advised to review Martin et al. (2008) with regard to installation and maintenance of UVGI in HVAC equipment (see also Strategy 4.5 – Consider Ultraviolet Germicidal Irradiation).

Smooth and Cleanable Surfaces

While microorganisms can grow on smooth but dirty surfaces in HVAC equipment, growth will usually be greatest on porous or irregular airstream surfaces where dust and dirt (nutrient) accumulation is highest. Figure 4.1-C shows that the most dense area of mold growth in a particular case occurred on a porous airstream surface downstream of the cooling coil. Removal of microbial growth, dirt, and dust from porous or fibrous airstream surfaces is more difficult than removal from nonporous surfaces such as sheet metal.

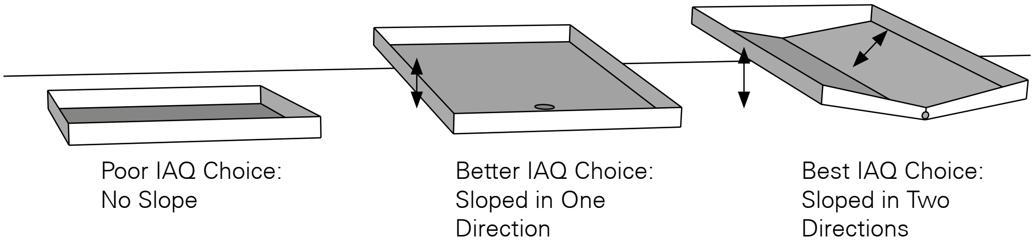

Figure 4.1-B Drain Pan Examples with and without Slope
Adapted from Stanke et al. (1998).

Antimicrobials should not be used as a substitute for removal of visible mold growth that may occur on HVAC airstream surfaces (AIHA 2008).

Designers should consider the following in order to reduce moisture and mold problems near the plenum housing cooling coils:

- Specify airstream surfaces that are smooth, readily cleanable, and not subject to corrosion or deterioration (see ACGIH [1999], Section 10.4.4.5).
- Design main air supply ducts for easy access for periodic inspection and future cleaning as necessary.
- Reduce reliance on antimicrobials; emphasize maintenance to achieve a minimal dust condition in this portion of the HVAC system. Excellent filtration is necessary to limit dust accumulation.
- Consider UVGI for control of microbial growth in HVAC system components such as drain pans and cooling coils. Safety considerations with the use of this technology must be considered by the designer (ASHRAE 2008) (see Strategy 4.5 – Consider Ultraviolet Germicidal Irradiation).

While mold growth will occur readily on dusty, porous airstream surfaces, growth can also occur on relatively smooth metallic surfaces in air-conditioning ductwork. Figure 4.1-C shows a porous airstream surface that is about 5 ft (1.5 m) downstream from cooling coils and is heavily colonized by visible mold growth. Figure 4.1-D shows dust and debris present on the metal airstream surface of an externally insulated supply air duct. Figure 4.1-E shows the mold growth (magnification about 400×) that has occurred on the dust and debris shown in Figure 4.1-D. Note the abundant presence of spores and hyphae in Figure 4.1-E. This illustrates the importance of maintaining all airstream surfaces of HVAC equipment to a minimal dust condition, especially in damp/wet locations. Remember, dust and dirt in a damp/wet environment is food (nutrient) for molds!

Residual oils and lubricants found on metal surfaces in newly fabricated ductwork and plenums are sticky and may accumulate dust deposits that may become nutrient sources for microbial growth in wet conditions. Removal of residual oils and lubricants from metallic airstream surfaces prior to equipment commissioning will help to limit these concerns, but such removal requires a significant amount of effort and is not a typical construction activity. If such cleaning is to take place, it needs to be included in the specifications, and the extra expense must be included in the construction budget

Figure 4.1-C Porous Airstream Surface Heavily Colonized by Visible Mold Growth
Photograph courtesy of Phil Morey.

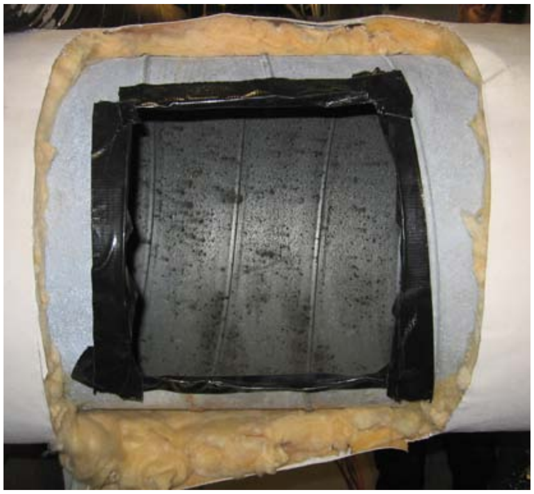

Figure 4.1-D Dust and Dirt Present on the Metallic Airstream Surface of Externally Insulated Supply Air Duct
Photograph courtesy of Phil Morey.

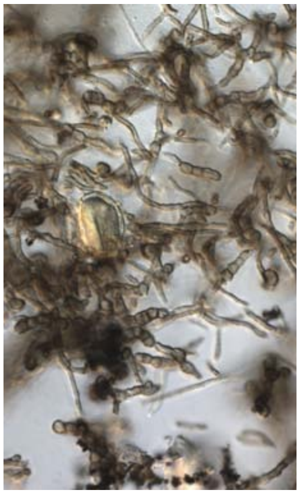

Figure 4.1-E Mold Growth (Spores and Hyphae) on the Dust and Dirt on a Metallic Airstream Surface
Photograph courtesy of Phil Morey.

Duct Liner

Metal and sometimes plastic ducts are typically thermally insulated with either an external or internal insulation. Various types of insulation are used, including fibrous rigid board, fibrous wrap, flexible fibrous wrap, and closed-cell foam insulation. While both internal and external insulations can provide the necessary thermal protection to reduce heat transfer and prevent condensation of moisture, the internal duct insulation (better known as *duct liner*) is often also used to better control the acoustic noise in a fan and air distribution system. However, installing insulation internally in a duct system may increase the potential for introducing unwanted particles, fungi, and bacteria.

From an IAQ perspective, the most important things are cleanability, erosion, and moisture absorption, but in terms of overall performance one must consider other factors including flammability, acoustical performance, adhesion, and cost.

The most common duct liners are typically constructed from fibrous materials. In theory, if kept clean and dry and protected from erosion or deterioration of the binder, fibrous materials can be acceptable liner material. However, the face of duct liner material is typically porous and not as smooth as the sheet metal surface to which it is mounted. Therefore, it may be difficult to maintain a clean and dry duct liner with a fibrous or rough surface over the life of the building with typical or even above-average airstream filtration. The duct liner's fibrous or rough surface presents a potential for mold growth since the dirt that accumulates on the surface promotes the retention of moisture and the organic material in the accumulated dirt provides nutrients for mold growth. It is difficult to remove mold hyphae that have grown in and around duct liner fibers, though mold growth as shown in Figure 4.1-E may be physically removed from metallic airstream surfaces by duct cleaning.

The acoustic noise control of an air distribution system is best achieved with a holistic approach that includes equipment selection, sizing and location, and proper air distribution design, which includes sizing, velocity, fabrication integrity, and diffuser selection. If necessary, the services of an acoustical engineer can be engaged.

If the use of internal duct liner is specified, the following information should be taken into consideration:

- Install all liner per the design specifications, applicable standards and guidelines of the Sheet Metal and Air Conditioning Contractors' National Association (SMACNA) and the North America Insulation Manufacturers Association (NAIMA), and the manufacturer's instructions. Ensure that there are no gaps or cavities in the installation and that all adjacent sections are properly connected. Seal and protect all edges of the insulation from the flow of the airstream. A comparison of fibrous and closed-cell duct liners is available in Table 4.1-A.
- Investigate the use of manufactured, double-walled ductwork. While potentially more expensive than conventional single-layer sheet metal duct, the liner in this product is completely enclosed, reducing the potential for liner deterioration and the direct exposure of the liner to the airstream. The inner wall of most double-wall ductwork is also perforated, which can provide better acoustical control.

Table 4.1-A Comparison of Fibrous and Closed-Cell Duct Liners

Liner	Material Standards	Installation Guide	Acoustical Performance	Dust Accumulation	Flammability Ratings	Airstream Surface Deterioration
Fibrous	ASTM C1071 (ASTM 2005)	NAIMA, SMACNA	Probably better	Probably not as good	Yes	Possibly more prone
Closed Cell	ASTM C1534 (ASTM 2007)	Per manufacturer	Probably not as good	Probably better	Typically not	Possibly less prone

Impact of Humidifier Moisture on Airstream Surfaces

Humidifiers, if used in HVAC systems, are usually incorporated into AHUs or main air supply ducts. Humidifiers that emit water droplets may draw their water supply directly from a potable cold water pipe or directly from a sump containing water that is recirculated. The potential for microbial contamination of humidifier water droplets is directly related to the contamination in the supply water that is aerosolized (ACGIH [1999], Section 10.4.4.4). It is well known that water droplets aerosolized from sumps containing recirculated water are heavily colonized by various microorganisms, including actinomycetes, gram-negative bacteria such as *Flavobacterium*, and yeasts.

Thus, it is a desirable practice to use humidifiers that work on the principle of aerosolization of water molecules (absence of carryover of microbes) instead of water droplets (where microbial components may be carried over).

If steam is used in humidifier operation, it is important to determine whether the steam source contains corrosion inhibitors. Corrosion inhibitors, which may be present in boiler steam, can carry over into humidifier aerosol and cause IAQ complaints from building occupants.

Regardless of the kind of humidifier used in an AHU or in supply ducts, it is important during HVAC design to verify that moisture emitted by the humidifier is completely absorbed by the ventilation airstream within the absorption distance recommended by the humidifier manufacturer (ASHRAE [2007a], Section 5.13.2). The use of airstream surface materials that are smooth and easily cleanable is desirable within that moisture-absorbing distance.

O&M procedures prepared by the designer should include periodic inspection of HVAC components containing humidifiers. Water present on airstream surfaces near humidifiers in AHUs or in supply ducts is a certain indication of moisture failure and possible microbial growth. Filters that may be present in AHUs near humidifiers should not be wetted by humidifier moisture.

Page 5-31 of the *62.1 User's Manual* (ASHRAE 2007b) contains additional design information for humidifiers used in HVAC equipment. Table 4.1-B can be used as a resource guide when designing and constructing HVAC system components.

Table 4.1-B Moisture and Dirt in HVAC Resource Guide

**See also 62.1 User's Manual (ASHRAE 2007b).*

Outdoor Air Intakes and Outdoor Air Intake Areaways*	
Rain entry	ASHRAE (2007), Sections 5.6.2 and 5.6.3
Snow entry	ASHRAE (2007), Section 5.6.4
Access for cleaning and water removal	Properly sized access panels allow removal of water, dirt, and debris in the outdoor air inlet plenum.
Below-grade or grade-level intakes	Preferably located above grade at a location minimally impacted by water and air pollutants.
Preventing HVAC Filters From Becoming Wet	
Evaluation of wetting potential	Verify that filters cannot be wetted by water from outdoor sources or sources in the AHU; ACGIH (1999), Section 10.4.4.1.
O&M program for filters	O&M program should verify that filters are maintained in a dry condition.
Standing Water in HVAC Drain Pans*	
Drainage characteristics of drain pans	ASHRAE (2007), Section 5.11.1; ACGIH (1999), Section 10.4.4.3
Properly trapped drain pans	ASHRAE (2007), Section 5.11.3; ACGIH (1999), Section 10.4.4.3
Monthly cleaning	ASHRAE (2007), Section 8.4.1.5; One per month (or more) cleanings during air-conditioning season.
Moisture Carryover from Coiling Coils; Smooth and Cleanable Surface	
Water droplet blow-through from coils	ASHRAE (2007), Section 5.11.4; ACGIH (1999), Section 10.4.4.2
Accumulation of dust and debris	Making airstream surfaces as smooth as possible reduces accumulation of dust and debris; ACGIH (1999), Section 10.4.4.5
O&M program for airstream surfaces	O&M program should include dust removal from smooth and non-smooth surfaces, especially in locations downstream from cooling coils.
Reliance on antimicrobials	Antimicrobials should be avoided because microorganisms can grow on dirt accretions that accumulate on treated surfaces.
Residual oils from airstream surfaces	Manufacturers can provide information on the removal of sticky residual oils from sheet metal surfaces.
Impact of Humidifier Moisture on Airstream Surfaces*	
Water droplet or water molecule emissions	ACGIH (1999), Section 10.4.4.4; Humidifiers that emit water droplets from a sump should be avoided.
Humidifier water source	ASHRAE (2007), Section 5.13.1; Boiler steam with corrosion inhibitors should be avoided.
Complete entrainment of humidifier moisture	ASHRAE (2007), Section 5.13.2
Smooth airstream surfaces	Preferable to use smooth materials on airstream surfaces within moisture-absorbing distance.

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Strategy 4.2

Control Moisture Associated with Piping, Plumbing Fixtures, and Ductwork

Introduction

Condensation and mold growth can occur on the insulation jacket of cold water piping for a number of reasons, including a) an inadequate R-value of the installed insulation, b) a failed vapor retarder, and c) an unanticipated high dew-point temperature in the microenvironment where the piping is located. Figure 4.2-A in the summary guidance portion of this Strategy (Part I of this Guide) shows water droplet formation on cold water piping in an unventilated ceiling location where the dew-point temperature was elevated. Mold growth occurred not only on the pipe jacket but also on ceiling tiles and paper-faced wallboard wetted by the water drops. This type of moisture/mold problem can be hidden from view (e.g., in a wall cavity) and can result in a significant mold growth/building damage problem and increase the risk of significant IAQ problems.

Limiting Condensation

Condensation on cold water pipes or cold air supply ducts occurs whenever the surface temperature is below the dew point of the air coming in contact with the pipe or duct surface. It is important, therefore, for the designer to anticipate dew-point temperatures in microenvironments such as ceiling spaces, wall cavities, mechanical equipment rooms, and utility chases where cold water piping and cold air supply ducts will be located. Additionally, it is important to specify an adequate insulation R-value and a continuous vapor retarder to prevent condensation.

Areas of particular risk that often are ignored include the following:

- Areas such as mechanical equipment rooms and utility tunnels where operation and maintenance (O&M) personnel must crawl over or walk on pipe or duct insulation jackets. In these locations, the designer needs to specify a polyvinyl chloride (PVC) or aluminum jacket for purposes of protecting the insulation and vapor retarder.
- Horizontal storm water piping above ceilings needs to be properly insulated to minimize condensation.
- Vertical piping (e.g., storm water, condensate, etc.) needs to be appropriately insulated in risers and wall cavities subject to infiltration in order to limit condensation.

Limiting Leaks

Mold growth problems associated with plumbing leaks can occur in wall cavities, utility chases, ceilings, and other interior spaces. The mold/moisture problem associated with plumbing leaks may be small (e.g., an occasional leak beneath a sink) or massive (e.g., slow leaks in plumbing in wall cavities in stacked restrooms in high-rise buildings such as hotels). Paper-faced wallboard, composite wood products, and ceiling systems are especially susceptible to damage and mold growth from plumbing leaks. Materials in occupied spaces may also be damaged.

The designer needs to take actions to reduce the potential for plumbing leaks, including the following:

- Testing water lines according to Section 312.5 of the *International Plumbing Code* (ICC 2006).
- Specifying a construction schedule with adequate time for water line testing while the plumbing is still accessible for inspection and repair.
- Testing the integrity of water-holding assemblies, including whirlpools and shower pans, before occupancy.

- Avoiding the placement of domestic water valves above ceilings in order to reduce water damage to ceiling systems.
- Avoiding the location of in-line humidifiers in areas where water leaks could cause building damage or mold problems

In building microenvironments where chronic leaks and floods are more likely occur over time (e.g., stacked restrooms in hotels and piping readily subject to corrosion, joint failure, and physical damage), the designer and the owner need to specify use of moisture-tolerant construction and finishing materials such as cement-based products, ceramics, plastics, metals, etc. The use of paper-faced wallboard and composite wood products needs to be significantly restricted in problematic wet microenvironments.

Providing a Plumbing System O&M Guide

An important aspect of controlling mold growth associated with cold water piping and plumbing systems is the assembly of O&M information in one location for the benefit of future users. A forthcoming book from EPA titled *Moisture Control in Public and Commercial Buildings: Guidance for Design, Construction, and Maintenance Professionals* (EPA n.d.) contains details on the types of documents that need to be assembled as well as a Plumbing Operation and Maintenance Checklist that needs to be followed for conducting inspections designed to limit plumbing leaks. Table 4.2-A outlines important subject areas contained in that guide.

Table 4.2-A Resource Guide for Mold Growth Associated with Piping and Plumbing

Limiting Condensation	
Dew-point conditions in piping locations	Plumbing System Design Goal #2 (EPA n.d.)
Insulation R-value and vapor retarder	Plumbing System Design Goal #2 (EPA n.d.)
PVC or aluminum jackets on exposed pipe surface	
Limiting Leaks	
Testing of water lines, fixtures, and assemblies	Section 312.5 (ICC 2006)
Testing when plumbing lines are open for inspection	Plumbing System Design Goal #1 (EPA n.d.)
Materials for pipe chases and locations susceptible to leaks (high moisture tolerance)	Plumbing System Design Goal #3 (EPA n.d.)
Plumbing System O&M Guide	
Locating the O&M information	Appendix G (EPA n.d.)
Inspection procedures	Appendix G (EPA n.d.)

References

EPA. n.d. *Moisture Control in Public and Commercial Buildings: Guidance for Design, Construction, and Maintenance Professionals*. Forthcoming. Washington, DC: U.S. Environmental Protection Agency

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Strategy 4.3

Facilitate Access to HVAC Systems for Inspection, Cleaning, and Maintenance

Introduction

Periodic inspection, routine maintenance, and cleaning of air-handling equipment have always been essential for maintaining acceptable IAQ during occupancy. In addition, assessing “soiling” of the HVAC system, monitoring the effectiveness of air cleaning, and validating the performance of monitors and sensors has become an increasingly important aspect of building operation and maintenance (O&M). It is therefore important to ensure access to HVAC system components, just as it is important to ensure access to the electrical panels and components. It is well recognized that routine maintenance can be significantly compromised by above-ceiling installations or locations requiring ladders or other equipment for access. In addition, systems with access doors or panels that can be opened without special tools are more likely to receive the appropriate inspection and maintenance.

Access in Design Documents

Locations that Facilitate Access

System access can be impacted by the initial decisions regarding the type and location of the HVAC system. That is, the design and selection of the HVAC system itself can either make access and maintenance easy for personnel or limit access and increase maintenance problems. For example, the installation of a small number of larger, central systems limits the number of locations requiring access, whereas the decision to install a network of smaller units increases the required access points. In addition, the location of the air-handling units (AHUs) can significantly impact access. While a properly located mechanical room or closet can simplify access to primary system components, the installation of HVAC systems or components in above-ceiling plenums or on rooftops can significantly complicate access.

A well-designed mechanical room can help facilitate proper maintenance by ensuring the appropriate positioning and clearances for access to the primary system components. However, the entire process of design, construction, equipment installation, and final commissioning needs to be controlled in order to prevent access from being compromised. As discussed in the sections that follow, even a well-designed mechanical room can be impacted by competition for space during construction, change order decisions in the field, and installation of other systems within the room.

The design of a decentralized system employing multiple “local” units frequently results in systems that are crammed into inaccessible spaces such as above-ceiling plenums or small utility closets (see this Strategy’s case study “Restricted Above-Ceiling Access Compromises Maintenance” in Part I of this Guide). Such installations introduce significant barriers for the maintenance staff because ladders or lifts are needed, the access point may necessitate disturbing building occupants, and the ability to access key system components is complicated. Couple those issues with the difficulty in moving tools and materials and you have a situation that encourages staff to defer or even neglect inspection and maintenance of the system.

Rooftop HVAC system installations also present significant maintenance challenges because of their location. The steep ladders that are typically provided for primary entry to the roof present a physical barrier that makes access difficult. While this issue can be partially addressed by proving stair access to the roof, the movement of people, tools, and materials can still be problematic. The thermal and weather conditions on the roof can also discourage access during certain times of the year.

Another location issue involves the positioning of HVAC equipment on a mezzanine structure. While this location can help minimize the footprint of the mechanical room/area, it presents several access concerns. One issue is the need to provide appropriate stairway access to the mezzanine, as ladder access is unacceptable. In addition, catwalks and work ways may need to be provided to permit uninhibited access to critical components.

Minimum Clearance Distances

It is essential that the design documents specify an adequately sized mechanical room that accommodates the AHU and other HVAC system components, along with the other mechanical systems, while providing sufficient working space for inspection and routine maintenance (e.g., filter replacement and fan belt adjustment and replacement). Most manufacturers provide guidance on the required service clearances. In addition, local code requirements may include clearance specifications. It is essential that such clearances take into account door swings and space for personnel to access the system, stand, and move tools and materials in and out.

Guidance to determine door swing is provided in SMACNA's *HVAC Duct Construction Standards—Metal and Flexible* (SMACNA 1997), which advises that casing access doors be 20 in. (508 mm) wide by 54 in. (1372 mm) high. SMACNA cautions that larger doors should be avoided since they will break the continuity of the wall reinforcement. They also emphasize that *doors should open against the air pressure*, as this arrangement utilizes the air pressure rather than the door latches to force the door against the sealing gasket. This same SMACNA source specifies the size for duct access doors and panels as 12–24 in. (305–610 mm), depending on static pressure conditions. Based on these recommended sizes for access doors and panels, the minimal suggested clearance distances include 2 ft 6 in. (0.8 m) on all sides of the AHU, except on the side where filters and coils are accessed, in which case clearance needs to be 2 ft (0.6 m) greater than the length of the coil. This type of guidance needs to be integrated into the total mechanical room/space design.

An additional consideration is the possible replacement of major equipment over the life of the building. Adequate space to allow for the replacement of coils or other large components needs to be provided by properly situating the equipment to allow a change-out without damage to the building.

Critical AHU Components

ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality (ASHRAE 2007a), provides requirements for ensuring appropriate access to all components of the HVAC system, including the AHU, air distribution system, controllers, and sensors (see Figure 4.3-E). The specific requirements state that access doors, panels, or other means shall be provided in ventilation equipment, ductwork, and plenums, located and sized to allow convenient and unobstructed access for inspection, cleaning, and routine maintenance of the following:

- Outdoor air intake, areaways, or plenums
- Mixed-air plenums
- Upstream surface of each heating, cooling, and heat-recovery coil having a total of four rows or fewer
- Both upstream and downstream surfaces of each heating, cooling, and heat-recovery coil having a total of more than four rows and air washers, evaporative coolers, heat wheels, and other heat exchangers
- Air cleaners
- Drain pans and drain seals
- Fans
- Humidifiers

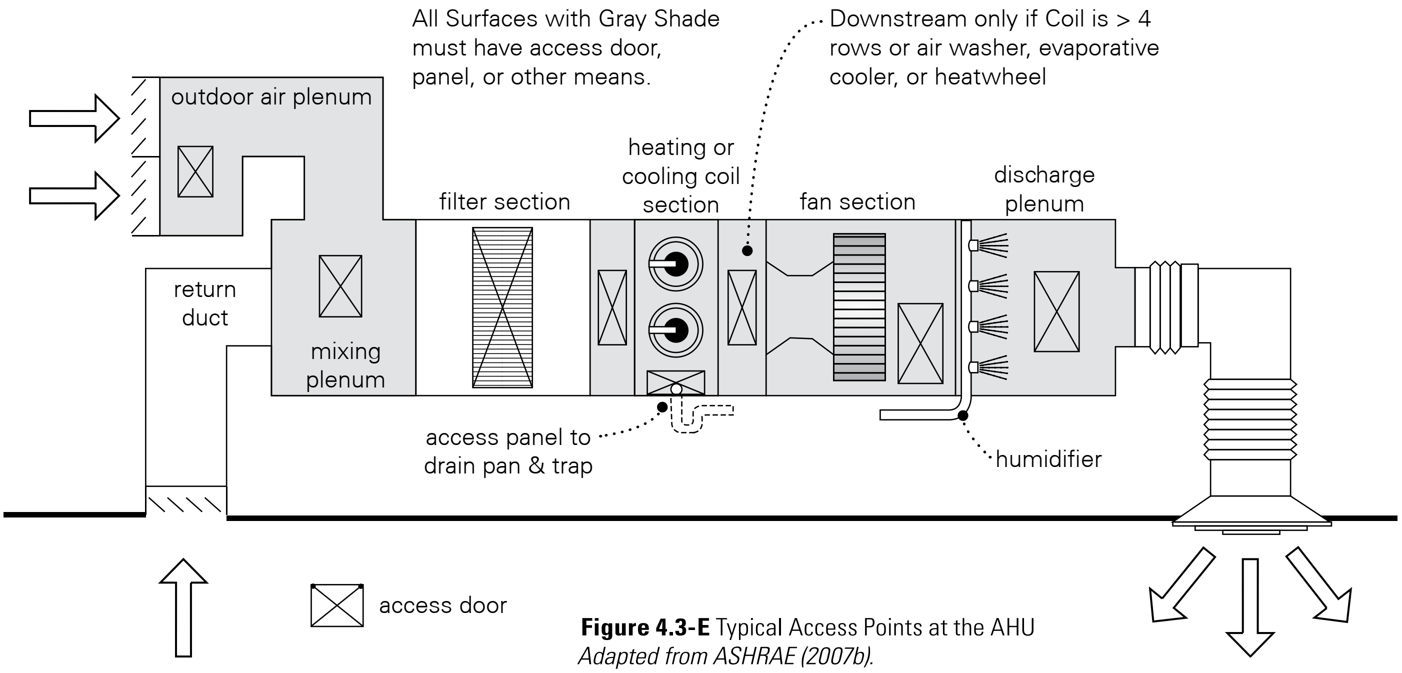


Figure 4.3-E Typical Access Points at the AHU
Adapted from ASHRAE (2007b).

Air Distribution System

Access to the air distribution system is frequently ignored except when fire codes or other requirements necessitate planned access for inspection or maintenance of dampers or monitoring equipment. Even ASHRAE Standard 62.1 (ASHRAE 2007a) does not require access to the air distribution system except at the outdoor air intake areaways or plenums. While this is clearly an important area, there are numerous other locations where access for routine inspection is desirable. For example, areas around turning vanes, 90° turns, and duct terminations are locations were dirt entrained in the airstream can accumulate because of impaction and/or settling. Periodic inspection of these locations can provide valuable information about the efficacy of the particulate matter filters and/or air cleaners. In addition, targeted maintenance/cleaning of these areas is greatly simplified by the installation of access panels or doors.

System Balancing and Monitoring Access

The location/placement of balancing and monitoring devices needs to be designed to ensure proper access and clearance. These devices are best installed either below the ceiling or in easily accessible above-ceiling locations (see Figure 4.3-F) whenever possible. It is wise to consider the future occupancy of the space and try to select locations that will not require the movement of furnishings or people in order to access these devices.

In the example shown in Figure 4.3-F, the floor-to-floor height is 20 ft (6.1 m) and a ceiling is installed 8 ft (2.4 m) above the finished floor. If the HVAC equipment, ductwork, and balancing devices are installed tight to the deck, they are nearly 12 ft (3.7 m) above the ceiling. There is no way to access this equipment once the ceiling is installed. It is critical to ensure that the devices that require access, including balancing dampers, controllers, etc., are located close enough to the ceiling so that a ladder can be used to reach the components through an access door or by removing one or two ceiling tiles.

As illustrated in Figure 4.3-G, the two balancing valves installed in this unit (factory installed) do not allow access to the test ports (circled) for flow measurement. The balancing valves could have been installed with the test ports facing out of the unit on the vertical piping to allow for insertion of the instrument test probes for flow measurement. If there is not enough clearance in the unit for the proper installation of the balancing valves, then the balancing valves need to be field-installed with proper access and clearance.

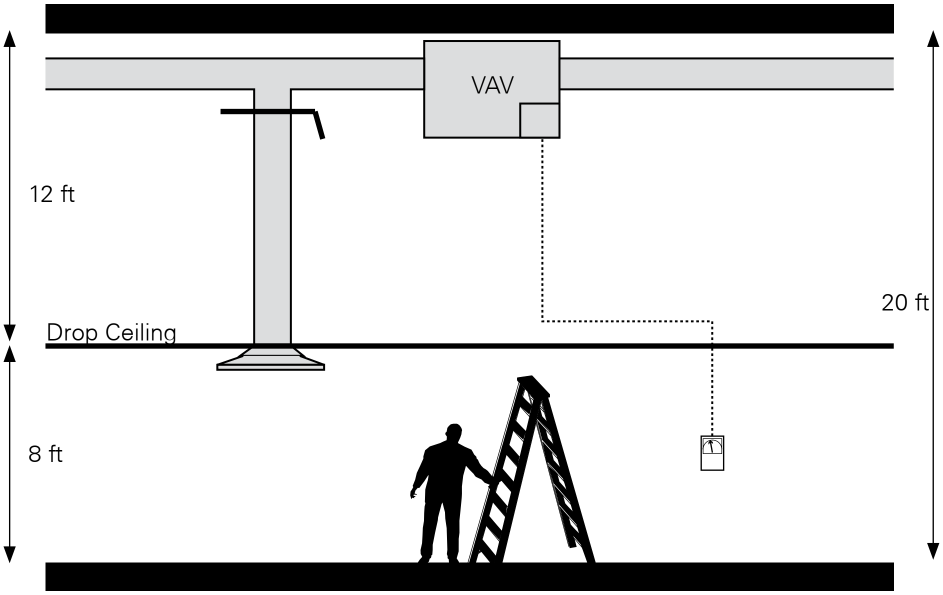


Figure 4.3-F Equipment Mounted High Above a Ceiling Can Be Impossible to Access

Terminal Equipment

Terminal equipment such as variable-air-volume (VAV) boxes and reheat units are locations where particles entrained in the airstream can accumulate. This dirt accumulation can impact the operation of the equipment and may lead to microbial growth at these locations. Thus, these units may require periodic inspection and/or cleaning. Designers can specify equipment with integrated access panels or doors to simplify this maintenance activity. If units without existing doors must be used, operable access doors can be installed to support future inspections.

Some terminal units are designed to draw ventilation or make-up air from the plenum space. This can result in a greater accumulation of particles and makes preexisting access panels all the more important.

Access to strainers on hot and chilled water systems need to be carefully planned. At terminal reheat devices in VAV boxes, the strainers are typically located above ceilings. Cleaning these strainers above ceilings in occupied areas can result in the release of water and dirt in the ceiling plenum or in occupied spaces. It is therefore preferable to locate the VAV boxes or reheat coils in areas that have minimal occupancy. Corridors or mechanical rooms are good locations for this equipment.

Figure 4.3-G Inaccessible Test Ports due to Balancing Valve Installation
Photograph courtesy of Jim Hall.

Electrical Code Access Criteria

There are multiple resources that offer guidance on providing adequate access and work space around HVAC equipment. The manufacturer's literature generally gives required service clearances. In addition, the National Fire Protection Agency (NFPA) *National Electrical Code* (2008) provides additional requirements related to service work space and access for electrical equipment that may be part of or near the HVAC system. Finally, Occupational Safety and Health Administration (OSHA) CFR 1910 (2008) also requires that sufficient space be provided and maintained around electrical equipment to permit ready and safe O&M of such equipment. While the NFPA and OSHA regulations/requirements focus on adequate work space around energized electrical equipment, they illustrate the need for clear access and adequate working space for equipment likely to require examination, adjustment, servicing, or maintenance. Their guidance establishes the width of the work space in front of the equipment as either the width of the equipment or 3 ft. (914 mm), whichever is greater. They also emphasize that the work space must permit at least a 90° opening of equipment doors or hinged panels.

Access Door/Panel/View Port Requirements

The type of access provided can vary based on the specific type of inspection or maintenance activity required at that location. For example, if visual monitoring is all that is required, a simple view port or panel may suffice. Such installations are less likely to leak air than an operable door. Air leakage can be a significant issue associated with providing access to the HVAC system because leakage of cooled air from the system can result in condensation, which can result in microbial growth within the HVAC system or on other building materials. Conversely, leakage on the negatively pressurized sections of the system can result in the infiltration of contaminants from the surrounding spaces, and these contaminants may degrade the IAQ in the occupied spaces serviced by the system. Nonetheless, operable access doors are preferred in any location where active maintenance is required.

Any access door, panel, or view port needs to be installed in compliance with SMACNA requirements as specified in their *HVAC Duct Construction Standards—Metal and Flexible* (2005). These standards provide great detail on the size, attachment, and locking of the access doors. This information is designed to ensure appropriate construction to facilitate access while maintaining the airtightness of the system.

As shown in Figure 4.3-H, SMACNA's *HVAC Duct Construction Standards—Metal and Flexible* provides specification for sizing and securing access doors and panels (SMACNA 1997).

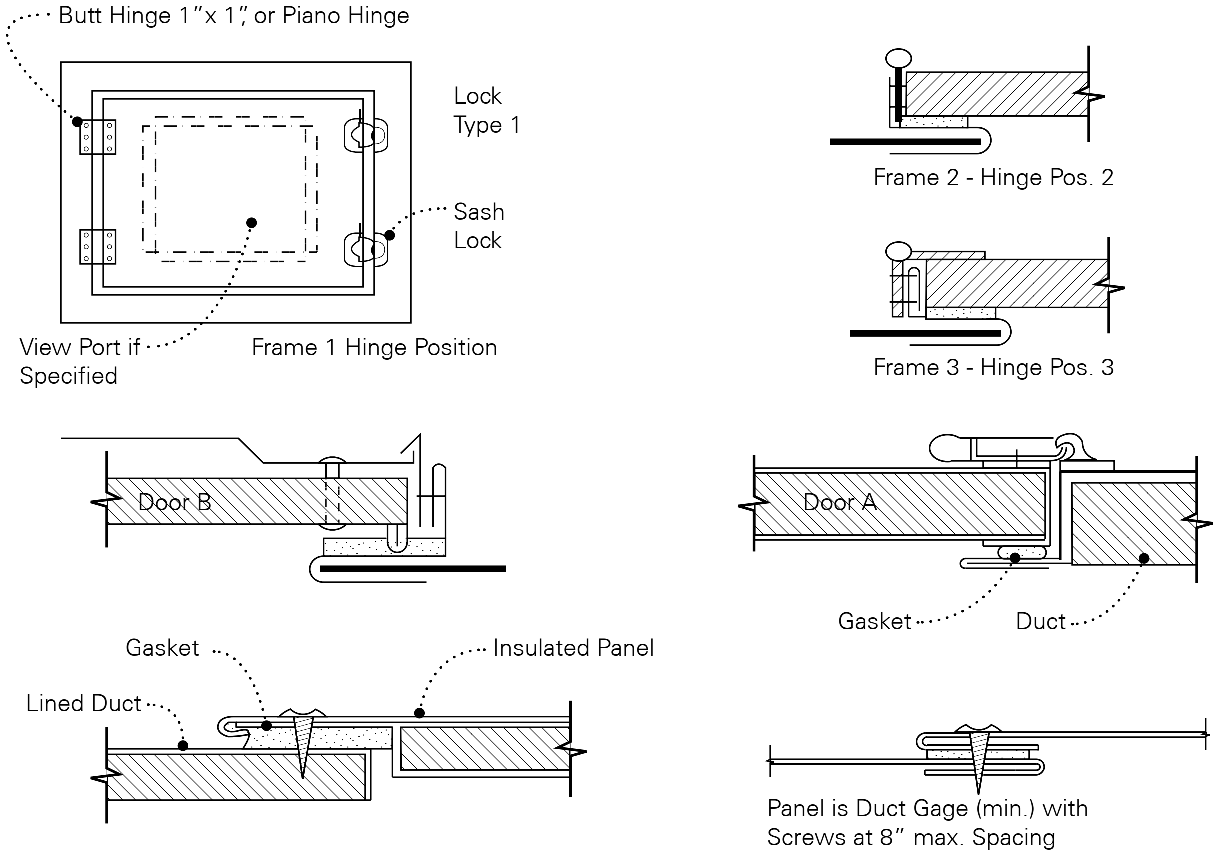


Figure 4.3-H Duct Access Doors and Panels
Adapted from SMACNA (1997).

Next Page

Strategy 4.3

Access During Construction

Coordination with Trades

Even with the best designs, access can be compromised during the construction and installation of any or all of the HVAC system components. In addition, installation of other building systems, such as plumbing systems, electrical systems, and telecommunication systems, can result in obstructions that either complicate or prevent direct access. Careful stewardship during the construction phase is essential for ensuring that clear access is maintained.

Review of Submittals

One means of helping to ensure the preservation of the design access specifications is to perform an ongoing review of all subcontractor submittals to confirm that the installation of additional mechanical systems/components does not interfere with designed access to the HVAC systems. Failure to conduct this proactive review can result in conditions that either necessitate expensive after-occupancy modifications or, if left uncorrected, present a permanent barrier to appropriate access for monitoring and maintaining the system.

Field Changes

Construction or design changes that are made in the field during the project represent another situation in which the original design intent can be compromised. Changes related to scheduling, changes in system layout, or even the type of equipment provided contribute to these potential problems. Certainly, a construction project is a dynamic environment where decisions may have to be made on the fly because of external pressures; however, the failure to assess and understand the long-term implications of such changes can significantly compromise access to the HVAC system. For example, the placement of the AHU may be adjusted to accommodate the installation of other mechanical system components, resulting in the

Compromised Access due to Contractor Activity

Activities by various trades can compromise access. In the example in this case study, the full opening of an appropriately sized access door was blocked by chilled-water piping that was installed after the positioning of the AHU.

Figures 4.3-I and 4.3-J show how the operation of the access door to the fan chamber of this AHU was blocked by chilled-water piping. While this may not have been identified when the piping was being installed, the addition of the pipe insulation and expanded hanger ultimately impacted the door opening. This condition may also present a risk to the chilled-water system if the vapor retarder is not protected from damage from the access door as it is opened during maintenance of the HVAC system.

Figure 4.3-I Access Door

Figure 4.3-J Access Door Blockage

Photographs courtesy of Wayne Thomann.

Strategy 5.1

Control Indoor Contaminant Sources through Appropriate Material Selection

Introduction

This Strategy, focusing on source control as an effective means to provide good IAQ, is organized into three major sections. The first section, "Contaminant Emissions: Basic Concepts," provides fundamental information on the key concepts related to IAQ contaminants and the evaluation of material as sources. The second section, "Emissions Data: Available Information," reviews the information sources available to assist building designers with material specification from an IAQ perspective and highlights the key differences between content- and emissions-based product labeling systems. The final section, "Priority Materials/ Finishes/Furnishings," builds on this knowledge to discuss available information and provide practical guidance on a product-by-product basis for materials that have been shown to have important impacts on IAQ. More detailed information is provided in Appendix F – Additional Information on Material Emissions for specific aspects related to these material selection strategies.

Contaminant Emissions: Basic Concepts

The contaminants found in nonindustrial indoor environments have been examined and characterized in many studies (including those by Wallace [1987, 2001], Tsuchiya [1988], Wolkoff [1995], Girman et al. [1999], Tucker [2001], Hodgson and Levin [2003a, 2003b], Alevantis [2006], and Alevantis et al. [2006]). Typically, indoor air contains complex mixtures of hundreds of individual compounds. The health or irritancy impact of individual compounds is highly variable. This important aspect of IAQ is briefly discussed in the section "VOCs—Total vs. Target: Irritancy, Odor, and Health Impact" in this Strategy.

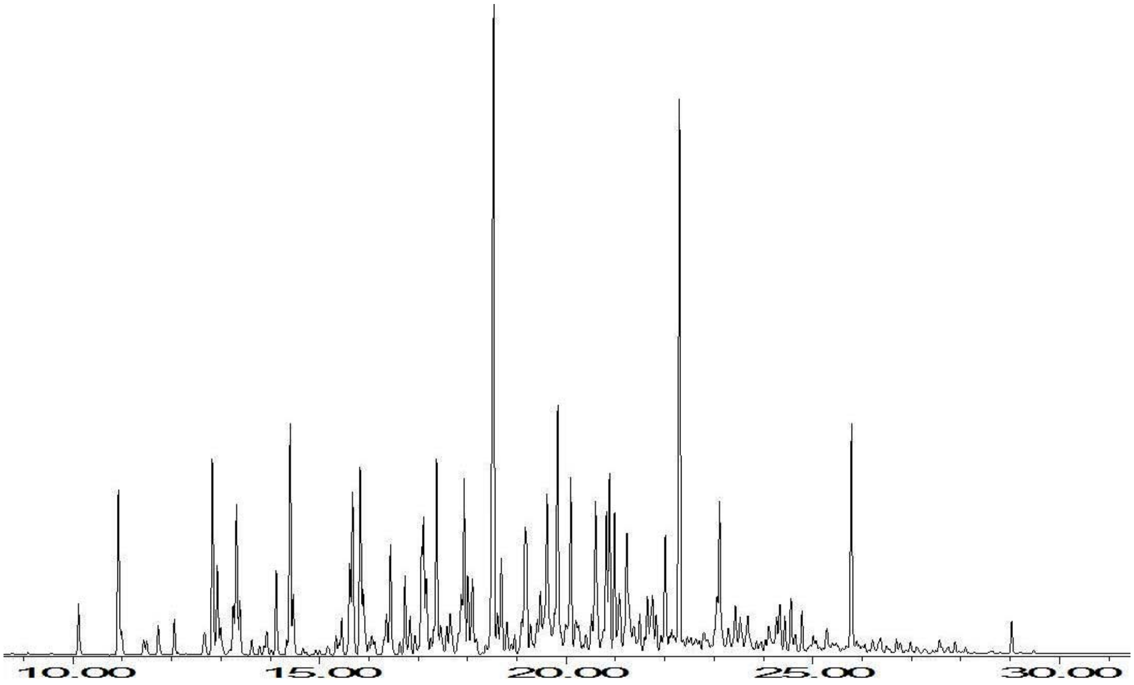


Figure 5.1-C Air Sample from Building Material Emissions Test: Each Peak Represents a Separate Compound
Image copyright NRC-IRC.

Evaluation of the emissions from building materials, finishes, and furnishings has revealed that these products are key sources of many of the identified indoor contaminants (Mølhave 1982; Hodgson and Girman 1983; Girman et al. 1984; Tichenor and Mason 1988; Tucker 1988; Levin 1989; Yu and Crump 1998; Won et al. 2003). As illustrated in Figure 5.1-C, a single material can be a source of an extremely large number of diverse compounds. The variable nature of individual materials in terms of emissions composition, complexity, and duration is the subject of the section in this Strategy titled "Emissions Behavior."

In the past, IAQ studies have focused on a class of contaminants referred to as *volatile organic compounds* (*VOCs*). The analytical methodology available has been the primary basis for this focus, but recent broadening of analytical methods has led to growing realization that other compounds beyond traditional VOCs are implicated in IAQ problems. Attention is shifting to semi-volatile organic compounds (SVOCs) as well as to transient, highly reactive secondary intermediates created through indoor chemistry interactions between indoor contaminants.

The current state of IAQ guidelines, standards, and specifications is a vital component in emissions-based selection of building materials and is therefore reviewed in this Strategy. The trend to adoption of "green" building practices, while key to environmental sustainability, needs to be reviewed with some caution. In certain cases, green products may be inappropriate for indoor usage due to contaminant emissions that can result from recycled material content or from adhesives employed to bind waste materials. Conversely, certain green materials have low emissions and are well-suited for indoor usage. There are thus "shades of green" when evaluating the IAQ impact of materials and furnishings.

Collectively, these fundamental concepts related to material emissions form the basis for rational selection of products that will have minimal adverse impact on IAQ. With a basic understanding of these principles, the building design team will be equipped to interpret product labeling systems and develop effective specifications for selection of priority materials, finishes, and furnishings. Common terms used in characterizing material emissions are summarized in Table 5.1-A.

Table 5.1-A Definitions of Terms Related to Material Emission

Term	Agency/Organization; *Report/Publication*	Definition
Volatile organic compound (VOC)	ASTM International; *ASTM D1356, Standard Terminology Relating to Sampling and Analysis of Atmospheres* (ASTM 2005a)	An organic compound with a saturation vapor pressure greater than 40.1e-3 in. H_2O (10^{-2} kPa) at 77°F (25°C) (where *organic chemical* = a carbon-based compound in which the element carbon is attached to other carbon atom(s), hydrogen, oxygen, or other elements in a chain, ring, or three-dimensional structure).
	International Society of Indoor Air Quality and Climate (ISIAQ); "Glossary of the Indoor Air Sciences" (ISIAQ 2006)	Organic compounds with boiling points ranging from a lower limit between 122°F (50°C) and 212°F (100°C) and an upper limit between 464°F (240°C) and 500°F (260°C), where the upper limits represent mostly polar compounds.
	U.S. Environmental Protection Agency (EPA); *Code of Federal Regulations* (40 CFR 51.100(s)) (GPO 2009)	Any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates, and ammonium carbonate, that participates in atmospheric photochemical reactions (with dozens of exceptions for compounds determined to have negligible photochemical reactivity).
Semi-volatile organic compound (SVOC)	ASTM International; *ASTM D1356, Standard Terminology Relating to Sampling and Analysis of Atmospheres*	An organic compound with a saturation vapor pressure between 40.1e-3 and 40.1e-9 in. H2O (10^{-2} and 10^{-8} kPa) at 77°F (25°C).
Very volatile organic compound (VVOC)	World Health Organization (WHO)	Compound with boiling point in range from below 32°F (0°C) to between 122°F and 212°F (50°C and 100°C).

Term	Agency/Organization; *Report/Publication*	Definition
Total volatile organic compounds (TVOCs)	ASTM International; *ASTM D1356, Standard Terminology Relating to Sampling and Analysis of Atmospheres*	The summed concentration of all the individual VOCs quantifiable in an air sample by both a precisely specified sampling protocol and a precisely defined analytical method.
PM10	EPA	Particulate matter with an aerodynamic diameter of up to 10 μm. Corresponds to *thoracic* fraction (penetrates the respiratory tract below the larynx).
PM3.5		Corresponds to *respirable* fraction, i.e., particles that penetrate/deposit exclusively into the pulmonary region of the deep lung.
PM2.5	EPA	Particulate matter with an aerodynamic diameter of up to 2.5 μm, referred to as the *fine* particle fraction.
PM0.1 or ultrafine particle	EPA	Particulate matter with an aerodynamic diameter of up to 0.1 μm, referred to as the *ultrafine* particle fraction.
Emission factor (EF)		The rate of contaminant release per unit of material surface (typically exposed surface area, *A*), μg/m^2/h.
Emission rate (ER)		The rate of contaminant release, expressed as mass/time, e.g., mg/h (ER = EF × *A*).

VOCs—Total vs. Target: Irritancy, Odor, and Health Impact

VOCs remain a cornerstone of IAQ assessment and therefore the characterization of building material emissions. But *VOC* is a somewhat vague term, the definition of which is not universally agreed upon (see Table 5.1-A). VOC has been defined in terms of vapor pressures and boiling points as well as molecular chain lengths detectable by chromatographic techniques. A regulatory definition developed by the U.S. Environmental Protection Agency (EPA) limits VOCs to those compounds that contribute to smog formation via atmospheric photochemical reactions (GPO 2009). This is useful for the intended purpose of outdoor air quality preservation but is restrictive when considering indoor air. Certain VOCs having impact on IAQ are not included in this definition. Product labeling systems that employ the EPA VOC definition need to be interpreted cautiously since the reported VOC content may not be comprehensive.

Due to the complexity of VOC emission profiles, it is tempting to simplify analysis and reporting of emissions by grouping all detected compounds together as total VOCs (TVOCs). There are two major problems with this approach. First, individual compounds have highly variable health and/or comfort impacts, the result being that concentration alone is not predictive of IAQ impact. Levels of concern vary by orders of magnitude, so a collective concentration will not correlate with IAQ. Refer to the section "IAQ Guidelines, Standards, and Specifications" in this Strategy for discussion and links to further information on health, irritation, and odor impacts of indoor contaminants.

Second, VOC detection and quantification is highly method dependent. A given sampling and analysis system cannot capture or fully respond to all the VOCs present in any indoor environment or in the test chamber for a given material. The term *total* is thus misleading. Mølhave (1982) used the term *TVOC* to describe a specific set of 22 individual compounds, but Mølhave and Nielsen (1992) warned about misinterpretation of the term. The European Commission (EC 1997a) advocated the inclusion of 67 compounds in the reporting of TVOCs. Other groups report TVOCs as simply the total of what their particular analytical system permits them to measure. In addition, the detectors utilized by any particular analytical system respond differently to individual compounds. The effect of this is that, if lumped together and reported as a single value, the final result will likely have significant error attached to it. Summing individual peaks is also error prone unless calibration of the system is performed using pure standards for each detected compound (see, for example, Lusztyk et al. [2005]).

As stated by ASTM (2005a),

> TVOC air concentrations are approximations and are typically determined by summing the areas of all gas chromatographic peaks derived from test methods such as D 5466 or D 6196. The TVOC air concentration values so derived depend on the type of air sampler; the type of gas chromatographic (GC) detector and how it is calibrated; the collection, retention, and recovery efficiencies of the sorbent trap, canister, or other sampling device; the efficiency of transfer to the GC column; the type and size of the GC column; the GC temperature program and other chromatographic parameters; how the concentration is derived from the peak area (for example, whether single or multiple internal standards are used, as well as the types of reference standards); and the composition of the air sample (for example, the relative abundances of hydrocarbon, halogenated, or oxygenated compounds). (p. 8)

Wolkoff and Nielsen (2001) bemoaned the fallacy that TVOC has any biological relevance, and Mølhave (2003) stated that the usefulness of the TVOC concept for prediction of health effects of chemicals mixtures is undocumented and cannot be used for risk assessment.

ASHRAE (2007) has similarly concluded that "There is insufficient evidence that TVOC measurements can be used to predict health or comfort effects. In addition, odor and irritation responses to organic compounds are highly variable. Furthermore, no single method currently in use measures all organic compounds that may be of interest. Setting target concentrations for TVOCs is not recommended. Setting target concentrations for specific VOCs of concern is preferred" (p. 29).

Increasingly, product evaluation systems are providing detailed reporting of specific compounds or compound classes (for example, aldehydes, aromatics, halocarbons, etc.). Identification of relevant target compounds is key to this process. To a certain extent, the targets are constantly moving as product manufacturers continuously modify material formulations and constituents. Ongoing target correction is therefore necessary (Wolkoff et al. 1997).

Table F-2 in Appendix F – Additional Information on Material Emissions presents the list of 90 target VOCs for building material emissions evaluation developed by National Research Council Canada Institute for Research in Construction (NRC-IRC) in collaboration with several academic and governmental partners, including Health Canada (Won et al. 2005a). The compounds were selected based on health impact, occurrence in indoor air, and known emission from building materials, as well as suitability for detection and quantification by gas chromatography–mass spectrometry (GC-MS) or high-performance liquid chromatography (HPLC). The table groups the compounds by chemical class and also indicates known odor and irritancy values for each chemical as well as available values from Occupational Safety and Health Administration (OSHA), American Conference of Governmental Industrial Hygienists (ACGIH), and California's Office of Environmental Health Hazard Assessment (OEHHA). Concurrently yet independently, a 121-compound VOC list (see Table F-3 in Appendix F – Additional Information on Material Emissions) was developed in California and released in the 2003 State of California Department of Health Services report "Building Materials Emissions Study" (64 of these compounds also appeared in the NRC-IRC list) (Alevantis 2003).

In 1997 the European Commission released a report on TVOCs in IAQ investigations that contained a list of 63 compounds to be included in any TVOC estimation (see Table F-4 in Appendix F – Additional Information on Material Emissions) (EC 1997a). This list was used by Business and Institutional Furniture Manufacturer's Association (BIFMA) to help set targets for VOC emissions from office furniture.

Semi-Volatile Organic Compounds (SVOCs)

SVOCs are by definition organic compounds with saturation vapor pressures between 40.1e-3 and 40.1e-9 in. H_2O (10^{-2} and 10^{-8} kPa) at 77°F (25°C) (ASTM 2005a). Less volatile than VOCs, SVOCs tend to be released slowly over long periods of time from their source materials. While acute exposure is thus typically low, the long-term chronic exposure that is typical with these compounds has been linked to IAQ concerns (Weschler and Nazaroff 2008). Several SVOCs have been implicated as carcinogens or in the development of asthma.

Common SVOCs found in indoor air include plasticizers such as phthalic acid esters (phthalates, a broad class of individual compounds used as softening agents in diverse materials) and organophosphate flame retardants (used in indoor materials such as fabrics/textiles, plastics, and wood-based materials). Certain pesticides, such as organochlorine agents, are also classified as SVOCs.

Potential emission sources of phthalates in indoor environments include wall coverings, wall paints, floor coverings, and electronic devices (Wensing et al. 2005). Review of the product labeling information presented in this Strategy's sections "Labels: Content-Based" and "Labels: Emissions-Based" as well as details in the subsections of "Priority Materials/Finishes/Furnishings" will reveal that many labeling systems and material specification criteria now specifically require documentation of phthalate levels.

Indoor Chemistry—Secondary Emissions

Primary emissions from building products and materials include very volatile organic compounds (VVOCs), VOCs, SVOCs, and particulates. Under conditions that may readily occur in indoor environments, however, these contaminants may react to form secondary products. The indoor environment can be considered a reaction vessel, generating by-products that are more reactive and/or irritating than the original precursors (Weschler and Shields 1997). These reactions tend to occur at material surfaces found indoors, hence the use of the terms *surface* or *interfacial chemistry* in addition to the common phrase *indoor chemistry* (Morrison 2008). The large surface-to-volume ratios typical of indoor environments facilitate the occurrence of these reactions (Nazaroff et al. 2003).

In terms of material specifications by building designers, this means that attention needs to be paid not only to the health or comfort impacts of primary emission products but also to limiting the emissions of these precursor compounds. An example is the emission of terpenes from wood-based materials that by themselves may not be problematic but in the presence of ozone at typical indoor levels (from outdoor sources as well as from office equipment) can react to produce aldehydes (e.g., formaldehyde—a known carcinogen) as well as strongly irritating compounds such as organic acids, carbonyls, and dicarbonyl compounds (Weschler 2004; Weschler et al. 2006). Formation of ultrafine particulates through secondary chemistry reactions between terpenes and ozone has also been observed (Weschler and Shields 2003).

Nitrogen oxides (NO_x) released indoors from combustion appliances or brought into a building from exterior sources is another oxidizing agent associated with secondary emissions. Hydrolysis reactions may also occur—for example, the hydrolysis of di(2-ethylhexyl)-phthalate (DEHP) plasticizer (refer to the subsection in this Strategy titled "PVC Materials"). DEHP hydrolysis occurs more readily when catalyzed by basic conditions provided by certain concrete flooring and gypsum board surfaces and leads to the formation of by-products (including 2-ethyl-1-hexanol) linked to asthma (Norback et al. 2000; Tuomainen et al. 2004).

Certain cleaning products used indoors have been highlighted as significant contributors to indoor chemistry. Those that contain terpenes, glycols, etc. in their formulation are of particular concern (CARB 2006). Refer to Strategy 5.3 – Minimize IAQ Impacts Associated with Cleaning and Maintenance, which deals with building cleaning, for a more detailed discussion of this aspect.

Solutions to reducing the impact of secondary emissions on IAQ include reducing indoor ozone levels. This may be achieved through the use of sorbent-based filtration (including activated carbon) of outdoor air, through direct venting of indoor combustion sources to remove NO_x, or through moisture control to reduce hydrolysis reactions. Reduction of the feedstock primary emissions through source control via careful selection of building products, materials, and furnishings is also desirable.

IAQ Guidelines, Standards, and Specifications

For industrial/occupational settings, specific regulations exist governing allowable concentrations of specific compounds (Table 5.1-B). Unfortunately, this is not the case for the indoor environments of commercial or institutional buildings.

Table 5.1-B Industrial/Occupational Air Quality Regulations

Agency	Report/Publication	Available Information
American Conference of Governmental Industrial Hygienists (ACGIH)	*Threshold Limit Values for Chemical Substances and Physical Agents and Biological Exposure Indices* (ACGIH 2007)	Updated annually; developed as guidelines to assist in the control of health hazards; intended for use in the practice of industrial hygiene, not for use as legal standards. *Example: Formaldehyde = 0.3 ppm (Ceiling)*
National Institute of Occupational Safety and Health (NIOSH)	*Registry of Toxic Effects of Chemical Substances (RTECS)* (NIOSH 2009)	Recommended exposure limits (RELs) *Example: Formaldehyde = 0.016 ppm (8h TWA)*
Occupational Safety and Health Administration (OSHA)	OSHA Standards	OSHA sets enforceable permissible exposure limits (PELs) to protect workers against the health effects of exposure to hazardous substances. PELs are regulatory limits on the amount or concentration of a substance in the air based on an eight-hour time-weighted average (TWA) exposure. *Example: Formaldehyde = 0.75 ppm (PEL, TWA), STEL 2 ppm, Ceiling 5 ppm*

Due to the large differences in the nature of the pollutant sources in commercial vs. industrial environments, both the compositions and concentrations of the indoor contaminants are widely different between these types of settings. Industrial workers are typically exposed to relatively high levels of specific contaminants for brief periods. In contrast, commercial environments are typified by relatively low-level, chronic exposures to a broad mixture of contaminants. In addition, nonindustrial indoor environments are also distinct in terms of the occupants themselves, having broader ranges in terms of age, sex, fitness, and general health. For these reasons the use of industrial guideline values, or fractions of these values, is generally considered inappropriate.

As stated in *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality*:

> Caution must be used in directly extending the ACGIH TLVs® or other workplace guidelines to spaces covered by this standard and to population groups other than workers. Industrial health practice attempts to limit worker exposure to injurious substances at levels that do not interfere with the industrial work process and do not risk the workers' health and safety. There is not an intention to eliminate all effects, such as unpleasant smells or mild irritation. Further, the health criteria are not uniformly derived for all contaminants. Irritation, narcosis, and nuisance or other forms of stress are not uniformly considered as the basis for the concentration limits. This is because different organizations use different end points and different contaminants have more or less information available on diverse end points of interest. The target population is also different from the occupants found in the spaces covered by this standard. Healthy industrial workers tend to change jobs or occupations if an exposure is intolerable. In contrast, workers in commercial environments such as offices do not expect to have elevated concentrations of potentially harmful substances, nor are monitoring programs in place, as may be the case with industrial contaminants. In addition, the general population may have less choice about where they spend most of their time and includes those who may be more sensitive, such as children, asthmatics, allergic individuals, and the elderly. (ASHRAE 2007, p. 24)

Some guideline values for indoor contaminants (nonindustrial) do exist (refer to Table 5.1-C). ASHRAE Standard 62.1 includes a brief discussion of existing guidelines, and Charles et al. (2005) recently conducted a review of IAQ guidelines and standards. It is important to distinguish, however, that these levels are *guidelines*, as opposed to the regulatory, enforceable values derived from the sources in Table 5.1-B. In addition, many of the documents listed in Table 5.1-C use TVOCs as the basis for gas-phase IAQ contaminant guidance (refer to the section in this Strategy titled "VOCs—Total vs. Target: Irritancy, Odor, and Health Impact" for discussion). Further information is provided in Appendix F – Additional Information on Material Emissions (see Table F-5 for sources of information on odor/irritancy/toxicity of indoor contaminants).

New guidelines are being developed, however, with specific recommendations for individual VOCs. As discussed previously, it is important to identify those VOCs with health/comfort impact and focus on setting realistic guidelines for these target compounds based on sound toxicological principles (Levin 1997; Nielsen et al. 1997a, 1997b; Seifert et al. 1999). *ASTM D7034, Standard Guide for Deriving Acceptable Levels of Airborne Chemical Contaminants in Aircraft Cabins Based on Health and Comfort Considerations* (ASTM 2005b), describes a methodology for deriving acceptable concentrations for airborne chemical contaminants based on health and comfort considerations. Nielson et al. (1996) similarly proposed a methodology for guideline value determination while also presenting values for 26 compounds developed for the Nordic Committee on Building Regulations.

Table 5.1-C Indoor Air Quality Guidelines/Standards

Country; Agency	Document, Details
USA; American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)	*ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007) Appendix B, Summary of Selected Air Quality Guidelines • Table B-1, Comparison of Regulations and Guidelines Pertinent to Indoor Environments • Table B-2, Concentration of Interest for Selected Contaminants Setting target concentrations for TVOCs is not recommended. Setting target concentrations for specific VOCs of concern is preferred.

USA; California Department of Health Services (CDHS)	"Reducing Occupant Exposure to Volatile Organic Compounds (VOCs) from Office Building Construction Materials: Non-Binding Guidelines" (Alevantis 1996)
	• Overview of process and factors related to evaluation of VOC emissions
	• Appendix E, Survey of Existing Guidelines for VOCs
	• Section E2, Health Effects and Concentration Guidelines for Selected VOCs
	  • Benzene
	  • Formaldehyde
	  • Methylene chloride
	  • Styrene
	  • Tetrachloroethylene
	  • Toluene

USA; California's Office of Environmental Health Hazard Assessment (OEHHA)	"OEHHA Acute, 8-hour and Chronic Reference Exposure Levels (RELs)" (OEHHA 2008) • Guideline values for list of ~80 chemicals with non-cancer chronic effects
Canada; Health Canada	*Exposure Guidelines for Residential Indoor Air Quality* (Health Canada 1987) • Guidelines/recommendations established for indoor levels of aldehydes (formaldehyde, acrolein, acetaldehyde), carbon dioxide, carbon monoxide, nitrogen dioxide, ozone, particulates, sulfur dioxide, radon, biological agents, fibrous materials (asbestos, man-made mineral fiber), polycyclic aromatic hydrocarbons, chlorinated hydrocarbons, pesticides, environmental tobacco smoke, lead, consumer products
Australia; National Health and Medical Research Council (NHMRC)	*Ambient Air Quality Goals and Interim National Indoor Air Quality Goals* (NHMRC)
Finland; Finnish Society of Indoor Air Quality and Climate (FiSIAQ)	"Classification of Indoor Climate 2000: Target Values, Design Guidance and Product Requirements" (FiSIAQ 2001) • TVOC based

Country; Agency	Document, Details
Germany; Federal Environmental Agency Indoor Air Hygiene Commission (IRK) and the Working Group of the Health Ministries of the Länder (AOLG)	*Guidelines for Indoor Air Quality: Basic Scheme* (AOLG 1996) • IAQ guidelines set by an ad hoc working group of members of the of Germany Indoor Air Hygiene Commission (Innenraum-lufthygiene-Kommission; IRK) of the Umwelt Bundes Amt (UBA)
Germany; Committee for Health-Related Evaluation of Building Products (AgBB)	*Health-related Evaluation Procedure for Volatile Organic Compounds Emissions (VOC and SVOC) from Building Products* (AgBB 2008) • Procedure for calculation of lowest concentration of interest (LCI) values; LCI values currently established for 178 compounds (AgBB 2008)
Hong Kong; Indoor Air Quality Information Centre (IAQIC)	"Hong Kong Objective" (IAQIC n.d.) • Sets objectives for "good" and "excellent" IAQ for offices and public spaces • "Good" IAQ includes objectives for 10 specific VOCs (benzene; carbon tetrachloride; chloroform; 1,2-dichlorobenzene; 1,4-dichlorobenzene; ethylbenzene; tetrachloroethylene; toluene; trichloroethylene; and xylene [*o*-, *m*-, *p*-isomers])
Japan; Ministry of Health, Labor and Welfare (MHLW)	*Guidelines of Indoor Chemicals* (MHLW 2002) • Based mainly on long-term exposure (except for formaldehyde)
International; World Health Organization (WHO)	*Air Quality Guidelines for Europe*, Second Edition (WHO 2000) • Lists following "organic air pollutants": acrylonitrile, benzene, butadiene, carbon disulfide, carbon monoxide, 1,2-dichloroethane, dichloromethane, formaldehyde, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), polychlorinated dibenzodioxins (PCDDs), polychlorinated dibenzofurans (PCDFs), styrene, tetrachloroethylene, toluene, trichloroethylene, vinyl chloride
International; WHO	*WHO Guidelines for Indoor Air Quality* (see WHO [2006] for a report on a working group meeting) [Currently under development]

Shades of Green—Environmentally Preferred Products

Green is an overused and sometimes misleading term, hence the emergence of the term *greenwashing*, which is used to refer to the recent overabundance of claims of environmentally friendly products, policies, or activities (TerraChoice 2007, Wilson 2006). Generally, the focus of green products/green labeling is on environmental sustainability, a worthy objective aimed primarily at global environmental concerns. IAQ impact is generally a secondary, but not necessarily excluded, concern. Many green products incorporate moderate to high recycled content (post-consumer and/or post-industrial), which can be a concern in terms of emissions if employed indoors. Again, this is not always the case, as some "green" materials with high recycled content have been shown to also have relatively low chemical emissions (Alevantis 2003).

Wilson (2000) outlines the criteria used by BuildingGreen, LLC (an independent publishing company) to screen products listed in its *GreenSpec Directory* (BuildingGreen 2008) (Table 5.1-D). Consideration of IAQ impact is included under this system (category 5 actually broadens this aspect to indoor environmental quality by including lighting and acoustical impacts as well). Identification of a product as "green" using this criteria remains a judgement call. As observed by Wilson (2000), a product with one or more green attributes might not qualify if it also carries significant environmental burdens. It is not clear in this context if IAQ impact is considered to be a veto-type "environmental burden." It should also be noted that GreenSpec, while listing over 2000 "environmentally preferable products," uses "available" information in assessing product suitability, does not conduct any testing itself, and does not list any quantitative criteria. Users of their database of products pay an access fee to do so.

Table 5.1-D Summary of Product Standards for GreenSpec

1. Products Made with Salvaged, Recycled, or Agricultural Waste Content
1a. Salvaged products
1b. Products with post-consumer recycled content
1c. Products with pre-consumer recycled content
1d. Products made with agricultural waste material
2. Products that Conserve Natural Resources
2a. Products that reduce material use
2b. Products with exceptional durability or low maintenance requirements
2c. Certified wood products
2d. Rapidly renewable products
3. Products that Avoid Toxic or Other Emissions
3a. Natural or minimally processed products
3b. Alternatives to ozone-depleting substances
3c. Alternatives to hazardous products
3d. Products that reduce or eliminate pesticide treatments
3e. Products that reduce storm water pollution
3f. Products that reduce impacts from construction or demolition activities
3g. Products that reduce pollution or waste from operations
4. Products that Save Energy or Water
4a. Building components that reduce heating and cooling loads
4b. Equipment that conserves energy and manages loads
4c. Renewable energy and fuel cell equipment
4d. Fixtures and equipment that conserve water
5. Products that Contribute to a Safe, Healthy Built Environment
5a. Products that do not release significant pollutants into the building
5b. Products that block the introduction, development, or spread of indoor contaminants
5c. Products that remove indoor pollutants
5d. Products that warn occupants of health hazards in the building
5e. Products that improve light quality
5f. Products that help noise control
5g. Products that enhance community well-being

Green product labeling systems typically, but not always, rely on content-based estimation of VOC impact (see the section in this Strategy titled "Labels: Content-Based") while using the U.S. federal government definition of VOCs for outdoor air (GPO 2009) (see the section in this Strategy titled "VOCs—Total vs. Target: Irritancy, Odor, and Health Impact" for discussion). A summary of green product resources is provided in Table 5.1-E.

The Pharos Project is relatively new and involves a process by which a product is evaluated on a 10-point scale for each of 16 categories. The categories are grouped into three main aspects (Health and Pollution, Environment and Resources, and Social and Community). IAQ is one of the five Health and Pollution categories. The 10-point rating system for evaluating IAQ performance of products is listed in Table 5.1-F.

Table 5.1-E Green Product Resources

Agency	Document
ASHRAE	*ASHRAE GreenGuide: The Design, Construction, and Operation of Sustainable Buildings* (ASHRAE 2003)
California Integrated Waste Management Board (CIWMB)	*Sustainable (Green) Building: Green Building Materials* www.ciwmb.ca.gov/GreenBuilding/Materials/#IAQ
BuildingGreen	*GreenSpec-Listed Green Building Products* www.buildinggreen.com/menus/index.cfm?
National Institute of Standards and Technology (NIST)	*NISTIR 6916, BEES® 3.0: Building for Environmental and Economic Sustainability—Technical Manual and User Guide* (NIST 2002)
Healthy Building Network (Pharos Project)	*IAQ and Other Toxic User Exposure (UseTox)* www.pharoslens.net/framework/categories/id/1
National Institute of Building Sciences (NIBS)	"Federal Green Construction Guide for Specifiers" www.wbdg.org/design/greenspec.php

Table 5.1-F Pharos Project—IAQ and User Exposure Scoring Criteria (HBN 2008)[1]

Level	Criteria
10	No VOC emissions AND no content of known or suspected carcinogens, mutagens, reproductive toxicants, teratogens, neurotoxicants, or endocrine disruptors or acute toxicants.
9	VOC emissions are 20% or less of the best standard on the market (no VOC concentrations exceeding 1/10 CREL[2] and 1/500 TLV[3]) AND no Prop 65[4] toxic chemicals (carcinogens or reproductive toxicants).
8	Passes Section 01350[5] VOC emission test, plus additional criteria to include more VOCs (no VOC concentrations exceeding 1/2 CREL or 1/100 TLV).
7	Passes Section 01350 VOC individual emission test (no VOC concentrations exceeding 1/2 CREL) OR if wet product, no TVOC content.
6	If wet product, TVOC content is half or less the best standard (California South Coast Air Quality Management District [SCAQMD]).
5	Passes basic low bar individual VOC emission test (no VOC concentrations exceeding 1/10 TLV) OR if wet product, TVOC content meets the best standard (SCAQMD).
4	Level 5 minus 1 point.
3	Passes most basic TVOC emissions tests (concentrations less than or equal 0.5 mg/m3) OR, if a paint or other wet product, TVOC content less than or equal to twice the best standard (SCAQMD).
2	Level 3 minus 1 point.
1	No VOC testing yet OR if wet product, TVOC content is more than twice the best standard (SCAQMD).
Blank	No Information Reported
Extra	Points are deducted for content in any of the categories listed: • Added formaldehyde • Halogenated flame retardants • Prop 65 Carcinogens or Reproductive toxicants >1% of mass • Heavy metal: lead, cadmium, hexavalent chromium, mercury, organotins • Phthalates • Perfluorochemical (PFC) related materials • Antimicrobials

[1] The IAQ/user exposure category rating is currently only applicable to interior finish products (such as carpet, wall covering, paint, etc.) and furnishings.

[2] Office of Environmental Health Hazard Assessment (OEHHA) Chronic Reference Exposure Level (OEHHA 2008)

[3] American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (ACGIH 2007)

[4] *Proposition 65, the Safe Drinking Water and Toxic Enforcement Act of 1986* (OEHHA 2007a)

[5] *Section 01350, Special Environmental Requirements Specification* (CIWMB 2000, DGS 2000)

Strategy 5.1

Several whole-building strategies exist for the design and operation of green buildings. In 1993, Natural Resources Canada (NRCan) introduced the C-2000 Program for Advanced Commercial Buildings (www.greenbuilding.ca/C2000/abc-2000.htm) for the design of high performance, low-energy buildings having minimal environmental impact (NRCan 2002). Indoor performance specifications to provide health, comfort, and productivity for building occupants were a foundation of the program and were based on avoiding contaminant emissions as a first priority, eliminating the contaminant or problem at the source as the second priority, and, finally, using dilution of the contaminant to an acceptable level if the first two strategies do not achieve the desired result. In the same year, the U.S. Green Building Council (USGBC) created the Leadership in Energy and Environmental Design (LEED) Green Building Rating System (USGBC 2008). LEED gives credits related to product emissions primarily through EQ Credit 4—Low-Emitting Materials.

Product Information—Composition vs. Emissions

Two major classes of product labeling systems are used to rate indoor materials: content-based systems and emissions systems. They can be distinguished in that

- content-based labels typically assess the VOC level of a product based on the mass percent of VOCs present (no attempt is made to measure the actual emissions of VOCs from the product) and
- many content-based labels have a primary focus on environmental sustainability and ambient (not indoor) air quality and often use the EPA definition of VOCs for outdoor air, which deals specifically with compounds involved in photochemical reactions leading to smog formation. As such, many VOCs (per the ASTM or ISIAQ definitions, for example) are excluded even though they may have significant occupant impact indoors. A "VOC-free" or "low-VOC" product may thus actually contain significant quantities of nonreported compounds that may adversely influence occupant comfort, irritation, or health.

A content-based assessment provides a useful initial screening of expected product performance but cannot indicate the true emission characteristics of a product (and hence the predicted contaminant concentrations indoors as a result of its use), nor can they indicate slow-decaying vs. fast-decaying emissions behavior. Content-based assessments can be misleading, as in the case of conversion varnish testing that fails to indicate formaldehyde release from the cured product.

Emissions-based evaluations, since they are typically performed under a standard set of test conditions, cannot inform regarding the impact of changing environmental conditions (temperature, relative humidity, air velocity, and air change rate) and can only estimate emissions rates for the test period conducted. They are expensive to conduct and report only those contaminants for which the test methodology is adapted. Some emissions-based labels report only TVOCs.

Emissions Behavior

For any individual VOC emitted by a given material, the rate of emission may be low or high and the duration for which the VOC is released may be relatively long or short. The overall emission rate (ER), expressed as mass per unit time (μg/h), depends on the unit-specific emission factor (EF), which is the rate of emissions per unit of product. EF is most often expressed relative to the emitting surface area of the material (μg/m^2/h), but this is not always possible. For a product such as a chair that may incorporate several materials, the surface area of any of which may be challenging to estimate, EF may be reported as emission rate per product (e.g., μg/product/h). ER due to product usage within a defined space is thus calculated by multiplying the EF by the number of product units or by the exposed emitting surface area (ft^2 [m^2]) within the space. The true emitting surface area in contact with indoor air can be difficult to determine, especially for hidden or obscured surfaces.

EFs, however, are not constants. A product's source strength (for individual VOCs, TVOCs, or classes of VOCs) will vary over time as the emission rate decays. The rate of this decay behavior, coupled with the magnitude of the contaminant reservoir within the material, determines whether the product will act as a long-term or short-term source.

ERs can depend significantly on environmental factors such as temperature and relative humidity (especially for polar compounds such as aldehydes). Products that are applied wet (such as architectural coatings, adhesives, caulks, etc.) will typically have high initial rates of emission, and during the initial evaporation-controlled stage of the emission profile the rates will be controlled by local air velocities. For dry materials, emission rates are primarily controlled by relatively slow diffusion from the material matrix. These materials will typically be characterized by slower, long-term emissions that will not be impacted greatly by air velocity conditions. The degree of homogeneity of the material, especially for relatively complex materials such as engineered wood products, can have significant impact on the variability of observed emissions (Magee et al. 2003).

Emission testing of individual materials is very informative and enables direct product-product comparisons but may not accurately reflect their true impact on indoor air if they will eventually be installed as part of an assembly of materials. The real impact of selecting carpeting as an office flooring material, for example, cannot easily be determined by testing the carpet alone if adhesives are required for the installation. The complete system of carpet + recommended adhesive product + concrete slab is best tested as a unit. Individual tests of the components are still needed to attribute sources, but true emissions impact is difficult to gauge unless testing of the whole assembly is performed.

Whenever possible, materials need to be tested in a manner that simulates their intended installation conditions. This applies as well to “edge effects” of materials: in many cases, emission rates from a cut edge of a product vary significantly compared with the normally exposed surfaces. Typically, to avoid this problem, holders or edge-sealing techniques are employed to limit the edge emissions during testing. Of course if the material will be installed with exposed edges, sealing them during an emissions test would be inappropriate.

Test assemblies may also include the substrate employed on which a product is supported or applied. Examples include the use of gypsum wallboard as a substrate for testing paint emissions. Here, the choice of wallboard type (standard, water-resistant, fire-retardant) may influence the emissions observed, as will the decision to seal the wallboard with a primer coat prior to application of the paint product to be tested. Again, substrate selections that mimic actual installation conditions are preferred.

Emissions behavior depends on material properties, age, exposure, and environmental conditions. Emission rates can vary by up to a factor of 1000 for different brands of similar products (Levin 1989): this is the reason that a material selection strategy is so important for controlling IAQ.

Figures 5.1-D and 5.1-E show emission profiles for two very different types of materials. The first, a carpet + adhesive assembly, demonstrates high initial VOC levels (due to evaporation of the adhesive employed) that decay rapidly by approximately 3 orders of magnitude over the 16-day test period. In contrast, the engineered wood product emissions test illustrated in Figure 5.1-C shows far lower initial VOC levels in the test chamber, but the extremely slow decay rate means that after nine days, the levels for several of the VOCs are within the same magnitude as the carpet + adhesive example. Formaldehyde levels are seen to be rising, not decaying, during the test period. The point during an emissions test at which air sampling is conducted can thus have a significant impact on reported emission rates for specific VOCs for any test material. This aspect of test design is discussed by Hodgson and Alevantis (2004).

Evaluation of the true impact of material emissions is thus not a simple process. Both the long- and short-term impacts of any given product need to be considered. When conducting product-product comparisons with the objective of selecting low-emission alternatives, it is essential to ensure that the test results utilized fairly evaluate the individual products under similar conditions and that data collection points are comparable in terms of timing.

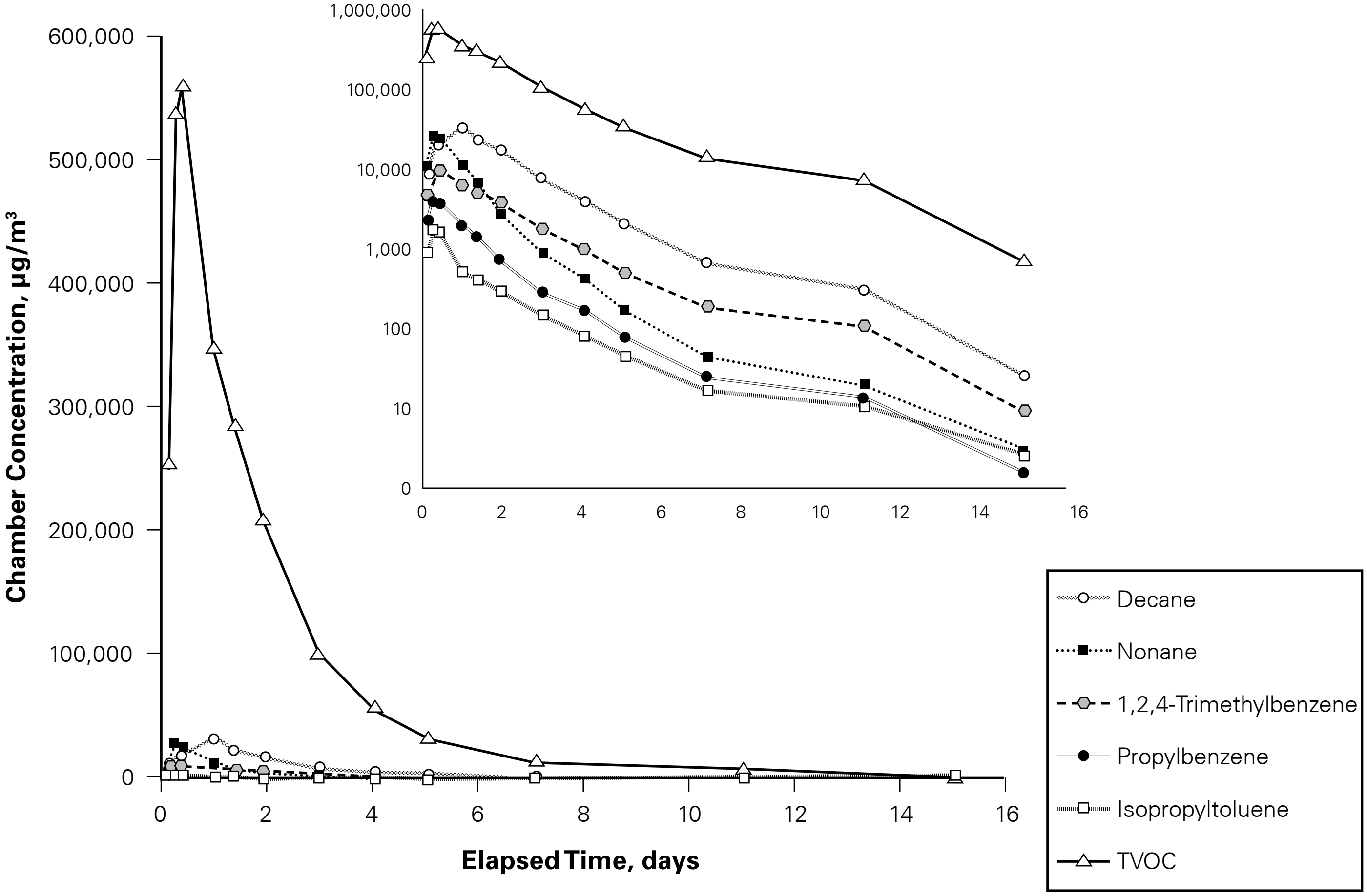


Figure 5.1-D Emissions Test for Glue-Down Carpet Assembly Showing High Initial VOC Concentrations and Rapid Decay
Adapted from data provided by NRC-IRC.

Emissions Data: Available Information

As introduced in the section "Product Information—Composition vs. Emissions," two major systems exist that generate information related to the IAQ impact of building products: the first is based on chemical content, while the second is based on contaminant emissions. This section reviews these systems and summarizes the key features of individual programs. For details of product-specific test protocols and specifications, refer to the "Priority Materials/Finishes/Furnishings" section of this Strategy.

Manufacturer-Supplied Information: MSDSs

Material safety data sheets (MSDSs) are the simplest form of content-based product assessment. MSDS information is required in the U.S. by OSHA under hazard communication regulation (OSHA 2009b) and in Canada under Workplace Hazardous Materials Information System (WHMIS) guidelines (Health Canada 2009) according to the Hazardous Products Act—Part II and the Controlled Products Regulations. The information provided is intended for occupational environments (listing ACGIH threshold limit values [TLVs] and OSHA permissible exposure limits [PELs]). However, information is seldom given on the complete chemical composition of the product, and chemical emission information is rarely provided. Further, chemicals deemed as propitiatory are not reported, and there is no enforcement of accuracy standards for MSDSs. Reliance on MSDS information to characterize IAQ impact of materials is generally discouraged. At best, MSDS data can be used to screen out problematic products.

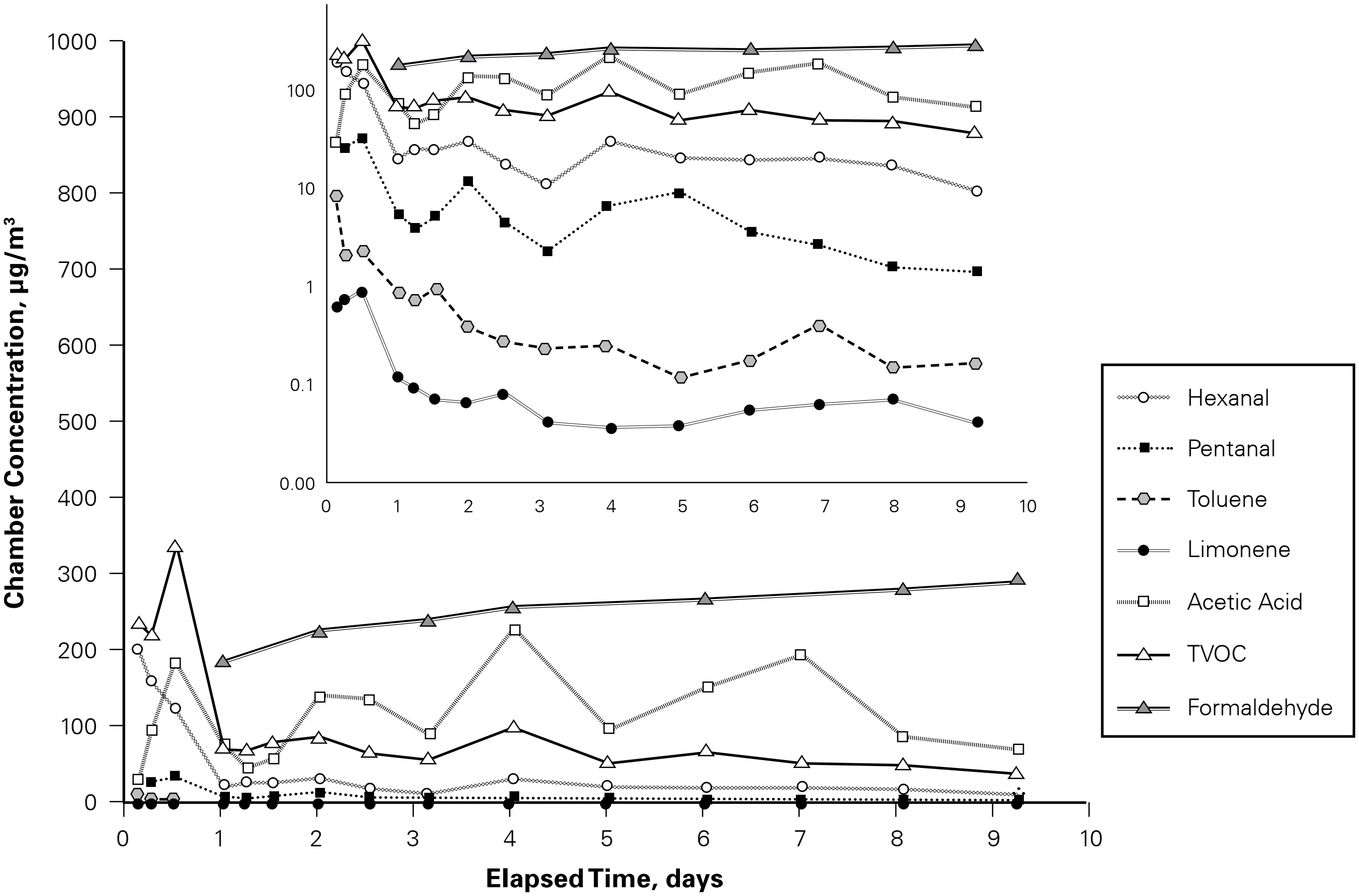


Figure 5.1-E Emissions Test for Engineered Wood Product Showing Slow Decay
Adapted from data provided by NRC-IRC.

As stated by Tichenor (2007),

> Information from MSDS to evaluate potential emissions from indoor material and products should be used with caution. Limited reviews of submitted MSDS are conducted. MSDS for many products are incomplete. Also, changes in manufacturing processes and chemicals can occur before MSDS are corrected. MSDS data may not reflect changes in the designated hazardous material list or the most current health hazard information. In summary, users of MSDS should carefully review the information and use it with care. (p. 28)

Labeling systems run by third-party agencies are clearly preferred sources of reliable data for evaluation of a product's potential IAQ impact.

Labels: Content-Based

Table 5.1-G summarizes product labeling systems that certify products on the basis of chemical content.

The TerraChoice Environmental Marketing Inc. EcoLogo Program, introduced by Environment Canada in 1988, was the first North American environmental product labeling system (TerraChoice 2009a). It currently lists some 7000 certified products in 120 distinct product classes (including those categorized as "Building & Construction Products" and "Office Furniture, Equipment & Business Products"). For each individual product class, EcoLogo develops Certification Criteria Documents (CCDs). Many of the CCDs specify limits on VOC content of the product covered (typically based on the U.S. federal government definition of VOCs for outdoor air [GPO 2009] and specified as mass percent) while also placing restrictions on specific compounds in the formulation of the final product.

Green Seal was the first labeling system introduced in the U.S. Founded in 1989 by the nonprofit organization Green Seal, the first Green Seal certifications for environmental products were issued in 1992. As described in Table 5.1-G, four Green Seal standards have been developed that address VOC content of materials and have been used, as a result, in the specification of products for indoor usage (Green Seal 2009).

Table 5.1-G Summary of Content-Based Labeling Systems

Program	Test Protocol and Compounds Specified

EcoLogo (Canada, TerraChoice Environmental Marketing Inc., established 1988, www.terrachoice-certified.com/en/index.asp)
• >7000 certified products in 120 categories with individual Certification Criteria Documents (CCDs)
• Requires detailed instruction by manufacturer regarding
  • proper application so as to minimize health concerns and maximize performance and
  • proper disposal methods.
• IAQ-related CCDs include the following:
  • CCD-016—Thermal Insulation Materials
  • CCD-019—Particleboard Manufactured from Agricultural Fibre
  • CCD-032—Demountable Partitions
  • CCD-033—Office Furniture and Panel Systems
  • CCD-035—Office Machines
  • CCD-045—Sealants and Caulking Compounds
  • CCD-046—Adhesives
  • CCD-047—Surface Coatings
  • CCD-152—Flooring Products
  • CCD-157—Resin for Engineered Wood Products
	• VOC ratings based on weight percent
	• Product-specific limits on VOCs
	• CCD-046—Adhesives (two general-purpose adhesives certified):
	  • bans use of aromatic or halogenated solvents, formaldehyde, borax, mercury, lead, cadmium, and chromium
	  • VOC content <5% by weight
	• CCD-047—Surface Coatings (1680 products certified; includes separate specifications for indoor and outdoor formulations of paint [flat, semi-gloss, non-flat], stain, and varnish)
	  • For paints (flat):
	    • VOC content of not more than 50 g/L (interior) or 80 g/L (exterior)
	    • Not to be formulated with
	    • aromatic or halogenated compounds,
	    • formaldehyde,
	    • ethylene glycol monomethyl ether or ethylene glycol monobutyl ether,
	    • methyl ethyl ketone or methyl isobutyl ketone,
	    • phthalates,
	    • isophorone,
	    • acrolein or acrylonitrile, or
	    • lead, cadmium, antimony, barium, mercury, or their compounds.

Green Seal (U.S., Green Seal, established 1989, www.greenseal.org)
• 32 environmental certification standards issued to date, of which four include VOC content limits:
  • GS-11—Paints
  • GS-36—Commercial Adhesives
  • GS-37—Industrial & Institutional Cleaners
  • GS-40—Industrial & Institutional Floor-Care Products
• 19 *Choose Green Reports* published to date, including 6 that deal with IAQ issues (but discussion of VOC emissions is limited):
  • Carpet
  • Floor Care Products—Finishes and Strippers
  • Office Furniture
  • Office Supplies
  • Particleboard and Medium Density Fiberboard
  • Wood Finishes and Stains
	• Composition-based analysis of VOC content (U.S. federal government definition [GPO 2009]) specified as weight percent
	• Product-specific limits on VOCs
	  • For example, GS-11—Paints: excluded VOCs include
	    • methylene chloride, 1,1,1-trichloroethane, benzene, toluene (methylbenzene), ethylbenzene, vinyl chloride, naphthalene, 1,2-dichlorobenzene,
	    • di (2-ethylhexyl) phthalate, butyl benzyl phthalate, di-n-butyl phthalate, di-n-octyl phthalate, diethyl phthalate, diethyl phthalate, dimethyl phthalate,
	    • isophorone, antimony, cadmium, hexavalent chromium, lead, mercury, and
	    • formaldehyde, methyl ethyl ketone, methyl isobutyl ketone, acrolein, and acrylonitrile.
	• Prohibitions on carcinogens (per International Agency for Research on Cancer [IARC] and National Toxicology Program [NTP])
	• Prohibitions on reproductive toxicants (per Prop 65 [OEHHA 2007a])

Labels: Emissions-Based

Product labeling systems are generally driven by the market expectations of the end user. As IAQ demands have increased for new buildings, product specifications put forward by building designers have advanced and, as a result, product labeling has tended to shift from content- to emissions-based systems. In the process, emissions labels that began by providing relatively simple information have matured to provide greater detail and precision.

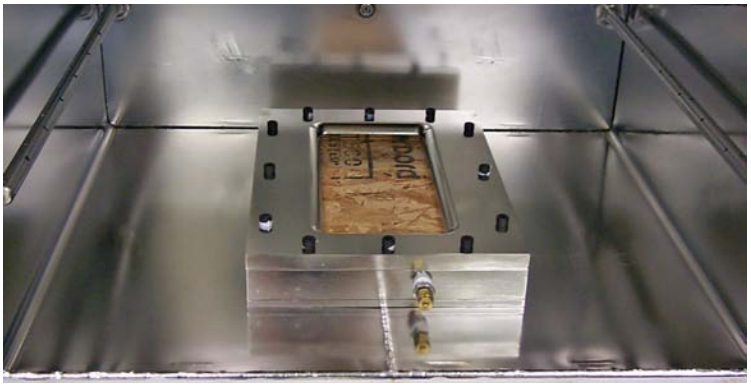


Figure 5.1-F Small (50L) Emissions Chamber
Photograph copyright National Research Council Canada (NRC).

Relative to content-based classification of products and materials, emissions-based labeling is a far more complex process. To generate reliable and comparable results, a precise methodology and documentation is required for each of the steps involved (see Table 5.1-H for a listing of key factors and control points). This is further complicated by the diversity and scale of products that are subject to emissions testing. To accommodate this diversity, different methodologies need to be developed. For example, the processes and requirements for measuring the contaminant emissions from a sample of paint are quite distinct from those required to characterize pollutants generated by a complete office workstation or from operating office equipment. The small emissions chamber shown in Figure 5.1-F is an example of one key element in this process.

Table 5.1-H Emissions Testing Parameters

General Aspect	Consideration
Specimen Collection	• Collection point (manufacturer, retail/wholesale outlet, construction site) • Age (from date of manufacture) • Handling (chain of custody, contamination control) • Conditioning (duration and environmental conditions)
Specimen Preparation	• Substrate/support devices/specimen holders • Edge effects/edge sealing measures • Application technique (wet products) • Material assembly

Chamber Testing	• Chamber characterization (mixing, sink effect, air velocity profiling, background contaminant levels)
	• Environmental conditions
	  • temperature
	  • relative humidity
	  • air velocity
	  • loading ratio
	  • air change rate
	• Test duration
	• Sampling frequency

Air Sampling and Analysis	• Target contaminants identification • Sampling technique (sorbents, canisters) • Analytical methodology (gas chromatography–flame ionization detector [GC-FID], GC-MS, HPLC, ozone, particulates)
Data Analysis and Interpretation	• Modeling/curve-fitting techniques • Emission factor calculation methods • Estimation of resulting room concentrations • Exposure assessment models

Some specific methods and protocols have been developed by various agencies (including standards associations and government bodies) to address these emission test parameters. Table 5.1-I gives a summary of key emissions test documents.

Matthews (1987), Tichenor (1989), Levin and Hodgson (1996), Wolkoff (1999), and Saarela et al. (2002) have described protocols for determining VOC emissions from building materials. As a guidance document (not a detailed method), ASTM D 5116 (ASTM 2006) serves as a basis for the development of emissions test protocols. Tichenor (2007) prepared a comprehensive review that evaluates emissions testing criteria, data analysis, and labeling systems as well as existing test laboratories established in the U.S. to conduct emissions testing.

As stated previously, test methods and labels tend to respond to designer specifications. Table 5.1-J lists several key specification systems, briefly describes the scope for each, and summarizes their main technical requirements related to contaminant emissions. The systems listed are broad in scope, applying generally to a wide range of products and materials. Specifications that relate to specific product types (e.g., flooring materials or architectural coatings) are listed separately in subsections of the “Priority Materials/Finishes/Furnishings” section of this Strategy.

Table 5.1-I Emissions Test Methods by Government Bodies or Standards Associations

Area	Agency	Standard/Protocol
Small-Scale Emissions Chambers	ASTM International	*ASTM D 5116, Standard Guide for Small-Scale Environmental Chamber Determinations of Organic Emissions From Indoor Materials/Products* (ASTM 2006)
	European Committee for Standardization (CEN)	*ENV Pr13419, Building products—determination of the emission of volatile organic compounds: Part 1: Emission test chamber method* (CEN 1999a)
	Danish Standard	*DS/INF 90, Directions for the determination and evaluation of the emission from building products* (DS 1994)
	European Commission (EC)	*Report No. 8: Guideline for the Characterization of Volatile Organic Compounds Emitted from Indoor Materials and Products Using Small Emission Test Chambers* (EC 1991)
	International Organization for Standardization (ISO)	*ISO 16000-9, Indoor Air—Part 9: Determination of the Emissions of Volatile Organic Compounds—Emission Test Chamber Method* (ISO 2006a)
	Nordtest	*Nordtest Method 358: Building Materials, Emission of Volatile Compounds, Chamber Method* (Nordtest 1990)
	California Department of Health Services (CDHS)	*CA/DHS/EHLB/R-174: Standard Practice for Emissions Testing of Various Sources of VOCs in Small-Scale Environmental Chambers* (CDHS 2004) www.cal-iaq.org/VOC/Section01350_7_15_2004_FINAL_PLUS_ADDENDUM-2004-01.pdf
Full-Scale (Large) Emissions Chambers	ASTM International	*ASTM D 6670, Standard Practice for Full-Scale Chamber Determination of Volatile Organic Emissions from Indoor Materials/Products* (ASTM 2007a)
	EPA	*Environmental Technology Verification (ETV) Test Protocol: Large Chamber Test Protocol for Measuring Emissions of VOCs and Aldehydes* (EPA 1999) www.epa.gov/nrmrl/std/etv/pubs/07_vp_furniture.pdf
Emission Cells	ASTM International	*ASTM D 7143, Standard Practice for Emission Cells for the Determination of Volatile Organic Emissions from Indoor Materials/Products* (ASTM 2005c)
	CEN	*ENV Pr13419, Building products—Determination of the emission of volatile organic compounds: Part 2: Emission cell method* (CEN 1999b)
	ISO	*ISO 16000-10, Indoor Air—Part 10: Determination of the Emissions of Volatile Organic Compounds—Emission Test Cell Method* (ISO 2006b)
Specimen Handling	CEN	*ENV Pr13419, Building products—Determination of the emission of volatile organic compounds: Part 3: Procedure for sampling, specimen preparation and preconditioning of materials and products* (CEN 1999c)
	ISO	*ISO 16000-11, Indoor Air—Part 11: Determination of the Emission of Volatile Organic Compounds—Sampling, Storage of Samples, and Preparation of Test Specimens* (ISO 2006c)

Table 5.1-J Summary of General Specification Systems for Emissions Testing (for Product-Specific Protocols and Specifications, Refer to the Subsections in the "Priority Materials/Finishes/Furnishings" Section of this Strategy)

Program/Publication	Emissions Test Protocol/Specified Compounds

Section 01350, Special Environmental Requirements Specification (U.S., California Integrated Waste Management Board, established 2000, www.ciwmb.ca.gov/GreenBuilding/Specs/Section01350/) and ***CA/DHS/EHLB/R-174, Standard Practice for the Testing of Volatile Organic Emissions from Various Sources Using Small-Scale Environmental Chambers*** (U.S., California Department of Health Services www.cal-iaq.org/VOC/Section01350_7_15_2004_FINAL_PLUS_ADDENDUM-2004-01.pdf)
• Requires specific procedures for specimen receiving, handling, and preparation
  • Conditioning of test specimens for 10 days at 73.4°F ± 3.6°F (23°C ± 2°C) and 50% ± 10% RH, followed by a 96-hour test
  • Sample collection at 24, 48, and 96 hours, following completion of 10-day conditioning period, based on small-chamber tests as per ASTM D5116-97 (ASTM 2006)
• Requires calculated emissions factors of the identified contaminants of concern used to calculate the "modeled" indoor air concentrations for a standard office space or a classroom application using default ventilation rates, quantities (surface area, fault length, or units) of the material to be installed, and space volumes.
	• Emissions at 14 days (10 day conditioning + 96 hour chamber)
	• Compounds on California's Office of Environmental Health Hazard Assessment (OEHHA) list of chemicals with non-cancer Chronic Reference Exposure Levels (CRELs) (www.oehha.ca.gov/air/allrels.html)
	  • Modeled results must not exceed 50% of the CREL value after 96 hours (plus 10 day conditioning)
	  • Formaldehyde: no single product's modeled concentration can contribute more than half of a total maximum concentration limit of 33μg/m^3 (27 ppb)
	  • Acetaldehyde: no single product's modeled concentration can contribute more than 100% of a total maximum concentration limit of 9 μg/m^3
	• Carcinogens and reproductive toxicants on Prop 65 list (OEHHA 2007a)—need to be reported
	• Compounds on the California Air Resources Board (CARB) California Air Toxics Program list (CARB 2008)—need to be reported
	• The ten most abundant VOCs not included on any of the above lists need to be reported.

Collaborative for High Performance Schools (CHPS) (U.S., California, established 2001, www.chps.net) • Materials satisfying criteria published in the Low-Emitting Materials (LEM) Table (www.chps.net/dev/Drupal/node/381) in the following materials categories: • Access Flooring; Acoustical Ceilings or Wall Panels; Acoustical Flooring; Adhesives, Sealants, Concrete Sealers; Building Insulation; Carpet; Countertops; Demountable Partitions; Doors; Flooring; Furniture; Gypsum Board; Resilient Flooring (Includes Rubber); Resilient Base and Accessories; Paint; Plastic Simulated Wood Trim; Specialty Coatings; Wall Coverings; Wood Doors; Wood Flooring; Composite Wood Boards	• Emissions at 14 days (10 day conditioning + 96 hour chamber) • Follows Section 01350 (CIWMB 2000) specification (see above for details)
SCS-EC10.2, Environmental Certification Program—Indoor Air Quality Performance (U.S., Scientific Certification Systems [SCS], www.scscertified.com/iaq/SCS-EC10.2-2007.pdf) • Section 01350-based certification	• See Section 01350 details above
Health-related Evaluation Procedure for Volatile Organic Compounds Emissions (VOC and SVOC) from Building Products (Germany, Committee for Health-related Evaluation of Building Products [AgBB], established 1997, http://www.umweltbundesamt.de/building-products/archive/AgBB-Evaluation-Scheme2008.pdf)	• Chamber testing according to ISO 16000-9 (ISO 2006a); measurements of TVOCs at 3 and 28 days; identification of carcinogenic VOC levels at 3 and 28 days; comparison of VOC levels vs. LCI values at 28 days (AgBB 2008)

Emissions-based labeling systems have proliferated since the introduction in 1977 of Germany's The Blue Angel system (FME 2009). A summary of such systems is provided in Table 5.1-K. The evolution of these labels is apparent by examining the specifications for Green Label Plus vs. Green Label, Greenguard Children & Schools vs. Greenguard, and Indoor Advantage Gold vs. Indoor Advantage. Where appropriate, details of emissions label methods are provided in the "Priority Materials/Finishes/Furnishings" section in this Strategy.

Previous discussion of the basic concepts related to emissions testing (see the section in this Strategy titled "Emissions Behavior") needs to be kept in mind, especially when attempting to compare results for similar products tested by different labeling systems. If the test conditions (Table 5.1-H) are not similar, then fair comparisons cannot be made.

Table 5.1-K Summary of Emissions-Based Labeling Systems
(For Additional Details of Product-Specific Labeling Systems, Refer to the Subsections in the "Priority Materials/Finishes/Furnishings" Section in this Strategy)

Program	Emissions Test Protocol and Specified Compounds
The Blue Angel (Germany, Federal Ministry for the Environment, established 1977, www.blauer-engel.de/en/index.php) • Original environmental label; now covers nearly 4000 products in about 80 categories • Includes low-emission requirements for certain products: • Composite wood panels (particleboard, fiberboard, plywood) • Wood products and wood-based products (flooring, residential furniture, office furniture, wood panels) • Floor covering adhesives and other installation materials • Upholstery • Wall paints	• Emissions at 1 day and 28 days • Test conditions: • 23°C • 45% RH • 1 ach • 1 m^2/m^3 • Product-specific limits on VOCs • Wood products: analysis for 141 target VOCs, specific concentration limits for Formaldehyde; low molecular weight VOCs (boiling point 50°C–250°C [122°F–482°F]); high MW VOCs (BP > 250°C [482°F]); and carcinogenic mutagenic teratogenic compounds
FloorScore (U.S., Resilient Floor Covering Institute [RFCI], http://www.rfci.com/) • Developed by RFCI in collaboration with Scientific Certification Systems (SCS) • SCS serves as third-party certifier • Section 01350-based certification of flooring materials including tile, sheet vinyl, linoleum, and rubber products for residential and commercial flooring	• Emissions at 14 days (10 day conditioning + 96 hour chamber) • Section 01350 (CIWMB 2000)
GEV-EMICODE (Germany, Association for the Control of Emissions in Products for Flooring Installation, Adhesives and Building Materials [GEV], established 1990, www.emicode.com) • Industry-managed; covers flooring installation products (including primers, leveling compounds, screed materials, adhesives, surface sealing compounds, underlays) • Three TVOC-based emissions classes: EC 1 (very low), EC 2 (low), and EC 3 (not low), with separate levels for Liquid, Powder-based, Pasty, Ready-to-use underlays, etc., and joint sealant products	• Test per ISO 16000-6 (ISO 2004) • Test conditions: • 23°C • 50% RH • 0.5 ach • 0.4 m^2/m^3
Green Label (U.S., Carpet and Rug Institute [CRI], established 1992, www.carpet-rug.com/index.cfm) • Industry-designed and administered, applies only to carpets, carpet adhesives, and carpet cushions. http://www.carpet-rug.com/index.cfm	• Emissions at 24 hours • Carpet: formaldehyde, 4-phenylcyclohexene (4-PC), styrene, TVOCs • Adhesive: formaldehyde, 2-ethyl-1-hexanol, TVOCs • Cushion: formaldehyde, butylated hydroxytoluene, 4-PC, TVOCs
Green Label Plus (U.S., CRI, established 2004, www.carpet-rug.com/index.cfm) • Revised version of Green Label program developed to satisfy the requirements of California's Collaborative for High Performance Schools (CHPS) criteria (CHPS 2006)	• Emissions at 1 day and 14 days • Future testing at 1 day only if first test finds good correlation • Carpet: • <1/2 of the current OEHHA CREL values (OEHHA 2008) • TVOCs, Acetaldehyde, Benzene, Caprolactam, 2-Ethylhexanoic Acid, Formaldehyde, 1-Methyl-2-Pyrrolidinone, Naphthalene, Nonanal, Octanal, 4-Phenylcyclohexene, Styrene, Toluene, Vinyl Acetate

Program	Emissions Test Protocol and Specified Compounds

Greenguard (U.S., Greenguard Environmental Institute [GEI], established 1996; www.greenguard.org/)
• Certification programs developed and administered by GEI
• Emissions testing conducted by Air Quality Sciences (AQS)
• Results are confidential
• Products meeting criteria listed in GEI Product Guide (www.greenguard.org/Default.aspx?tabid=12) for 19 product categories including office equipment, adhesives/sealants, air filters, ceiling systems, cleaning products, millwork, electronic equipment, floor finishes, flooring, furniture, construction materials, insulations, paints/coatings, surfacing/countertops, textiles, wall finishes, and window treatments
	• Emissions typically at 168 hours (7 days)
	• Test conditions:
	  • 23°C
	  • 50% RH
	  • 0.4–1 m^2/m^3
	• Product-specific, GEI-established allowable emission levels (in ppm or mg/m^3) based on the material/product being used in a room volume of 32 m^3 with an outdoor air change rate of 0.8 ach (product loading not specified) for certain VOCs (formaldehyde, total aldehydes, 4-phenylcyclohexene, and styrene), TVOCs, and, where applicable, respirable particles, ozone, and other pollutants
	• Carcinogens and reproductive toxins found in Prop 65 (OEHHA 2007a) or by the National Toxicology Program (NTP) or International Agency for Research on Cancer (IARC)
	• EPA's National Ambient Air Quality Standards (NAAQS)
	• 1/10 of ACGIH 8-hour TWA-TLV value (ACGIH 2007)

Greenguard Children & Schools (U.S., GEI, established 2005, www.greenguard.org/)
• Revised version of Greenguard certification, developed to meet Section 01350 (CIWMB 2000) and CHPS specifications (CHPS 2006)
	• Same as Greenguard except:
	  • 1/100 TLV
	  • 1/2 OEHHA CREL
	  • Plus limits on TVOCs, formaldehyde, aldehydes, phthalates, and particles ≤10 µm

GUT (Germany, German Association for Environmentally Friendly Carpets, established 1990, www.gut-ev.de) • Based on the ECA-18-system (EC 1997b)	• Emissions at 72 hours (3 days) • Includes odor testing • Uses the Lowest Concentration of Interest (LCI) table published by AgBB (2008) • Prohibits carcinogens vs. EU list Classes 1 and 2 (EU 1992)
Indoor Advantage (U.S., SCS, established 1984, www.scscertified.com/gbc/indooradvantage.php) • For office furniture and seating that meet the requirements of BIFMA M7.1 (BIFMA 2007a), BIFMA X7.1 (BIFMA 2007b), and LEED for Commercial Interiors (v. 2.0) EQ 4.5 (USGBC 2008)	• See BIFMA M7.1 and X7.1 (see Table 5.1-S of this Strategy)
Indoor Advantage Gold (U.S., SCS, established 1984, www.scscertified.com/gbc/indooradvgold.php) • Designed to meet the indoor emissions limits required by the Section 01350 program (CIWMB 2000) • Applies to any nonflooring product generally used within an enclosed indoor environment such as wall coverings, systems furniture, casework, and insulation	• Product-dependent protocols • Refer to *Section 01350, Special Environmental Requirements Specifications* (CIWMB 2000) (see details provided in Table 5.1-J of this Strategy)

Indoor Climate Label (Denmark and Norway, Danish Society of Indoor Climate and Norwegian Forum of Indoor Climate Labelling, established 1995, www.dsic.org/dsic.htm)
• Assessment protocols developed for:
  • Wall and ceiling systems
  • Carpets
  • Interior doors and folding partitions
  • Windows and exterior doors
  • Resilient floors, wood-based floors, and laminated floors
  • Oils for wood-based floors
  • Kitchen, bath, and wardrobe cabinets
  • Interior building paint
  • Furniture
	• Emissions at 28 days (in cells or conventional chambers)
	• Includes sensory odor testing
	• Threshold values for odor and irritation used are those given in VOCBASE (Jensen and Wolkoff 1996)
	• Indoor-relevant time-value calculated = time required for most slowly emitting individual substances to fall below their odor and irritation thresholds

M-1 Classification, M-2 Classification (Finland, The Building Information Foundation RTS and Finnish Society of Indoor Air Quality and Climate [FiSIAQ], established 1995, www.rts.fi/english.htm)	• Emissions at 28 days
	• Test conditions:
	  • 73.4°F (23°C)
	  • 50% RH
	• Carcinogens identified vs. IARC
	• Includes sensory odor testing

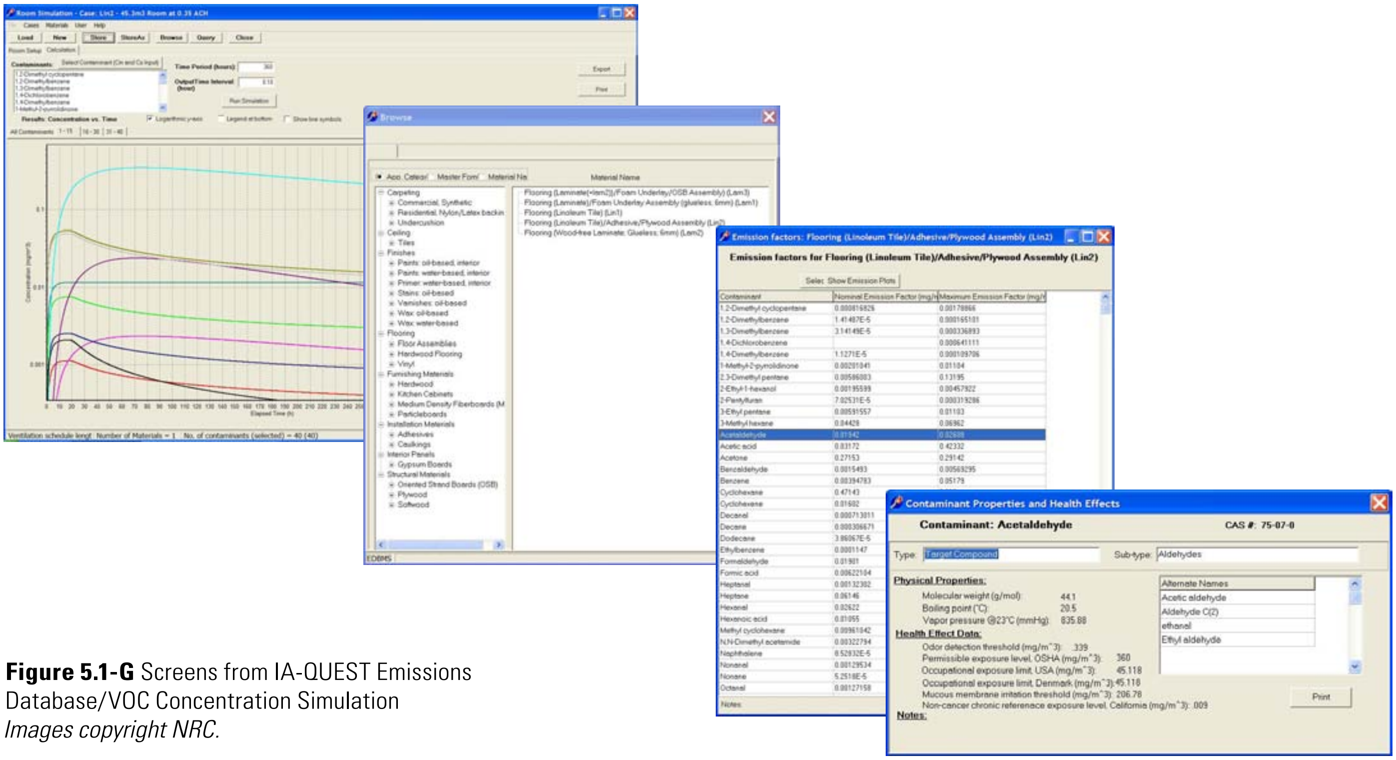
Emissions Databases

In addition to published reports on emissions data from building materials (e.g., Hodgson and Girman [1983], Tichenor and Mason [1988], Cinalli et al. [1993], Clausen et al. [1996], Yu and Crump [1998], and Alevantis [2003]), several limited databases containing product emission information currently exist (see Table 5.1-L). They vary greatly in the type and detail of the information provided. Most contain data for single conditions of temperature and humidity. Since emissions may be strongly dependent on environmental factors, the data are not appropriate for predicting impact for conditions outside those employed during testing. This includes materials subject to direct solar gains, radiant heating, and air velocity conditions in the case of wet-applied products where evaporation is key to initial emission rates.

Table 5.1-L Available Databases/Reports Providing Detailed Material Emissions Information

Agency	Database Title	Comments/Scope
CIWMB	*Building Material Emissions Study* (*BMES*) www.ciwmb.ca.gov/greenbuilding/Specs/Section01350/METStudy.htm	Products tested per Section 01350 (CIWMB 2000) 77 materials in total tested (including products with recycled content) in 11 material classes: • Acoustical Ceiling Panels (7) • Carpeting (14) • Fiberboard (5) • Gypsum Board (4) • Paints (10) • Particleboard (2) • Plastic Laminates (4) • Resilient Flooring (23) • Tackable Wall Panels (2) • Thermal Insulation (4) • Wall Base (2) Analyzed vs. 121 target chemical list (Alevantis 2003)
National Research Council Canada Institute for Research in Construction (NRC-IRC)	*Indoor Air Quality Emission Simulation Tool* (*IA-QUEST*) www.nrc-cnrc.gc.ca/eng/projects/irc/simulation.html	Emission coefficients for 10 product classes (# of sub-classes / # tests in class): • Paint + Stain (4/6) • Finishes (4/6) • Caulking (3/3) • Adhesives (3/3) • Flooring (14/21) • Ceiling Tile (3/3) • Wallboard (4/4) • Wood (2/2) • Engineered Wood (4/19) • Cabinetry (1/2) Each test analyzed vs. 90 Target VOC list (Won et al. 2005a) Includes tool for estimating VOCs in simulated single-zone environments as a function of emitting surface area, entry/removal times, and variable ventilation conditions
NIST	*ContamLink* www.bfrl.nist.gov/IAQanalysis/software/CONTAMLINKdesc.htm	Combines data originally located in EPA's Source Ranking Database (EPA 2007) and IA-QUEST into single database for use in CONTAM simulation of indoor environments

As discussed in the "Emissions Behavior" section of this Strategy, product variability is also a concern when using emissions data. Batch-batch variability, product inhomogeneity, and the changing nature of product formulations and manufacturing processes can significantly influence emission characteristics and render older data obsolete. Careful attention needs to be paid to both the relevance of the data for current



Emission factors for Flooring (Linoleum Tile)/Adhesive/Plywood Assembly (Lin2)

Contaminant	Nominal Emission Factor (mg/h	Maximum Emission Factor (mg/h
1,2-Dimethyl cyclopentane	0.000816826	0.00178866
1,2-Dimethylbenzene	1.41487E-5	0.000165101
1,3-Dimethylbenzene	3.14149E-5	0.000336893
1,4-Dichlorobenzene		0.000641111
1,4-Dimethylbenzene	1.1271E-5	0.000109706
1-Methyl-2-pyrrolidinone	0.00201041	0.01104
2,3-Dimethyl pentane	0.00586083	0.13195
2-Ethyl-1-hexanol	0.00195599	0.00457922
2-Pentylfuran	7.02531E-5	0.000319286
3-Ethyl pentane	0.00591557	0.01103
3-Methyl hexane	0.04428	0.06962
Acetaldehyde	0.01542	0.02688
Acetic acid	0.03172	0.42332
Acetone	0.27153	0.29142
Benzaldehyde	0.0015493	0.00563295
Benzene	0.00394783	0.05179
Cyclohexane	0.47143	
Cyclohexene	0.01602	
Decanal	0.000713011	
Decane	0.000306671	
Dodecane	3.86067E-5	
Ethylbenzene	0.0001147	
Formaldehyde	0.01901	
Formic acid	0.00622104	
Heptanal	0.00132302	
Heptane	0.06146	
Hexanal	0.02622	
Hexanoic acid	0.01055	
Methyl cyclohexane	0.00961042	
N,N-Dimethyl acetamide	0.00322794	
Naphthalene	8.52832E-5	
Nonanal	0.00129534	
Nonane	5.2518E-5	
Octanal	0.00127158	

Contaminant Properties and Health Effects

Contaminant: Acetaldehyde CAS #: 75-07-0

Type: Target Compound Sub-type: Aldehydes

Physical Properties:
Molecular weight (g/mol): 44.1
Boiling point (°C): 20.5
Vapor pressure @23°C (mmHg): 835.88

Health Effect Data:
Odor detection threshold (mg/m^3): .339
Permissible exposure level, OSHA (mg/m^3): 360
Occupational exposure limit, USA (mg/m^3): 45.118
Occupational exposure limit, Denmark (mg/m^3): 45.118
Mucous membrane irritation threshold (mg/m^3): 206.78
Non-cancer chronic referenece exposure level, California (mg/m^3): .009

Notes:

Alternate Names
Acetic aldehyde
Aldehyde C(2)
ethanal
Ethyl aldehyde

Figure 5.1-G Screens from IA-QUEST Emissions Database/VOC Concentration Simulation
Images copyright NRC.

applications and the test conditions employed. For design purposes, the preference is always to obtain test specimens directly from manufacturers of products that will actually be used in the building's construction.

NRC-IRC's IA-QUEST database and simulation tool (Figure 5.1-G) provides detailed emissions data for a limited set of generically identified products analyzed vs. NRC-IRC's 90 target compound list (Won et al. 2003, 2005b). IA-QUEST provides designers and manufacturers with a tool to assess product impact and facilitate development of low-emission alternatives. It can estimate the impact of multiple products on the indoor concentration of individual VOCs for either constant or changing ventilation conditions. As guideline values develop, this capability will support evaluation of product acceptability for different indoor conditions and thus support labeling systems. Analysis of the impact of adjusting ventilation rates while maintaining acceptable guideline VOC values is possible with the tool in support of the IAQ Procedure in ASHRAE Standard 62.1 (Strategy 8.5) (ASHRAE 2007). Suitability of any product used indoors depends not only on area-specific (or unit-specific) emission rates but also on product loading rates and ventilation conditions of the intended space. Tools such as IA-QUEST can simulate the impact of any or all of these parameters. Standardized scenarios may also be tested. By simulating defined material surface areas under set ventilation regimes for a given room volume, chemical exposures in school or office environments may be estimated.

NIST's ContamLink tool makes use of both the EPA and NRC-IRC databases, linking the contained data for access by their CONTAM multi-zone model (NIST 2006). The Collaborative for High Performance Schools (CHPS) Low-Emitting Materials (LEM) Table (CHPS 2008b) provides emissions data for products that have been tested according to the Section 01350 protocol (CIWMB 2000; CDHS 2004), while the BMES reports results for 77 materials containing both recycled and non-recycled materials (Alevantis 2003). The EPA Source Ranking Database (EPA 2007) contains information on a wide range of products, but the information is on chemical content rather than emissions.

Priority Materials/Finishes/Furnishings

A general description of material specifications and labeling systems is provided in the sections “Labels: Content-Based” and “Labels: Emissions-Based.” This section summarizes more detailed sources of information and gives basic guidance to assist building designers on the basis of specific product classes. Far from exhaustive, the 13 subsections here provide reviews of key materials known to have significant impact on IAQ.

The focus here is on contaminant emissions, but this of course is only one (important) aspect of material specification. Many factors, such as structural strength, durability, cleanability, and flame resistance, are important in the selection of materials that are appropriate for use in buildings. Local building codes and regulations need always to be consulted.

As a general note, resistance to microbial contamination may also be of concern for certain materials, but caution is advisable when selecting these products. In general, widespread use of treatments or use of materials specifically formulated to prevent microbial growth (including isothiazolinines, azoles, and pyrethiones) is discouraged. Materials that are well designed for a given indoor application and that receive proper care and maintenance will not likely be subject to problematic biocontamination, whereas the treatments employed may release contaminants indoors and also promote the development of microbial resistance. Triclosan (2,4,4’ –trichloro-2’-hydroxydiphenyl ether), for example, is a chlorinated aromatic compound added as an antifungal agent to a broad range of products. It is persistent in the environment, is bioaccumulative, and has been identified as a possible endocrine disruptor. Recently, the voluntary cancellation of its use in paints has been requested (EPA 2008b).

General reviews of VOC emissions from building materials are given in Levin (1989) and more recently in Yu and Crump (2002).

Architectural Coatings

The term *architectural coatings* refers to a broad class of products including sealers, primers, paints, enamels, clear wood finishes (lacquers, varnishes, etc.), shellacs, stains, and fire-retardant coatings. As products that are wet-applied within buildings, they can represent a major source of IAQ contaminants. As stated by the Master Painters Institute on their Specify Green Web site, “Historically the world of paint and coatings was not an environmentally friendly one! Some paints contained mercury, some arsenic and most of us know about paints that contained lead. Paints (today) contain both organic and inorganic compounds or materials, some of which may adversely impact our environment by releasing solvents or other toxic materials at various stages of the product life-cycle” (MPI 2007).

Not surprisingly, architectural coatings have received significant attention in terms of emissions test protocols (e.g., ASTM D 6803 [ASTM 2007b]), exposure scenarios (ASTM 2007c), and labeling schemes. Table 5.1-M summarizes relevant testing protocols and specifications.

Table 5.1-M Labels, Test Methods, and Specifications—Architectural Coatings

Type	Agency/ Organization	Name and Details

Label—Content	TerraChoice Environmental Marketing Inc. (EcoLogo Program)	*CCD-047-2005, Architectural Surface Coatings* (www.ecologo.org/common/assets/criterias/CCD-047.pdf)
		• Subcategories are:
		  • flat paints
		  • non-flat paints
		  • gloss paints
		  • stains
		  • varnish

Label—Content	Green Seal	*GS-11, Green Seal Environmental Standard for Paints and Coatings*, Second Edition (www.greenseal.org/certification/standards/paints_and_coatings.pdf)
		• Content limits on:
		  • VOCs
		  • Aromatics
		  • Banned compounds:
		    • 1,2-dichlorobenzene
		    • Alkylphenol ethoxylates (APEs)
		    • Formaldehyde-donors
		    • Heavy metals, including lead, mercury, cadmium, hexavalent chromium, and antimony in the elemental form or compounds
		    • Phthalates
		    • Triphenyl tins (TPTs) and tributyl tins (TBTs)

Test Method—VOC Analysis	ASTM	*ASTM D 6886, Standard Test Method for Speciation of the Volatile Organic Compounds (VOCs) in Low VOC Content Waterborne Air-Dry Coatings by Gas Chromatography* (ASTM 2009)
Test Method—VOC Content	EPA	*Method 24—Determination of Volatile Matter Content, Water Content, Density, Volume Solids, and Weight Solids of Surface Coatings* (www.epa.gov/ttn/emc/promgate/m-24.pdf)
Test Method—VOC Emissions	ASTM	*ASTM D 6803, Standard Practice Testing & Sampling of VOCs (Including Carbonyl Compounds) Emitted from Paint Using Small Environmental Chambers* (www.astm.org/Standards/D6803.htm)
Specification—Content	Master Painters Institute (MPI)	*GPS-1-08, Green Performance Standard For Paints & Coatings* (www.paintinfo.com/GPS/GPS-01-08%20_July%202008%20revision_%20and%20GPS-2-08.pdf) • Subcategories include: Architectural Coatings (Interior, Exterior, Flat, or Non-Flat); Concrete/Masonry Sealers; Enamels; Fire Retardant coatings; Floor Coatings; Lacquer; Primers; Sealers; Shellac; Stains; Varnishes • Specifies VOC content (by EPA Method 24 [EPA 2000]) ranging from 50 to 730 g/L depending on coating type
Specification—Content	MPI	*GPS-2-08, Green Performance Standard For Paints & Coatings* (www.paintinfo.com/GPS/GPS-01-08%20_July%202008%20revision_%20and%20GPS-2-08.pdf) • Subcategories include: Architectural Coatings (Interior, Exterior, Flat, or Non-Flat) • Specifies VOC content (by EPA Method 24 [EPA 2000]) of 50 g/L
Specification—Content	California South Coast Air Quality Management District (SCAQMD)	*Rule 1113, Architectural Coatings* ("South Coast Rule"): to limit the VOC content of architectural coatings used in the District …so their actual emissions do not exceed the allowable emissions (www.aqmd.gov/rules/reg/reg11/r1113.pdf) • Note: the primary SCAQMD objective is not improved IAQ but reduction of outdoor smog, thus the VOC definition is the U.S. federal government definition (GPO 2009).

Conversion varnishes provide a familiar example of how content-based labels can be misleading. Howard et al. (1998) demonstrated that due to the chemical reaction involved in the conversion process, formaldehyde emissions could be eight times higher than content analyses of the individual components would indicate. This highlights the importance of testing materials in a manner that reflects actual usage and demonstrates their true emission potential.

Strong dependence can also be seen on the substrate used to test emissions behavior of architectural coatings: paint applied to untreated gypsum wallboard will have markedly different emissions behavior than if applied to a less porous substrate. Similarly, wood stain applied to maple or birch will show different emissions behavior than when applied to oak with its characteristic pore structure. Interpretation of emissions data for architectural coatings thus requires a careful examination of the exact test protocol employed.

In general, water-based acrylic latex paints are lower in VOC content than solvent-based paints. Products identified as “low-VOC” and “zero-VOC” can still vary significantly in toxicity (as well as in cost and performance) (EPA 2009b). These claims are typically based on the U.S. federal government definition of VOCs for outdoor air (GPO [2009]; refer to Table 5.1-A) and need to be viewed with caution.

The VOC content of paints is typically evaluated for the base paint only. Tinting can, however, add significantly to the emissions potential. When specifying paint, it is advisable to request emissions data for the final paint formulation that will be applied. Currently, Green Seal GS-11 states specifically: “The calculation of VOC shall exclude water and colorants added at the point-of-sale” (Green Seal 2008, p. 15). Effective January 1, 2010, GS-11 will require testing of VOC content including colorants (additional contribution to VOC content of the paint of 50 g/L allowed) (Green Seal 2008).

The EPA’s I-BEAM document provides the following guidance for the indoor application of paints (EPA 2008a):

- Use low-VOC-emission, fast-drying paints where feasible.
- Paint during unoccupied hours.
- Keep lids on paint containers when not in use.
- Ventilate the building with significant quantities of outdoor air during and after painting. Insure a complete building flush prior to occupancy.
- Use more than normal outdoor air ventilation for some period after occupancy.
- Avoid spraying, when possible.

VOC emissions from furniture coatings were examined by Salthammer (1997). It needs to be noted that primary emissions from applied architectural coating products are not the sole factor in determining overall product-related emissions. Durability, for example, affects the overall emissions over time and is an important consideration from two aspects: 1) a long-lasting product requires less frequent touch-up or re-application, hence lower emissions, and 2) a finished surface that requires less cleaning and/or re-surfacing will contribute fewer emissions due to the use of cleaning agents or waxes, sealers, etc. Refer to Strategy 5.3 – Minimize IAQ Impacts Associated with Cleaning and Maintenance for further discussion of these aspects.

Flooring Materials

The selection of flooring materials is dependent on many design factors, including aesthetics, thermal comfort, building acoustics, and even light levels (reflectivity effects on daylighting performance). Their impact on IAQ via building cleaning requirements is discussed in Strategy 3.5 – Provide Effective Track-Off Systems at Entrances and in Strategy 5.3 – Minimize IAQ Impacts Associated with Cleaning and Maintenance (including any contaminants generated through waxing, refinishing, vacuuming, or steam/ solvent/detergent cleaning). Due to their large exposed surface areas, flooring materials can have a large direct impact on IAQ via emissions of contaminants. Thus, selection of flooring materials will have a major impact on a building’s indoor environment.

Flooring choices include hardwood, laminates, ceramics, and carpeting, as well as “resilient flooring” (which includes vinyl composition tile and sheet or tile formats of vinyl, linoleum, rubber, and cork). Flooring is typically an assembly of materials. When evaluating potential emissions, the impacts of any adhesives, underlayments, or cushion materials need to be considered. For example, Figure 5.1-H shows a test specimen composed of an assembly of linoleum, its plywood "substrate," and the adhesive required by the flooring manufacturer. Table 5.1-N provides a summary of test protocols and specifications related to flooring material emissions.

Table 5.1-N Labels, Methods, and Specifications—Flooring Products

Type	Agency/Organization	Name and Details
Label—Content	Carpet and Rug Institute (CRI)	**Green Label** (www.carpet-rug.org/commercial-customers/green-building-and-the-environment/green-label-plus/index.cfm) • Industry-designed and administered; applies only to carpets, carpet adhesives, and carpet cushions • See Table 5.1-K of this Strategy for additional details
Label—Content	CRI	**Green Label Plus** (www.carpet-rug.org/commercial-customers/green-building-and-the-environment/green-label-plus/index.cfm) • Revised version of Green Label program developed to satisfy California's Collaborative for High Performance Schools (CHPS) criteria (CHPS 2006) • See Table 5.1- K of this Strategy for additional details
Label—Emissions	Association for the Control of Emissions in Products for Flooring Installation, Adhesives and Building Materials (GEV)	**GEV-EMICODE** (www.emicode.com) • Industry-managed; covers flooring installation products (including primers, leveling compounds, screed materials, adhesives, surface sealing compounds, underlays) • Three TVOC-based emissions classes: EC 1 (very low), EC 2 (low), and EC 3 (not low), with separate levels for Liquid, Powder-based, Pasty, Ready-to-use underlays, etc. and joint sealant products

Label—Emissions	Resilient Floor Covering Institute (RFCI)	**FloorScore** (www.rfci.com/int_FloorScore.htm)
		• Developed by RFCI in collaboration with Scientific Certification Systems (SCS) (SCS serves as third-party certifier) for flooring products including vinyl, linoleum, laminate flooring, wood flooring, ceramic flooring, rubber flooring, and wall base
		• Flooring products must satisfy the requirements of *SCS-EC-10-2004, Environmental Certification Program—Indoor Air Quality Performance* (SCS 2004)
		• Products bearing the FloorScore label meet the indoor air emissions criteria of:
		  • CHPS
		  • LEED Green Building Rating Systems
		  • *Green Guide for Health Care* (GGHC 2007)

Test Method—VOC Content	European Committee for Standardization (CEN)	*EN 13999, The testing of VOCs, volatile aldehydes and diisocyanates from flooring adhesives (Parts 1-4)* (CEN 2007)
Test Method—VOC Emissions	European Commission (EC)	*Report No. 18, Evaluation of VOC Emissions from Building Products—Solid Flooring Materials* (www.inive.org/medias/ECA/ECA_Report18.pdf and www.inive.org/medias/ECA/ECA_Report18-2.pdf)
Test Method—VOC Emissions	Greenguard Environmental Institute (GEI)	*GGTM.P056, Standard Method for the Evaluation of Chemical Emissions from Flooring Products using Environmental Chambers* (www.greenguard.org/uploads/TechDocs/GGTM%20P056%20R4%20Flooring.pdf)
Test Method—VOC Emissions	German Association for Environmentally Friendly Carpets (GUT)	• Based on the ECA-18 system (EC 1997b) • Uses the Lowest Concentration of Interest (LCI) table published by AgBB (2008) • See Table 5.1-C in this Strategy for additional details
Test Method—VOC Emissions Analysis	ASTM	*ASTM D7339, Standard Test Method for Determination of Volatile Organic Compounds Emitted from Carpet using a Specific Sorbent Tube and Thermal Desorption / Gas Chromatography* (ASTM 2007d)

Type	Agency/Organization	Name and Details
Specification—VOC Content	TerraChoice Environmental Marketing Inc. (EcoLogo Program)	*CCD-152, Flooring Products* (www.ecologo.org/common/assets/criterias/CCD-152.pdf) • Includes the following flooring products: • CCD-152A—Bamboo flooring • CCD-152B—Commercial modular carpeting • CCD-152C—Commercial non-modular textile flooring • CCD-152D—Resilient flooring • CCD-152E—Flooring from other virgin wood substitutes • CCD-152F—Rubber-backed textile flooring • CCD-152G—Area rugs
Specification—VOC Emissions	California Department of General Services (DGS)	*California Gold Sustainable Carpet Standard* (www.documents.dgs.ca.gov/green/epp/standards.pdf)
Specification—VOC Emissions	CEN	*EN 14041, Resilient, textile and laminate floor coverings—Essential characteristics* (CEN 2004a)
Specification—VOC Emissions	CEN	*EN 14342, Wood flooring—Characteristics, evaluation of conformity and marking* (CEN 2008)
Specification—VOC Emissions	CEN	*prEN 15052, Resilient, textile and laminate floor coverings—Evaluation and requirements of volatile organic compounds (VOC) emissions* (CEN 2004b) • This dynamic chamber testing standard proposes emission limits based on an extensive list of VOCs with recommended LCI values (AgBB 2008). (This list and the LCI values are not comparable to or consistent with the OEHHA CREL list [2008].)

When considering using resilient flooring, EPA's *IAQ Design Tools for Schools* (2009b) recommends that

- the flooring has been tested for VOC emissions under the Resilient Floor Covering Institute (RFCI) FloorScore program (RFCI 2009),
- the flooring can be easily cleaned and maintained with low-VOC cleaners and finishes,
- the flooring can be installed with low-VOC adhesives and coatings to minimize the indoor air pollution load and health risks to both installers and occupants,
- the installer uses the smallest amount of adhesive necessary to fulfill the manufacturer's performance specifications for that product, and
- the space is provided with additional ventilation for a minimum of 72 hours after installation.

Morrison and Nazaroff (2002) found that ozone reacts with the oils in linoleum to form the persistent strong odors associated with this material. They also reported that linoleum-derived oils can lead to formation of aldehydes including formaldehyde.

Carpeting describes a diverse group of products. The fibers and yarns that make up the pile or face of the carpet may be produced from wool, nylon, polypropylene (olefin), polyester, or blends of these. Primary and secondary backing materials include jute, cotton, kraft cord, and carpet rayon and may be coated in latex.

Carpeting is a system: it may either be glued down using various adhesives (Figure 5.1-I) or laid on top of a cushion material (or *underlay*) that may be composed of polyurethane, rubber-hair, rubber-jute, synthetic fiber, resinated or coated synthetic fiber, rubber, or rubberized polyurethane. In addition, carpeting may be treated with an assortment of chemicals including dyes, color-fast agents, anti-microbial agents, flame retardants, anti-static compounds, and stain guards.

Figure 5.1-H Linoleum/Adhesive/Plywood Tested as an Assembly
Photograph copyright NRC.

Figure 5.1-I Carpet/Adhesive/Concrete Test Assembly
Photograph copyright NRC.

A by-product of the styrene-butadiene rubber latex manufacturing process, 4-phenylcyclohexene (4-PC) is an off-gassed contaminant common to latex-backed carpeting and was suspected to be responsible for IAQ complaints at Washington's Waterside Mall in the late 1980s (Benda 1998). Weschler et al. (1992) found that 4-PC reacts rapidly with ozone indoors to form formaldehyde, acetaldehyde, and other, higher-molecular-weight aldehydes. It is quite possible that these secondary by-products are responsible for the irritation experienced by building occupants. Ten Brinke et al. (1998) reported that styrene from carpet was strongly associated with reported symptoms (including eye, nose, throat, and skin irritation) of occupants of 12 buildings.

The Waterside Mall incident led directly to the establishment of the Green Label system in 1992 by the Carpet and Rug Institute (CRI) through the Carpet Policy Dialogue (CPDG 1991), which set guideline emission levels for 4-PC and styrene (in addition to TVOCs and formaldehyde) from carpeting (CRI 2009). The Association of Environmentally Friendly Carpets (GUT) in Germany had established their carpet emissions testing system two years earlier, in 1990 (GUT 2009). In response to growing knowledge regarding the nature of emissions from building materials in general (and carpet in particular), the Green Label Plus program was released by CRI in 2004 (to meet the more stringent requirements of the CHPS criteria in California [CHPS 2006]). Testing was expanded to include emissions after 14 days for a broader range of specific compounds (see Table 5.1-D), including caprolactam (a monomer used in the manufacture of nylon known to be an irritant and toxic by inhalation).

In addition to acting as a diverse source of emitted chemicals, the vast surface area typical of carpet fabric enables it to act as large sink for indoor VOCs from other sources (Won et al. 2000). See the section in this Strategy titled "Porous or Fleecy Materials" for further discussion of this aspect.

The dirt-trapping properties of carpet and the resulting impact on IAQ have been carefully studied. Shaughnessy (2005) found that open-weave backing of "flow-through" carpet allows passage of debris beyond the product backing, creating a reservoir between the carpet backing and subfloor leading to elevated levels of resuspended particulates. They recommended use of closed-cell cushion backing that retains dust and moisture above the backing layer, facilitating carpet cleaning.

Strategy 6.1

Properly Vent Combustion Equipment

Introduction

Common sources of indoor combustion include

- dedicated combustion equipment such as furnaces, boilers, water heaters, and emergency generators; and
- open-flame processes and equipment such as laboratory burners, cooking appliances, kerosene space heaters, gas-fired laundry equipment, fireplaces, wood-burning heating stoves, and equipment used in numerous industrial processes.

The products of combustion include a number of gases and particles. Some of these combustion products are potentially harmful to human health. The most prevalent of these are the following:

- *Carbon Dioxide (CO_2)*—A colorless, odorless gas that is also exhaled during breathing by humans and animals. In very large quantities, however, CO_2 can cause dizziness, headache, and fatigue.
- *Carbon Monoxide (CO)*—A poisonous colorless and odorless gas. Breathing CO reduces the ability of the bloodstream to carry oxygen. The symptoms of CO poisoning include dizziness, fatigue, flu-like symptoms, and confusion. Sufficient CO exposure can cause loss of consciousness and even death.
- *Nitrogen Dioxide (NO_2)*—A colorless gas with a distinct odor. Exposure causes irritation in the eyes, throat, and lungs that could lead to respiratory illness.
- *Combustion Particles (or Particulate Matter)*—A subset of solid and liquid particles suspended in the air. Examples of this type of particulate matter include smoke, ash, fumes, and soot. Exposure to particulate matter has been associated with respiratory problems, decreased lung capacity, and cardiopulmonary system diseases.
- *Water Vapor*—Excessive water vapor released indoors from combustion can lead to problems associated with indoor condensation.

To avoid exposure to these harmful products, combustion equipment used within a building must be designed and installed with proper venting and exhaust ventilation.

Capture and Exhaust of Combustion Products

The appropriate exhaust capture system depends on the fuel, process, and type of equipment being vented. There are several different types of exhaust capture systems, as discussed in the following subsections.

Chimneys (Nonmechanical, Natural Exhaust)

Chimney systems are natural draft systems that are powered by the differential pressure between warmer conditions at the chimney inlet and cooler conditions at the chimney outlet. The difference in pressures causes the combustion gases to rise up and out of the building. The amount of pressure differential is determined by the height of the chimney and the difference in temperatures from the inlet and outlet of the chimney.

Chimney systems are typically used to ventilate fireplaces, most wood-burning stoves, smaller (less than 100 gal) gas-fired water heaters, and some open-flame cooking appliances. Chimney systems should always be selected and designed so that the temperature of the gases within the chimney is always above dew point. If water vapor is allowed to condense in the chimney system, it could flow back into the combustion equipment and damage it. Condensed water vapor can also combine with the sulfur that is produced during combustion to form corrosive sulfuric acid on the walls of the chimney.

Induced Draft (Powered, Negative-Pressure Exhaust)

Induced-draft systems are mechanical systems that use one or more fans to *pull* combustion gases out of the building. The fans are typically located at the exit of the exhaust system, where the resulting movement of air by the fan causes an induced negative pressure within the exhaust duct that draws combustion gases through the duct to the outdoors.

Many furnaces and boilers that utilize atmospheric pressure gas or oil burners use induced-draft fans for exhaust. Most industrial ventilation exhaust systems, laboratory exhaust systems, and range hoods over gas-fired cooking appliances also use induced-draft exhaust. It is best if the intakes for an induced-draft system are located as close to the source of combustion as is physically possible. Since the fan is typically in the airstream of the exhaust gas, fan equipment must be able to withstand both the expected temperatures of the exhaust gases as well as any potential reactions with the chemical composition of those gases.

Forced Draft (Powered, Positive-Pressure Exhaust)

A forced-draft exhaust system is a mechanical system that uses one or more fans to *push* fresh air for combustion into the equipment. The combustion chamber of the equipment is, consequently, pressurized, and the resulting combustion gases are forced out through the exhaust system.

Most large combustion equipment, including boilers, generators, and even some residential furnaces, use forced-draft burner and exhaust systems. In any combustion system that is under positive pressure, the equipment combustion chamber and the entire connected exhaust duct system must be designed, constructed, and sealed to be airtight to prevent any leakage of harmful combustion products into the surrounding building spaces.

Design and Installation

Regardless of the type of system used, all components of any capture and exhaust system must be designed and installed to adequately remove the products of combustion. Fan and duct materials must be selected to not be damaged by the temperature or chemical makeup of the gases being exhausted. Duct systems should be sealed airtight to prevent any leakage that may affect the system operation or contaminate the spaces in the building.

The location of exhaust flue and vent terminations is extremely important. These terminations should **never** be located near building windows or other outdoor air intakes (see Strategy 3.2 – Locate Outdoor Air Intakes to Minimize Introduction of Contaminants); otherwise, combustion products could be reintroduced into the building.

Outdoor Air for Combustion

An adequate supply of fresh outdoor air for combustion is needed to prevent incomplete combustion, which increases the production of harmful combustion by-products. An inadequate amount of outdoor air can also cause a negative pressure at the equipment burner. This negative pressure condition would interfere with the proper flow of the exhaust gases and could result in a back draft of air returning down the exhaust duct.

Combustion processes and equipment that are connected to natural draft (chimney) or mechanical induced-draft systems typically use the available air in the room for combustion. Therefore, the design of the room space must include provisions for continually introducing a new supply of outdoor air into the building spaces to make up for the air being used in combustion. This makeup air is normally provided through grilles, or additional ductwork, connecting the room to adjacent spaces or to the outdoors. The combustion supply air is normally introduced into the room in at least two separate locations (typically high and low) in order to eliminate the effects of stratification and the natural convective movement of the air due to temperature differentials.

Much forced-draft burner equipment also uses the available room air for combustion supply. Therefore, makeup air must be continually provided to the areas near the burner. Connections to an outdoor supply of air, similar to the systems described for induced-draft exhaust, should be designed as part of the equipment installation.

Many newer, more efficient combustion systems use a direct-vent system for outdoor air. This system connects the equipment directly to the outdoors through a supply air duct. The advantage of this system is that no air is pulled from the room in which the equipment is located—therefore there are no resulting room pressure problems. When designing and installing direct-vent systems, always locate the outdoor inlet away from any potential contaminants.

Proper Operation and Maintenance of Equipment

Even if the exhaust and combustion supply air systems are properly designed and installed, there is still great potential for contamination from harmful combustion products if the combustion equipment itself is not well maintained. It is important to ensure the combustion system and associated equipment are installed per the manufacturer's instructions and to always provide adequate access so it can be easily maintained. The operation and maintenance manual should provide information regarding the manufacturer's recommended inspection intervals.

Commissioning

Given the potential hazards from combustion equipment are prevented, the design and installation of combustion equipment, along with the exhaust and supply duct systems, should be included as a part of the building commissioning process.

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Strategy 6.2

Provide Local Capture and Exhaust for Point Sources of Contaminants

Introduction

The effective capture and exhaust of contaminants generated by a point source within occupied zones of a facility is needed to reduce the impact of these contaminants on occupants. Spaces in which contaminants are generated and subject to exhaust ventilation include laboratories (commercial and school), commercial kitchens, kitchenettes and break rooms, copy/printing facilities, beauty and nail salons, food courts in shopping malls, technology shops in schools, woodworking shops, art classrooms, photography darkrooms, janitorial closets, chemical storage areas, maintenance facilities, parking garages, automotive shops, and other locations where strong contaminant sources are located.

Exhaust methodologies at the point of generation and system design strategies for some of these applications are addressed in other publications and are not repeated in this Guide (for commercial kitchens, see Chapter 31 of *ASHRAE Handbook—HVAC Applications* [ASHRAE 2007a], *NFPA Standard 96, Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations* [NFPA 2008], and applicable model codes for individual project sites, including the *International Mechanical Code* [ICC 2006a] and the *International Fuel Gas Code* [ICC 2006b]; for laboratories, see Chapter 14 of *ASHRAE Handbook—HVAC Applications* [ASHRAE 2007a], which includes a listing of resource materials for various laboratory applications).

Three primary issues need to be addressed to ensure that the exhaust system is effective in removing contaminants from the building: 1) capture the exhaust as close to the source as possible and exhaust directly to the outdoors, 2) maintain the area in which these contaminants are generated at negative pressure relative to the surrounding spaces to reduce the potential impact on occupants in adjacent spaces, and 3) enclose and exhaust the areas where contaminants are generated. Additional information concerning the relative pressures of adjacent spaces can be found in Strategy 6.4 – Maintain Proper Pressure Relationships Between Spaces. Also, there are often specific requirements in model building codes as well as recommendations for these areas in ASHRAE standards and governmental publications.

While maintaining negative pressure in the spaces where contaminants are generated, it is important to ensure that the overall building is maintained at the appropriate pressure (positive, except for a few exceptions) relative to the outdoor environment. Additional information on this subject is provided in Strategy 6.4 – Maintain Proper Pressure Relationships Between Spaces.

The following information will address a few of the specific areas where point sources of contaminants can present challenges in providing acceptable IAQ.

Capturing Contaminants as Close to the Source as Possible and Exhausting Directly to the Outdoors

In any application where contaminants are generated, a direct connection at the source is the preferred method of exhaust, if this is possible. One of the occupancy categories in which direct connection is recommended is automobile repair rooms. Table 6-4 of *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007b), suggests an exhaust air quantity of 1.5 cfm/ft^2 (7.5 L/s·m^2) and also denotes that repair stands where engines are operated for testing and repair "shall have exhaust systems that directly connect to the engine exhaust and prevent escape of fumes" (p. 17). Another example of direct connection for exhaust is the typical clothes dryer. In addition, most manufacturers of large copy machines have an exhaust kit that attaches directly to the copier to allow direct exhaust at the source of the contaminants.

In most cases, however, a direct connection is not possible. But there are other techniques to capture the contaminants close to the source. One prevalent example is beauty and nail salons. Beauty and nail salons use chemicals extensively in the processes common to these facilities. As mentioned previously, capturing contaminants close to the source is the most effective method of exhausting contaminants from an occupied space. This may be accomplished by the use of a hood or snorkel placed over the treatment area or, in the case of nail treatment, at table height of the workstation. An example of a localized exhaust at a worktable is shown in Figure 6.2-B.

Figure 6.2-B Exhaust Vent Embedded in Nail Care Workstation
Source: EPA (2007).

The *IMC* (ICC 2006a) and ASHRAE Standard 62.1 (ASHRAE 2007b) also address minimum exhaust requirements for these facilities. Per Table 403.3 of the *IMC*, the contaminants and any associated odors shall be captured at the source, an exhaust rate of 50 cfm (25 L/s) intermittent or 20 cfm (10 L/s) continuous is required per station (with a general ventilation requirement of 25 cfm [12.5 L/s] per person in a beauty salon), and recirculation of air from this space is prohibited. In Table 6-4 of ASHRAE Standard 62.1, there is a general exhaust requirement of 0.6 cfm/ft^2 (3 L/s·m^2) for beauty and nail salons.

There are recommendations concerning exhaust systems in this application prepared by the U.S. Environmental Protection Agency (EPA), which are summarized in *Protecting the Health of Nail Salon Workers* (EPA 2007). This document recommends that nail salons should have one or a combination of the following:

- A worktable with an exhaust vent embedded in it that is vented to the outdoors.
- A ceiling- or wall-mounted exhaust system with the exhaust intake suspended above the worktable.

Another example of the need for capturing contaminants close to the source is commercial laundry facilities. These facilities extensively utilize chemicals that need to be removed before they pass through occupied spaces. In addition, in the drying area of these facilities, the air is heavily moisture-laden. The failure to effectively exhaust the dryers close to the source and direct to the outdoors will increase the potential for moisture and mold problems inside the space.

Maintaining Areas in which Contaminants are Generated at Negative Pressure Relative to the Surrounding Spaces

The design intent for any area where contaminants are generated is to maintain this area at a negative pressure relative to the surrounding spaces in order to reduce the migration of contaminants to any of the adjacent spaces. To maintain the space at negative pressure, the total exhaust airflow needs to exceed the supply airflow delivered to the space. The balance of the supply air for the exhausted space will infiltrate or transfer from adjacent spaces. In evaluating the total building, a designer needs to be careful to maintain a proper building pressure relative to the outdoors to reduce infiltration of unfiltered, untreated outdoor air directly into the occupied spaces.

One example of the need to maintain pressure differentials for different areas is health-care facilities, such as hospitals and medical care facilities. Tables 3 and 6 in Chapter 7 of *ASHRAE Handbook—HVAC*

Applications (ASHRAE 2007a) include specific tabular data about the recommended pressure relationships to adjacent spaces for hospitals, outpatient facilities, and nursing facilities. The information provided in Table 6 is reproduced in this Strategy as Table 6.2-A. Additional design guidance for health-care facilities is contained in the American Institute of Architects (AIA) publication titled *Guidelines for Design and Construction of Health Care Facilities* (AIA 2006)

Because chemicals are often used in natatoriums to maintain acceptable water quality for swimmers, it is important to negatively pressurize natatoriums. Chapter 4 of *ASHRAE Handbook—HVAC Applications* states, "Pool and spa areas should be maintained at a negative pressure of 0.05 to 0.15 in. of water (12.5 to 37.5 Pa) relative to adjacent areas of thet building to prevent chloramine odor migration" (ASHRAE 2007a, p. 4.6). The chloramine compounds are not only objectionable in odor but also corrosive in nature, which can be detrimental to construction components and furnishings in the adjacent areas. Figure 6.2-C shows the direct exhaust of a typical natatorium area to the outdoors that maintains a negative pressure relative to adjacent spaces.

Table 6.2-A Pressure Relationships and Ventilation of Certain Areas of Nursing Facilities
Source: ASHRAE (2007a).

Function Area	Pressure Relationship to Adjacent Areas	Minimum Air Changes of Outdoor Air per Hour Supplied to Room	Minimum Total Air Changes per Hour Supplied to Room	All Air Exhausted Directly to Outdoors	Air Recirculated within Room Limits
Resident Care					
Resident room (holding room)	*	2	4	Optional	Optional
Resident corridor	*	Optional	2	Optional	Optional
Toilet rooms	Negative	Optional	10	Yes	No
Resident gathering (dining, activity)	*	2	4	Optional	Optional
Diagnostic and Treatment					
Examination room	*	2	6	Optional	Optional
Physical therapy	Negative	2	6	Optional	Optional
Occupational therapy	Negative	2	6	Optional	Optional
Soiled workroom or soiled holding	Negative	2	10	Yes	No
Clean workroom or clean holding	Positive	2	4	Optional	Optional
Sterilizing and Supply					
Sterilizer exhaust	Negative	Optional	10	Yes	No
Linen and trash chute room	Negative	Optional	10	Yes	No
Laundry, general	*	2	10	Yes	No
Soiled linen sorting and storage	Negative	Optional	10	Yes	No
Clean linen storage	Positive	Optional	2	Yes	No
Service					
Food Preparation corner	*	2	10	Yes	Yes
Warewashing room	Negative	Optional	10	Yes	Yes
Dietary day storage	*	Optional	2	Yes	No
Janitor closet	Negative	Optional	10	Yes	No
Bathroom	Negative	Optional	10	Yes	No
Personal services (barber/salon)	Negative	2	10	Yes	No

*Continuous directional control not required.

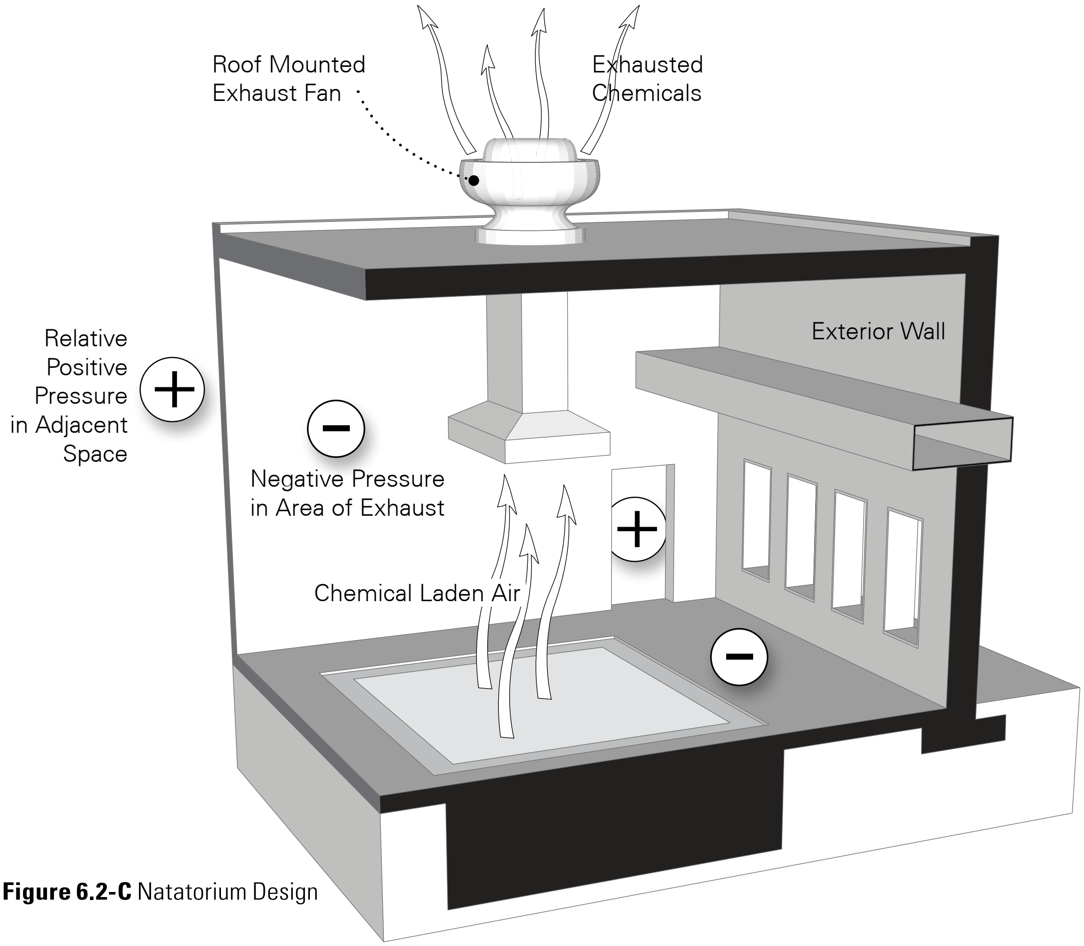

Figure 6.2-C Natatorium Design

Similarly, there are specific code requirements for ventilation airflows in applications of duplication and printing workrooms. Table 430.3 of the *IMC* (ICC 2006a) specifies a minimum outdoor ventilation air requirement of 0.5 cfm/ft^2 (2.5 L/s·m^2) for these areas. In ASHRAE Standard 62.1 (ASHRAE 2007b), this same 0.5 cfm/ft^2 (2.5 L/s·m^2) is required as a minimum exhaust rate for copy and printing rooms.

Enclosing Areas where Contaminants are Generated

Enclosing the area being exhausted assists in maintaining the space under negative pressure and also adds a physical barrier to the transfer of contaminants to adjacent spaces.

The exhaust, enclosure, and negative pressure constitute a system of controls that are to be used in conjunction with each other. For example, if enclosing the space in which contaminants are generated is utilized without appropriate exhaust and negative pressure, the pressure differential relative to adjacent spaces may become positive relative to the surrounding spaces and allow the contaminants to migrate to other areas of the facility. If, however, the space enclosure is the primary strategy to reduce migration of contaminants to adjacent spaces, it is important to ensure that all penetrations of the enclosure walls and openings into the room are properly sealed to reduce leakage into the surrounding areas (see Strategy 6.4 – Maintain Proper Pressure Relationships Between Spaces for more information).

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Strategy 6.3

Design Exhaust Systems to Prevent Leakage of Exhaust Air into Occupied Spaces or Air Distribution Systems

Introduction

The effective capture and exhaust of odors and contaminants generated within the occupied zones of facilities is addressed in Strategy 6.2 – Provide Local Capture and Exhaust for Point Sources of Contaminants of this Guide. It is important to take steps to reduce the potential for leakage of the odors and contaminants into other areas of the building or air distribution systems prior to discharge to the outdoors and, when discharged, also limit the potential for the exhausted air to be re-entrained into ventilation air intakes of the subject building or adjacent facilities.

Areas that require exhaust include toilet rooms, soiled laundry storage rooms, pet shops (animal areas), and spaces where contaminants are generated as part of such processes as cooking, scientific procedures and experimentation, generation and reproduction of paper materials, personal nail treatments, and woodworking and metal shop procedures as well as areas where chemicals are utilized extensively (such as natatoriums, photographic material facilities, and hair salons). The potential impacts on the occupants in these spaces and the surrounding areas include skin irritations, nose/sinus irritations, objectionable odors, and damage to interior building construction materials and/or finishes. Any leakage from the exhaust system has the potential to migrate into the makeup airstream during a smoke removal mode of operation. In addition, if the building design requires the use of a smoke control system, the potential impact of leakage of the exhaust system can have health or life-safety consequences.

Exhaust methodologies at the point of generation and system design strategies for some of these applications are addressed in other publications and are not repeated in this Guide (for commercial kitchens, see Chapter 31 of *ASHRAE Handbook—HVAC Applications* [ASHRAE 2007a], *NFPA Standard 96, Standard for Ventilation Control and Fire Protection of Commercial Cooking Operations* [NFPA 2008], and applicable model codes for individual project sites, including the *International Mechanical Code* [ICC 2006a] and the *International Fuel Gas Code* [ICC 2006b]; for laboratories, see Chapter 14 of *ASHRAE Handbook—HVAC Applications* [ASHRAE 2007a], which includes a listing of resource materials for various laboratory applications).

In each of the applications addressed in this Guide, there are three primary considerations in order to limit the possibility of impacting other occupied spaces and/or air distribution systems due to duct leakage or location of exhaust discharge outlets: 1) effectively seal ductwork to reduce the potential for leakage from the duct system, 2) provide outdoor discharge position and configuration to reduce re-entrainment of exhausted air into outdoor air ventilation systems of the same or adjacent buildings, and 3) maintain exhaust ducts in plenum spaces under negative pressure.

Strategy 6.4 – Maintain Proper Pressure Relationships Between Spaces contains additional information concerning exhaust systems and adjacent spaces. Also, there are often requirements in model building codes, as well as recommendations for these areas in ASHRAE standards and governmental publications, that address specific issues such as hazardous and flammable exhaust.

The following information addresses a few of the specific design and installation considerations where exhaust air routing and termination can present challenges in providing acceptable IAQ.

Effectively Sealing Ductwork to Limit the Potential for Duct Leakage

Exhaust duct systems need to be effectively sealed in order to reduce leakage from the ductwork. A wide variety of sealing methods and products exist for ductwork in the construction industry. The focus of this

Guide is on the potential effects of improper sealing of the exhaust ductwork. For more specific information about the sealing methods and products, refer to the SMACNA *HVAC Duct Construction Standards—Metal and Flexible* (SMACNA 2005).

The leakage rates for unsealed ductwork vary considerably with the type of fabrication utilized, the method of assembly, and the installation quality. The resulting leakage rates of specific installations indicate the potential for issues with exhaust airstreams in an occupied facility. In Chapter 35 of *ASHRAE Handbook—Fundamentals* (ASHRAE 2005), test results are provided that indicate that the leakage rates for unsealed, longitudinal seams in ductwork average from 0.08 to 0.16 cfm per foot (0.10 to 0.25 L/s per meter) of seam length at 1 in. w.g. (250 Pa), depending on the duct construction method. Also, the test results indicate that the leakage rate equates to approximately 10%–15% of the total duct leakage.

Section 5.3 of *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality*, states the following concerning sealing of exhaust ducts: "Exhaust ducts that convey potentially harmful contaminants shall be negatively pressurized relative to spaces through which they pass, so that exhaust air cannot leak into occupied spaces; supply, return, or outdoor air ducts; or plenums." The following exception is stated for this requirement: "Exhaust ducts that are sealed in accordance with SMACNA Seal Class A" (ASHRAE 2007b, p. 6). This seal class is defined in SMACNA's *HVAC Duct Construction Standards—Metal and Flexible* (SMACNA 2005).

Table 8A of *ASHRAE Handbook—Fundamentals* recommends a B seal class for exhaust ductwork installed indoors, either in unconditioned or conditioned spaces (ASHRAE 2005). This seal class requires that all transverse joints and longitudinal seams be effectively sealed. Seal class A, which requires the sealing of duct wall penetrations in addition to the sealing of joints and seams, may be advantageous if the exhaust duct is not routed in a chase isolated from the occupied space or if the exhaust system is part of a smoke control system for the facility. These seal classes are consistent with SMACNA's *HVAC Duct Construction Standards—Metal and Flexible* (SMACNA 2005).

The following information concerning duct leakage tests is excerpted from *ASHRAE Handbook – Fundamentals*: "Leakage tests should be conducted in compliance with SMACNA's HVAC Air Duct Leakage Test Manual (1985) to verify the intent of the designer and the workmanship of the installing contractor. Leakage tests used to confirm leakage class should be conducted at the pressure class for which the duct is constructed. Leakage testing is also addressed in ASHRAE Standard 90.1" (ASHRAE 2005, p. 35.16). Since the publication of the *2005 ASHRAE Handbook—Fundamentals*, SMACNA's *HVAC Duct Construction Standards—Metal and Flexible* was updated; the 2005 edition is the current edition.

For additional guidance, refer to the following:

- For guidance in the selection and use of metal duct sealants and tapes, refer to SMACNA's *HVAC Duct Construction Standards—Metal and Flexible* (SMACNA 2005).
- Fibrous glass ducts and their closure systems are covered by the Underwriters Laboratories (UL) publications *UL Standard 181, Standard for Factory-Made Air Ducts and Air Connectors* (UL 2005a), and *UL Standard 181A, Standard for Closure Systems for Use With Rigid Air Ducts* (UL 2005b).
- For fibrous glass duct construction standards, consult the North American Insulation Manufacturers Association (NAIMA) and SMACNA publications titled *Fibrous Glass Duct Construction Standards* (NAIMA 1997; SMACNA 1992).
- Flexible duct performance and installation standards are covered by UL Standard 181 (UL 2005a), *UL Standard 181B, Standard for Closure Systems for Use With Flexible Air Ducts and Air Connectors* (UL 2005c), and the Air Diffusion Council (ADC) publication *Flexible Duct Performance and Installation Standards* (ADC 1996).

Soldered or welded duct construction is necessary where sealants are not suitable. Sealants used on exterior ducts must be resistant to weather, temperature cycles, sunlight, and ozone.

Any leakage of the installed ductwork can be significantly reduced by effectively sealing the ductwork as indicated in this section. Based on observations of installed systems, it has been found that the amount of leakage will be significantly greater if the ductwork is eliminated and a chase constructed of shaft wall or drywall is utilized to convey the exhaust air from the space to the outdoors. Therefore, use of chases rather than ducts needs to be avoided.

Figure 6.3-C provides an example of a duct installation resulting in excessive leakage due to improper installation and sealing.

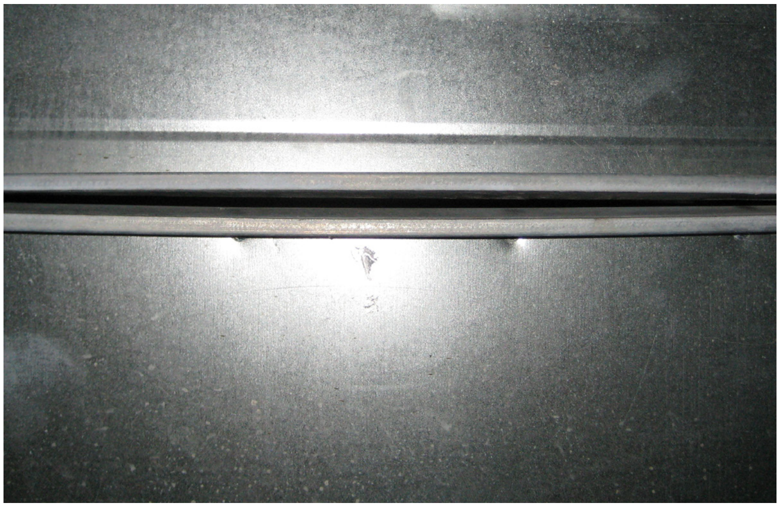

Figure 6.3-C Example of Excessive Duct Leakage Due to Improper Installation/Sealing
Photograph courtesy of Jim Hall.

Providing Proper Outdoor Discharge Position and Configuration
After effectively sealing the ductwork to prevent leakage of the exhaust air and associated contaminants, the air needs to be discharged to the building exterior. The position and configuration of the exhaust termination needs to avoid re-entrainment of the exhaust airstream into outdoor air ventilation systems of the subject building or adjacent buildings.

Table 5-1 of ASHRAE Standard 62.1 (ASHRAE 2007b) provides required minimum separation distances between air intake locations and various types of exhaust airstreams (see Table 6.3-A of this Guide). Some of these separation distances exceed the current requirements of the model codes, which do not differentiate separation distances based on the type of exhaust airstream. For example, the current edition of the *IMC* (ICC 2006a) requires a minimum of 10 ft (3.05 m) of separation between exhaust and intake locations or, alternatively, an intake opening located a minimum of 2 ft (0.61 m) below the contaminant source.

In addition, Chapter 44 of *ASHRAE Handbook—HVAC Applications* includes recommendations for the stack discharge of exhaust airstreams (ASHRAE 2007a).

Previous ASHRAE research (Wilson and Winkel 1982) indicates that stacks terminating below the level of adjacent walls and architectural enclosures frequently do not effectively reduce roof-level exhaust contamination. To take full advantage of their height, stacks need to be located on the highest roof of a building. Architectural screens used to mask rooftop equipment adversely affect exhaust dilution, depending on porosity, relative height, and distance from the stack. Prevailing wind conditions also need to be evaluated to determine the potential impact on the exhaust plume.

Table 6.3-A Air Intake Minimum Separation Distances
Source: ASHRAE (2007b), Table 5-1.

Object	**Minimum Distance, ft (m)**
Significantly contaminated exhaust (Note 1)	15 (5)
Noxious or dangerous exhaust (Notes 2 and 3)	30 (10)
Vents, chimneys, and flues from combustion appliances and equipment (Note 4)	15 (5)
Garage entry, automobile loading area, or drive-in queue (Note 5)	15 (5)
Truck loading area or dock, bus parking/idling area (Note 5)	25 (7.5)
Driveway, street, or parking place (Note 5)	5 (1.5)
Thoroughfare with high traffic volume	25 (7.5)
Roof, landscaped grade, or other surface directly below intake (Notes 6 and 7)	1 (0.30)
Garbage storage/pick-up area, dumpsters	15 (5)
Cooling tower intake or basin	15 (5)
Cooling tower exhaust	25 (7.5)

Note 1: "Significantly contaminated exhaust" is exhaust air with significant contaminant concentration, significant sensory-irritation intensity, or offensive odor.

Note 2: Laboratory fume hood exhaust air outlets shall be in compliance with NFPA 45 (NFPA 1991) and ANSI/AIHA A9.5 (AIHA 1992).

Note 3: "Noxious or dangerous exhaust" is exhaust air with highly objectionable fumes or gases and/or exhaust air with potentially dangerous particles, bioaerosols, or gases at concentrations high enough to be considered harmful. Information on separation criteria for industrial environments can be found in the American Conference of Government Industrial Hygienists (ACGIH) publication *Industrial Ventilation: A Manual of Recommended Practice* (ACGIH 1988) and in the *ASHARE Handbook—HVAC Applications* (ASHRAE 2007a).

Note 4: Shorter separation distances are permitted when determined in accordance with a) Chapter 7 of ANSI A233.1/NFPA 54 (NFPA 2002) for fuel gas burning appliances and equipment, b) Chapter 6 of NFPA 31 (NFPA 2001) for oil burning appliances and equipment, or c) Chapter 7 of NFPA 211 (NFPA 2003) for other combustion appliances and equipment.

Note 5: Distance measured to closest place that vehicle exhaust is likely to be located.

Note 6: No minimum separation distance applies to surfaces that are sloped more than 45° from horizontal or that are less than 1 in. (3 cm) wide.

Note 7: Where snow accumulation is expected, distance listed shall be increased by the expected average snow depth.

In addition, adjacent structures or terrain close to the emitting building can adversely affect stack exhaust dilution because the emitting building can be within the recirculation flow zones downwind of these nearby flow obstacles. Also, an air intake located on a nearby taller building can be contaminated by exhausts from a shorter building. Wherever possible, facilities emitting toxic or highly odorous contaminants need to be located away from taller buildings and away from the bases of steep terrains.

Stacks need to be vertically directed and uncapped. Stack caps that deflect the exhaust jet have a detrimental effect on the exhaust plume. Small conical stack caps often do not completely exclude rain. Periods of heavy rainfall are often accompanied by high winds that deflect raindrops under the cap and into the stack. A stack exhaust velocity of about 2500 fpm (13 m/s) prevents condensed moisture from draining down the stack and keeps rain from entering the stack. For intermittently operated systems, protection from rain and snow needs to be provided by stack drains rather than by stack caps.

High stack exhaust velocities and temperatures increase plume rise, which tends to reduce contamination of intakes in the surrounding area. Exhaust velocities, in general, need to be maintained above 2000 fpm (10 m/s) to provide adequate plume rise. Velocities above 2000 fpm (10 m/s) may result in objectionable noise and vibration from exhaust fans. A nozzle on the stack discharge can be used to increase exhaust velocity and plume rise. If the exhaust system utilizes variable-volume fans, the stack exhaust velocity calculation needs to be based on the minimum total flow rate from the system.

An exception to these exhaust velocity recommendations may be when corrosive condensate droplets are discharged. In this case, a velocity of 1000 fpm (5 m/s) in the stack and a condensate drain are recommended to reduce droplet emission. At this low exhaust velocity, a taller stack may be needed to counteract downwash caused by low exit velocity. Downwash occurs where low-velocity exhausts are pulled downward by negative pressures immediately downwind of the stack.

For unique exhaust applications, Chapter 44 of *ASHRAE Handbook—HVAC Applications* (ASHRAE 2007a) provides additional detailed calculation methodologies for estimating stack height and exhaust-to-intake dilution.

Maintaining Exhaust Ducts in Plenum Spaces under Negative Pressure

As noted previously, Paragraph 5.3 of ASHRAE Standard 62.1 (ASHRAE 2007b) indicates that exhaust ducts shall be negatively pressurized relative to spaces through which they pass so that exhaust air cannot leak into occupied spaces; supply, return, or outdoor air ducts; or plenums. The model building codes also address this application. For example, under a paragraph titled "Contamination prevention," the *IMC* (ICC 2006a) requires that exhaust ducts under positive pressure, chimneys, and vents shall not extend into or pass through ducts or plenums. To achieve this objective, the exhaust fan on any system that requires routing of the ductwork through a plenum space needs to be located at the end of the duct run closest to the building exit point. This does not alter the methodology of sealing of the exhaust duct as discussed previously.

In Strategy 6.2 – Provide Local Capture and Exhaust for Point Sources of Contaminants, the importance of exhausting close to the source of the contaminant is emphasized. However, in applying this philosophy, if the system design or type of contaminant dictates the need for the fan location closer to the location of the source contaminant, it is important to avoid routing of the ductwork through a plenum space. Sealing of the ductwork (as described in the previous section) becomes even more important to limit leakage of the contaminant-laden exhaust airstream into the plenum space. Figure 6.3-D demonstrates the correct location of the exhaust fan for maintaining exhaust ducts in plenum spaces under negative pressure.

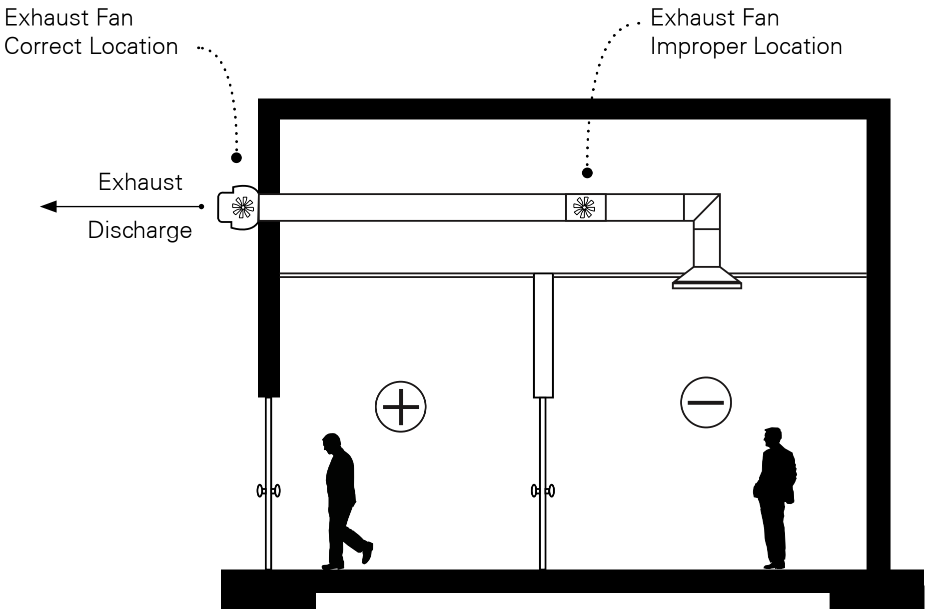

Figure 6.3-D Correct Location of Exhaust Fan to Maintain Exhaust Ducts in Plenum Spaces under Negative Pressure

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Strategy 6.4

Maintain Proper Pressure Relationships Between Spaces

Introduction

Proper space pressurization reduces moisture and contaminant transfer between adjacent spaces, thereby reducing contamination of occupied spaces and unwanted condensation and mold growth. Space pressurization refers to the static pressure difference between the adjacent spaces of a building, with the air tending to move from higher-pressure spaces to lower-pressure spaces. This static pressure difference will influence where exfiltration and infiltration occur across the adjacent spaces. Maintaining proper pressure relationships between adjacent spaces is critical to ensure airflow in the preferred direction, from clean spaces to dirty spaces. Many HVAC systems are designed to achieve a space-to-space differential pressure from 0.01 to 0.05 in. w.c. (2.5 to 12.5 Pa) where pressure relationships are needed.

Space Usage

Space usage needs to be addressed so that proper design considerations may be applied. All contaminants and moisture levels within the space need to be identified so that contamination of adjacent spaces will be reduced. In addition, spaces that are to be positively or negatively pressurized need to be identified. The following are some common space types that need to be identified for proper space pressurization.

Common Space Types

Finished or Occupied Spaces During Construction of Remodeling and Phased Projects. During construction, pressurization strategies will keep the moisture and contaminants from being drawn from the building exterior or areas under construction into the occupied or finished areas. These strategies can include sequencing HVAC equipment operation or lock-out during construction to insure that the finished areas are positively pressurized relative to the construction areas. For example, it is important to avoid negatively pressurizing the finished areas (e.g., avoid operating exhaust fans with no ventilation air) or positively pressurizing the areas under construction by oversupplying ventilation air. As noted in Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ, avoid utilizing permanent HVAC equipment during construction and remodeling.

Medical Office Buildings and Surgery Spaces. Medical office buildings require special attention to space pressurization. Most surgery spaces are required to be positively pressured to adjacent spaces, while certain laboratory areas are required to be negatively pressurized to adjacent spaces. Standards for surgery spaces and other medical-related spaces and their application are discussed by the American Institute of Architects (AIA), ASHRAE, and the Joint Commission on Accreditation of Healthcare Organizations (JCAHO). In addition to these organizations, the American Society of Hospital Engineers (ASHE), Centers for Disease Control and Prevention (CDC), National Institutes of Health (NIH), and National Institute of Occupational Safety and Health (NIOSH) define the expectations for space pressurization for care and service areas in health-care facilities.

Janitorial and Chemical Storage Spaces. Janitorial and chemical storage spaces need to be negatively pressured with respect to adjacent spaces to contain the chemical odors and contaminants.

Natatoriums. The natatorium space needs to be negatively pressured with respect to adjacent spaces to contain the associated pool odors.

Kitchens. Kitchen spaces need to be negatively pressured with respect to adjacent spaces to contain the associated cooking gases and particulates.

Laboratories. Laboratory spaces need to ensure airflow in the proper direction, from clean area to dirty area. A chemistry laboratory located in a school needs to be negatively pressurized to adjacent spaces to contain the chemicals and particulate matter utilized in the laboratory space. See *ASHRAE Laboratory Design Guide* (ASHRAE 2001) for specific requirements on laboratory design.

Parking Garages. Parking garages that are connected to office building structures need to be kept at negative pressure with respect to the office building to keep the moisture and contaminants from entering the building from the parking garage. Revolving doors are a good option for the building entrance from the garage to help compartmentalize to two spaces and thereby limit contaminant transfer into the building.

Mixed-Used Facilities. In many multi-family residential buildings there are multiple types of space usage. For example, there could be a restaurant, beauty salon, dry cleaner, and the residences all located in the same building. There needs to be a clean space to dirty space pressure relationship for these mixed uses utilizing proper space pressurization and directional airflow.

Core and Shell Construction with Future Tenant Finish. Space pressurization cannot be addressed during initial building design since the space usage has not been defined and adjacent spaces to the space of concern can constantly be changing. Evaluation and coordination of the complete building and the existing tenants needs to be performed every time a tenant is to be added. This evaluation needs to include tenant location, adjacent tenant usage, and the pressurization and airflow affects the new tenant will have on the existing tenants and on the pressurization of the building as a whole (effects on total building pressure).

Space Layout

If moisture or contaminants are a concern, it is helpful to select a space layout within the building early in the design process for the most advantageous movement of air. For example, consider the location of spaces in exterior zones versus interior zones. If a space is required to be negative relative to adjacent spaces, consider locating this space on an interior zone to reduce possible infiltration of unconditioned air into the space from outside.

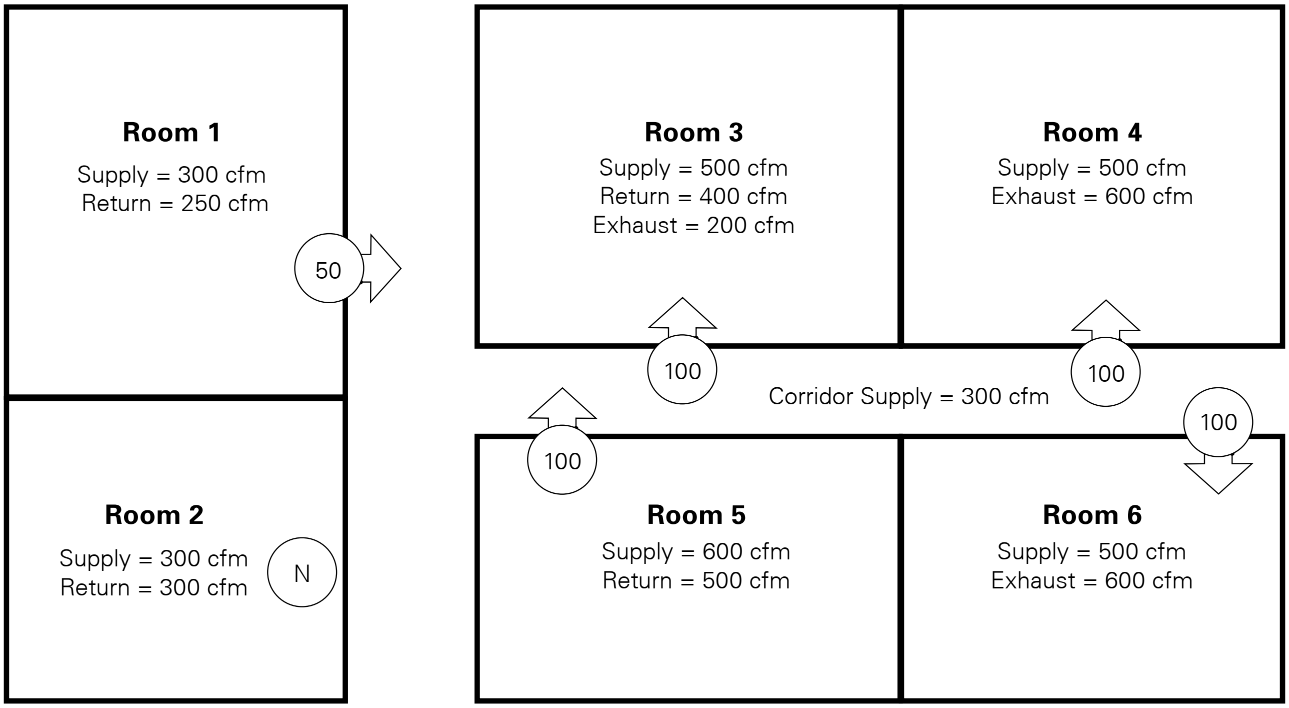
In some space layout arrangements an anteroom might be required. An anteroom is a transition room between areas of substantially different pressures or a space that is used to gain access to a room that needs to maintain its pressure even during disturbances such door openings. The use of anterooms provides assurance that pressure relationships are constantly maintained and air remains flowing from clean to dirty, and they reduce the need for the HVAC control system to respond to large disturbances (ASHRAE 2001).

In addition, consider the air pressures in unoccupied spaces as well as occupied areas of the building. If the air pressure in crawlspaces, basements, or underground ducts falls below the air pressure in the soil, radon and other soil gases could be drawn into those spaces and into the building. If you are concerned that depressurization of ground contact spaces could draw radon (or other contaminants) into the building, see Strategy 3.3 – Control Entry of Radon.

These considerations need to be addressed in the planning phase. In this phase it is important to develop a preliminary pressure map that identifies the space usage/layout and lists the supply airflow rate, return airflow rate, and exhaust airflow rate. Once the space airflows are listed, the directional airflow between spaces can be shown with arrows and airflow values. Figure 6.4-C displays the pressure mapping process.

Space Envelope

The effectiveness of the space pressurization is reduced by the leakiness of the space envelope. Therefore, the space envelope needs to be designed to limit exfiltration, infiltration, and leakage. Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces provides information on the design and construction of the space envelope. It is important to identify and address planned openings



	Supply (cfm)	Return (cfm)	Exhaust (cfm)	Net (cfm)
Room 1	300	250	-	+50
Room 2	300	300	-	-
Room 3	500	400	200	-100
Room 4	500	-	600	-100
Room 5	600	500	-	+100
Room 6	500	-	600	-100
Corridor	300	-	-	+300
Total	**3000**	**1450**	**1400**	

Figure 6.4-C Pressure Mapping Diagram (cfm)

in the space envelope that may reduce the ability of the HVAC system to provide proper pressurization by inadvertently increasing envelope leakiness. These planned openings can include roof vents, louvers, floor drains (traps), conduit penetrations, electrical outlets, lights, and ductwork penetrations. Architectural planned openings such as windows and doors (exterior and interior) also need to be considered. This would include the undercut height of the door serving the space._

Unplanned openings also need to be addressed. Verification of proper construction material usage and proper installation techniques during the construction process is important. Jobsite visits, making inspections, and taking photographs can help confirm that the space envelope will meet or exceed design requirements. It is important that this becomes part of the commissioning (Cx) process (see Strategy 1.2 – Commission to Ensure that the Owner's IAQ Requirements are Met).

Compartmentalization

If space pressurization is not an option, sealing and other construction techniques can be used to compartmentalize space to contain sources of moisture and contaminants. This includes proper use of construction materials such as sealants, wall coverings, air barriers, and vapor barriers. See Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces for a more complete discussion on proper envelope construction.

HVAC System

Airflow Rate Considerations

Space pressurization is a method to reduce infiltration and airflow from dirty and contaminated areas to cleaner areas. This is usually accomplished by exhausting at a different rate than is supplied. If more air is exhausted than supplied, the space will be negatively pressurized; if less air is exhausted than supplied, the space will be positively pressurized. Such an approach is usually applied within a room where the air distribution system is designed to have the air flowing from cleaner areas to dirtier/contaminated areas. However, since movement of personnel and opening of doors can disturb the desired flow pattern, this approach is less applicable where it is critical that airborne contaminants are not spread to sensitive areas within the room (ASHRAE 2001, p. 191).

Air quality for return, transfer, or exhaust can be classified as noted in Section 5.17 of *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007a). This air classification can help identify the clean-to-dirty relationship and pressurization or directional airflow requirements.

A room's differential airflow rate is often called *offset flow*, which is the sum of all the system flows (in or out) of the room. Figure 6.4-D shows the relationship between leakage flow rates at a specific pressure differential across an opening. Each curve on the chart represents a different leakage area.

Once a leakage area along a doorframe is estimated, then leakage through the crack while the door is closed can be calculated based on the pressure difference across the door. Room airtightness is the key element in the relationship between the room's offset flow value and the resulting pressure differential, and each room airtightness is unique and unknown unless tested (ASHRAE 2007b). The airtightness of the room depends on the space envelope design and construction.

If a space requires being negative in pressure in relationship to its adjacent spaces, a basic rule of thumb is that the exhaust airflow from the space needs to exceed the supply airflow into the space by 10% to 20%. If the space is to be positive in pressure relative to its adjacent spaces, the supply airflow from the space needs to exceed the exhaust airflow into the space by 10% to 20%. The goal is to maintain a 0.05 in. (12.5 Pa) pressure differential between adjacent spaces. For more critical contaminant control, see the information provided in *ASHRAE Laboratory Design Guide* (ASHRAE 2001).

STRATEGY OBJECTIVE 6.4

Airflow Monitoring and Control

The following are methods, adapted from the *ASHRAE Handbook—HVAC Applications*, used to pressurize spaces relative to adjacent spaces (ASHRAE 2007b).

Constant-Volume Differential Airflow. There is technically no monitoring or control of a constant-volume differential airflow setup. The HVAC system is designed with a constant airflow offset to maintain proper space pressurization. The airflows are tested and balanced to the designed supply and exhaust airflow rates to maintain the desired airflow offset and the proper space pressure. These exhaust and supply airflow systems operate at a constant airflow value. An example of a constant-volume airflow differential system is a kitchen located in a school: the exhaust airflow through the kitchen exhaust hoods exceeds the supply airflow into the kitchen to create a negatively pressurized kitchen relative to the adjacent areas that in turn provide the makeup offset airflow with transfer air.

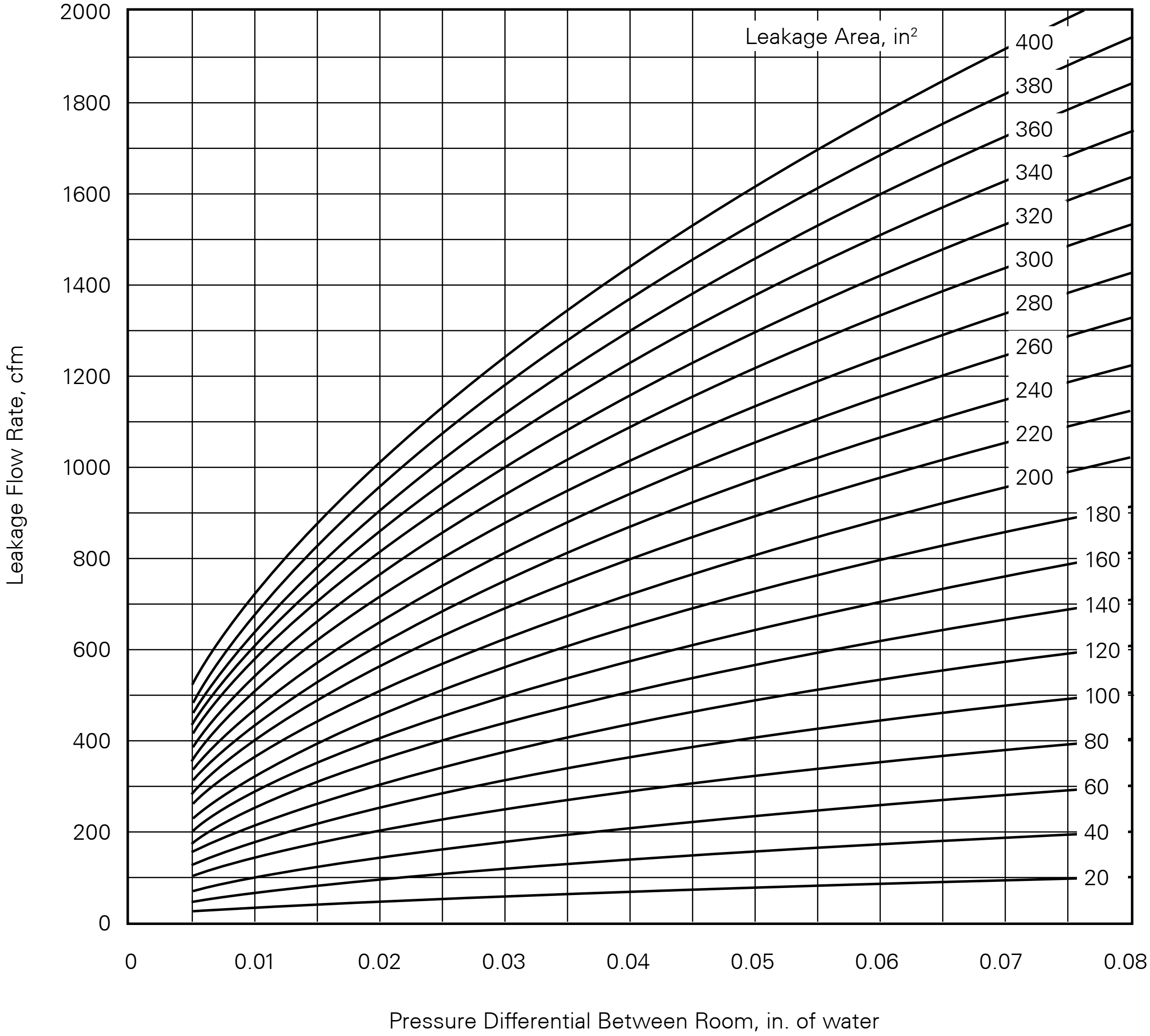


Figure 6.4-D Flow Rate through Leakage Area under Differential Pressure
Adapted from ASHRAE (2007b), p. 16.6.

Differential Static-Pressure Control. Differential static-pressure control uses a pressure differential sensor to measure the pressure difference between a controlled room and an adjacent space (e.g., a corridor). This is suitable for a tightly constructed room with limited traffic. It directly controls the airflow control devices (e.g., variable-air-volume [VAV] boxes or air valves) to achieve the required pressure differential between the controlled room and an adjacent space. The location of measurement for the static pressure needs to be selected carefully, away from drafts or diffusers and in a representative area. A door switch is often useful for triggering a reduced pressure-differential setpoint if the door is opened.

Differential Flow Tracking Control. Differential flow tracking control assumes an offset value based on intuitive guesswork; this value is then used as a volumetric or mass flow difference between entering and leaving airflows through their airflow control devices (e.g., VAV boxes or air valves). This method is suitable for open-style rooms or rooms with frequent traffic. Differential flow tracking control normally maintains the same offset value throughout operation to keep pressurization constant. A constant-percentage offset value is sometimes used, but this creates a weaker pressurization at a lower flow.

Hybrid Control (Cascaded Control). Hybrid control, or cascaded control, combines the pressure accuracy of differential static-pressure control and the stability of differential flow tracking control. The offset value is resettable based on the pressure differential reading. The offset value reset schedule is predetermined, and the controller's parameters are fixed manually in field.

Return Air Plenums

If the HVAC system uses an open plenum above a dropped ceiling for returning air instead of a hard connected duct, the plenum will be at a negative pressure with respect to the occupied space. If contaminants and moisture are drawn into the return air plenum, they will likely be distributed in the building through the HVAC system. For this reason it is important to use sealed return ducts rather than open plenums in spaces with high contaminant and moisture levels, i.e., laboratories, kitchens, and copier rooms.

Mechanical rooms that also serve as the return air plenum and/or mixing plenum for the HVAC systems will draw air from the adjacent spaces, which could contaminate the return air to the HVAC system. In addition, storage of materials and chemicals in such spaces can seriously contaminate the return air and create significant IAQ problems.

Duct Leakage

Ducts running through unconditioned spaces need to be carefully sealed because leaks can create serious problems. For example, leaking supply airflow from ductwork can positively pressurize a space and force moisture or contaminants to other spaces of lower pressure, resulting in mold or contamination in those areas. The reverse is true for exhaust or return ductwork, where leakage could negatively pressurize the space and draw in moisture or contaminants. In addition, this leaking airflow is uncontrolled and the paths the airflow takes cannot be determined. Wall cavities, ceiling plenums, etc. can become the paths of least resistance, drawing in the contaminants and moisture. Microbial growth can thus occur in areas that are not exposed for visual inspection. Leaky return ducts could also draw in unwanted moisture and contaminants and deliver them to occupied spaces.

SMACNA guidelines for proper construction and sealing of ductwork need to be followed to eliminate excessive ductwork leakage. The ductwork can be pressure tested for air leakage where this is a critical area of concern. SMACNA's *HVAC Duct Air Leakage Test Manual* (SMACNA 1985) provides procedures and guidelines for leak-testing ductwork.

Airflow Measurement

To evaluate space pressurization performance one needs to determine the actual airflow quantities into and out of the space. It is therefore important to allow for accurate and repeatable field measurement of supply airflow, return airflow, and exhaust airflow. One of the most accurate methods for determining airflow rates is the duct traverse. For all ducted fan systems, the Air Movement and Control Association (AMCA) publication *Field Performance Measurement of Fan Systems* (AMCA 1990) identifies an ideal duct traverse plane as 2.5 equivalent duct diameters from condition (discharge, elbow, etc.) for air speeds up to 2500 fpm (13 m/s) both upstream and downstream of the duct traverse. If the air velocity exceeds 2500 fpm (13 m/s), one needs to add 1 equivalent diameter for each additional 100 fpm (0.5 m/s). For rectangular duct the equivalent length $E_L = (4a \cdot b/\Pi)^{0.5}$, where *a* and *b* are the duct dimensions. A flow hood could also be utilized to measure space airflow rates at the individual outlets. Careful judgment needs to be utilized with flow hoods. In some cases an airflow factor needs to be established for the flow hood depending on the type of outlet being measured, and this affects the measured values of airflow patterns and air velocities. This airflow factor is normally established utilizing a duct traverse and comparing the traverse airflow measurement to the flow hood measurement.

Strategy 6.4

For a description of proper design and installation considerations for accurate and repeatable measurement of airflows, refer to Strategy 7.2 – Continuously Monitor and Control Outdoor Air Delivery.

Verification

The following are suggested for verification of space pressurization.

1. Verify proper construction of the space envelope, including but not limited to proper use of air barriers and sealing of all pipe, conduit, ductwork, and any other envelope penetrations. Refer to Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces.
2. Provide the design information for the space pressurization requirements on the contract drawings. It is important to include total airflows into and out of the spaces, required directional airflow, and/or the required pressure differential for the spaces. A summary of the space pressurization requirements and airflow and pressure values in a tabular format is extremely helpful.
3. Test, adjust, and balance the HVAC system and verify outdoor, exhaust, supply, and return airflows to ensure that the spaces are maintaining the proper pressurization. This includes testing the systems in minimum and maximum airflow modes. Refer to Associated Air Balance Council (AABC), National Environmental Balancing Bureau (NEBB), ASHRAE, and Testing, Adjusting, and Balancing Bureau (TABB) for standards and procedures required for the testing, adjusting and balancing of HVAC systems.
4. Perform pressure differential mapping to verify actual pressure relationships. Pressure differential measurements identify the potential for airflow between spaces. Multiple pressure readings inside the building can identify pressure differences between the spaces and wall cavities. It cannot be assumed that a wall cavity has the same pressure gradient as the space. A wall cavity may be positively pressurized relative to the space because of infiltration or leaky ductwork. An electrical outlet could let this infiltrated air migrate into the space and potentially contaminate the space with moisture and contaminants from the infiltrated air. These pressure readings need to also include the ceiling plenum pressures to verify that they are positive in pressure with respect to the outdoors. Measurements need to be taken after all HVAC systems have been tested and balanced. If possible the pressure measurements need to be taken at varying system operating conditions (i.e., maximum and minimum airflows for VAV systems, room fan-coil units on and off) (Odom et al. 2005). Refer to Figure 6.4-C, which displays the pressure mapping prEnsure that steps 1–4 are included in the Cx plan. See also Strategy 1.2 –Commission to Ensure that the Owner's IAQ Requirements are Met.
5. If proper pressure relationships cannot be obtained utilizing the HVAC systems, additional space envelope requirements will need to be addressed.

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Strategy 7.1

Provide Appropriate Outdoor Air Quantities for Each Room or Zone

Introduction

Outdoor air has been provided to indoor rooms for centuries. Initially the outdoor air was used as makeup air for fireplaces or to provide cool air to indoor spaces during hot weather. The nature of building ventilation changed with the advent of electricity and the ability to mechanically provide ventilation to buildings without relying on natural drafts.

ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality, defines ventilation air as "that portion of supply air that is outdoor air plus any recirculated air that has been treated for the purpose of maintaining acceptable indoor air quality" (ASHRAE 2007, p. 4). The following discussion uses *ventilation* in the terms of ventilation air as defined by ASHRAE Standard 62.1.

Basic Theory

A simplified approach to building ventilation is shown in Figure 7.1-B.

In the space shown in Figure 7.1-B, a source emits pollutants at a rate S and outdoor air ventilation is provided at rate V. The resulting steady-state indoor concentration C_i of a given pollutant is calculated by

$$C_i = S/V\,.$$

Or, for a given target concentration and known source emission rate, the desired ventilation rate is calculated by

$$V = S/C_i\ .$$

These equations are correct only if

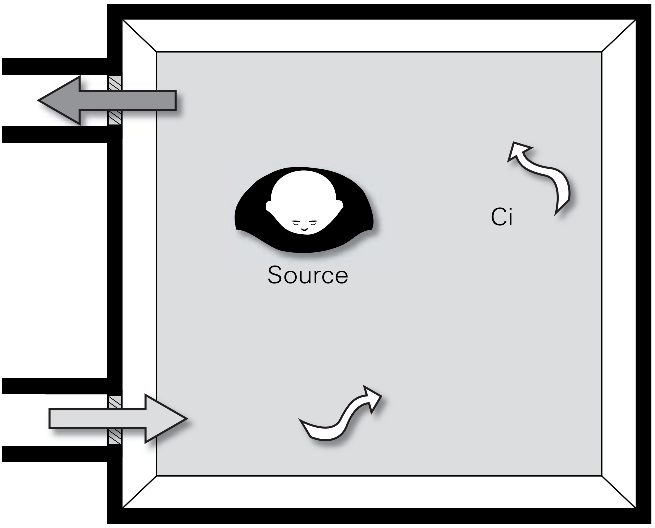

Figure 7.1-B Steady State, where V = Ventilation Rate (Volume/Time), C = Concentration (Mass/volume), and S = Emission Generation Rate (Mass/Time)

- there is only one source,
- the source strength generation rate is known and constant,
- the target concentration is known,
- the air in the room is perfectly mixed (the concentration is the same everywhere in the space),
- the source generation rate is constant,
- steady-state conditions are reached, and
- the concentration of the contaminant outdoors is zero ($C_o = 0$).

From Theory to Reality

In real buildings, the simplifying assumptions in the previous list are almost never met. In many common real situations,

- there are multiple sources, with source generation rates that are unknown and that vary over time;
- there are many indoor compounds, for which appropriate target concentrations are not readily available;
- the air in the room is not perfectly mixed;
- steady-state conditions are never approached; and
- the pollutants of concern are also present in the outdoor air.

Because real-world conditions vary considerably from location to location, from time to time, and from building to building, the minimum ventilation rates for the Ventilation Rate Procedure in ASHRAE Standard 62.1 (ASHRAE 2007) are designed around average expectations for each building occupancy category. The rates were established by a consensus process considering information from laboratory tests of sensory perception, field data from surveys of perception and health effects related to differing ventilation rates, and reports of engineers' experience with past ventilation rates in typical buildings.

Current minimum ventilation rates are published in ASHRAE Standard 62.1-2007, but local codes may differ. Some codes refer to ASHRAE Standard 62.1-2007 as meeting code, and some codes incorporate the ventilation rates from older versions of ASHRAE Standard 62.1. Local building codes that specify rates greater than those in ASHRAE Standard 62.1-2007 must be followed.

People-Related and Space-Related Ventilation Requirements

ASHRAE Standard 62.1 specifies two distinct ventilation rate requirements (ASHRAE 2007). The first is a "per person" requirement to account for pollutant sources associated with human activity and is considered to be proportional to the number of occupants. This rate is referred to as R_p. The rate is determined by the maximum number of people expected to occupy the zone.

The occupancy category determines which per-person ventilation rate to use. For example, in Figure 7.1-C, the emissions from a person engaging in heavy activity in room 4 are different from the emissions from people who are more sedentary (rooms 2 and 3) The values of R_p vary from 5 to 20 cfm (2.5 to 10 L/s) per person depending on expected activity.

The second ventilation rate requirement is a "per unit area" requirement designed to account for pollutants generated by building materials, furnishings, and other sources not associated with the number of occupants. The rate per unit area is referred to as R_a.

Standards in some countries specify multiple levels of ventilation, each for a different level of acceptability (e.g., ON [2007]). In the U.S., only minimum rates are specified. Different levels of acceptability may be addressed using the IAQ Procedure (IAQP) in ASHRAE Standard 62.1 (ASHRAE 2007).

Calculating Minimum Ventilation Rates for Each Zone Using the Ventilation Rate Procedure in ASHRAE Standard 62.1-2007

The design outdoor airflow required in the breathing zone of the occupiable space or spaces in a zone, i.e., the breathing zone outdoor air ventilation rate (V_{bz}), is determined in accordance with Equation 6-1 in ASHRAE Standard 62.1 (ASHRAE 2007):

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z$$

where
A_z = zone floor area: the net occupiable floor area of the zone, (ft^2) m^2
P_z = zone population: the largest number of people expected to occupy the zone during typical usage
R_p = outdoor airflow rate required per person as determined from Table 6-1 of ASHRAE Standard 62.1

> (Note: These values are based on adapted occupants. This means that the rate per person is less than the rate per person in the 1989 version of the standard because the 1989 version was based on the perception of visitors to the space. Visitors are more sensitive to odors than occupants who become "adapted." Therefore, to make air acceptable to visitors would require more ventilation than the air required to make air acceptable to adapted occupants.)

R_a = outdoor airflow rate required per unit area as determined from Table 6-1 of ASHRAE Standard 62.1

Occupancy Category

The occupancy category accounts for the type of space and the activities expected in that space. The factor R_a is based on occupancy category and is intended to provide minimum ventilation to dilute pollutants from all non-people-related sources in the room. For an office space, for example, the R_a required by ASHRAE Standard 62.1 is 0.06 cfm/ft^2 (0.3 L/s·m^2), based on typical expectations for furnishings, walls, floors, ceilings, equipment, and accessories in offices. The standard does not consider whether the office is densely or sparsely furnished (as are rooms 3 and 2, respectively, in Figure 7.1-C). One should take care in situations that are not typical to determine if there is enough ventilation air when using the Ventilation Rate Procedure. As illustrated in Figure 7.1-C, room 1 has a significant pollution source (the copier). This would call for exhaust ventilation (see Strategy 6.2 – Provide Local Capture and Exhaust for Point Sources of Contaminants). Also, in room 4 the emissions from minor processes and chemical compounds are different from a typical office, so even if room 4 is in an office building it would be inappropriate to use the ASHRAE Standard 62.1 equation for office occupancy. Additional ventilation would be required and further analysis is called for.

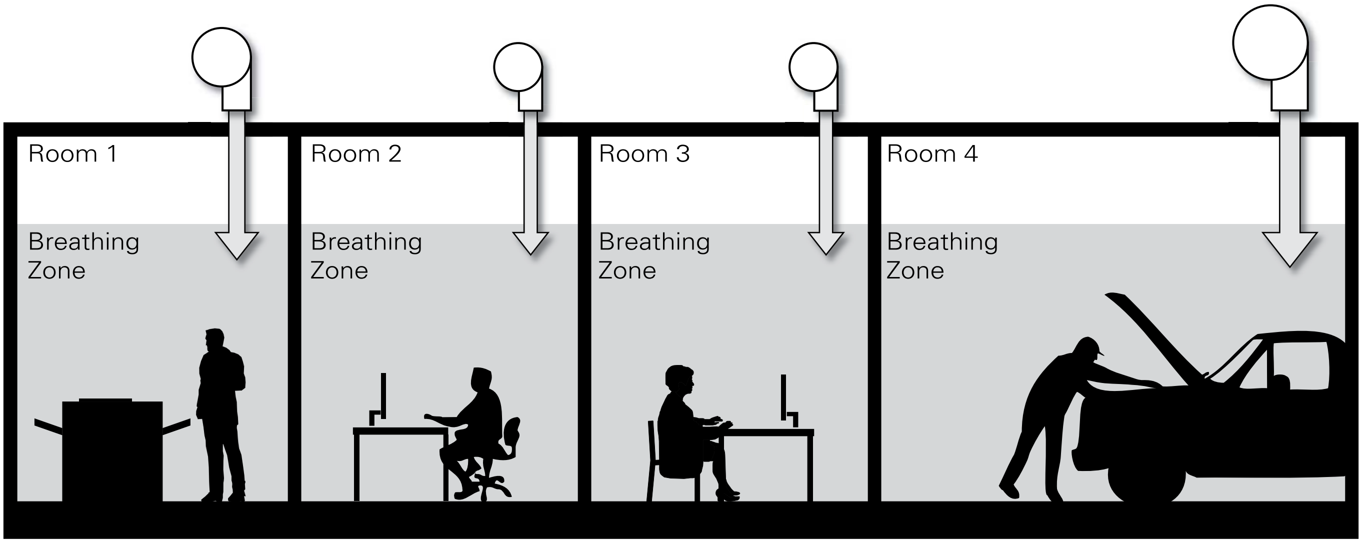

Figure 7.1-C Occupancy Category Examples

Boundaries for Zones and Corresponding Areas

In design, rooms with similar functions often are grouped together and treated as a single zone. Occasionally there are enough differences in conditions or activities in a large room that it is divided into more than one zone. ASHRAE Standard 62.1 defines a ventilation zone as the following:

> one occupied space or several occupied spaces with similar occupancy category… *occupant density*, *zone air distribution effectiveness*…, and *zone primary airflow*… per unit area. Note: A ventilation zone is not necessarily an independent thermal control zone; however, spaces that can be combined for load calculations can often be combined into a single zone for ventilation calculations. (ASHRAE 2007, p. 5, italics in original)

In Figure 7.1-C, rooms 2 and 3 may be combined into one zone.

Adjusting Outdoor Airflow Rates

Increasing Outdoor Airflow Rates when Outdoor Air Quality is Good

When outdoor air quality is good (or acceptable according to the requirements of Section 4 of ASHRAE Standard 62.1), increased ventilation may be beneficial for the following reasons:

- Increased ventilation is related to decreased health symptoms. Rates greater than the current minimums are associated with decreases in symptoms (Seppanen et al. 2002; Sundell and Levin 2007).
- Increased ventilation is correlated with increased productivity in the office and in the classroom (Fisk 2002).
- Increased ventilation is related to increased acceptability of the air as reported by visitors to a room.
- Increased ventilation can save energy during mild weather, as in air-side economizer operation.

Temporarily Decreasing Outdoor Airflow Rates

During short-term episodes of poor outdoor air quality, ventilation can be temporarily decreased using a short-term conditions averaging procedure provided in ASHRAE Standard 62.1. The design may be based on average conditions over a time: $T = 3v/V_{bz}$, where v is the volume of the space.

If this process is considered, proceed as follows:

1. Determine the outdoor air quality and the extent of the problem and whether it is related to time of day, is seasonal, or is a year-round occurrence. (See Strategy 1.3 – Select HVAC Systems to Improve IAQ and Reduce the Energy Impacts of Ventilation for more information.)
2. Provide minimum required filtration. (See Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ for more information).
3. Consider providing additional improvements to ventilation air quality using the IAQP (ASHRAE 2007). (See Strategy 8.5 – Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate for more information.)
4. If short-term reduction in ventilation is still warranted, determine the allowable operating parameters for reducing introduction of pollutants into the space.

Advanced Ventilation Design

Exposures that relate to adverse health effects and people's perception of odor are both functions of concentration. Ventilation is one of many tools used to control or limit concentrations of air pollutants in a room. It is unlikely that increasing ventilation by 30% will make the indoor air 30% better. To determine the benefit (if any) requires a more detailed analysis.

- *Occupancy Needs.* There is little to no benefit in increasing ventilation of a seldom-used corridor beyond the minimum. However, the benefits of increased ventilation might be substantial in a room that is occupied for a long time or is occupied by susceptible individuals.

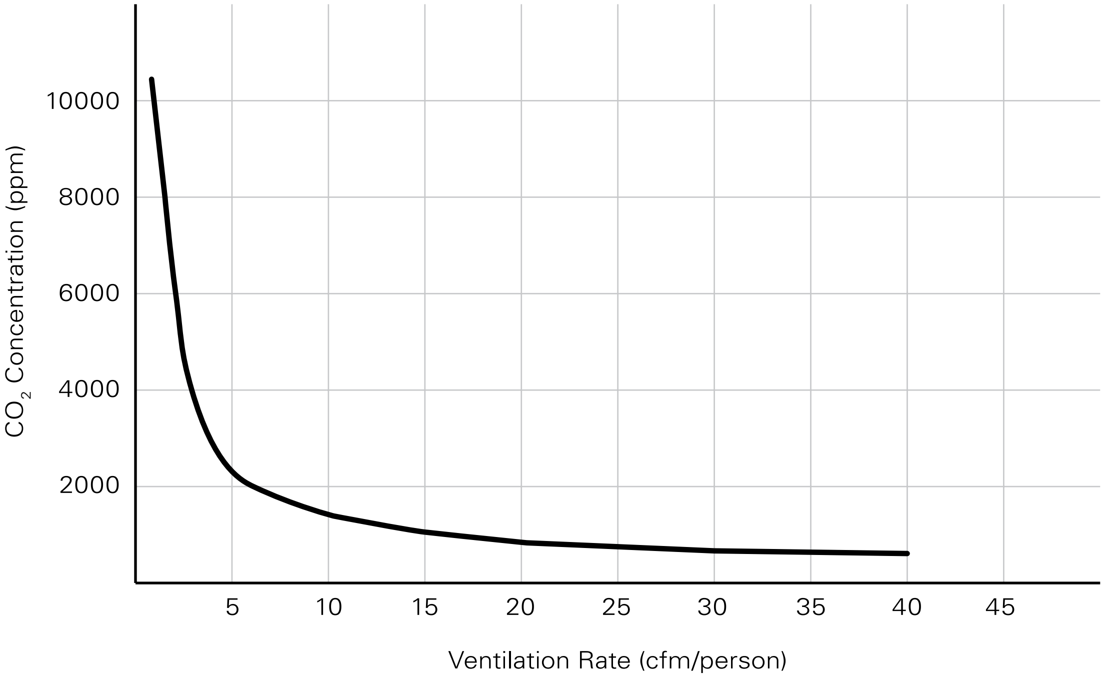

Figure 7.1-D Ventilation vs. CO_2 Concentration

- *Initial Ventilation Rate.* Figures 7.1-D and 7.1-E illustrate the general relationship between pollutant concentration and outdoor air ventilation rate at steady-state conditions and demonstrate the fact that there are diminishing returns from increasing the ventilation rate. Figure 7.1-D shows the relationship of carbon dioxide (CO_2) concentration in parts per million versus ventilation rate in cubic feet per minute (liters per second) per person given certain assumptions. This theoretical graph is intended to illustrate the relationship between ventilation and concentration. When ventilation is very low to begin with, even a modest increase will provide substantial reductions in concentrations. However, when the initial ventilation rate is high, the same increase in ventilation provides very little reduction in pollutant concentrations.

Figure 7.1-E illustrates that the shape of the steady-state ventilation vs. concentration curve is the same if one considers a source or sources with constant continuous emissions in a room. This graph illustrates the ventilation in terms of room air changes with the concentration assumed to be equal to 100 units at one air change per hour. Note that the effects of ventilation on concentration for a source within a room are the similar to the effects of ventilation on emissions from a person in a room.

- *Outdoor Air Quality.* If the quality of the outdoor air is poor, increased ventilation may reduce the concentration of pollutants from indoor sources but raise the concentration of contaminants from outdoor sources. The net effect on IAQ must be carefully considered in deciding whether to increase ventilation rates. For example, ozone is known to react with other chemicals indoors to create reaction products that may be more harmful than the initial constituents. Thus, increasing outdoor air ventilation rates in areas with high outdoor ozone concentrations may well make IAQ worse.

One process for determining the effect of changing ventilation on concentration and is the IAQP (ASHRAE 2007) (see Strategy 8.5 – Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate for more information). One may also use other mass balance formulae or other established methods for quantifying the improvement expected by increasing ventilation. These calculations may assume steady state or may address dynamic conditions.

Enhanced ventilation design must include

- an evaluation of occupancy,
- an evaluation of the benefits of increased ventilation, and
- quantification of the reduction in concentration using a mass balance calculation method.

Documentation of the occupancy evaluation, a statement of the benefits of increased ventilation, and quantification of the reduction in the concentrations of contaminants of concern using the IAQP is enhanced ventilation design.

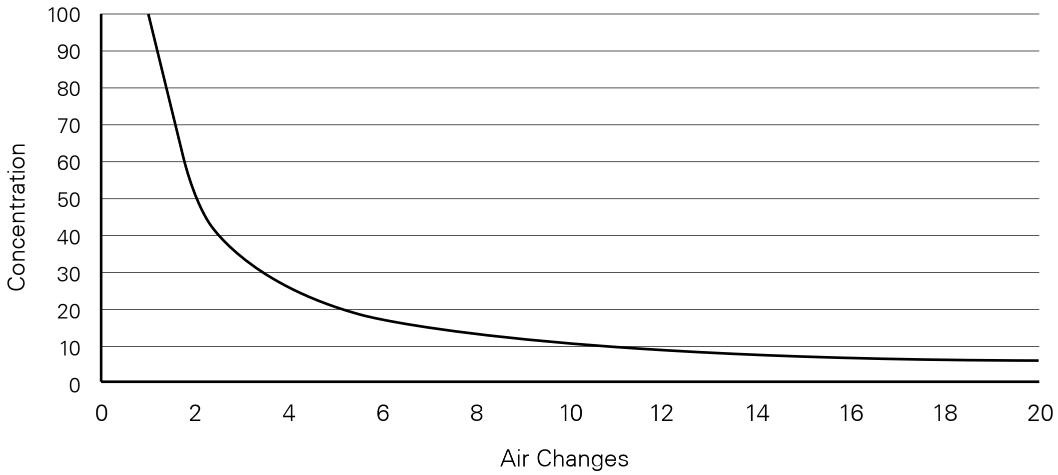

Figure 7.1-E Steady-State Ventilation vs. Concentration Curve

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Strategy 7.2

Continuously Monitor and Control Outdoor Air Delivery

Introduction

Accurate monitoring and control of outdoor air intake at the air handler is important for ensuring that the target outdoor airflow rates are provided to the main supply airstream. It has been common practice for designers to use fixed minimum outdoor air dampers with no airflow monitoring. For example, a study of 100 existing U.S. buildings found that the majority (88%) of these buildings' minimum outdoor airflow rates were based on fixed minimum outdoor air dampers without any continuous airflow monitoring (Persily and Gorfain 2004; Persily et al. 2005). The same study found that these buildings were overventilated relative to per-person outdoor air requirements primarily because the actual occupancy was lower than the design value. It is estimated that the current amount of energy for ventilating U.S. buildings could be reduced by as much as 30%[1] if the average minimum outdoor rate is reduced to meet current published standards on minimum outdoor airflow rates (Fisk et al. 2005a). While accurate monitoring of outdoor air intake rates at the air handler is difficult, the potential for wasted energy with overventilation and the risk of poor IAQ with underventilation justify increased attention to this issue.[2]

Direct Measurement of Airflow

Accurate measurement of airflows in ducts requires careful design, proper commissioning (Cx), and ongoing verification. Under carefully controlled laboratory conditions, commercially available airflow sensors are very accurate. However, in most cases, laboratory conditions and accuracies cannot be replicated in the field and therefore appropriate corrections may be needed in the programming of the HVAC controls.

Straight Ducts

Accurate airflow measurements require long, straight duct runs. This presents a challenge to the designer because space and architectural constraints often limit achieving sufficient straight duct lengths. Chapter 36 of *ASHRAE Handbook—Fundamentals* (ASHRAE 2009) recommends that measuring points be located at least ~7.5 hydraulic diameters downstream and ~3 hydraulic diameters upstream from any disturbance. Hydraulic diameters are calculated based on the following equation:

$$D_h = 4A/P$$

where
D_h = hydraulic diameter, in. (m)
A = duct cross-sectional area, in^2 (m^2)
P = duct wetted perimeter, in (m)

Tables 2 and 3 in Chapter 21 of *ASHRAE Handbook—Fundamentals* (ASHRAE 2009) list hydraulic equivalents for rectangular ducts.

Straightening vanes installed 1.5 duct diameters upstream of measurement points help improve measurement precision.

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[1] This is a first-order estimate of savings potential.

[2] Continuous monitoring of the outdoor rates at the air handler does not guarantee that the proper amount of ventilation is delivered locally within the building. Poor air mixing both in the ductwork and in the occupied space, especially in larger and more complex air distribution systems, can result in parts of a building receiving less than the design minimum amount of ventilation. In addition, infiltration, especially in buildings with leaky envelopes, can lead to large local variations in ventilation rates.

HVAC Systems with Economizers

In HVAC systems with outdoor air ductwork sized for use with an economizer cycle, accurate measurement of minimum outdoor airflow rates can be difficult for some sensor technologies because there is a wide range of airflow velocities (very high in the economizer mode and very low in the minimum outdoor air intake flow mode). Therefore, sensor technologies need to be selected carefully for the range of expected airflow rates. Another way to address this problem is to separate the economizer airstream from the minimum outdoor air intake stream, using appropriate sensor technology in each stream (Krarti et al. 1999). In tests of a limited sample of airflow sensors, researchers have reported that in systems with separate minimum airflow streams, measurement errors of reasonably accurate measurements are between 10% and 30% (Fisk et al. 2005a). Although accuracies better than 10% to 30% have been reported with some technologies and careful placement conditions (Dougan 2003), the technologies tested may not be practical in all real-world applications. In a recent limited study of electronic air velocity probes placed either between the fixed blades of the outdoor intake louvers or at the outlet faces of these louvers, it was found that the measurement errors in most cases were significantly less than 12% (Fisk et al. 2008).

A long-term study of five newly constructed office buildings with continuous monitoring and control of the outdoor airflow rates reported that in 9 of the 16 measurement scenarios, the average airflow rates measured in each building's HVAC systems were within 30% of the design values; however, in 7 of the 16 cases, the measured airflow rates ranged from 35% to 110% above their design values despite the fact that the HVAC systems were locked in their minimum outdoor airflow setting (CDHS 2006).

For built-up variable-air-volume (VAV) systems with air-side economizers, a dedicated outdoor air intake fan with speed control, along with a separate intake duct for minimum outdoor air, may be the best choice to ensure accurate measurement of the outdoor airflow. VAV systems with single outdoor air intakes need to be designed with modulating dampers and with airflow sensors appropriate for the expected airflow range.

Separate Minimum Outdoor Air Intake of a Built-Up HVAC System

The following is an example of a built-up system with separate outdoor air intake and fan. Figure 7.2-B shows the minimum outdoor air fan and the main outdoor dampers. The main dampers are closed when the minimum outdoor air fan is in operation. Figure 7.2-C provides a close-up of the minimum outdoor intake fan. The close-up in Figure 7.2-D shows the main air filters, which are covered with protective drape during building flush-out prior to occupancy.

Figure 7.2-B Minimum Outdoor Air Fan and Main Outdoor Air Dampers

Figure 7.2-C Close-Up of Minimum Outdoor Air Intake Fan

Figure 7.2-D Close-Up of Main Air Filters

Photographs courtesy of Leon Alevantis.

Small Packaged HVAC Systems

Small packaged units typically do not have continuous measurement of outdoor airflows. Due to the lack of economical instruments for field measurements with limited damper or fan controls, these systems deserve even greater attention to confirm the delivery of design airflow rates through balancing, Cx, and periodic recommissioning.

For small packaged HVAC systems, straight runs of ductwork in both the supply and return airstreams will allow for accurate measurements of airflows in these airstreams. Assuming that there is no exhaust (or relief) in the HVAC system, outdoor airflows can then be estimated by deducting the measured return airflow rate from the measured supply airflow rate. Caution needs to be exercised when taking the difference between supply and return airflow measurements in small packaged HVAC systems without sufficient straight ductwork for the supply and return airstreams; such measurements may not meet reasonable accuracy requirements due to cumulative errors in airflow measurement and the generally small outdoor airflow rates relative to supply and return airflow rates. If practical, ductwork needs to be added on the unit's outdoor air intake to allow for a traverse of outdoor air, thus eliminating the need for measuring the difference between the supply and return airstreams.

As mentioned previously, recent limited research of electronic air velocity probes between the blades of outdoor air intake louvers or at the outlet faces of these louvers appears to be highly promising for accurately measuring airflows in small packaged HVAC systems equipped with fixed outdoor air louvers (Fisk et al. 2008).

Placement of Airflow Sensors

Design velocities of outdoor air intake louvers need to be low enough to minimize entrainment of rain and snow. Fisk et al. (2005a) reported that maximum air velocities within the "free area" of these louvers is between 700 and 2500 fpm (3.6 and 12.7 m/s). The upper range of most common louvers is about 1250 fpm (6.3 m/s); however, in areas with strong wind-driven rain, louvers with higher maximum velocities are usually specified and installed. For an HVAC system with an economizer and a single outdoor air intake, velocities at minimum outdoor air conditions are typically about 20% of the maximums. In the Fisk et al. (2005a) study, velocities at minimum outdoor air conditions were between 140 and 500 fpm (0.7 and 2.5 m/s) at the free area of the louver. Because the cross-sectional area inside the louver is less than the nominal face of the louver, velocities upstream and downstream of the louver could be 30% to 50% of the velocities in the free area of the louver. The resulting velocity pressures are too low to measure accurately in the field with pressure-based velocity sensors and challenging for some types of electronic velocity sensors. Furthermore, the air velocity profiles between outdoor air louvers and controlling dampers can be spatially non-uniform and in some cases large eddies can develop (see Figure 7.2-E)

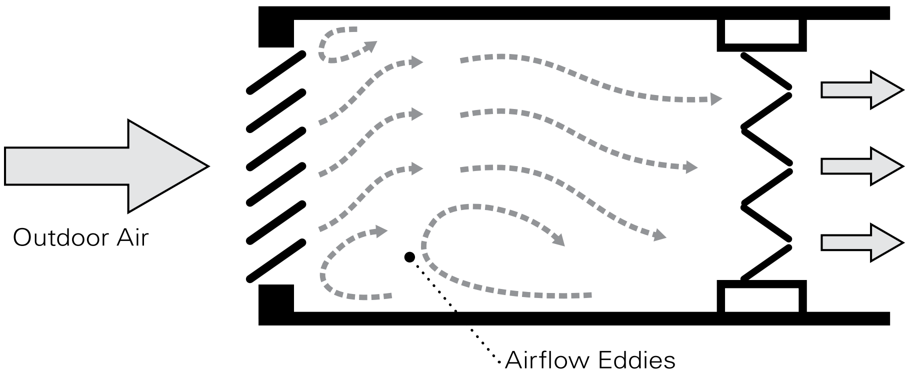

Figure 7.2-E Illustration of Airflow Patterns at the Outdoor Air Intake
Adapted from Fisk et al. (2005b).

In general, the best accuracies can be expected when sensors are placed within the manufacturer's guidelines and are field-verified for optimum performance. Some recent limited research has shown that accuracies of certain measurement technologies may be improved when installed in the following locations: a) between the fixed louver blades where the air speeds are more uniform compared to air speeds downstream of the louvers or b) at the outlet faces of these louvers (Fisk et al. 2008).

The same research has shown that in some applications, airflows downstream of the louvers and upstream of the dampers with or without airflow straightening devices were highly non-uniform and airflow or pressure sensors placed in these locations resulted in higher air velocities than the reference value by more than 25% most of the time. The researchers of this limited study found that for the two types of airflow straighteners used, the eddies shown in Figure 7.2-E sometimes extended through the airflow straighteners and at some locations air flowed backward through the airflow straightener and toward the louver (Fisk et al. 2008).

In order to avoid airflow backward through the outdoor air damper during fully or substantially open conditions, a minimum pressure difference of 0.04 in. H_2O (10 Pa) needs to be maintained across the outdoor air dampers.

Accuracy and Calibration of Airflow Sensors

Regardless of whether airflow sensors are factory or field installed, accuracy of the measured total airflows needs to be verified with appropriately calibrated equipment at start-up and at regular time intervals during occupancy.

It is very important that SMACNA and ASHRAE procedures be implemented during field-based verification of measurement systems in order to maintain that accuracy. These procedures are described in SMACNA's *HVAC Systems—Testing, Adjusting, & Balancing* (SMACNA 2002) and *TAB Procedural Guide* (SMACNA 2003) and in Chapter 14 of *ASHRAE Handbook—Fundamentals* (ASHRAE 2005).

Table 7.2-A lists the characteristics of the various airflow measurement methods. The accuracies reported in Table 7.2-A were developed under controlled laboratory conditions. Actual accuracies in measurement of outdoor airflow rates can be far less than those listed in Table 7.2-A because air speeds and directions are highly variable and not easily predicted.

Separate Minimum Outdoor Air Intake with Airflow Sensors of a Large Packaged HVAC

Figure 7.2-F Separate Minimum Outdoor Air Intake with Honeycomb-Type Louvers

Figure 7.2-G Downstream View of Intake as in Figure 7.2-F

Figure 7.2-F shows a separate minimum outdoor air intake with honeycomb-type louvers. The main outdoor airflow dampers shown are adjacent to the minimum outdoor air intake. Figure 7.2-G shows a downstream view of the same minimum outdoor air intake.

Photographs courtesy of Leon Alevantis.

As can be seen from Table 7.2-A, most airflow sensors listed have limitations on the airflow ranges that can be applied. For example, measurement of low airflows using pressure-based (i.e., pitot) sensors may not always be the best choice, unless the sensor was specifically designed for very low airflow measurements. Sensor manufacturers' specifications and field conditions need to be considered before a sensor is selected.

Ideally, airflow sensors should be capable of measuring flow within an accuracy of ±15% of the minimum outdoor airflow rate.

Table 7.2-A Range and Accuracy of Various Airflow Measurement Methods
Adapted from ASHRAE (2005), Table 4.

Measurement Means	Application	Range, fpm (m/s)	Precision	Limitations
Smoke puff or airborne solid tracer	Low air velocities in rooms; highly directional	5 to 50 (0.03 to 0.25)	10% to 20%	Awkward to use but valuable in tracing air movement
Deflecting vane anemometer	Air velocities in rooms, at outlets, etc.; directional	30 to 24,000 (0.15 to 121.8)	5%	Needs periodic check calibration
Revolving vane anemometer	Moderate air velocities in ducts and rooms; somewhat directional	100 to 3000 (0.51 to 15.2)	2% to 5%	Subject to error due to variations in velocities over space or time; subject to damage; needs periodic calibration
Thermal anemometer	a. Low air velocities; directional and nondirectional available b. Transient velocity and turbulence	1 to 10,000 (0.01 to 50.8)	2% to 10%	Requires accurate calibration at frequent intervals; some are relatively costly
Pitot-static tube	Standard instrument for measuring duct velocities	180 to 10,000 (0.9 to 50.8) with micro-manometer; 600 to 10,000 (3.5 to 50.8) with draft gages; 10,000 (50.8) and up with manometer	1% to 5%	Less accurate at low end of range
Impact tube and sidewall or other static tap	High velocities, small tubes, and where air direction may be variable	120 to 10,000 (0.6 to 50.8) with micro-manometer; 600 to 10,000 (3.1 to 50.8) with draft gages; 10,000 (50.8) and up with manometer	1% to 5%	Accuracy depends on constancy of static pressure across stream section
Cup anemometer	Meteorological	Up to 12,000 (60.9)	2% to 5%	Poor accuracy at low air velocities (<500 fpm [<2.5 m/s])
Laser Doppler velocimeter	Calibration of air velocity instruments	1 to 6000 (0.01 to 30.5)	1% to 3%	High cost and complexity limits to laboratory applications
Pitot array, self-averaging	In-duct assemblies or ducted or fan inlet probes	600 to 10,000 (3.05 to 50.8)	±2% to 40% of reading	Performance depends on quality and range of associated differential pressure transmitter; susceptible to measurement errors caused by duct placement and temperature changes; nonlinear output (square-root function); mathematical errors likely because of sampling method; must be kept clean to function properly; must be set up and field-calibrated to hand-held reference
Vortex-shedding	In-duct assemblies or ducted or fan inlet probes	450 to 6,000 (2.3 to 30.5)	±2.5% to 10% of reading	Highest cost per sensing point; largest physical size; low-temperature accuracy questionable; must be set up and field-calibrated to hand-held reference

Measurement Means	Application	Range, fpm (m/s)	Precision	Limitations
Thermal (analog)	In-duct assemblies or ducted probes	50 to 5000 (0.3to 25.0)	±2% to 40% of reading	Mathematical averaging errors caused by analog electronic circuitry in averaging non-linear signals; sensing points are not independent; unable to compensate for temperatures beyond a specific range; must be set up and field-calibrated to hand-held reference; must be recalibrated regularly to counteract drift
Thermal dispersion (microcontroller-based)	Ducted or fan inlet probes, bleed velocity sensors	25 to 10,000 (0.13 to 50.8)	±2% to 10% of reading	Cost increases with number of sensor assemblies in array; not available with flanged frame; honeycomb air straighteners not recommended by manufacturer; accuracy verified only to –20°F (–29°C); not suitable for abrasive or high-temperature environments
Ultrasonic	Large instruments: meteorological— Small instruments: in-duct and room-air velocities	1 to 6000 (0.01 to 30.5)	+1% to 2%	High cost

Note: The accuracies reported in this table were developed under controlled laboratory conditions. Actual accuracies in measurement of outdoor airflow rates can be much less because air speeds and directions are highly variable and not easily predicted.

Indirect Methods of Measuring Minimum Outdoor Airflows

Direct measurement methods for measuring minimum outdoor airflows are considered to be substantially more accurate than indirect methods. However, indirect methods exist that are sometimes employed in the field, and practitioners need to understand the limitations of these methods. Therefore, although indirect methods of measuring minimum outdoor airflows are not recommended, they are included in this Guide for informational purposes.

Indirect methods for measuring minimum outdoor airflows include plenum pressure control, carbon dioxide (CO_2) concentration balance, CO_2 mass balance, supply/return differential calculation, variable-frequency-drive-controlled fan slaving, adiabatic proration formulae, and fixed minimum position intake dampers. The most common of these methods are discussed in the following subsections (Krarti et al. 1999).

Plenum Pressure Control

The plenum pressure control strategy involves measuring and maintaining a constant pressure drop across a fixed orifice, such as the outdoor air damper and louver. This requires that a dedicated minimum outdoor air damper be used to create a fixed orifice. For VAV systems with economizers, using a minimum damper position to create the fixed orifice is usually not accurate due to lack of repeatability of the damper position assembly (damper, actuator, and linkage). The pressure drop needs to be large enough so that it can be accurately measured but not large enough to create a significant energy penalty. Proper selection of the differential pressure transmitter used to measure the pressure drop across the outdoor air damper is essential.

The CO_2 or Temperature Method

The CO_2 method uses the concentrations of the outdoor air, return air, and supply air to determine the percentage of outdoor airflow in the supply air using the following equation (ASTM 2007):

$$\% \text{ OA} = (CO_{2\text{-RA}} - CO_{2\text{-MA}}) / (CO_{2\text{-RA}} - CO_{2\text{-OA}}) \times 100$$

where
% OA = percentage of outdoor air in the supply airstream
$CO_{2\text{-RA}}$ = CO_2 concentration in the return airstream
$CO_{2\text{-MA}}$ = CO_2 concentration in the mixed airstream
$CO_{2\text{-OA}}$ = CO_2 concentration in the outdoor airstream

The accuracy of this method is reduced as the difference in the CO_2 concentrations of the return and outdoor air becomes small and as the outdoor air becomes a smaller fraction of the supply airflow. Furthermore, accurate measurement of the supply air concentration can be difficult due to poor air mixing downstream of the mixing chamber. Repeatability can also be a significant source of error when multiple CO_2 sensors are used. Using a central measuring device with extraction of the sample by tubing connected to the sampling point reduces the potential for error that can occur when independent sensors are used in each location.

Temperature, instead of CO_2, can also be used to estimate the amount of outdoor airflow. ASHRAE (2007a, 2008) recommends that the temperature difference between outdoor and return airstreams be greater than 20°F (6.7°C) when doing so. An equation similar to the one shown above for CO_2 can be used to calculate the percentage of outdoor air in the supply airstream. The potential sources of error described for estimating the percentage of outdoor air based on CO_2 concentrations are also applicable for estimating it based on temperature.

Section 8.4.1.8 of ASHRAE Standard 62.1

The total quantity of outdoor air to air handlers except for units under 2000 cfm (1000 L/s) of supply air shall be measured in minimum outdoor air mode once every five years. If measured minimum airflow rates are less than the design minimum rate (±10% balancing tolerance) documented in the O&M Manual, they shall be adjusted or modified to bring them to the minimum design rate or evaluated to determine if the measured rates are in compliance with this standard.

$$\% \text{ OA} = (t_{RA} - t_{MA}) / (t_{RA} - t_{OA}) \times 100$$

where
% OA = percentage of outdoor air in the supply airstream
t_{RA} = air temperature of the return airstream
t_{MA} = air temperature of the mixed airstream (before any conditioning)
t_{OA} = air temperature of the outdoor airstream

Due to the potential accuracy problems associated with the indirect methods discussed here, the limitations associated with each method should be evaluated carefully and compared to those of the direct methods before using them in the field.

Design Issues for Commissioning, Operation, and Maintenance

The designer needs to make provisions for measurement and verification of the minimum outdoor airflows during the initial Cx as well during the ongoing Cx of a building (see Section 8.4.1.8 of *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* [ASHRAE 2007b]). Such provisions include

- easy access to the airflow sensors and
- software that can detect sensor (e.g., airflow) and equipment (damper motor) malfunctions, etc.

Separate Minimum Outdoor Air Intake of a Large Packaged HVAC without Airflow Sensors

Figure 7.2-H Minimum Outdoor Air Dampers (to the Right) and Return Air Dampers (at the Bottom)
Photograph courtesy of Leon Alevantis.

The example in this case study shows a typical mixing chamber of a large packaged HVAC system. Figure 7.2-H shows minimum outdoor air dampers (to the right) and return air dampers (at the bottom). Not shown in the figure are the mixed air dampers (to the left) and the economizer intakes. Minimum outdoor airflow measurement and control were not provided in this system at project close-out.

In addition, the design criteria and occupancy assumptions need to be listed in a clear format in the operation and maintenance manual. The building maintenance staff needs to be encouraged to adjust the minimum amount of outdoor air on regular intervals (e.g., annually) based on actual maximum occupancy data.

Adjustment of the minimum airflows needs to be made easier by the provision of convenient access and effective adjustment mechanisms. Also, it is very helpful if the occupancy data are displayed on the building management system and can be easily modified.

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Strategy 7.3

Effectively Distribute Ventilation Air to the Breathing Zone

Introduction

ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality, requirements for outdoor air ventilation are stated in terms of the outdoor air that is delivered to the breathing zone, not to the zone itself (ASHRAE 2007). The extent to which outdoor air reaches the breathing zone is dependent on what is referred to as the *zone air distribution effectiveness*, which is stated as a proportion. Therefore, the amount of outdoor air delivered to the zone needs to be sufficient so that the air reaching the breathing zone meets the minimum requirement in ASHRAE Standard 62.1. An air distribution configuration for which the air is fully mixed will have a zone air distribution effectiveness value of 1 so that the outdoor air rate delivered to the breathing zone is equal to the rate delivered to the zone; less efficient mixing configurations will have values less than 1 and will require more outdoor air to the zone than the fully mixed configuration; configurations in which the outdoor air is delivered to the breathing zone with greater efficiency than fully mixed configurations will have a zone air distribution effectiveness value of greater than 1 and require less outdoor air to the zone than the fully mixed configuration. Zone air distribution effectiveness of the HVAC system is therefore a critical aspect of design and determination of HVAC load capacity.

Zone Air Distribution Effectiveness

The minimum outdoor air delivery rate to the breathing zone is defined in ASHRAE Standard 62.1 as the sum of the rate required as a function of the zone population and as a function of the zone area. This is covered in detail in Strategy 7.1 – Provide Appropriate Outdoor Air Quantities for Each Room or Zone. The rate required to the zone is determined by Equation 6.2 in ASHRAE Standard 62.1, which is restated below:

$$V_{oz} = V_{bz}/E_z$$

where

V_{oz} = quantity of ventilation air delivered to the occupied zone, cfm (L/s)

V_{bz} = quantity of ventilation air delivered to the breathing zone, cfm (L/s)

E_z = zone air distribution effectiveness

The air distribution effectiveness values for alternative air distribution configurations are given in Table 7.3-A.

The designer needs to be aware of the effects of E_z on the total amount of air required to be delivered to the zone. There are many options and approaches that can be considered for every design. For example, there are techniques that can be used to improve E_z even when conditions dictate overheat heating. Two of these are illustrated in the *ASHRAE Journal* article "Overhead Heating: Revisiting a Lost Art" (Int-Hout 2007).

Figure 7.3-C illustrates airflow in design with proper velocity and temperature difference between the incoming air and the room air. For a 75°F (24°C) room, the delivered air needs to be no more than 90°F (32°C). Figure 7.3-D illustrates separating the heating and cooling system so that the heated air is delivered to the space using down-blow nozzles. Either of these approaches will improve the effectiveness from 0.8 to 1.0.

The Effect of Ducted Systems on Air Delivery

In addition to the distribution effectiveness of outdoor air delivered to the breathing zone from the diffuser, how the air is delivered to the diffuser is also an important consideration.

Table 7.3-A Zone Air Distribution Effectiveness
Source: ASHRAE (2007), Table 6-2.

Air Distribution Configuration	E_z
Ceiling supply of cool air	1.0
Ceiling supply of warm air and floor return	1.0
Ceiling supply of warm air 15°F (8°C) or more above space temperature and ceiling return	0.8
Ceiling supply of warm air less than 15°F (8°C) above space temperature and ceiling return provided that the 150 fpm (0.8 m/s) supply air jet reaches to within 4.5 ft (1.4 m) of floor level Note: For lower velocity supply air, $Ez = 0.8$	1.0
Floor supply of cool air and ceiling return provided that the 150 fpm (0.8 m/s) supply jet reaches 4.5 ft (1.4 m) or more above the floor Note: Most underfloor air distribution systems comply with this proviso	1.0
Floor supply of cool air and ceiling return provided low-velocity displacement ventilation achieves unidirectional flow and thermal stratification	1.2
Floor supply of warm air and floor return	1.0
Floor supply of warm air and ceiling return	0.7
Makeup supply drawn in on the opposite side of the room from the exhaust and/or return	0.8
Makeup supply drawn in near the exhaust and/or return location	0.5
Notes: *Cool air* is air cooler than space temperature. *Warm air* is air warmer than space temperature. *Ceiling* includes any point above the breathing zone. *Floor* includes any point below the breathing zone. As an alternative to using the above values, E_z may be regarded as equal to air change effectiveness determined in accordance with *ANSI/ASHRAE Standard 129, Measuring Air-Change Effectiveness* (ASHRAE 2002) for all air distribution configurations except unidirectional flow (Int-Hout 2007).	

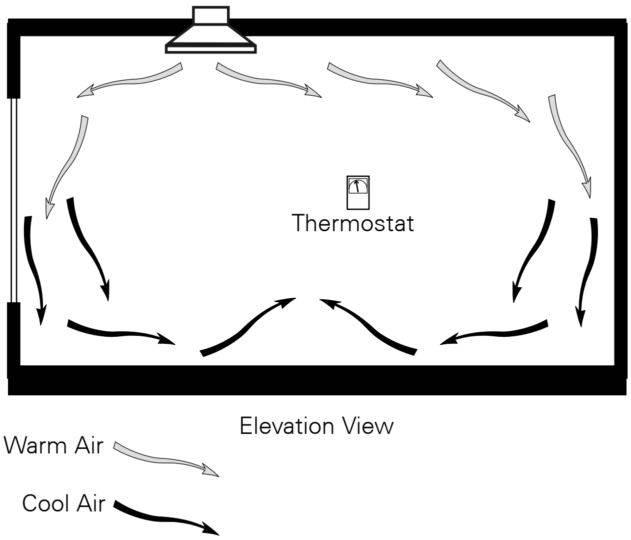

Figure 7.3-C Proper Overhead Heating Design
Adapted from Int-Hout (2007).

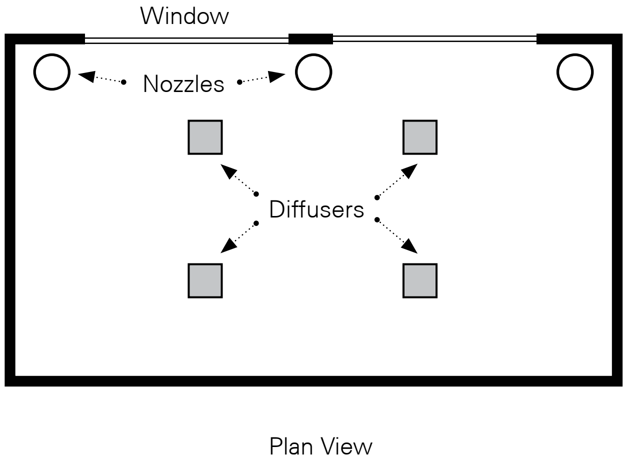

Figure 7.3-D Alternate Overhead Heating Design
Adapted from Int-Hout (2007).

Ducted

With a ducted air system, the air is distributed directly to the zone. Ducts need to be properly constructed and sealed. Provisions need to be made in design for proper balancing. Once a properly designed and constructed ducted system is balanced, one is assured that the air is efficiently delivered to the zone.

Non-Ducted

Non-Ducted—Plenum Systems. In the past, some systems were designed to introduce air into a plenum under the assumption that the air would somehow mix and be distributed into the building. Such "dumping" systems no longer meet current standards. Current research demonstrates that air does not mix or distribute effectively using this strategy (Yuill et al. 2007).

Non-Ducted—Designed. There are special cases with designed non-ducted systems such as underfloor air distribution (UFAD) and dual plenum systems. These systems require special attention to maintaining the integrity of the plenum. Many recently installed systems have suffered from leaks. The area that needs to be sealed in a designed non-ducted system is usually far greater than that in a ducted system.

Many systems have also suffered from inadequate airflow at the furthest distances from supply air introduction. In these cases, increasing fan speeds/sizes to provide adequate air compounds problems by increasing energy usage, increasing the volume of leaks, increasing system noise, and increasing noise at nearby diffusers because of increased pressure.

In response to these distribution issues, many systems are now designed with a hybrid of ductwork under the floor for a certain distance and then open distribution to the area or zone of the floor where the air is delivered.

Provisions for proper balancing need to be made in the design. Because the pathways are numerous and sometimes unknown at the beginning of design, techniques such as pressure regain that work on ducted systems may not work for non-ducted systems.

It is possible for IAQ to be improved with an underfloor system using displacement ventilation. The distribution effectiveness in this case is superior to most other systems. However, one needs to also account for the cleanliness of the distribution system. In ducted systems, there is usually limited access, and if the air is properly cleaned prior to introducing it into the duct, the duct stays clean. Underfloor systems allow multiple access to almost any part of the floor—the air distribution system. Experience in data centers with long-term underfloor systems may lead one to question how to keep those air pathways clean of dust, construction, and renovation debris or other possible pollutant sources.

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Strategy 7.4

Effectively Distribute Ventilation Air to Multiple Spaces

Introduction

ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality, provides methodology for calculating the outdoor airflow rate required at the outdoor air intake for single- and multiple-zone recirculation systems (ASHRAE 2007a). These calculations are a part of design of an HVAC system. The first step in ventilation system design is to provide the appropriate outdoor airflow to each room or zone (see Strategy 7.1 – Provide Appropriate Outdoor Air Quantities for Each Room or Zone). Within each room or zone it is important to distribute ventilation air effectively (see Strategy 7.3 – Effectively Distribute Ventilation Air to the Breathing Zone).

The purpose of the calculations is to ensure that the requisite outdoor airflow rate is ultimately delivered to the breathing zone in each space. Because space uses and needs may differ, and because each air handler may serve multiple spaces, the outdoor air fraction (the proportion of outdoor air to total supply air) needed at each zone may differ. Thus, the outdoor air fraction at the air handler must satisfy the differing needs of each zone. This presents a challenge to the mechanical engineer, who should follow the calculation procedures in ASHRAE Standard 62.1 to design the system.

HVAC system design is beyond the scope of this document. The following discussion is limited to identifying types of systems and critical factors and does not delve into design calculation details, which can become increasingly complex as multiple airflow paths are introduced in system design. The reader is advised to refer to ASHRAE for standards, additional technical information, and training resources.

Constant-Volume (CV)

A constant-volume (CV) system provides a fixed amount of air to each room or zone. Thermal comfort is maintained by varying the temperature of the air. For all multiple-zone systems, the system ventilation efficiency E_z determines the minimum volume of outdoor air required at the outdoor air intake (V_{ot}). ASHRAE Standard 62.1 provides the following equation:

$$V_{ot} = V_{ou}/E_v$$

where

V_{ot} = design outdoor air intake flow required at the outdoor air intake
V_{ou} = uncorrected outdoor air intake flow, unadjusted for system efficiency
E_v = system ventilation efficiency value

The value of E_v is a function of the discharge outdoor air fraction (Z_d) for the critical zone(s) and the average outdoor air fraction (X_s) of the HVAC system. In order to perform the calculations, one needs to determine the supply airflow to each zone (V_{pz}), the zone outdoor airflow for each zone (V_{oz}) and the system primary airflow (V_{ps}), which is the supply airflow from the air handler.

A simple method for determining E_v in a CV system is to calculate the air fraction for all the zones to determine the critical zone using the following equation for each zone (ASHRAE 2007a):

$$Z_p = V_{oz}/V_{pz}$$

where V_{pz} is the zone primary airflow, i.e., the primary airflow to the zone from the air handler including outdoor air and recirculated return air.

Strategy 8.1

Use Dedicated Outdoor Air Systems Where Appropriate

Characteristics of DOASs

100% Outdoor Air

Dedicated outdoor air systems (DOASs) are 100% outdoor air systems designed to provide outdoor air ventilation to occupied spaces in conjunction with the requirements of *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007). Additional airflow may also be called for to pressurize, for space latent load control, or to provide extra ventilation. At virtually no time is the outdoor air (OA) flow established by the space sensible load; hence the flow is generally as low as 20% of that required to meet space sensible loads. The DOAS approach makes calculation of ventilation air required for any space more straightforward than for multiple-space recirculating systems (see Strategy 7.4 – Effectively Distribute Ventilation Air to Multiple Spaces) and, significantly, from a sustainable perspective, requires that less outdoor air be treated and conditioned. Thus, having the ventilation system decoupled from the heating and air-conditioning system provides many advantages in terms of HVAC system design. Facilities served with a DOAS generally require parallel equipment such as fan-coil units to handle sensible cooling or heating loads.

Latent Load Capability

DOASs must address the latent loads. The largest latent load is from the outdoor air and must be addressed in the DOAS design. The DOAS may also be designed to remove the latent load from the building. If the system is designed for the total latent load (outdoor air load + space load) then there are multiple advantages, such as the following:

- The cooling coils in interior spaces are no longer dehumidification (wet) surfaces. This eliminates many potential IAQ issues (potential mold reservoirs) that are present in traditional designs.
- The airflow can be limited to only the DOAS and the cooling provided by chilled beams or panels, a potential sustainable advantage of reduced transportation energy (hydronic systems almost always consume less energy when taking heat out of a building than an all-air system).
- Total energy recovery can reduce the outdoor air latent load on the cooling coil by up to 80%, often reducing the size of the cooling plant by 40% or more—which means significant first cost, energy demand, and operational cost savings.

Energy Recovery

Air-to-air total energy recovery generally requires that the exhaust airstream, including toilet exhaust, be ducted back to the total energy recovery device. For a variety of reasons this is not always possible. The real advantage of total energy recovery is that the cooling coil sees a very narrow set of conditions (a psychrometric bull's-eye), as illustrated in Figure 8.1-D. When total energy recovery is employed, it is not necessary that the exhaust and supply airflows be exactly the same rate, but if they differ, the difference must be accounted for in the equipment sizing calculations.

Components of DOASs

DOASs may contain a combination of the components discussed in the following subsections.

Cooling Coils

Cooling coils are required in almost all locations to cool and dehumidify the outdoor air during hot and humid conditions. Cooling coils may be either chilled water or direct expansion (DX). The coil design must address the latent load.

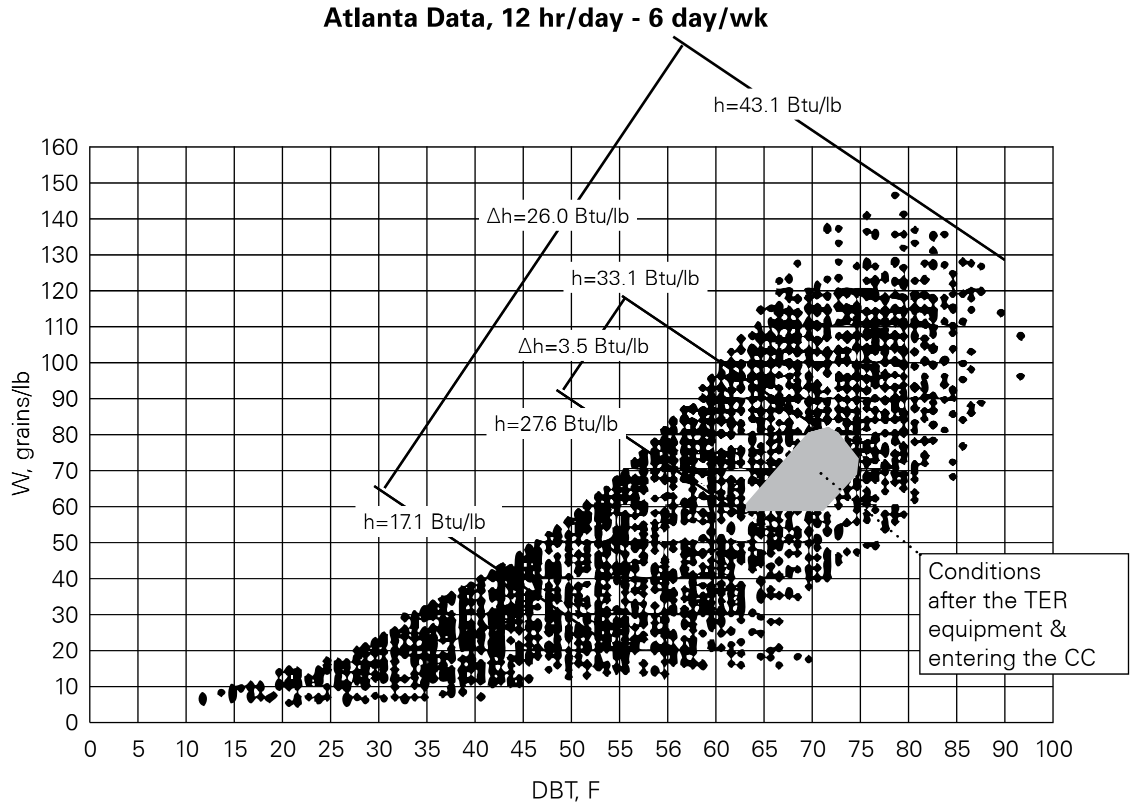

Figure 8.1-D Cooling Coil Conditions with Total Energy Recovery
Adapted from data provided by Stanley Mumma.

Total (Enthalpy) Energy Recovery

Enthalpy energy recovery can be either by wheels or by plate-type total energy recovery devices. See Strategy 8.2 – Use Energy Recovery Ventilation Where Appropriate.

Sensible Energy Recovery

Sensible energy recovery is represented as wheels, plate type, heat pipe, or run around, but may be one of many device types. Some are more appropriate in terms of IAQ depending on the quality of the exhaust airstream. See Strategy 8.2 – Use Energy Recovery Ventilation Where Appropriate.

Passive Dehumidification Component (PDHC)

A passive dehumidification component (PDHC) transfers moisture from a high-humidity airstream (80%–100%) to a lower-humidity airstream (40%–60%) while transferring only minimal sensible heat. These wheels operate at very low revolutions per minute and do not require additional heat.

Active Desiccant Wheel

An active desiccant wheel transfers moisture between airstreams but requires a heat source for regeneration (temperatures 150°F to 300°F [66°C to 149°C]).

Air Distribution

After the air is conditioned by the DOAS it still needs to be delivered to the space. Fundamental design issues include the following:

- What is the temperature (or range of temperatures) of the air? Generally it is difficult to overcool with the low-flow DOAS, so avoid the temptation to supply the air at a neutral temperature. In the winter, in an effort to provide an air-side economizer, it may be necessary to supply the outdoor air without the use of tempering energy. In this case, very cold air could be introduced into the space. Creating cold drafts must be avoided, and tempering the air can be accomplished with proper utilization of the terminal cooling equipment.
- Is reheat required? If so, how, when, and where?
- Is the DOAS air independently delivered to the space or is the air connected to other air systems in the space? If the air is connected to other systems, the DOAS air will usually be in parallel with the central or terminal cooling coil.
- Will the air distribution airflow rates vary based upon occupancy (demand-controlled ventilation)? If so, how will the system be controlled and what happens at part load to the DOAS performance? Note that with an energy recovery DOAS, the conditioning energy required for the outdoor air will be low and therefore the potential energy savings may be very small (not offsetting the costs of added controls).

DOAS Combinations

Enthalpy Energy Recovery + Cooling Coil

A straightforward and efficient DOAS can be constructed with a cooling coil and an enthalpy air-to-air energy recovery device when the exhaust airstream is available for energy recovery. In some cases and climates, heating may be appropriate. This depends on the overall building heating design. (See Figure 8.1-E.)

Enthalpy Energy Recovery + Cooling Coil + Passive Dehumidification Component

Another efficient DOAS system can be constructed using a cooling coil, passive dehumidification, and enthalpy energy recovery. This system also requires that an exhaust airstream be available. (See Figure 8.1-F.)

Other DOAS Combinations

There are many other combinations of components that are appropriate for differing applications. Neither of the previous configurations will work without an exhaust airstream, but a DOAS without access to exhaust can be configured that will also have energy and IAQ benefits. The arrangement in Figure 8.1-G may be appropriate depending on design conditions.

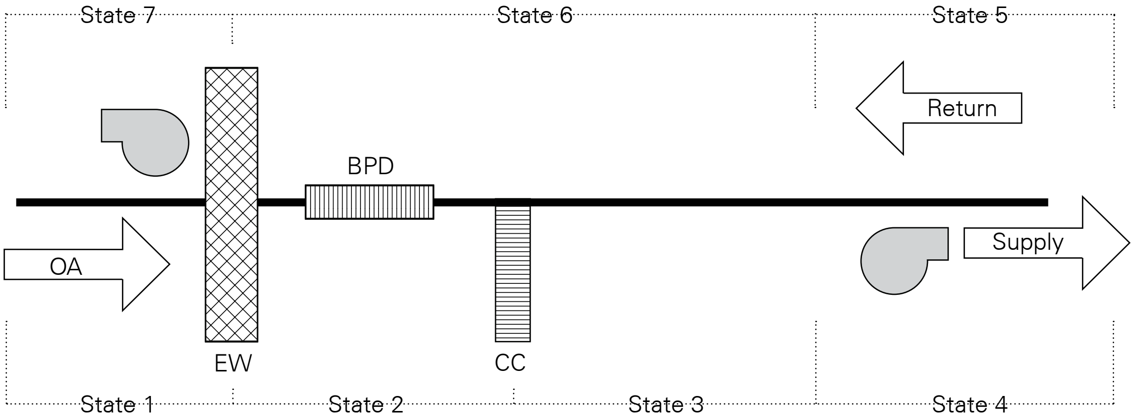

Figure 8.1-E DOAS with Enthalpy Wheel and Cooling Coil

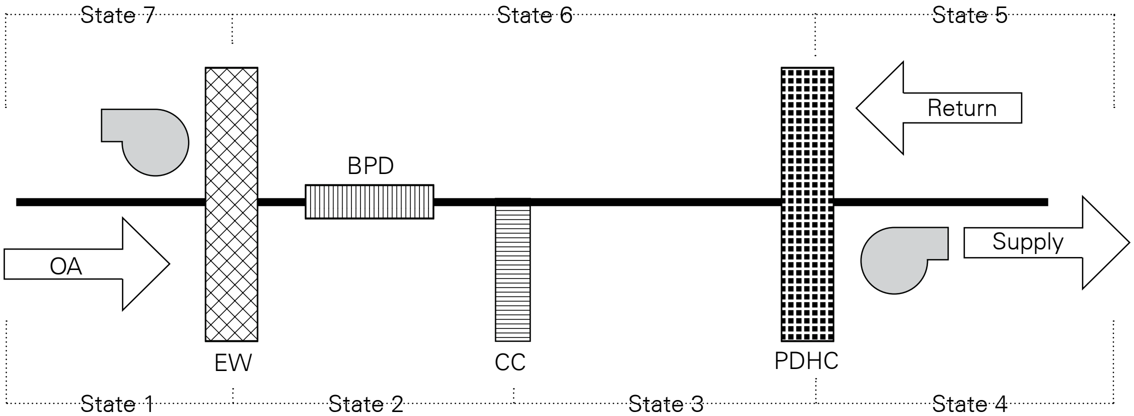

Figure 8.1-F DOAS with Enthalpy Wheel, Cooling Coil, and Passive Dehumidification Component

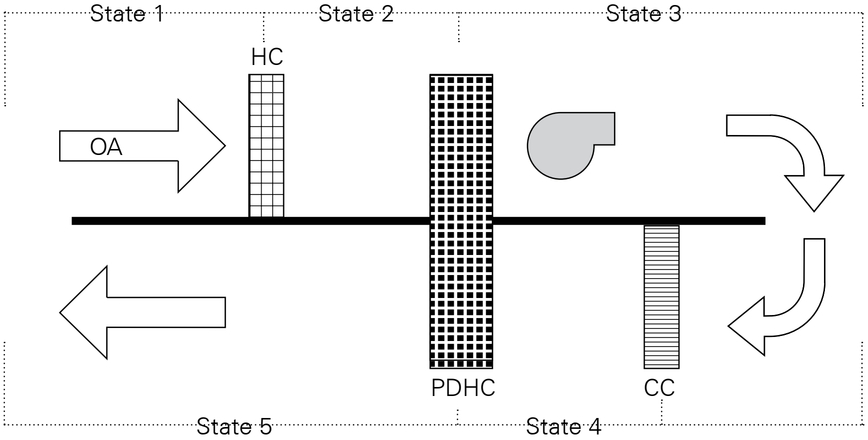

Figure 8.1-G DOAS Configuration without Energy Recovery

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Use Energy Recovery Ventilation Where Appropriate

Introduction

(ASHRAE 2007a), requires energy recovery for certain large outdoor air systems. Systems that are designed to provide more than 5000 cfm (2400 L/s) of supply air with a minimum of 70% outdoor air are required to have an energy recovery system that is at least 50% effective. Additional requirements for air-to-air energy recovery are in the process of being added to the standard; please refer to the latest edition of the standard and its addenda for the most current requirements.

In addition, many other buildings can benefit from applying air-to-air energy recovery. These systems can improve humidity control as well as reduce the energy used for conditioning outdoor air. Humidity control is crucial to controlling condensation and mold as well as for thermal comfort. For example, energy recovery was found to be very effective where direct expansion (DX) units had trouble controlling humidity in southern schools. This is because packaged DX units with large outdoor air loads need to be selected with higher supply airflow than their corresponding water-coil units to meet packaged cfm/ton (L/s per kW) limitations. High supply airflow means higher supply air temperature for the same zone load (e.g., 60°F [16°C] instead of 55°F [13°C]), which in turn means higher dew-point supply air and higher space relative humidity, even at design conditions. For constant-volume units, supply air temperature needs to be even warmer at part load, so space relative humidity rises even more.

Types of Air-to-Air Energy Recovery Devices

In general, there are two types of air-to-air energy recovery devices: total energy recovery ventilators (ERVs) that transfer heat and moisture between incoming and exhaust air and heat recovery ventilators (HRVs) that do not transfer moisture. Air-to-air energy recovery equipment is tested in accordance with (ASHRAE 2008a), and rated and certified in accordance with (AHRI 2005). (Residential ERVs and HRVs are rated by the Home Ventilating Institute.) Certified ratings need to be used to select and design systems with energy recovery ventilation. All devices require proper design and application and, as with any mechanical equipment, all require cleaning and maintenance.

A heat pump can also be used as an air-to-air energy recovery device in certain cases. A properly designed heat pump system will keep the airstreams separate. To be effective, the heat pump evaporator and condenser conditions need to match those of the airstreams. A heat pump can also be a part of a dedicated outdoor air system. (See Strategy 8.1 – Use Dedicated Outdoor Air Systems Where Appropriate. Heat pumps are more complex and are rated differently from air-to-air energy recovery devices. The remainder of this chapter deals with air-to-air energy recovery as the term is used within American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and Air-Conditioning, Heating, and Refrigeration Institute (AHRI).

Energy Recovery Wheel

Rotating energy recovery wheels work by passing a porous wheel through the outdoor air and exhaust airstreams then transferring heat energy stored on the wheel surfaces. A desiccant coating adsorbs and desorbs moisture. A total energy recovery wheel is efficient in transferring both heat (sensible energy) and moisture (latent energy).

IAQ considerations include the effects of cross leakage of contaminants from the exhaust stream to the incoming airstream. In most applications, the only impact on design is to account for leakage in sizing to meet ventilation requirements. If necessary, there are a variety of methods for dealing with cross leakage, including fan placement, differential pressures, or a purge section. Cross leakage from leakage and carryover is quantified in ratings of the ERV in terms of the exhaust air transfer ratio. If there is significant cross leakage, then the outdoor airflow rate should be adjusted using the outdoor air correction factor. Details for these calculations are given in , Chapter 25 (ASHRAE 2008b). As with any other rotating device, structural integrity during installation is very important to proper operation.

Fixed Plate with Latent Transfer

Another ERV is a fixed plate with latent transfer. In this device a permeable membrane separates the airstreams. Heat is transferred through the membrane. The membrane is designed to let water pass through but block other molecules. Different membranes may pass different molecules.

Fixed Plate

A fixed-plate HRV transfers sensible energy only and will have little or no crossover between airstreams, as the air is separated by metal plates that transfer the heat energy from the separated airstreams. If it is designed to be condensing, it is important that it drains properly and that air is well filtered to avoid fouling or clogging. If the application is noncondensing, the device is very reliable since it has no moving parts.

Heat Pipe

A heat pipe transfers sensible energy only and works with a fluid that evaporates and condenses at temperatures consistent with the application. Similar to air conditioning and refrigeration, there are fixed temperature limits for different fluids. In comfort cooling and heating applications, heat pipes need a tilt control to change over from heating to cooling. The tilt control can also be used in the frost control scheme as well as to exchange heat in the opposite direction during transition seasons.

Runaround Loops

Coil energy recovery or runaround loops transfer sensible energy only and consist of a coil in the outdoor airstream and another coil in the exhaust airstream. A fluid is pumped through the coils to transfer heat energy. A three-way valve is used for control. This device is also very simple and uses common HVAC components, coils, pipes, valves, and a pump.

General Design Considerations

There are several design considerations that are important to the choice and installation of ERVs and HRVs. These include the following.

Appropriate Filtration

Like ductwork coils and other parts of the HVAC system, energy recovery devices need to be kept clean to work properly and avoid dirt- and moisture-related problems. (See Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives). The devices ought to be protected with a minimum of MERV 6 filtration similar to other equipment. If the outdoor air contains PM2.5 or other pollutants, then additional filtration is either required by (ASHRAE 2007b), or needs to be considered. (See Strategy 3.1 – Investigate Regional and Local Outdoor Air Quality.)

Controls

Different energy recovery equipment requires different controls. Different climates require different controls. Most devices require some controls to change efficiencies and to change operation during differing weather conditions. One cannot devise the proper control sequence without considering the various outdoor weather conditions for the climate, the likely indoor exhaust conditions, and the characteristics of the device selected.

For example, if the outdoor air is cool and dry and it is desirable for the indoors to be cool and dry, one needs to avoid transferring heat (and/or humidity) from the exhaust air into the outdoor air ventilation airstream.

This will happen if the device is installed without any controls.
If an economizer is being used, the energy recovery device can work against energy savings without a properly devised control sequence. Certain applications may require bypass dampers for adequate control.

Sizing of Equipment
Equipment needs to be properly sized to maximize energy benefits, meet ventilation requirements, and avoid pressurization problems. Different devices have different pressure capabilities. Take into account the effect of unbalanced flows and leakage on airflow and effectiveness. Also note that, for a given flow, a larger device will recover more energy. In addition, a larger device will exhibit lower pressure loss. Higher pressure loss uses additional fan energy; selecting a smaller component will increase fan power and decrease recovered energy.

Reduced loads due to the use of energy recovery need to be reflected in heating and particularly in cooling equipment sizing. In addition to the obvious economic implications, failure to resize may result in oversized systems with shorter run times, decreased energy efficiency, and possible loss of humidity control. In addition to reducing humidity loads and cooling requirements, ERVs also reduce requirements for humidification in cold dry climate applications.

Condensation
Condensation needs to be dealt with for almost all equipment (except wheels) in almost any climate. Severe climates may require frost protection, depending on the frosting threshold, which varies with the device and application. Frost avoidance is usually handled with controls. Manufacturer guidance needs to be followed.

Fouling and Corrosion
Fouling and corrosion need to be considered but are usually related to industrial applications.

Sensible Heat Ratio
Selection of the type of energy recovery device needs to take into account its impact on the sensible heat ratio of the load. If a large portion of the outdoor air load is latent, for example, use of a sensible-only device will shift the sensible heat ratio and potentially result in a mismatch between the load and the capacity of the system.

Table 8.2-A, adapted from , Chapter 25, "Air-to-Air Energy Recovery" (ASHRAE 2008), provides a comparison of various energy recovery devices.

Table 8.2-A Comparison of Air-to-Air Energy Recovery Devices

	Fixed Plate	**Membrane Plate**	**Energy Wheel**	**Heat Wheel**	**Heat Pipe**	**Runaround Coil Loop**	**Thermosiphon**	**Twin Towers**
Airflow arrangements	Counterflow cross-flow	Counterflow cross-flow	Counterflow parallel flow	Counterflow	Counterflow parallel flow	—	Counterflow parallel flow	—
Equipment size range, cfm (L/s)	50 and up (25 and up)	50 and up (25 and up)	50 to 74,000 and up (25 to 35,000 and up)	50 to 74,000 and up (25 to 35,000 and up)	100 and up (50 and up)	100 and up (50 and up)	100 and up (50 and up)	—
Typical sensible effectiveness (=), %	50 to 80	50 to 75	50 to 85	50 to 85	45 to 65	55 to 65	40 to 60	40 to 60
Typical latent effective-ness,* %	—	50 to 72	50 to 85	0	—	—	—	—

Strategy 8.2

	Fixed Plate	**Membrane Plate**	**Energy Wheel**	**Heat Wheel**	**Heat Pipe**	**Runaround Coil Loop**	**Thermosiphon**	**Twin Towers**
Total effectiveness,* %	—	50 to 73	50 to 85	—	—	—	—	—
Face velocity, fpm (m/s)	200 to 1000 (1 to 5)	200 to 600 (1 to 3)	500 to 1000 (2.5 to 5)	400 to 1000 (2 to 5)	400 to 800 (2 to 4)	300 to 600 (1.5 to 3)	400 to 800 (2 to 4)	300 to 450 (1.5 to 2.2)
Pressure drop, in. H_2O (Pa)	0.4 to 4 (100 to 1000)	0.4 to 2 (100 to 500)	0.4 to 1.2 (100 to 300)	0.4 to 1.2 (100 to 300)	0.6 to 2 (150 to 500)	0.6 to 2 (150 to 500)	0.6 to 2 (150 to 500)	0.7 to 1.2 (170 to 300)
EATR, %	0 to 5	0 to 5	0.5 to 10	0.5 to 10	0 to 1	0	0	0
Outdoor air correction factor	0.97 to 1.06	0.97 to 1.06	0.99 to 1.1	1 to 1.2	0.99 to 1.01	1.0	1.0	1.0
Temperature range, °F (°C)	–75 to 1470 (–60 to 800)	15 to 120 (–10 to 50)	–65 to 1470 (–55 to 800)	–65 to 1470 (–55 to 800)	–40 to 105 (–40 to 40)	–50 to 930 (–45 to 500)	–40 to 105 (–40 to 40)	–40 to 115 (–40 to 46)
Typical mode of purchase	Exchanger only Exchanger in case Exchanger and blowers Complete system	Exchanger only Exchanger in case Exchanger and external blowers Complete system	Exchanger only Exchanger in case Exchanger and blowers Complete system	Exchanger only Exchanger in case Exchanger and blowers Complete system	Exchanger only Exchanger in case Exchanger and blowers Complete system	Coil only Complete system	Exchanger only Exchanger in case	Complete system
Advantages	No moving parts Low pressure drop Easily cleaned	No moving parts Low pressure drop Low air leakage	Moisture or mass transfer Compact large sizes Low pressure drop Available on all ventilation system platforms	Compact large sizes Low pressure drop Easily cleaned	No moving parts except tilt Fan location not critical Allowable pressure differential up to 2 psi (15 kPa)	Exhaust airstream can be separated from supply air Fan location not critical	No moving parts Exhaust airstream can be separated from supply air Fan location not critical	Latent transfer from remote airstreams Efficient microbiological cleaning of both supply and exhaust airstreams
Limitations	Large size at higher flow rates	Few suppliers Long-term maintenance and performance unknown	Supply air may require some further cooling or heating Some EATR without purge	Some EATR without purge	Effectiveness limited by pressure drop and cost Few suppliers	Predicting performance requires accurate simulation model	Effectiveness may be limited by pressure drop and cost Few suppliers	Few suppliers Maintenance and performance unknown
Heat rate control methods	Bypass dampers and ducting	Bypass dampers and ducting	Bypass dampers and wheel speed control	Bypass dampers and wheel speed control	Tilt angle down to 10% of maximum heat rate	Bypass valve or pump speed control	Control valve over full range	Control valve or pump speed control over full range

*Rated effectiveness values are for balanced flow conditions. Effectiveness values increase slightly if flow rates of either or both airstreams are higher than flow rates at which testing is done.

Notes: EATR = exhaust air transfer ratio.

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Strategy 8.3

Use Demand-Controlled Ventilation Where Appropriate

Introduction

Demand-controlled ventilation (DCV) is a control strategy that varies the amount of outdoor airflow rate to reflect changes in the number of occupants. It does this by resetting the design outdoor air intake flow at the air handler (V_{ot}) setpoint and the design zone outdoor airflow (V_{oz}) setpoint for the occupied space. The primary goal is to reduce energy use by avoiding overventilating occupied spaces while still ensuring that the design outdoor airflow conditions are being met under all operating conditions. It has been estimated that in U.S. commercial buildings, DCV has the potential to reduce heating and cooling loads by as much as 20% (Roth et al. 2005), or \$0.05/ft^2 (\$0.54/m^2) to more than \$1/ft^2 (\$10.75/m^2), annually (FEMP 2004). However, actual savings can vary widely depending on climate, variability in population density and occupancy schedule, type of building, whether or not the HVAC system has an economizer, and other factors. An additional benefit of DCV is avoidance of underventilation and thus poor IAQ.

The simplest approach to DCV is controlling the outdoor air rate in an on-off manner based on a signal from a room occupancy sensor, time clock, or light switch. A more sophisticated approach uses a signal that is proportional to the number of persons in a space to automatically modulate the amount of outdoor air. Carbon dioxide (CO_2) is the most common signal used, though other signals are also available and may be preferable in some situations.

DCV Applications

DCV is most often applied in densely occupied spaces (≥25 people/1000 ft^2 [27 people/100m^2] or 40 ft^2/person [3.7 m^2/person]) at peak with intermittent or variable population. For these spaces, DCV offers the potential for both energy savings and improved IAQ. The benefit of DCV increases with the level of density, transiency, and cost of energy.

Occupancy categories most often associated with DCV include theaters, auditoriums/public assembly spaces, gyms, some classrooms such as lecture halls, restaurants, office conference rooms, etc. Densely occupied spaces with people-related pollutants other than normal bioeffluents, such as waiting areas of health-care facilities, are inappropriate for DCV despite their intermittent or variable population. Densely and continuously occupied office spaces, such as call centers, are also inappropriate for DCV.

DCV Systems

There are various methods for estimating occupancy variations, such as CO_2-based DCV, occupancy schedules by time-of-day, direct counts of occupants, or estimation of occupancy. In addition, new technologies are emerging, such as dynamic infrared imaging. Infrared imaging enables the automated and direct counts of occupants entering and exiting a space and thus may avoid some of the calibration and accuracy problems associated with chemical-sensing technologies.

Design Considerations

Section 6.2.7 of *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality*, allows designers to reset outdoor air intake flow (V_{ot}) and/or zone outdoor airflow (V_{oz}) as operating conditions change based on "variations in occupancy or ventilation airflow in one or more individual zones for which ventilation airflow requirements will be reset" (ASHRAE 2007a, p. 15). Additionally, Section 6.4.3.9 of *ANSI/ASHRAE/IESNA Standard 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings* (ASHRAE 2007b), requires DCV for spaces larger than 500 ft^2 (46 m^2), with average design occupancy densities exceeding 40 people/1000 ft^2 (43 people/100 m^2) and served by systems with a design outdoor air capacity greater than 3000 cfm (142 L/s) or with an air-side economizer or with automatic modulating control of the outdoor air damper. Section 403.3.1 of the *International Mechanical Code* (*IMC*; ICC 2006) allows that the minimum flow rate of outdoor air shall be permitted to be based on the actual number of occupants present.

A number of considerations need to be made during the design of any DCV system. These considerations include the following.

Minimum Ventilation for Occupied Zones. The minimum outdoor airflow required in the breathing zone supplied for all occupancy levels and load conditions must be no less than the sum of the people total outdoor airflow rate for the zone ($R_p \times P_z$) plus the area total outdoor airflow rate ($R_a \times A_z$) as determined from Table 6-1 of ASHRAE Standard 62.1 (ASHRAE 2007a):

$$(R_p \times P_z) + (R_a \times A_z)$$

where

R_p = people outdoor air rate, determined from Table 6-1 of ASHRAE Standard 62.1
R_a = area outdoor air rate, determined from Table 6-1 of ASHRAE Standard 62.1
P_z = zone population
A_z = zone floor area

Diversity (D) cannot be used in determining the number of people. See Appendix A of the *62.1 User's Manual* (ASHRAE 2007c) for more information.

Minimum Ventilation for DCV Zones. The minimum outdoor airflow rate supplied to a space with variable occupancy during regular business hours (when expected to be occupied, such as a conference room) should not be less than all of the following limits:

- R_a times the floor area.
- The exhaust airflow prescribed in Section 6.2.8 of ASHRAE Standard 62.1 (ASHRAE 2007a) for single-zone and 100% outdoor air systems. (To reduce infiltration in multiple-zone systems, outdoor air intake flow must be no less than the total system exhaust airflow for all zones. Also see the section "DCV in Multiple-Zone Systems" in this Strategy.)
- In no case should intake airflow be less than the sum of exhaust airflow plus exfiltration due to positive pressure in cooling or less than exhaust minus infiltration due to negative pressure in heating.
- The corrected amount for the calibrated precision of the measuring and controlling methods employed, as verified by factory calibration to a recognized national reference standard. Additionally, field calibration should be required to adjust the setpoints to account for precision.

For spaces that are not expected to be occupied during regular business hours (such as auditoriums), provide at least 3 ach prior to occupancy. (The California Title 24 requirements for pre-occupancy ventilation require the lesser of 1) the minimum required rate of outdoor air or 2) 3 ach to the entire building during the one-hour period immediately before the building is normally occupied [CEC 2005a].)

Pressure Controls of DCV Systems. DCV systems should be capable of providing stable space pressurization control and should operate in concert with changes in the ventilation rate as conditions internal and external to the building change (Dougan 2004).

Variable-Air-Volume (VAV) Systems. Utilize continuous measurement and proper control of outdoor airflow rates to ensure that sufficient ventilation air is supplied to the breathing zone. Even if sufficient outdoor air is supplied to the occupied zone, it may not reach the breathing level if there is poor mixing within the space.

Single-Zone Constant-Volume Systems. Provide continuous measurement and control of the outdoor airflow rates *or* provide a simple damper control as described in Appendix A of the *62.1 User's Manual* (ASHRAE 2007c). If continuous measurement of the outdoor airflow rates is provided, it should be capable of measuring flow within an accuracy of ±15% of the minimum outdoor airflow rate.

Documentation. As with any other HVAC component, it is important for the designer to develop a written description of the equipment, methods, control sequences, and intended operational functions necessary for commissioning (Cx) and reporting as well as the maintenance of DCV systems.

- Commissioning authorities need to implement requirements and document the results during building and IAQ Cx.
- Maintenance personnel need written guidance on how to properly maintain the DCV after completion of construction.
- Health and safety staff need guidance on how to validate that the proper amount of ventilation is supplied under all variable occupancy levels and load conditions.

CO_2-Based DCV

Measurement and control of indoor CO_2 concentration has been the most popular DCV method because CO_2 sensors and associated controllers are relatively inexpensive and, in carefully controlled environments (such as environmental chambers), the outputs of these sensors have been shown to correlate well with people-related contaminant levels. This is because the rate of CO_2 generation (and bioeffluent generation) indoors by occupants is proportional to the number of occupants and their activity levels (an excerpt from Persily [1997] is included in this Guide in Appendix H – Carbon Dioxide Generation Rates with an expanded discussion on this topic). Note that the CO_2 generation rates listed in Appendix C of ASHRAE Standard 62.1 (ASHRAE 2007a) are for sedentary adults and therefore should not be used for other applications, such as those involving children. DCV is based on the fact that at steady state, the indoor/outdoor CO_2 concentration difference is inversely proportional to the current outdoor airflow rate per person (assuming that there are no other interfering CO_2 sources).

Some practitioners consider CO_2 to be a direct indicator of the pollutant that the ventilation system is trying to control (i.e., bioeffluent) so it inherently takes into account the time delays that occur due to space volume when people enter or leave a space. However, other practitioners maintain that ventilation in a space should be increased immediately as soon as it is occupied. The controller design can address either of these scenarios.

In real-world environments, CO_2 sources other than people (such as combustion sources) and removal mechanisms (such as plants) may also be present and in some cases they may be significant compared to the contribution from occupants.

ASTM D 6245-07, Standard Guide for Using Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation (ASTM 2007), provides guidance on how to use CO_2 concentrations to evaluate IAQ and ventilation. However, this standard specifically states that is does not address the use of indoor CO_2 to control outdoor air intake rates.

Since indoor minus outdoor CO_2 concentration, at steady state, is directly proportional to outdoor airflow per person if occupancy is stable, a single CO_2 setpoint approach can be used to maintain a constant outdoor airflow rate per person. This single CO_2 setpoint approach satisfied earlier editions of the *IMC* and ASHRAE Standard 62.1 in which ventilation rates were prescribed in cfm (L/s) per person, implying that occupancy is the most important factor in determining ventilation rates. However, satisfying the current versions of the *IMC* (ICC 2006) and ASHRAE Standard 62.1 (ASHRAE 2007a) is more complicated because cfm (L/s) per person is no longer constant as zone population changes (ASHRAE 2007c; Trane 2005; Stanke 2006).

The use of CO_2-based DCV in general office buildings may not be very cost-effective because CO_2 levels may never increase substantially above ambient (Mudarri 1997). However, certain aspects of DCV controls may still be useful for ensuring that the design ventilation rates are supplied under all operating conditions. For example, continuous measurement of outdoor airflow and indoor CO_2 levels can help building personnel find ventilation system faults or make adjustments to the HVAC system setpoints and thus avoid large amounts of overventilation or underventilation.

A number of packaged HVAC equipment manufacturers now offer CO_2 sensors and controllers as an option for their equipment. A study funded by the U.S. Department of Energy (DOE) published in 2004 lists about a dozen manufacturers of CO_2 sensors and controls (FEMP 2004).

Design and Other Considerations

During the design of a CO_2-based DCV system, one needs to consider the basic relationship between CO_2 and occupancy and also understand the strengths and limitations of measurement methods and some practical recommendations, as follows.

Relationship between Outdoor Airflow Rate and Steady-State CO_2 Concentration. At steady-state conditions, the outdoor airflow rate per person can be calculated based on the following equation[1] (ASHRAE 2007a):

$$V_o = N/(C_s - C_o)$$

where

V_o = outdoor airflow rate per person
N = CO_2 generation rate per person
C_s = CO_2 concentration in the space
C_o = CO_2 concentration in outdoor air

For sedentary (1.2 met) adult persons, N = 0.011 cfm/person (0.005 L/s/person). Therefore, based on a target V_o, a trigger value for $C_s - C_o$ could be set in the CO_2 control system for purposes of ventilation fault detection. Demand-control approaches based on CO_2 are generally more complex than the above steady-state equation. Several approaches have been proposed in the literature (Stanke 2006).

It is worth pointing out that the generation rate of N = 0.011 cfm/person (0.005 L/s/person) does not apply to children or to non-sedentary adults and therefore should not be used for these types of occupants. For adults, Figure C.2 of ASHRAE Standard 62.1 (ASHRAE 2007a) and Figure 1 of Appendix H – Carbon Dioxide Generation Rates show the relationship between CO_2 generation rate, breathing rate, and physical activity. ASTM D 6245 (ASTM 2007) provides guidance on calculating CO_2 generation rates for non-sedentary adults. Mudarri (1997) lists correction factors for gender, age, and activity level. Finally, Appendix A of the *62.1 User's Manual* (ASHRAE 2007c) offers guidance on the equations that can be applied for CO_2-based ventilation.

CO_2 Sensor Technology, Accuracy and Drift. Most CO_2 sensors available on the market today are based on non-dispersive infrared photometric principles. CO_2 absorbs infrared light at 4.26 μm and the amount

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[1] This equation is valid under steady-state conditions only. Errors in the order of 100% to 200% can be expected when estimating ventilation rates under non-steady-state CO_2 conditions (Mudarri 1997).

of absorption increases with the CO_2 concentration (ASHRAE 2009). However, aging of the infrared light source leads to sensor drift. In order to address the drifting of the sensors, manufacturers of CO_2 sensors developed self-calibrating sensors using various technologies and self-calibrating algorithms. These technologies include using the lowest reading over a period of time, measuring light transmissions at a wavelength other than that where CO_2 and other common air components absorb light, or using a second light source or splitting the light source to assess aging of the primary light source. A limited multi-month evaluation of three of these self-calibrating sensors indicated considerable drift for one of the three sensors (House 2007; Apte 2006).

Despite the relatively low cost and short payback of CO_2-based DCV, the market has grown slowly since 1990 and has not reached its peak potential (FEMP 2004). This is partially due to the limited data on the long-term performance of these sensors (Apte 2006). In 2001, National Institute of Standards and Technology (NIST) researchers published a review of available literature on CO_2-based DCV and also identified knowledge gaps (Emmerich and Persily 2001). Also in 2006/2007, Lawrence Berkeley National Laboratory (LBNL) researchers published the results of a pilot study of the accuracy of 44 CO_2 sensors located in 9 commercial buildings (Fisk et al. 2007). These studies have indicated that there are numerous issues that need to be addressed with further research. Some of the reported issues with the CO_2 sensors relate to the accuracy of the sensors, while others relate to maintenance/calibration and to the inherent sensor lag times (time required for concentration to rise to a pre-determined level before ventilation is increased; time constants of rise and decay of occupant-generated CO_2 concentrations vary from many minutes to several hours).

In 2009, researchers at Iowa State University published the results of a rigorous chamber-based, multi-month assessment of 45 sensors used for DCV (Shrestha and Maxwell 2009a, 2009b, 2010). The sensors included 15 different models of CO_2 sensors and were tested over ranges of pressure, temperature, humidity, and CO_2 concentration that are representative of HVAC applications. All available technologies were represented in this study, including single-beam/dual-wavelength, dual-beam/single-wavelength, and automatic background calibration. Testing included an assessment of performance characteristics such as accuracy, repeatability, linearity, and hysteresis as well as the effects of humidity, pressure, temperature, and aging. The researchers reported that manufacturers' available specifications vary widely on reported accuracy, linearity, repeatability, hysteresis, and pressure/temperature sensitivity. Only very few manufacturers reported some or all of these parameters. None of the manufacturers reported humidity sensitivity. Test results showed wide variation in sensor performance among the 15 models tested, and in some cases there were significant variations in sensor performance among sensors of the same model. The researchers suggested that calibration should be performed prior to placing sensors into service. The performance of sensors with automatic baseline adjustment was impossible to predict over time, and only a few of the auto-adjusting sensors tested performed reasonably well. The researchers also concluded that based on their data there was no particular sensor technology clearly superior to the others. Finally, the results also indicated some dependence on temperature and humidity as well as barometric pressure. Based on the results, there is a need for standard testing practices and for improvements in some of these devices.

Lag between Occupancy and CO_2 Concentration. Some practitioners believe that lag times are not a problem if the CO_2 tracks the bioeffluents. However, other practitioners suggest that ventilation be increased immediately after occupancy begins. Because sensor responses can be slow, the sensed CO_2 value can be lower than the actual bioeffluent level, resulting in a DCV system that does not provide very good control. Systems with sensor response time constants in units of minutes may be satisfactory, but systems with sensor response time constants in units of hours would not work at all. This is a control system design issue that must be addressed during design. Figure 8.3-D is a graphical representation of the lag issue for an assembly space during varying occupancies. The difference between the two curves labeled "instantaneous ventilation requirement" and "approximate ventilation rate with CO_2 control and minimum building component ventilation rate of 600 cfm (283 L/s)" is the lag.

In spaces without regular business hours (e.g., auditoriums) where the building component ventilation may not be provided prior to occupancy, an occupancy sensor can be considered in combination with the CO_2 sensor to reduce the impact of lag times. The occupancy sensor can be used to immediately start the ventilation system when someone enters the zone, and the CO_2 controller takes over the control of the ventilation when a pre-determined concentration of CO_2 has been achieved. Use of occupancy sensors for DCV control is not allowed by some energy codes such as California Title 24 (CEC 2005a)

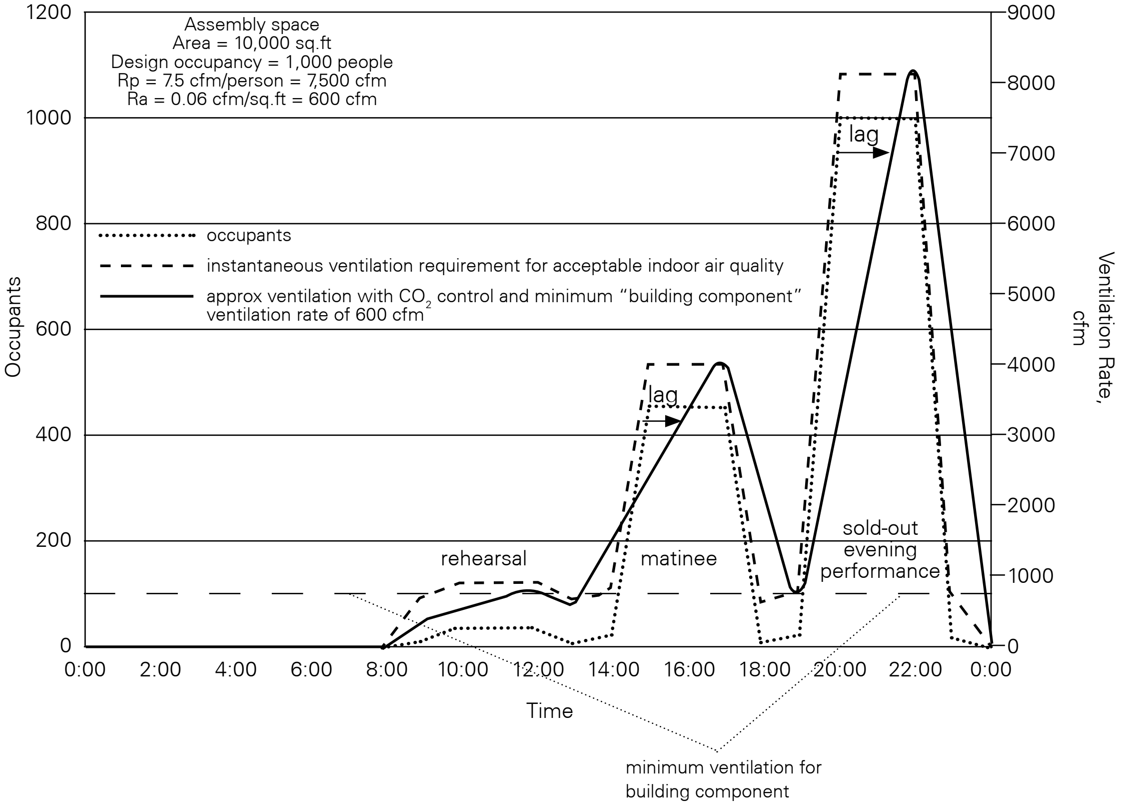

Figure 8.3-D Illustration of the Lag between Occupancy and Minimum Ventilation Rate in CO_2-Based DCV

Location of Indoor CO_2 Sensors—HVAC Systems with Open Plenum Returns. In HVAC systems with open plenum returns, CO_2 sensors should be in a room location that reflects the average concentrations at breathing level. A sufficient number of sensors should be placed within a space in order to increase the certainty of the sensed average space CO_2 concentration. Sensors placed in return air plenums will not necessarily yield a reliable value representative of the average breathing concentration for the space.

Location of Indoor CO_2 Sensors—HVAC Systems with Ducted Returns. In HVAC systems with ducted returns, CO_2 sensors may be placed in the return air duct from a zone if the designer can demonstrate that the CO_2 measurement in the return duct is equivalent to breathing-level average measurements provided that the occupancy type and space usage are the same in that zone.

Location of Outdoor CO_2 Sensors. Outdoor air CO_2 concentration should be measured continuously using a CO_2 sensor located in close proximity to the outdoor air intake. Alternatively, outdoor air CO_2 concentration can be assumed to be constant, provided the constant level is conservatively high and based on recent historical data for the area where the building is located. If an assumed value is used, consideration should be given in the controls to offset potential errors such as the tendency to overventilate at higher densities and underventilate at lower densities (ASHRAE 2007c).

Control of CO_2 Concentrations. In all rooms with CO_2 sensors, DCV controls should maintain CO_2 concentrations (with respect to the outdoor air CO_2 concentration) between the maximum level expected at design population and the minimum level expected at minimum population.

Certifications for CO_2 Sensors. CO_2 sensors should be certified by the manufacturer to have an uncertainty no greater than ±50 ppm (90 mg/m^3) for concentration ranges typically found in HVAC applications (e.g., 400 to 2000 ppm [720 to 3600 mg/m^3]), be factory *and* field calibrated, and require calibration no more frequently than once every five years while operating under typical field conditions per manufacturer specifications. (Limited research to date indicates that field-based calibration should be performed once every one to two years [Fisk 2008].)

Access of CO_2 Sensors and Verification of Proper Operation. Provisions (such as physical access and verification that the sensor is operating correctly) should be provided for periodic maintenance and calibration. This will assist in a) properly maintaining the DCV system and components and b) validating that the proper amount of ventilation is supplied under all variable occupancy levels and load conditions. Data logging of CO_2 concentrations can be considered, which allows review of CO_2 trend data in part to ensure that the CO_2 sensors and controls are operating as intended.

Code and Green Building Requirements for CO_2-Based DCV

CO_2-based DCV is required by some building codes. For example, California Title 24 requires CO_2-based DCV in single-zone high-occupancy areas ≤40 ft^2/person (3.7 m^2/ person) served by HVAC systems with outdoor air economizers (a number of exceptions are listed such as classrooms) (CEC 2005b). Similarly, the *Oregon Structural Specialty Code* requires that all systems with ventilation capacities of 1500 cfm (708 L/s) or more serving areas with an average occupant load factor of 20 ft^2/person (1.9 m^2/person) or less include a means to automatically reduce outdoor air intake below design rates when spaces are partially occupied (OOE 2007). Also, the U.S. Green Building Council (USGBC) gives one point in its Leadership in Energy and Environmental Design (LEED) Green Building Rating System for a) measuring CO_2 concentrations in all densely occupied spaces (25 people/1000 ft^2 [27 people/100 m^2] or 40 ft^2/person [3.7 m^2/person]) and b) generating an alarm when concentrations vary by 10% or more from a setpoint (USGBC 2008).

Non-CO_2-Based DCV

In certain limited applications, such as classrooms, where occupancy is either 0 or nearly 100%, the control of the outdoor air rate in an on-off manner based on a signal from a room occupancy sensor, time clock, or light switch is a practical and low-cost energy-saving solution. Other simple forms of DCV may include direct counts of occupants or estimation of occupancy and programming the ventilation supply accordingly. However, some energy codes, such as California Title 24, specifically exclude these types of DCV controls (i.e., non-CO_2-based) for non-classroom applications (classrooms are exempt from the DCV requirements of California Title 24). Stanke (2006) offers a detailed description of the various DCV options that a designer can chose for a single-zone variable-occupancy application. Note that approaches that determine population must include the capability to calculate the breathing zone and intake airflow required for the current population. CO_2-based approaches incrementally change intake airflow in direct proportion to the differential (indoor minus outdoor) CO_2 level.

More sophisticated forms of DCV are based on technologies that can count the number of persons entering and exiting a space and adjust ventilation accordingly (Apte 2006). New advances in sensing and microcomputing technologies may automate DCV. Dynamic infrared imaging hardware and software are emerging technologies with some significant potential advantages. These technologies are already available for people counting and are used for marketing, security, and facility management applications. Some of the potential advantages of these technologies may include reduced signal delay problems (as discussed previously) or drifts typically found in chemical sensors. To date these technologies have not been tested with DCV, but a number of research proposals have been written and it is likely that research in this area will be done in the near future.

The DCV controls described in this Strategy are used to adjust the occupant component of the outdoor airflow rate. That is the component intended to dilute pollutants generated by occupants (bioeffluents) and their activities. These systems cannot be used to adjust the area-based building component, which is intended to dilute pollutants off-gassed from building materials, furnishings, cleaning products, and other non-occupant-related sources. In theory it may be possible to adjust the area-based building component by measuring the concentrations of target building-related pollutants. However, for nonindustrial environments there is no consensus on a list of target building-related pollutants and associated maximum allowable concentrations that can be used as indications of "acceptable" or "healthy" indoor air. Measuring total volatile organic compounds (TVOCs) has been proposed as an alternative to CO_2, but many IAQ studies have concluded that there is insufficient evidence that TVOC concentrations can be used to predict health or comfort effects (see Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection for a more detailed discussion of the TVOC issue). Until another indicator of building-related pollutant concentrations can be developed, the building component cannot be reduced below the building component design rates (ASHRAE 2007a).

Sensors detecting specific volatile organic compounds (VOCs) or a range of VOCs are now commercially available. Since there are hundreds of VOCs in the nonindustrial indoor environment, it is nearly impossible to correlate certain unique VOCs with occupants. VOC-based DCV may be appropriate in certain industrial environments where few known chemicals typically exist at large concentrations. Research in nonindustrial environments has shown that people-specific VOCs are those emitted by perfumes and that these chemicals are difficult to detect and measure (Alevantis et al. 2006).

DCV in Multiple-Zone Systems

Application of DCV in single-zone systems is fairly straightforward. Neither ASHRAE Standard 62.1 (ASHRAE 2007a) nor the associated *62.1 User's Manual* (ASHRAE 2007c) address the design and operation of DCV for systems that serve multiple spaces. Stanke (2008) has listed a number of multiple-zone system design and part-load challenges, including assumptions about occupant/visitor movement (zone to zone or entering/leaving the system), occupant diversity, etc. In addition, Warden (2004) has proposed supply-air-based CO_2 for multiple-space systems.

ASHRAE, in coordination with designers and researchers, will be addressing these multiple-zone system dynamic reset issues in the future. Further research maybe needed to develop design equations and any associated new technology for multiple-zone DCV.

The California Energy Commission has expanded its requirement for DCV for single-zone, high-occupancy spaces to multiple-zone systems. This does not present the previously listed challenges because California Title 24 defines outdoor air and recirculated air as equivalent at the zone level (CEC 2005a). Therefore, if the minimum supply airflow rate meets California Title 24's ventilation rate requirements (either per person or by area, whichever is greater), then the ventilation requirements are met regardless of the percentage of outdoor air in the supply air.

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STRATEGY OBJECTIVE 8.3

Strategy 8.4

Use Natural or Mixed-Mode Ventilation Where Appropriate

This Strategy draws heavily on the CIBSE applications manual AM10: National Ventilation in Non-Domestic Buildings (CIBSE 2005), which is the principal guidance document on the application of natural ventilation.

Introduction

Using open fenestrations and natural physical forces to provide outdoor air ventilation and control thermal comfort predates modern systems that use mechanical means to ventilate and cool buildings. In general, occupants prefer natural ventilation over mechanical ventilation, in part because it provides some personal controls, and research shows fewer adverse health symptoms in naturally ventilated spaces. When natural ventilation is combined with conventional mechanical systems, it is referred to as *mixed-mode ventilation*. Societal benefits of natural ventilation systems include reduced energy consumption, lower greenhouse gas emissions, and superior indoor environments for health, comfort, and productivity. Refer to the sidebar titled "Natural Ventilation Glossary" for terms commonly used in discussions of natural and mixed-mode ventilation.

The cooling capability of a natural ventilation system is limited by the outdoor air temperature, humidity, and pollution. Clearly there are locations in the U.S. that are not suitable for natural ventilation/natural cooling. But, in areas with suitable outdoor climatic conditions, buildings designed for natural ventilation with solar and internal thermal gains less than 13 Btu/ft^2 (40 W/m^2) and adaptive occupant expectations, such as acceptance that the indoor summertime temperature will exceed 77°F (25°C) for a limited period of time, natural ventilation/natural cooling strategies can be very effective and energy efficient (CIBSE 2005).

Natural/Mixed-Mode/Hybrid Ventilation Systems

Design Principles

Naturally conditioned buildings do not aim to achieve constant indoor environmental conditions but to take advantage of and adapt to dynamic outdoor conditions to provide a comfortable, controllable indoor environment for occupants. This deviation from the accepted norm will require the buildings owner's approval and possibly education of building operating staff and end users to make the required manual fenestration adjustments, such as opening and closing windows and blinds, to maintain comfortable conditions. It may also be necessary to have sensors in the fenestration openings, interlocked with the space heating and cooling, to ensure that energy is not wasted when the occupants decide to open the windows to allow outdoor air to enter the building (Barnfield 2007; CIBSE 2005).

Natural ventilation systems must be designed to provide sufficient outdoor air to the building to achieve the required thermal cooling and ventilation. The thermal cooling capacity of natural ventilation is limited by the outdoor air temperature, humidity, wind, and buoyancy forces as well as the configuration/location of the building. The shape/massing of the building and the ventilation openings are critical and must be configured to take full advantage of natural forces such as the wind and buoyancy effects.

There are many different types of natural ventilation strategies. The most appropriate strategy depends on the type of space (i.e., open plan, cellular), the use of the space (e.g., classroom, gym, office), and whether wind or buoyancy forces are likely to predominate. As stated in CIBSE's *AM10: Natural Ventilation in Non-Domestic Buildings*:

> The form of the building has to be designed to facilitate the chosen [natural ventilation] strategy; the strategy then has to be engineered to ensure the air can flow along the chosen path at the required flow rates under the naturally available driving pressures….
>
> The pattern of air flow must be considered for all operational regimes, winter and summer, as well as special operating modes such as cooling by night ventilation. This must include consideration of the impact of variations in weather conditions. For example, although one wind direction might

STRATEGY OBJECTIVE 8.4

> predominate, the strategy will have to be sufficiently robust to work in all likely weather conditions. As well as the general pattern of air movement through the building, the needs of the occupants and the way in which these interact with the ventilation system must be considered. (CIBSE 2005, p. 8)

Naturally ventilated buildings are becoming more common in North America in part because of the increase in the cost of energy and the desire to reduce greenhouse gas emissions. Having stated this, it should be pointed out that care needs to be taken in the design and application of natural ventilation systems to ensure that the desired energy and greenhouse gas emission reductions are achieved. For example, it may be necessary to design automatic heating and/or cooling interlock control on ventilation openings to prevent higher than required outdoor air quantities with uncontrolled space heating/cooling, consequently causing an increase in energy consumption as compared to a conventional mechanically ventilated building.

As global climate change progresses and outside temperatures experience greater variation, achieving good summertime thermal comfort with low energy consumption may become increasingly challenging for both naturally and mechanically ventilated buildings (because different areas will experience different effects even though the overall change will be higher temperatures). Regardless of how the climate changes, natural ventilation will likely play an important role as a lead strategy, particularly in more moderate climate locations. Also, as the climate changes, a mitigating factor could be that the occupants will adapt to the changed outside temperatures and find the corresponding changes in inside temperatures more acceptable (CIBSE 2005).

Natural Ventilation Glossary

The following definitions are adapted from the Stantec Engineers Design Manual (Stantec 2009).

Comfort criteria: Agreed-upon interior design conditions for a project, such as maximum temperature or annual hours above temperature thresholds.

Cross ventilation: Taking advantage of natural breezes to draw air across a space; requires operable windows on opposing facades of the building and unobstructed paths for airflow.

Daylighting: The use of natural sunlight to provide light to a space rather than electric light; typically most effective when light is diffuse rather than direct-beam sunlight.

Mixed-mode/hybrid system: In this context refers to a natural ventilation system with supplementary mechanical cooling and or ventilation, usually used only to meet peak loads.

Night flush: Opening windows and dampers at night to purge hot air from the building and allow outdoor air to precool the building structure for the next day; most effective when used in combination with thermal mass. This is also sometimes referred to as nighttime flush-out or night flush-out.

Natural ventilation: Strictly, this refers only to providing outdoor air to a building's occupants without the use of mechanical means (i.e., fans); often it is incorrectly used to imply natural cooling.

Natural cooling: Keeping a space from overheating by introducing cooler outdoor air without the use of mechanical means (i.e., fans, chillers, etc.); often requires preventing air from entering spaces if the outdoor temperature exceeds the indoor temperature; also known as natural conditioning or passive cooling.

Operable windows: Glazing or dampers that can be opened to allow outdoor air to enter a space.

Operative temperature: The temperature that an occupant "experiences" in a space, including the effects of air temperature, air movement, and radiant temperature.

Radiant heating/cooling: A cool surface will radiantly "pull" heat away from occupants, thereby cooling them; a hot surface will give heat to a person radiantly. This allows for heating and cooling without mechanically conditioning air.

Stack ventilation: Using the natural buoyancy of hot air to create vertical air movement; typically involves high-level venting through chimneys, vent shafts, or atriums.

Thermal mass: Dense building materials such as concrete, brickwork, or stone that moderate space temperatures by absorbing heat during hot periods and releasing it during cool periods.

Comfort Expectations

Although naturally ventilated and cooled buildings are less controlled than buildings with typical mechanical HVAC systems, studies have shown high levels of occupant satisfaction in buildings with occupant control. This is because occupants are given control over their surroundings and have ample access to outdoor air. Thus, a certain level of user buy-in is required—if it is too hot or stuffy occupants can close blinds, open windows, switch on desk fans, etc., and when it cools down they can close the windows and switch off the fans, etc.

When building occupants have direct access to ambient weather conditions they tend to dress appropriate to the natural climate. In the summer they might wear short sleeves, and in the winter they might put on a sweater. This adaptation allows a naturally ventilated and cooled building to expand the normal indoor temperature range without sacrificing comfort levels. Section 5.3 of *ANSI/ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2004), recognizes that human thermal comfort responses/expectations are different in naturally conditioned spaces as compared to fully air-conditioned spaces. Also, recent research shows that in prolonged spells of warm weather, people's expectations of comfort change and that occupants who have more control over clothing, activity level, and air speed will find a broader range of temperatures and relative humidity acceptable (Brager et al. 2004).

The CIBSE applications manual *AM10: Natural Ventilation in Non-Domestic Buildings* states that a "key criterion when assessing overheating is to define the thermal comfort conditions that are considered acceptable. Thermal comfort is a complex mix of physiology, psychology and culture. What is deemed acceptable will depend on activity and clothing level as well as temperatures, air speeds and humidity" (CIBSE 2005, p. 6).

Effects of Air Movement. It has been shown that in the summer the "comfort envelope" can be expanded by increasing the airflow within the occupied space. Increased air movement from properly sized/located openings can provide an enhanced perception of thermal comfort. Figure 8.4-G shows that an air speed of 59 ft/min (0.3 m/s) is sufficient to provide a cooling effect of 2.25°F (1.25°C) (CIBSE 2005).

In larger buildings with a degree of automatic control, designing the natural ventilation system for the variation of airflow rates requires careful design consideration of the air intake and relief openings (both location and size) and control to ensure that the airflow rates under different environmental conditions can maintain the required occupant comfort without causing nuisance draft and building pressurization.

Integrated Design

An integrated design approach is essential for successful implementation of natural or mixed-mode ventilation because it crosses traditional boundaries of design and installation responsibilities and impacts virtually all disciplines, including architectural, mechanical, electrical, interior design, and acoustics as well as installation contractors and component suppliers.

It is vital to involve all design team disciplines in these integrated design discussions. Successful natural or mixed-mode ventilation and cooling systems often involve cost trade-offs between disciplines. For example, with natural/mixed-mode ventilation, the mechanical system will likely be smaller and less expensive, but the structural budget might increase in order to provide more thermal mass or the need for operable windows might increase the architectural costs. The earlier in the process the entire design team has a common understanding of the intent of the building design, the easier it will be to incorporate the necessary elements into the design at the lowest overall cost.

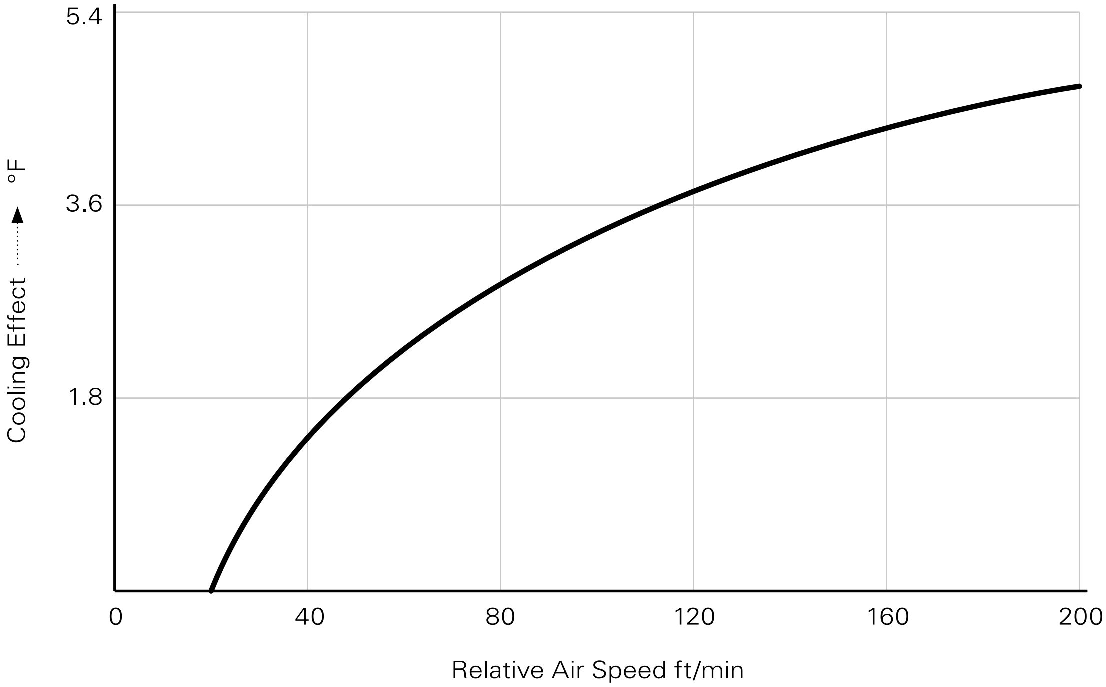

Figure 8.4-G Effect of Air Speed on Thermal Comfort
Adapted from CIBSE (2005), Figure 2.4.

Before design begins it is important to obtain buy-in from the building owner/operator and, if possible, from the users. The design team and client need to agree on comfort standards for the occupants of the building. For example, as stated previously, if building occupants are given control over operable windows and are allowed to adapt their dress to weather conditions, the acceptable comfortable temperature range can be expanded without sacrificing occupant comfort. Where appropriate, standards such as ASHRAE Standard 55 (ASHRAE 2004) and the Bounding Comfort Parameters from LEED (USGBC 2003) should be used by the integrated design team to guide/inform the thermal comfort performance requirements for the project.

It is also important that the building owner understand the design intent of the active and passive building systems and that the building users and maintenance staff are educated on the proper use of the systems to maintain comfort (i.e., opening and closing solar shades, opening windows for night flushing, closing windows in the winter to reduce heating requirements). These need to be part of the operation and maintenance (O&M) manuals and training. For more information on O&M, see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ.

Local environmental data need to be collected and analyzed before design begins, including hourly ambient pollutants, temperature, humidity, and wind speed and direction, etc. Combining this knowledge with the thermal comfort criteria can lead to an initial assessment regarding the appropriateness of natural ventilation as well as the necessity of supplementary cooling, etc. (Stantec 2009).

Applications for Natural Ventilation Cooling

As stated in the CIBSE natural ventilation applications manual (CIBSE 2005):

> In most cases, achieving acceptable [indoor] summer conditions requires three main features in the design and use of the building:

> - good solar control to prevent excessive solar gains entering the occupied space
> - modest levels of internal gains (people, small power loads and lighting loads)
> - acceptance that during peak summer conditions, temperatures in the space will exceed [77°F] 25°C for some periods of time; air temperatures may be higher still, but in a well-designed building, such higher air temperatures will be offset by cooler mean radiant temperatures of surrounding surfaces and enhanced air movement.
>
> (CIBSE 2005, p. 4)

Figure 8.4-H shows how critical design-related issues or constraints need to be considered during the design of a naturally ventilated and cooled building. It is a "[f]low chart that takes the user through a broad-brush decision tree to identify the most appropriate forms of ventilation" (CIBSE 2005, p. 9).

Even in a well-designed passively cooled building there may be times during the year when outdoor temperatures remain elevated for prolonged periods and thus indoor temperatures rise above the comfort range. The building owner and design team must decide if it is acceptable to tolerate these infrequent "peak" periods. Thermal modeling software can help predict the amount of time that elevated temperatures occur to assist in this decision and in building design in general.

The following sections describe when and where natural ventilation and cooling systems are applicable and their interactions with other aspects of the building design.

Appropriate Climatic Conditions

Natural ventilation and cooling systems are most effective in climates where ambient temperatures and humidity levels naturally fall into comfortable ranges. Additionally, consideration of wind pattern, diurnal temperature swings, and outdoor pollution should be considered. In less humid environments, outdoor air typically drops sufficiently at night to enable a nighttime cooling effect to flush out the heat that has been stored inside a building and precool it for the next day. Additionally, microclimate issues should be considered during design. These can vary from the shading due to foliage to the wind effect of surrounding buildings.

The combination of favorable climate and location makes much of the Pacific Northwest and other coastal regions, as well as some higher-altitude mountain areas in the West, ideal locations for the implementation of natural ventilation and cooling. As a sample of a climate/building analysis, the psychometric chart in Figure 8.4-I shows outdoor air temperature/time plots and the comfort envelope (showing that natural ventilation alone will satisfy comfort conditions for 31% of the year and that supplementary heating or cooling will be required for 59% of the year) (Stantec 2009).

Appropriate Building Programming

It is important to know the intended building programming before the design begins. Building programming in this sense refers to the periods of occupancy in a building and the corresponding intended use. Nearly any type of building can take advantage of natural ventilation and cooling, but there are some conditions that greatly benefit or hinder a properly functioning system. For example, the natural ventilation and cooling strategy for an office building with only daytime use would be very different from a 24-hour data processing facility.

The following list of programming conditions should be considered and mitigated in the design and use of a naturally ventilated and cooled facility (Stantec 2009).

***Highly Concentrated Cooling Loads (i.e., Data Centers*). **Typically, if these highly concentrated cooling loads are in the design, an air-conditioning unit will be included to serve only these spaces. Such spaces may offer an opportunity for heat recovery.

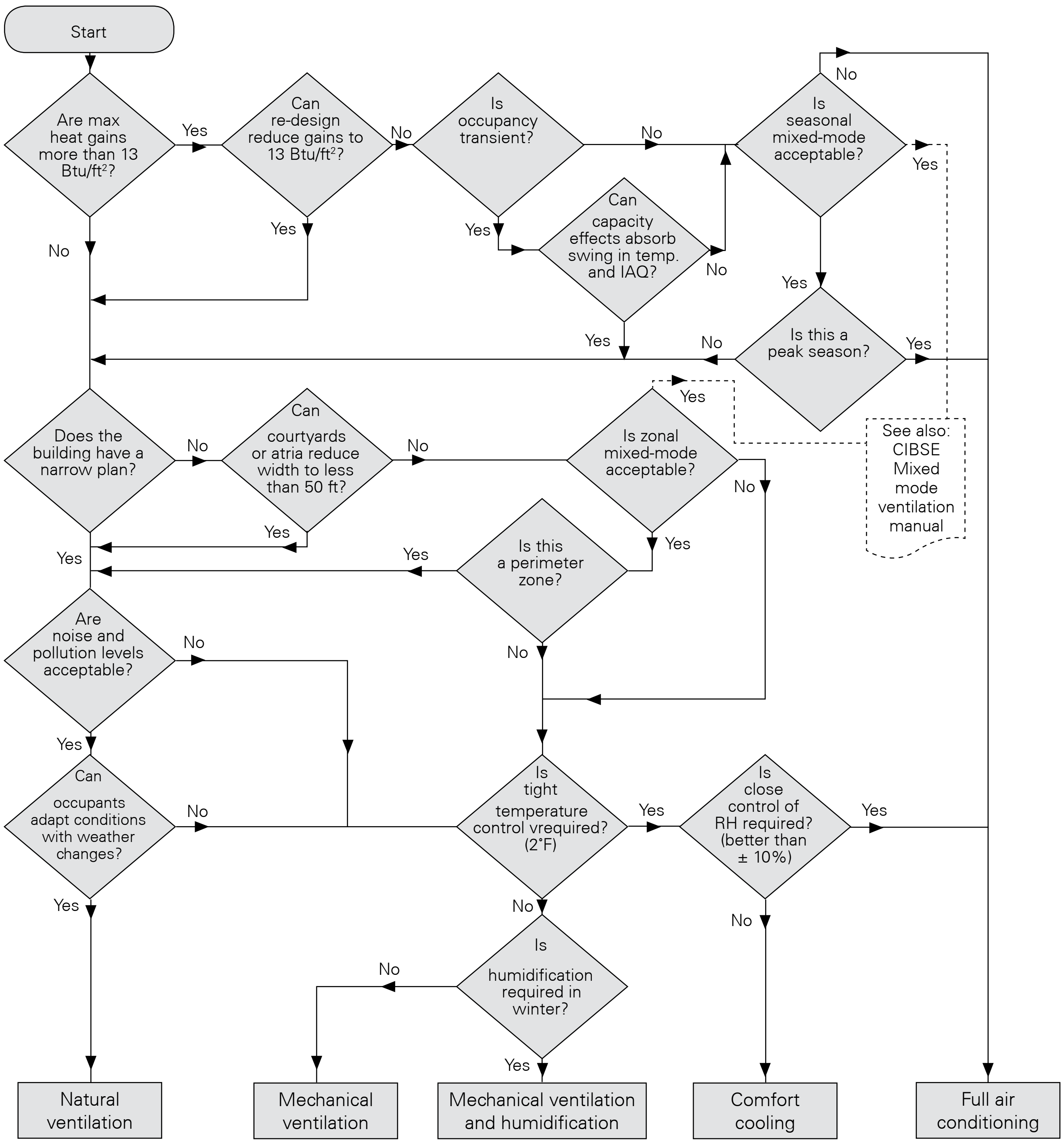

Figure 8.4-H Selecting a Ventilation Strategy
Adapted from CIBSE (2005), Figure 2.8.

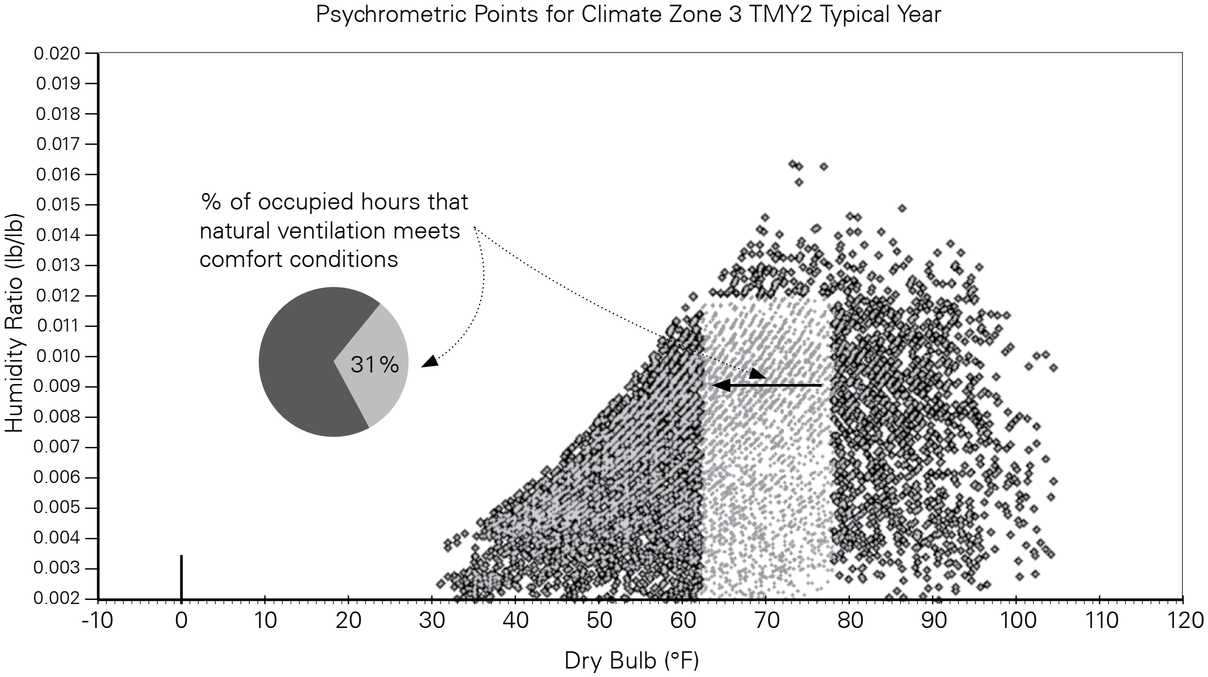

Figure 8.4-I Psychrometric Points for Climate Zone 3
Adapted from Stantec (2009).

Indoor Air Quality (IAQ). The principal role of outdoor air ventilation is to provide an appropriate level of IAQ by removing and diluting airborne contaminants. Higher rates of ventilation may be provided than proposed in the applicable ventilation standard, which may enhance the perception of freshness, but in some cases this will come at a price because energy costs will increase correspondingly (higher ventilation loads may require higher supplementary heating and/or cooling to maintain the required comfort conditions within the occupied space).

- If the volume of the space is sufficiently large, then the pollutants from the activities in the space will affect the IAQ in the occupied zone more slowly, especially if a displacement-type ventilation strategy is adopted, with the pollutants being concentrated in a stratified layer above occupant level. As an illustration, consider ventilating a theatre, where there the design occupancy is 1000 people. This occupancy will only last for the duration of the performance and will build up to that peak for the hour or two preceding the curtain rise.
- Typically IAQ improves with a naturally ventilated and cooled building due to the significant increase in outdoor air. However, the design team should be aware of the surrounding environmental conditions, such as idling vehicles or allergenic-pollen producing foliage. Typically it is not possible to practically filter outdoor air in a natural ventilation and cooling system without a fan-assisted system.

Security Issues. If relying on using operable windows during unoccupied hours (i.e., night flushing), it is important to take into account security concerns. Typically first-floor windows should not be left open at night; thus, the design may require louvers at lower building elevations or may not make use of those openings.

Occupant Dress Code. As stated previously, it is most beneficial if the users of the building are able to wear seasonally appropriate attire to increase their comfort (i.e., short sleeves, sweaters, etc.). If uniform requirements make this unacceptable, extra attention needs to be paid to giving the occupants a high level of control over their indoor environment. This can mean easy access to operable windows or using a mixed-mode system to more tightly control temperatures.

High-Occupancy Periods. For areas such as conference rooms or dining areas where the space is fully occupied for short periods of time but that is not its typical condition, there may be a "recovery" period required for the space to flush out the built-up cooling load before it can be fully occupied again. If this is not possible, supplementary cooling may be required. If incorporated properly into the overall space design, a ceiling fan can make a space feel much more comfortable without the need to add mechanical cooling.

Noise. To increase the effectiveness of a natural ventilation and cooling system it is important to allow for free airflow across spaces, facilitated by unobstructed paths from one side of a space to the other. Depending on the floor layout and design, this may mean there can be noise pollution from adjacent spaces or the outdoor environment. Sometimes a little ambient noise can be beneficial because with no mechanical system humming away in the background occupants may be more sensitive to surrounding conversations or noises. But naturally ventilated buildings often include large areas of exposed concrete in order to increase the thermal capacity of the space. Such large areas of hard surface will require careful attention to achieve a satisfactory internal acoustic environment.

The presence of significant external noise sources can inhibit the application of natural ventilation. There are a number of solutions to this problem.

- Place the ventilation inlets on the sides of the building away from principal noise sources. If the noise source is road traffic, this has the added benefit of locating the ventilation inlets away from the source of pollutants.
- Baffle the external noise with the use of suitable physical acoustic barriers.

Smoke Control. Since smoke can follow natural ventilation paths, the integration of the fire safety strategy must be an important part of the design for natural ventilation.

Health and Safety. Many natural ventilation openings will be at significant heights above floor level, so it is important to provide safe working maintenance access to all high-level components.

Existing Buildings. When existing buildings are being renovated, the form, structure, and siting of the building should be considered. These may prove to be either constraints or opportunities for natural ventilation. For example, many older buildings have high-mass structural components—masonry, concrete, and brick. These provide thermal mass that can potentially enhance the effectiveness of a natural ventilation design. On the other hand, challenges are introduced if the existing building is oriented on a north/south axis such that the east and west facades experience large afternoon solar heat gains during the summer.

Nighttime Cooling. Facilities with daytime occupancy only and with cooler nighttime temperatures can be ideal candidates for natural ventilation since they can take advantage of night flush. Areas that are primarily unoccupied during the night can be flushed out and precooled for the following day. However, if there are work spaces that are occupied around the clock, supplemental cooling may be required during the day, as flush-out during the night may cause discomfort if temperatures drop too low. A significant advantage of 24-hour facilities using nighttime cooling is that security concerns may be lessened, particularly if there is always someone on duty. This should be evaluated on a case-by-case basis.

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Strategy 8.4

Mixed-Mode Ventilation

Most building projects use natural ventilation in combination with a mechanical system to maintain comfort conditions and IAQ levels throughout the year, under all modes of occupancy and outdoor environmental conditions. This combination of systems is often referred to as a hybrid ventilation system. These strategies may be applied at different times to different parts of a building. These approaches are not mutually exclusive; several of them can be combined in a single building. As described in the CIBSE natural ventilation applications manual (CIBSE 2005), the various approaches to mixed-mode ventilation are as follows.

Contingency Mixed-Mode

Per CIBSE AM10, "where flexibility of space is required, then it is important to 'design-in' the potential to upgrade the services so that additional cooling can be installed to meet tenant requirements or the changing climate. This provision will include space allowances for additional distribution systems incorporated into floor and/or ceiling voids. The cost of the additional flexibility will need to be set against the savings in initial and operating costs accruing from the avoidance of unnecessary air conditioning" (CIBSE 2005, p. 8).

Zoned Mixed-Mode

Zoned mixed-mode ventilation recognizes that "different parts of any building will have different uses. Air conditioning is provided only to those parts of the building where there is a real need. In areas of lower heat gain [or in those areas that are occupied for short periods], heating and natural ventilation only would be provided. Such an approach relies on the requirements of the individual spaces being reasonably constant over the life of the building. Such an approach can also create tensions, if one group of occupants feels that another group has been provided with what they believe is a better working environment"(CIBSE 2005, p. 8).

Changeover Mixed-Mode

Changeover mixed-mode ventilation recognizes that "the cooling requirements of any space will vary from season to season. An example of changeover mixed-mode would be to use mechanical ventilation in extreme weather conditions (hot and cold), but rely on natural ventilation in milder weather. This reduces the problem of cold draughts in winter, and allows the use of mechanical night ventilation for precooling in hot summer periods" (CIBSE 2005, p. 8).

Concurrent Mixed-Mode

Concurrent mixed-mode ventilation "provides mechanical and natural ventilation simultaneously. The mechanical system is designed to provide the [outdoor] air requirement, with additional ventilation by opening windows to provide summer cooling. The mechanical system can also provide night ventilation without the security problems that may be associated with opening windows" (CIBSE 2005, p. 8). If mechanical cooling is also provided, care should be taken to avoid excess ventilation in very hot weather.

A mixed-mode system may include air-handling units, chillers, cooling towers, pumps, fans, piping, and ductwork, etc., but overall the scale and scope of the mixed-mode mechanical equipment would typically be smaller than that required for a conventional HVAC system, providing more usable space for the occupants, greater floor-to-ceiling height, and lower maintenance cost.

Control of Ventilation

The control of natural ventilation airflow is critical for the satisfactory performance of a fully naturally ventilated building or a building using a mixed-mode strategy. The CIBSE applications manual states:

> If natural ventilation is to be adopted, then the system has to be able to provide controllable ventilation rates across a wide range, from say 0.5 to 5 ach or even more. Indeed, it should be possible to shut down the ventilation rate to near zero when the building is unoccupied, especially if occupancy is the principal source of pollutants. (CIBSE 2005, p. 4)

In small buildings, shutting down the ventilation rate can be done manually, but in larger/more complex buildings automated control is generally used to monitor and control the natural ventilation flow rates. The CIBSE manual continues:

> The wide range of flow rate that is required means that the different modes of ventilation (whole-building, purge etc.) are likely to be provided via different devices such as trickle ventilators, opening windows and/or purpose provided ventilators. (p. 4)

Natural and mixed-mode ventilation designs in larger/more complex buildings require a high degree of integration between the facade design and the control strategy. According to CIBSE (2005):

> As well as providing the required ventilation rates, the ventilators should be designed so as to minimise discomfort from draughts, especially in winter. In office-type buildings, this usually involves placing the inlets at high level, typically [5.6 ft] 1.7 m or more above floor level. (p. 4)

It could also mean having integrated heating elements to temper the air prior to entering the occupied space in the winter.

Automatic Integrated Control for Windows/Vents

Automatic integrated control for windows/vents is normally used when the indoor environment is dependent upon precise control of the window/vent openings. The automatic integrated control for windows/vents ensures this is achieved typically using a number of parameters such as indoor/outdoor temperature, carbon dioxide (CO_2), wind speed/direction, and precipitation. The automatic integrated control for windows/vents system can be designed to automatically control the window/vent opening and closing to achieve the best indoor climate.

The automatic integrated control for windows/vents system may contain the following preprogrammed modes of operation:

- Integrated smoke ventilation
- Integrated control of sunscreening
- Combined control of heating and cooling installations
- Hybrid/mixed-mode ventilation
- Comfort ventilation
- Night flushing/precooling
- Temperature regulated with limited opening (heating and cooling, window, vent interlock)
- Trickle ventilation (Figure 8.4-J)

Complementary Design Techniques

There are many synergies between natural ventilation and cooling systems and other building design techniques. Often it is possible to take advantage of double-duty design to get several functions out of one building element, thus reducing costs and increasing functionality.

The following list is of design techniques that mesh with a natural ventilation and cooling design. It will not always be possible to include them all in a building, but as many as possible should be considered (Stantec 2009).

Operable Windows. The key feature of naturally ventilated and cooled spaces is occupant control of windows (including operable louvers/dampers). Operable windows on opposite sides of a space allow for cross ventilation when a breeze blows. High and low combinations of operable windows create stack-effect ventilation caused by temperature stratification and pressure differentials. Ideally a space should have both cross and stack ventilation. For energy control in mixed-mode systems, it may be necessary to have interlocks (window sensors) between the window opener and the supplementary heating or cooling systems.

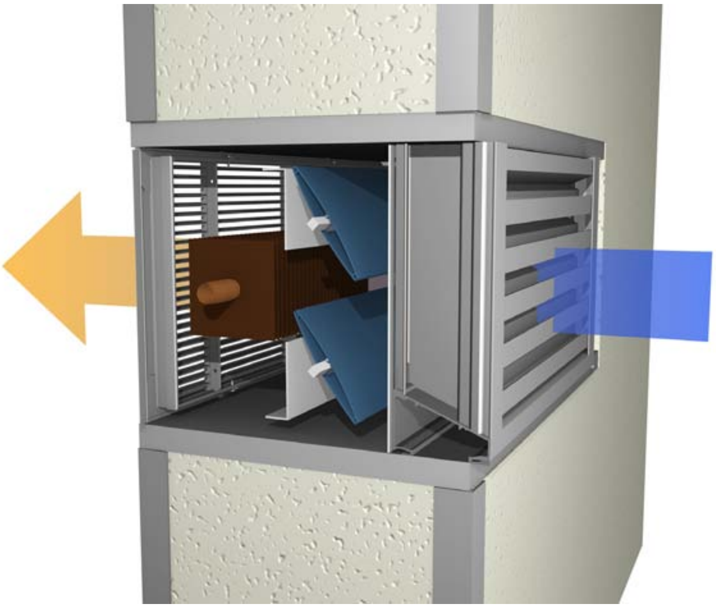

Figure 8.4-J Trickle Vent Example

Radiant Heating. With natural ventilation there is no mechanical air delivery, which limits options to condition the space during the heating season. Radiant heating in the floor or ceiling can be used if supplementary heating is required. There can be significant comfort gains and operating cost savings in using radiant heating (either in-slab or overhead). Rather than heating all of the air in the occupied space, radiant heating provides heat directly to the occupants and work areas. In addition, it has been shown that lower wintertime setpoint temperatures can be considered when radiant heating is used.

Radiant Cooling. Radiant cooling is generally only used in mixed-mode systems. With radiant cooling, most of the cooling will still be passive using outdoor air or thermal mass to cool the space, but during peak times radiant cooling can keep the spaces comfortable. If a radiant slab or panel is used for heating it can be switched over during the summer months to provide cooling, though it has to be closely controlled to limit condensation. Climates well situated for chilled slabs or panels typically have low humidity levels in summer, thus allowing slab or panel temperatures to remain lower and more cooling effect to be provided with a lower risk of condensation. Chilled slabs are very effective when used to prevent solar load striking a floor from heating the space. Figure 8.4-K illustrates the use of mixed-mode/hybrid ventilation and a chilled slab.

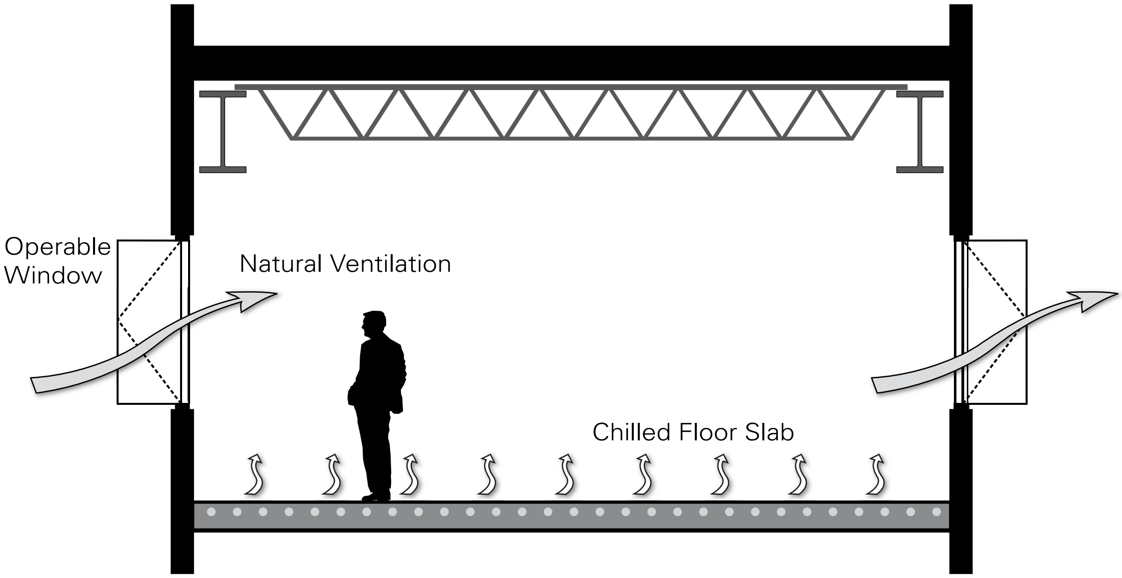

Figure 8.4-K Mixed-Mode/Hybrid System Combining Natural Ventilation with Chilled Slab

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Shading. The best way to keep a space cool is to never allow it to get hot in the first place. Optimized active or passive shading can help counteract the increased solar gain caused by windows. Controlling solar gains is crucial in any natural ventilation and cooling design.

Thermal Mass. This is one of the oldest yet most effective passive building design techniques. Buildings with heavy construction and exposed thermal mass (concrete, brickwork, rock, etc.) can greatly reduce their peak cooling loads. During the night, the building typically cools down (especially if assisted with night flushing), then during the day the cooler thermal mass slowly absorbs the heat, resulting in a space that does not feel as hot. After a long spell of hot days, the effect of thermal mass may become minimal if the building never gets a chance to cool down (because of long occupancy periods or warm nighttime temperatures).

Daylighting. This technique uses natural sunlight rather than electric lighting to provide light to a space. It can save significantly on electricity usage and reduce cooling loads. On the surface it seems that daylighting is counterproductive to a natural ventilation and cooling system because daylighting requires sunlight, while natural ventilation and cooling prefer to have it blocked out. In reality these strategies can coexist and benefit each other. This is because a key element of daylighting is glare control, meaning preventing direct sunlight from striking a surface. This also prevents direct solar gain. Often shading devices can double as daylighting features by allowing in diffuse light or bouncing light off of the ceiling. Figure 8.4-L illustrates the combination of daylighting with proper shading and natural ventilation.

Per the Santa Monica Green Building program information on daylighting, views, and natural cooling (OSE 2009a):

> The area of interior space that can use daylight through windows depends on both building depth and floor-to-ceiling height. Single-story buildings and the top floors of multi-story buildings can be top lit using skylights, roof monitors or light wells. Since useful daylight from typical windows can only reach 15 to 25 ft. [4.6 to 7.6 m] into spaces with 8 or 9 ft. [2.4 or 2.7 m] floor-to-ceiling heights, floor plans deeper than ~ 56 ft. [17 m] (two rooms flanking a double-loaded corridor) will require constant

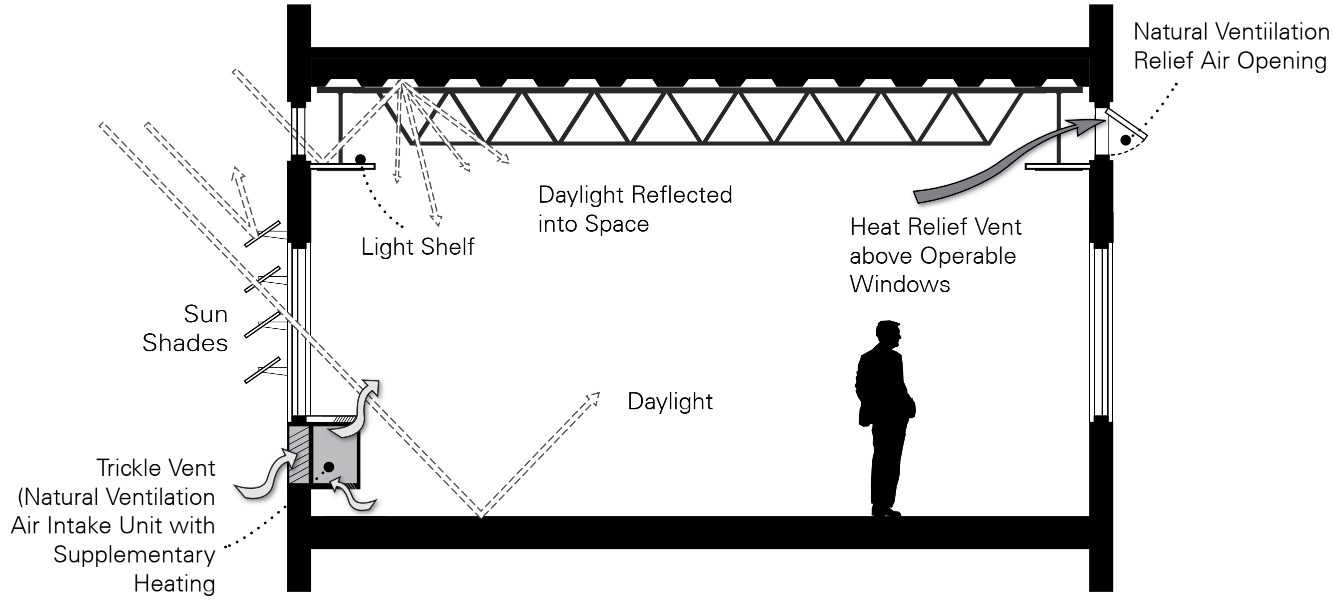


Figure 8.4-L Daylighting Used in Combination with Shading and Natural/Mixed-Mode Ventilation

> electric lighting. Redirecting daylight with light shelves, prismatic glazing and other reflective systems can extend naturally lit interior space to 30 to 35 ft. [9.1 to 9.7 m] deep.
>
> An occupant's view of the exterior depends on the distance from the window, the visible transmissivity of the glazing, and obstructions to light. To ensure good views for most occupants, limit the maximum distance of workstations from the building exterior to 20 to 25 ft. [6.1 to 7.6 m], or use atria and outdoor courtyards to increase the variety and number of views.

Floor Plan Depth. According to the Santa Monica Green Building program information, floor plan depth can be "one of the most important considerations that affects the potential for daylighting, exterior views and natural ventilation. Floor plans with relatively narrow wings, such as I-, H-, U-, or T-shaped plans, ensure that most interior spaces have good access to natural light and winds. Courtyards and atria can also be used to bring light and air to surrounding narrow spaces" (OSE 2009b).

The Green Building Web site continues: "Narrow floor plans increase the potential for effective cross ventilation: bringing outdoor air into one side of a space and exhausting it on an adjacent or opposite side. Cross ventilation can move air effectively over deep floor plans, but air temperature increases and air quality drops as it moves across the room." The practical limit for airflow path length is listed as 3.5 times the ceiling height (~35 ft for a 10 ft ceiling [10.7 m for a 3 m ceiling]).

The Santa Monica Green Building program information on daylight, views, and cooling (OSE 2009a) states:

> Single-sided ventilation, where only one exterior wall has operable windows or vents, is also possible but less effective, since air speed (with its cooling effect) is typically lower than in cross-ventilation situations.
>
> With a single operable window or vent, natural ventilation relies on wind turbulence and buoyancy, instead of the higher pressures available from wind. In single-sided ventilation, air flows in the bottom, is heated within the space, and flows out at the top of the same opening. The larger the height between the top and bottom, and the higher the temperature change, the greater the airflow.

"Single-sided, single-opening natural ventilation is effective to a depth of approximately 1.5 times the ceiling height," according to OSE (2009b). This implies that the maximum room depth can be approximately 13 to 15 ft (4.0 to 4.6 m) for a ceiling that is 9 to 10 ft (2.7 to 3.0 m) high and has a window about 5 ft (1.5 m) high (OSE 2009b).

In addition, "[w]here separate high and low openings are used, warm air leaves through the upper vent, inducing inflow through the lower vent. In this situation, if the vertical separation between the openings is approximately 5 ft [1.5 m], ventilation is effective for" up to 2 times the ceiling height, which gives a maximum room depth of 16 to 20 ft (4.9 to 6.1 m) (OSE 2009b).

Table 8.4-A summarizes some of the natural ventilation options and related design and operational considerations (Stantec 2009).

Table 8.4-A Ventilation and Cooling Design Options
Data source: Stantec.

Option	Description	Design Considerations	Related Strategies	O&M Issues
Reduce loads	Mitigate or prevent solar, conductive, and process loads	High-performance envelope and shading; avoid concentrated process loads	High-occupancy space flush-out after use; daylighting to reduce lighting load	May require automatic shading control, which requires ongoing maintenance
One-sided natural ventilation	Draw outdoor air and vent relief air through openings along one exterior side of a space	Only appropriate in shallow spaces (i.e., private offices); include high and low openings to create stack effect	Ceiling fans to create airflow during stagnant periods	None
Two-sided natural ventilation	Draw outdoor air and vent relief air through openings on opposite sides of a space	High and low openings on opposing facades create cross and stack airflow	Clerestories, solar wells, ventilation chimneys, narrow floor plates, and "I," "E," or "O" shaped floor plans	None
Occupant control	Allow building users to open and close windows to control space temperature	Can be manual (operable window) or mechanical (switch-controlled damper)		Motorized windows require maintenance; operable windows may present security risk
Automated control	Automated windows or dampers controlled by temperature, wind velocity, or CO_2 level sensors	Can be a primary method of introducing air or as fail-safe; a solution for areas with high-occupancy spaces; requires more robust controls system	Can be good way to implement night flush	Automated systems require more maintenance than passive systems
Thermal mass (acoustical treatments should be considered when designing for thermal mass)	Reduce peak building space temperatures with exposed dense building materials (i.e., concrete) that absorb heat during hottest times and slowly release it during cooler periods	Can be walls, ceilings, or slabs; finishes (carpeting, drywall, etc.) greatly diminish effect	Radiant chilled slab can be combined with exposed floor to increase cooling effect	Durable materials require less maintenance than alternative finishes
Night flush	Introduce cool outdoor air into building at night to allow structure to precool for the next day	Requires either automated system or early morning and evening occupants to open and close windows; only effective if nighttime temperatures are cool	Most effective when combined with thermal mass effects to store "cool" into the next day	Automated systems require maintenance; passive systems may require custodial crew to be in charge of window control; potential security issues
Supplementary cooling	Add cooling to areas with peak loads to maintain comfort conditionings	Optimal choice is radiant cooling rather than forced-air units; ceiling fans can provide significant cooling effect without mechanical cooling		Cooling systems require maintenance

Design Tools and Calculations

In a traditional HVAC design, compliance with thermal comfort criteria can be demonstrated through peak-load calculations, unit capacities, and temperature setpoints. Thermal comfort compliance in a natural ventilation and cooling design can be more difficult to prove, as indoor temperatures are a function of frequently changing factors such as wind speed and direction, cloud cover, outdoor temperature, and occupancy levels. Some comfort criteria, such as those provided in ASHRAE Standard 55 (ASHRAE 2004), are based on peak indoor operative temperatures while others, such as the LEED Bounding Comfort Parameters (USGBC 2003), refer to the number of annual hours allowed at different temperature thresholds.

Natural and mixed-mode ventilation design tools are covered in depth in the CIBSE (2005) application manual AM10, which shows how the basic textbook equations can be used/ manipulated to provide solutions to most design problems. CIBSE (2005) summarizes the following main design tools:

- Simple manual airflow calculations (for rough guidance calculations only)
- Computational fluid dynamics (CFD)
- Combined thermal and ventilation modeling and
- Physical scale modeling

Manual Calculations

The manual calculations shown in this section can be used to provide very rough steady-state design guidance information (for more comprehensive manual calculations refer to CIBSE [2005]). For example, there are two main types of passive natural ventilation to aid in airflow: cross and stack ventilation.

Cross-ventilation techniques rely on wind force (high and low pressure zones) to draw outdoor air into the building and across the space. The following simple calculation can determine the approximate steady-state airflow through the building.

$$Q = (K)(A)(V)$$

where

Q = cross ventilation airflow rate, ft^3/h (m^3/h)
K = outlet to inlet variable
A = area of inlet, ft^2 (m^2)
V = wind speed, mph (m/s)

Stack ventilation, or *stack effect*, relies on buoyancy (using high and low pressure zones), which is created by temperature differences, rising heat, and the resultant convection currents. The design principle is implemented by using relief vents near the top of the building that relieve warm air out of the building and intake vents near the lower levels of the building that allow cooler air to enter the building. The following simple calculation, which is demonstrated in Figure 8.4-M, can determine the approximate steady-state airflow through the building.

$$Q = 60 \times K \times A \times \surd(2g \times H \times (T_i - T_o)/T_i)$$

where

Q = stack vent airflow rate, ft^3/min (m^3/min)
K = discharge coefficient for opening; assume 0.65 for multiple inlets
A = area of inlet, ft^2 (m^2)
g = gravitational constant, ~32.2 ft/s^2 (9.81 m/s^2)
H = height of stack from inlet to outlet, ft (m)
T_i = temperature at inlet, °F (°C)
T_o = temperature at outlet, °F (°C)

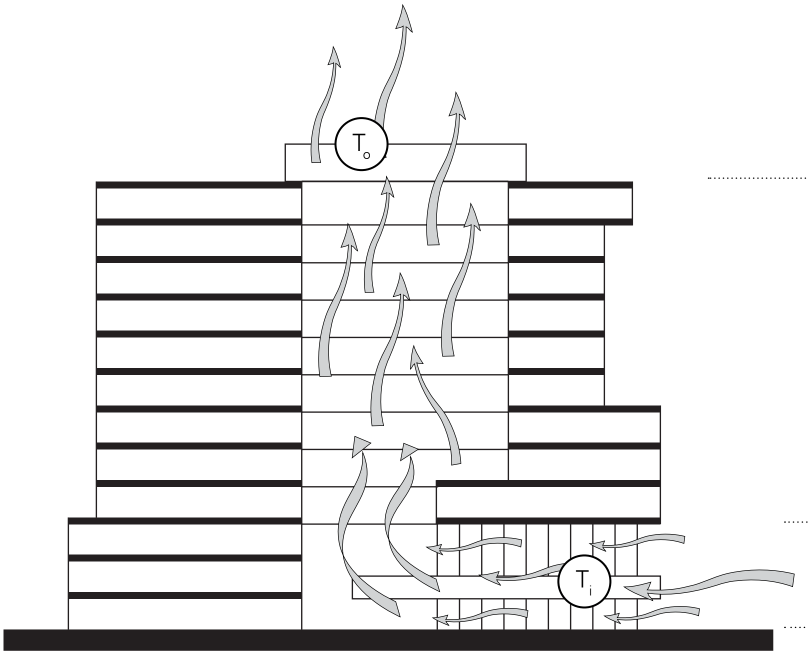


Figure 8.4-M Stack Ventilation

Computerized Explicit Envelope Flow Models

These CFD tools are available for basic natural ventilation design purposes. A class of tools known as is the most appropriate. These models allow basic dimensioning of the system components. They then explain how other, more sophisticated tools (such as implicit envelope flow models, combined thermal and ventilation models, CFD and physical scale models) can be used to check the performance of the sized system under a variety of operating modes.

The best way to demonstrate compliance with the design comfort criteria is to conduct thermal modeling for those portions of a building that are naturally ventilated. This requires software capable of performing dynamic hourly load, airflow, and temperature calculations, including the effects of operable windows, and natural airflow, with the ability to use location-appropriate weather files.

Thermal modeling is useful for much more than simply demonstrating compliance. It can be used to test different options or iterated to optimize the design. For example, thermal modeling software can be used to find the optimal quantity, sizes, and locations of operable windows or to evaluate the effect of changing building materials, interior openings, or other design features. For example, Figure 8.4-N shows CFD models of the temperature distribution in a naturally ventilated building addition. The first model shows an uneven temperature distribution, while the second model, which eliminates openings between floors, provides much more uniform temperatures. The CFD modeling also provides information on air velocities that can be used to assess comfort and other issues.

Cost-Benefit Analysis

The example in this section is from an actual project of capital and annual energy costs for natural ventilation designs as compared to traditional systems. Dollar values in the examples are not current and therefore should be considered only as indicators of relative costs.

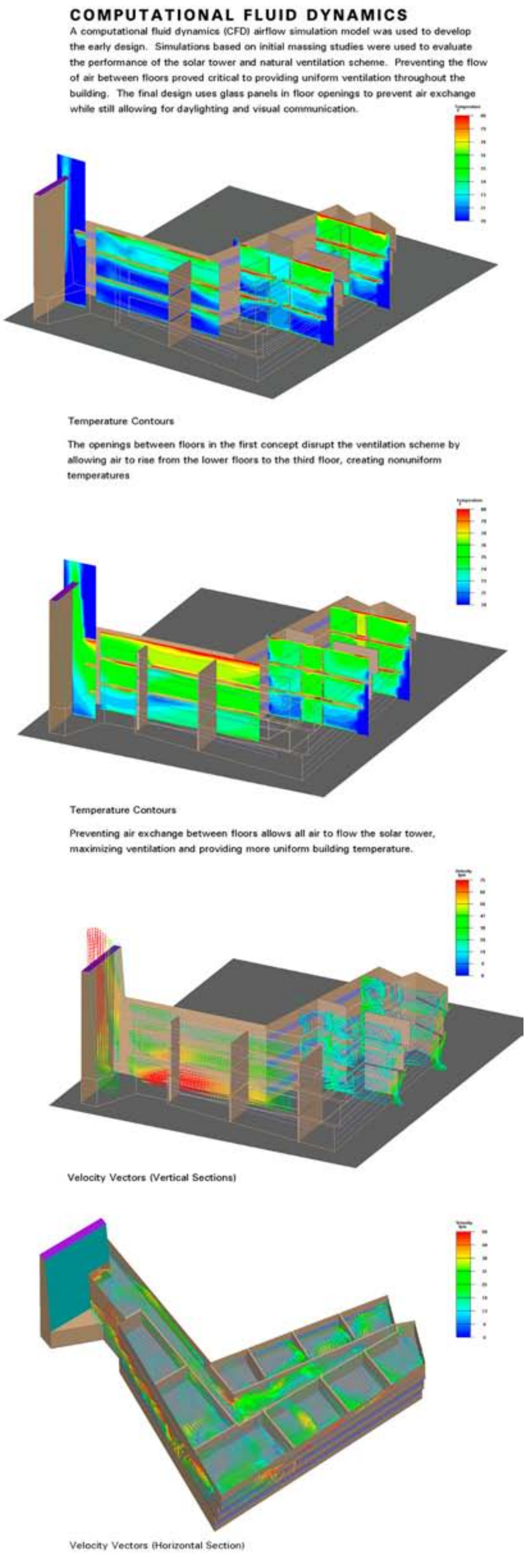
Capital Costs

Table 8.4-B shows a sample capital cost comparison (in $/ft^2 [$/m^2]) of a passive natural ventilation cooling system vs. a hybrid system vs. a traditional ducted variable-air-volume (VAV) system. The data are taken from a report for a classroom design created by Stantec in May 2006. Building performance/indoor environmental quality outcomes are not necessarily equivalent for all of the system options compared. This type of analysis is very much dependant on the building location, client expectation, etc.

The comparison illustrates some of the cost trade-offs involved with natural ventilation and cooling design. Notably, in this project, the architectural costs are higher while the mechanical costs are lower. In this case the hybrid system not only includes mechanical cooling but also fully automated operable windows

Next Page

Strategy 8.4



COMPUTATIONAL FLUID DYNAMICS

A computational fluid dynamics (CFD) airflow simulation model was used to develop the early design. Simulations based on initial massing studies were used to evaluate the performance of the solar tower and natural ventilation scheme. Preventing the flow of air between floors proved critical to providing uniform ventilation throughout the building. The final design uses glass panels in floor openings to prevent air exchange while still allowing for daylighting and visual communication.

Temperature Contours

The openings between floors in the first concept disrupt the ventilation scheme by allowing air to rise from the lower floors to the third floor, creating nonuniform temperatures

Temperature Contours

Preventing air exchange between floors allows all air to flow the solar tower, maximizing ventilation and providing more uniform building temperature.

Velocity Vectors (Vertical Sections)

Velocity Vectors (Horizontal Section)

Figure 8.4-N CFD Modeling of Temperature Distribution and Airflow in a Building Addition

controlled by the direct digital control system. This is why the architectural elements in the hybrid system are more expensive than those in the passive system.

One opportunity to further reduce capital costs of naturally ventilated high-performance buildings that is not represented in Table 8.4-B is to make use of green incentive programs such as local utility, municipal, state, federal, and other programs. Many programs exist that can reduce the initial investment cost of energy-conserving features in buildings, including natural ventilation.

For the examples, the overall construction costs on a square-foot (square-meter) basis are lowest for the passive natural ventilation and cooling design coupled with perimeter baseboard heating. This system is expected to have the lowest annual energy costs, even though heating costs may be slightly higher than the hybrid natural ventilation case, which has the more efficient radiant floor heating system. Conversely, energy costs are highest for the conventional system, primarily because of the fan energy.

Abbreviations and Acronyms

AABC = Associated Air Balance Council
AAMA = American Architectural Manufacturers Association
ACGIH = American Conference of Governmental Industrial Hygienists
ADC = Air Diffusion Council
AHAM = American Home Appliance Manufacturers
AHU = air-handling unit
AIA = American Institute of Architects
AIHA = American Industrial Hygiene Association
AMCA = Air Movement and Control Association
ANSI = American National Standards Institute
AQS = Air Quality Sciences, Inc.
ASD = active soil depressurization
ASHE = American Society of Hospital Engineers
ASHRAE = American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM = ASTM International (formerly the American Society for Testing and Materials)
BIFMA = Business and Institutional Furniture Manufacturer's Association
BoD = Basis of Design
BOMA = Building Owners and Managers Association International
CARB = California Air Resources Board
CDC = Centers for Disease Control and Prevention
CDHS = California Department of Health Services
CEC = California Energy Commission
CHPS = Collaborative for High Performance Schools
CO = carbon monoxide
CO_2 = carbon dioxide
CoC = contaminants of concern
CREL = Chronic Reference Exposure Level
CV = constant volume
Cx = commissioning
CxA = commissioning authority
DCV = demand-controlled ventilation
DDDF = dual duct dual fan
DOAS = dedicated outdoor air system
DOE = U.S. Department of Energy
DX = direct expansion
EDR = Energy Design Resources
EPA = U.S. Environmental Protection Agency
ERV = energy recovery ventilator
EU = European Union
FAC = filtration and gas-phase air cleaning
FEMA = Federal Emergency Management Agency
HE = high efficiency
HEPA = high-efficiency particulate air
HVAC = heating, ventilating, and air conditioning
IAQ = indoor air quality
IAQP = IAQ Procedure
IEQ = indoor environmental quality
IEST = Institute of Environmental Sciences and Technologies
IPCC = Intergovernmental Panel on Climate Change
ITRC = Interstate Technology & Regulatory Council

JCAHO = Joint Commission on Accreditation of Healthcare Organizations
MDF = medium density fibreboard
ME = medium efficiency
MERV = Minimum Efficiency Reporting Value
NAAQS = National Ambient Air Quality Standards
NAIMA = North America Insulation Manufacturers Association
NASA = National Aeronautics and Space Administration
NCARB = National Council of Architectural Registration Boards
NEBB = National Environmental Balancing Bureau
NEHA NRPP = National Environmental Health Association National Radon Proficiency Program
NFPA = National Fire Protection Association
NFRC = National Fenestration Rating Council
NIBS = National Institute of Building Sciences
NIH = National Institutes of Health
NIOSH = National Institute of Occupational Safety and Health
NO_2 = nitrogen dioxide
NO_x = nitrogen oxides
NRCan = Natural Resources Canada
NRC-IRC = National Research Council Canada Institute for Research in Construction
NRSB = National Radon Safety Board
O&M = operation and maintenance
OPR = Owner’s Project Requirements
OSB = oriented strand board
OSHA = Occupational Safety and Health Administration
OTA = U.S. Congress Office of Technology Assessment
PM10 = particulate matter with a diameter of 10 µm or less
PM2.5 = particulate matter with a diameter of 2.5 µm or less
PVC = polyvinyl chloride
QA = quality assurance
RH = relative humidity
RTU = rooftop unit
SMACNA = Sheet Metal and Air Conditioning Contractors’ National Association
SO_2 = sulfur dioxide
SVOC = semi-volatile organic compound
TAB = testing, adjusting, and balancing
TABB = Testing, Adjusting, and Balancing Bureau
TLV = threshold limit value
TVOC = total volatile organic compound
TWA = time-weighted average
UL = Underwriters Laboratories
USGBC = U.S. Green Building Council
UVGI = ultraviolet germicidal irradiation
VAV = variable-air-volume
VFD = variable-frequency drive
VOC = volatile organic compound
VRP = Ventilation Rate Procedure
WHO = World Health Organization

Introduction

Why Good IAQ Makes Sense

Indoor air quality (IAQ) is one of many factors that determine building functionality and economics. IAQ affects building occupants and their ability to conduct their activities; creates positive or negative impressions on customers, clients, and other visitors to a building; and can impact the ability to rent building space. When IAQ is bad, building owners and managers can find themselves devoting considerable resources to resolving occupant complaints or dealing with extended periods of building closure, major repair costs, and expensive legal actions. When IAQ is good, buildings are more desirable places to work, to learn, to conduct business, and to rent.

The High Cost of Poor IAQ

The costs of poor IAQ can be striking. There have been many lawsuits associated with IAQ problems, though most are settled with no financial details released. However, some publicly disclosed cases have involved legal fees and settlements exceeding $10 million. For example:

- In 1995, Polk County, Florida, recovered $47.8 million in settlements against companies involved in the construction of the county courthouse (including $35 million from the general contractor's insurer), due to moisture and mold associated with building envelope problems. The original construction cost for the building was $35 million, but $45 million was spent to replace the entire building envelope, clean up the mold, and relocate the court system.
- Occupants of a courthouse in Suffolk County, Massachusetts, received a $3 million settlement in 1999 following a series of IAQ problems associated with a combination of inadequate ventilation and fumes from a waterproofing material applied to the occupied building.

Numerous IAQ problems have also occurred in private-sector buildings, but these tend to be settled out of court and are therefore not in the public record. As in public buildings, the causes of the problems vary and the settlement costs can be very expensive. A conservative estimate puts the lower bound of litigation costs during the early 2000s well over $500 million annually.

IAQ directly affects occupant health, comfort and productivity. Well-established, serious health impacts resulting from poor IAQ include Legionnaires' Disease, lung cancer from radon exposure, and carbon monoxide (CO) poisoning. More widespread health impacts include increased allergy and asthma from exposure to indoor pollutants (particularly those associated with building dampness and mold), colds and other infectious diseases that are transmitted through the air, and "sick building syndrome" symptoms due to elevated indoor pollutant levels as well as other indoor environmental conditions. These more widespread impacts have the potential to affect large numbers of building occupants and are associated with significant costs due to health-care expenses, sick leave, and lost productivity. The potential reductions in health costs and absenteeism and improvements in work performance from providing better IAQ in nonindustrial workplaces in the U.S. are estimated to be in the high "tens of billions of dollars annually" (EPA 1989; Fisk 2000; Mendell et al. 2002).[1]

Despite these significant impacts, many building design and construction decisions are made without an understanding of the potentially serious consequences of poor IAQ and without benefit of the well-established body of knowledge on how to avoid IAQ problems. While controlling indoor pollutant levels and providing adequate ventilation and thermal comfort have motivated the design and use of buildings for centuries, awareness of and concerns about IAQ have increased in recent decades. However, in most cases IAQ is still not a high-priority design or building management concern compared to function, cost, space, aesthetics, and other attributes such as location and parking.

Given the very real benefits of good IAQ and the potentially serious consequences of poor IAQ, building owners, designers, and contractors can all benefit from an increased focus on providing good IAQ in their buildings. This Guide can enhance all parties' ability to design, construct, and operate buildings with good IAQ using proven strategies that do not incur significant additional costs.

What is Good IAQ?

This Guide is intended to help architects, contractors, and building owners and operators move beyond current practice to provide "good IAQ." Good IAQ is achieved by providing air in occupied spaces in which there are no known or expected contaminants at concentrations likely to be harmful and no conditions that are likely to be associated with occupant health or comfort complaints and air with which virtually no occupants express dissatisfaction. It includes consideration of both indoor air pollution levels and thermal environmental parameters. However, the limits

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[1] Other research related to impacts of IAQ is available at the IAQ-SFRB at http://eetd.lbl.gov/ied/sfrb/sfrb.html.

of existing knowledge regarding the health and comfort impacts of specific contaminants and contaminant mixtures in nonindustrial environments, coupled with the variations in human susceptibility, make it impossible to develop a single IAQ metric that can provide a summary measure of IAQ in buildings.

In the context of this Guide, then, good IAQ results from diligent compliance with both the letter and intent of ASHRAE Standard 62.1 (ASHRAE 2007a), technically sound and well-executed efforts to meet or exceed these minimum requirements, and the application of IAQ-sensitive practices in building and system design, construction, commissioning (Cx), and operation and maintenance (O&M) throughout the life of a building. It is reasonable to assume that adherence to today's minimum standards, i.e., ASHRAE Standard 62.1, and to good engineering and O&M practices will result in acceptable IAQ. However, current practice does not always achieve compliance with minimum standards or with good practice, and many building owners and practitioners desire to achieve better-than-acceptable IAQ. These are the primary motivations for the development of this Guide.

Importance of the Design and Construction Process

While there is ample information and experience on achieving good IAQ in commercial and institutional buildings, it doesn't happen automatically. It takes a level of awareness and commitment that isn't typical of most projects, including an effort to make IAQ part of the design at the very beginning of the project. There are two primary reasons to include IAQ considerations in the earliest stages of project planning: avoiding problems that occur when IAQ is treated as an afterthought and allowing consideration of alternative design concepts that involve decisions made early in the design process.

Incorporating IAQ at the very beginning of conceptual design gets a number of key issues before the design team, enabling them to make informed decisions that will affect the project through the construction and occupancy phases. These issues and decisions are addressed in more detail in this document but include the owner's expectations for IAQ in the building, outdoor contaminant sources in or near the site, the activities expected to occur in the building (and the contaminants that might be associated with these activities), the characteristics of the occupants (e.g., their age range and health status, as well as the possibility of short term visitors that may have very different expectations than occupants who will remain in the building for a long time), and the approaches used to heat, cool and ventilate the building. If these considerations are not addressed until after the building layout is defined, the ventilation system type is selected, and the ventilation rate design calculations are complete, it will be difficult if not impossible to accommodate the particular needs of the building, its owner, and its occupants.

Many design decisions that can lead to poor IAQ are made in the early phases of design and are difficult to modify or correct later on. Early design missteps can be avoided if IAQ is put on the table as a key design issue at the start. Examples are inadequate space for mechanical equipment, limiting access for inspection and maintenance, and selection of interior finishes that can lead to high levels of volatile organic compound (VOC) emissions or to moisture problems in the building envelope.

Making IAQ part of the initial discussion of design goals—on par with building function, image, and energy use—allows consideration of high-performance design concepts that can support good IAQ, energy efficiency, and other important design goals. Examples include mechanical systems that separate outdoor air ventilation from space conditioning, the application of natural ventilation, high-efficiency air cleaning in conjunction with lowered ventilation rates, and the selection of low-emitting materials based on sound technical consideration of the options.

Making a commitment to good IAQ at the beginning of a project and maintaining that focus through design, construction, and Cx will result in a building that is more successful in meeting its design goals and achieving the desired level of performance throughout its life.

What are the IAQ Problems in Buildings?

The information in this Guide is based on the IAQ problems that have been occurring in commercial and institutional buildings for several decades and the authors' experience in investigating, resolving, and avoiding these problems. The causes of these problems were used to develop the organization of this Guide.

IAQ during Design and Construction

Many IAQ problems are the result of IAQ not being considered as a key issue at the very beginning of the design process. Basic design decisions related to site selection, building orientation, and location of outdoor air intakes and decisions on how the building will be heated, cooled, and ventilated are of critical importance to providing good IAQ. Efforts to achieve high levels of building performance without diligent considerations of IAQ at the beginning of the design process often lead to IAQ problems and represent missed opportunities to ensure good IAQ.

Lack of Commissioning

While a good design is critical to providing good IAQ, if the building systems are not properly installed or commissioned so that they operate as designed, IAQ conditions may be seriously compromised. Therefore, a key factor in achieving good IAQ is a serious commitment to a comprehensive Cx effort that starts in the design phase and continues well into occupancy. This effort should include a focus on Cx of systems and assemblies critical to good IAQ.

Moisture in Building Assemblies

There have been many notable cases of building IAQ problems associated with excessive levels of moisture in building assemblies, particularly in the building envelope. Such situations can lead to mold growth that can be very difficult to fix without major renovation efforts and costs. Moisture problems arise for a variety of reasons, including roof leaks, rain penetration through leaky windows, envelope design and construction defects such as low-permeability wall coverings in hot and humid climates, and poor building pressure control. These problems are largely avoidable but require an understanding of building moisture movement and attention to detail in envelope design and construction and in mechanical system selection, installation, and operation.

Poor Outdoor Air Quality

As noted previously, the traditional means of dealing with IAQ is through outdoor air ventilation. While ventilation can be an effective means to dilute indoor contaminants, it assumes that the outdoor air is cleaner than the indoor air. In many locations and for many contaminants, this is not the case, and insufficiently treated ventilation air can actually make IAQ worse. Poor outdoor air quality includes regionally elevated outdoor contaminant levels as well as local sources, such as motor vehicle exhaust from nearby roadways and contaminants generated by activities in adjacent buildings. Some programs encouraging higher levels of building performance recommend increasing outdoor air ventilation rates, but such recommendations should be based on the consideration of the potential impacts of poor outdoor air quality. ASHRAE Standard 62.1 requires the assessment of outdoor air quality in the vicinity of a building and requires outdoor air cleaning under some circumstances. Given the key role of outdoor air ventilation in IAQ control, this Guide covers outdoor air quality and air cleaning alternatives in detail.

Moisture and Dirt in Ventilation Systems

Dirt accumulation in ventilation systems, combined with poor management of water, can lead to biological growth in the airstream and serious IAQ problems. These conditions generally result from inadequate levels of particle filtration, poor filter maintenance, and problems with cooling coil condensate or other moisture sources. ASHRAE Standard 62.1 contains several requirements related to dirt and moisture management in ventilation systems. Given the seriousness of the problems that can result, this Guide addresses the topic in more detail.

Indoor Contaminant Sources

Many IAQ problems are associated with indoor contaminant sources that are unusually strong or otherwise cannot be handled by typical or code-compliant levels of outdoor air ventilation. Many contaminants are released by normal building materials and furnishings, especially when new, and also by materials and substances brought into the building during operation. Unusual, unexpected, or atypically high contaminant emissions from indoor sources are associated with many IAQ problems, and this Guide speaks to the issues of material selection, cleaning, and other indoor sources.

Contaminants from Indoor Equipment and Activities

The wide range of occupancies and activities in commercial and institutional buildings involve many different types of equipment and activities. IAQ problems have resulted from improper equipment operation, inadequate exhaust ventilation, and poor choices of materials used in some of these activities. This Guide contains information on how to decrease the likelihood of such problems.

Inadequate Ventilation Rates

While building codes and standards have addressed outdoor air ventilation for decades, many buildings and spaces are poorly ventilated, which increases the likelihood of IAQ problems. There are a variety of reasons for inadequate ventilation rates, including lack of compliance with applicable codes and standards, installation or maintenance problems that lead to the design ventilation rate not being achieved in practice, or space use changes without an assessment of the need for updated ventilation rates. Also, system-level outdoor air intake rates may be adequate, but air distribution problems can lead to certain areas in the building being poorly ventilated. While ASHRAE Standard 62.1 covers the determination of design ventilation rates, additional guidance is provided in this Design Guide to help address these issues.

Ineffective Filtration and Air Cleaning

Filtration and air cleaning are effective means of controlling many indoor air pollutants, particularly those associated with poor outdoor air quality. Air filtration or air cleaning, therefore, can provide an important adjunct, and in some cases substitute, for outdoor air ventilation. This Guide provides a detailed treatment of filtration and air-cleaning alternatives that, when properly administered and maintained, can improve both IAQ and energy performance.

SCOPE: What Is and Isn't Covered in this Document?

As noted previously, this document addresses the design and construction of commercial and institutional buildings, including but not limited to office, retail, educational, lodging, and public assembly buildings, with no restrictions as to the building sizes or system types to be covered. These buildings are the same as those covered by ASHRAE Standard 62.1 and are the focus of the bulk of the recommendations in this Guide.

The scope of this Guide is necessarily limited due to both the resources available for its development and the practical need to bound the effort so that could be completed in a reasonable amount of time. Other IAQ issues and other spaces types still need to be considered, and ideally guidance will be provided for these through other efforts in the future.

Several space types and issues are not covered directly in terms of providing specific design guidance, but this Guide does attempt to address their interactions with the rest of the building and other systems. These include commercial kitchens, medical procedure rooms, natatoriums, cold buildings such as cold storage facilities and ice arenas, and laboratory, residential, and industrial spaces.

Multiple chemical sensitivity is not specifically addressed in this Guide. However, improved IAQ will benefit those who experience this condition. The National Institute of Building Sciences (NIBS) recently published a report for the U.S. Access Board that speaks directly to these concerns and contains detailed recommendations to accommodate individuals who experience these sensitivities. That report is available at http://ieq.nibs.org (NIBS 2006).

Extraordinary incidents, both natural (earthquakes, fire, floods) and intentional (terrorist attacks) are not addressed in this Guide. Information on design and planning for such events are available from a number of sources, including Federal Emergency Management Agency (FEMA, www.fema.gov) and National Fire Protection Association (NFPA, www.nfpa.org) documents.

This Guide does not address indoor smoking, as it is incompatible with good IAQ based on the health risks associated with environmental tobacco smoke and the inability of engineering controls to adequately control those risks (see the 2008 ASHRAE Position Document on Environmental Tobacco Smoke at www.ashrae.org/docLib/20090120_POS_ETS.pdf for more information and references) (ASHRAE 2008a).

How This Guide is Organized

Based on the known causes of the IAQ problems discussed in this introduction, this Guide is organized around eight Objectives for improving building IAQ:

Objective 1 – Manage the Design and Construction Process to Achieve Good IAQ
Objective 2 – Control Moisture in Building Assemblies
Objective 3 – Limit Entry of Outdoor Contaminants
Objective 4 – Control Moisture and Contaminants Related to Mechanical Systems
Objective 5 – Limit Contaminants from Indoor Sources
Objective 6 – Capture and Exhaust Contaminants from Building Equipment and Activities
Objective 7 – Reduce Contaminant Concentrations through Ventilation, Filtration, and Air Cleaning
Objective 8 – Apply More Advanced Ventilation Approaches

Within each Objective are several Strategies designed to help achieve that Objective.

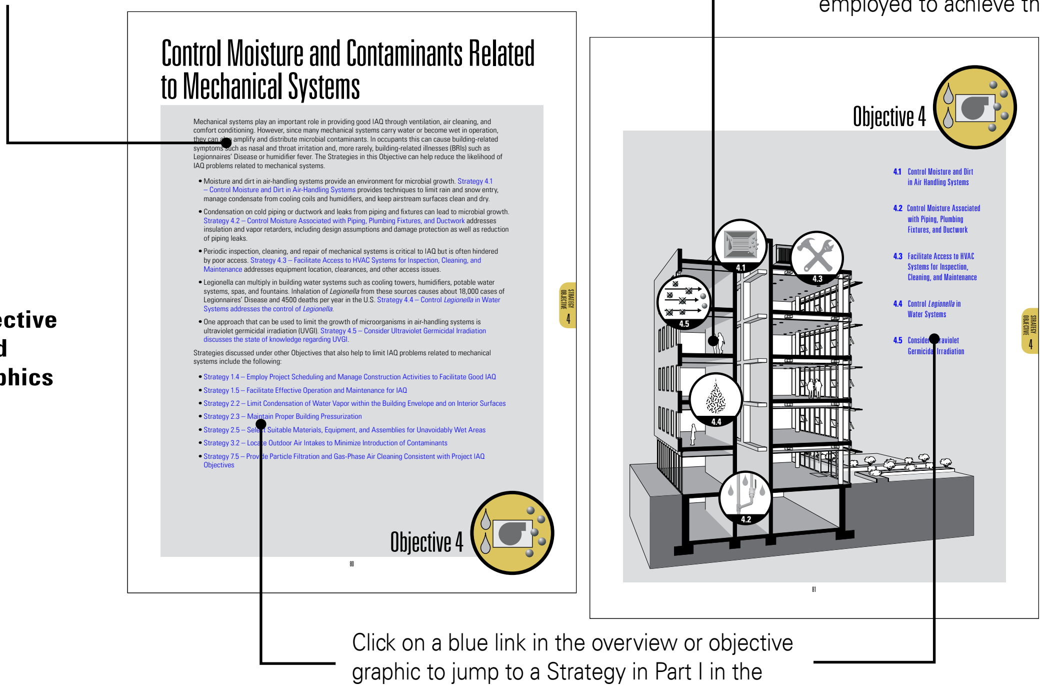
How to Use this Guide

Starting with the eight Objectives and the Strategies for each, the information in this Guide is broken into summary guidance (Part I) and detailed guidance (Part II). Both Part I and Part II are included in the electronic version of this Guide; only Part I is included in the printed version of this Guide.

Part I—Summary Guidance

Objectives and Strategies. An overview for each Objective in Part I provides an understanding of why the Objective is important for good IAQ. Each overview is followed by brief descriptions of the Strategies that can be employed to achieve that Objective. An objective graphic for each Objective provides a visual reference to the Strategies intended to achieve the Objective. In the electronic version of this Guide, the objective graphic contains blue interactive links to the summary guidance for each Strategy in Part I.

Using the Objective Overviews and Objective Graphics



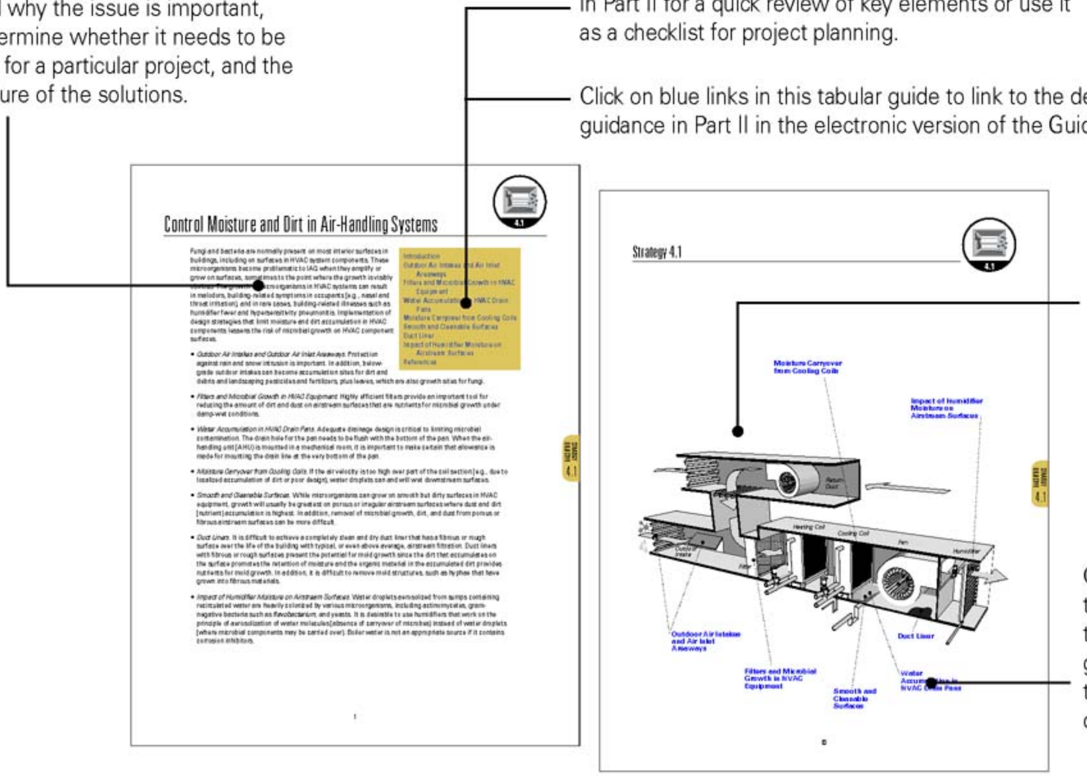
Read the overview for each Objective to understand why it is important for good IAQ.

Review the objective graphic for a visual summary of Strategies that can be employed to achieve this Objective.

Click on a blue link in the overview or objective graphic to jump to a Strategy in Part I in the electronic version of the Guide.

Each Strategy in Part I has an overview that describes why the Strategy is important, how to determine whether it needs to be considered in a particular project, and the general nature of the solutions. Each Strategy contains tabular and graphical guides to the detailed information in Part II that act as roadmaps and outline specific elements to be considered when implementing each Strategy. The tabular guides can also be used as checklists in project planning. The graphical guide provides a visual reference for each element of the Strategy. In the electronic version of this Guide, both the tabular and graphical guides in Part I contain blue interactive links that take the reader directly to the corresponding detailed information for each Strategy in Part II.

All sources cited in the Objectives and Strategies in Part I are listed in the single References section at the end of Part I.



Read the overview for each Strategy to understand why the issue is important, how to determine whether it needs to be considered for a particular project, and the general nature of the solutions.

Review the tabular guide to the detailed information in Part II for a quick review of key elements or use it as a checklist for project planning.

Click on blue links in this tabular guide to link to the detailed guidance in Part II in the electronic version of the Guide.

Review the graphical guide to the detailed information in Part II to help with visualization of the issue.

Click on blue links in the graphical guide to go to the detailed guidance in Part II in the electronic version of the Guide.

Control Moisture and Dirt in Air-Handling Systems

Strategy 4.1

Using the Strategy Overviews and Tabular and Graphical Guides

4.1

Poorly Designed and Maintained Drain Pan

The AHU shown in Figure 4.1-A was poorly designed and maintained. Access to the pan was achieved only after removal of more than ten fasteners, and the drain pan outlet was not flush with the bottom of the pan. The tan-yellow mass in the pan is a biofilm consisting of a gelatinous mass of fungi, bacteria, and protozoa. This plenum was opened for inspection because of concerns about building-related symptoms and building-related illnesses in the occupied space served by the AHU.

Figure 4.1- A Drain Pan that was Poorly Designed and Maintained
Photograph courtesy of Phil Morey.

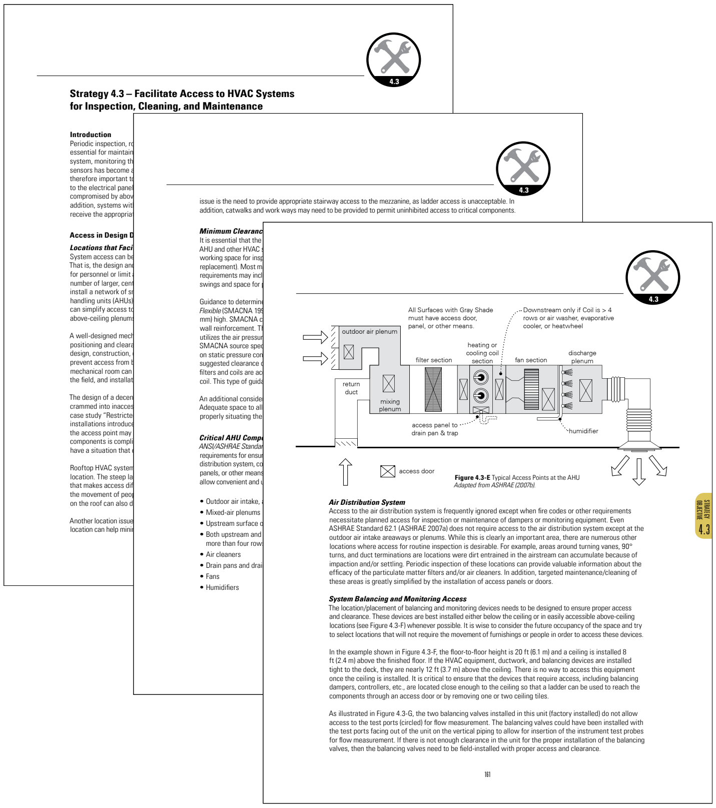
STRATEGY OBJECTIVE 4.1

Using the Case Studies

Check out the case studies for insights from other projects.

Case Studies. Case studies are included in the summary discussions of the Strategies in Part I. They provide insights into the IAQ problems and successes others have had in dealing with each topic.

Sidebars. There are sidebars interspersed throughout Part I to provide further explanation of code guidance or of terms or examples.



4.3

Strategy 4.3 – Facilitate Access to HVAC Systems for Inspection, Cleaning, and Maintenance

Introduction

4.3

issue is the need to provide appropriate stairway access to the mezzanine, as ladder access is unacceptable. In addition, catwalks and work ways may need to be provided to permit uninhibited access to critical components.

4.3

Figure 4.3-E Typical Access Points at the AHU
Adapted from ASHRAE (2007b).

Air Distribution System
Access to the air distribution system is frequently ignored except when fire codes or other requirements necessitate planned access for inspection or maintenance of dampers or monitoring equipment. Even ASHRAE Standard 62.1 (ASHRAE 2007a) does not require access to the air distribution system except at the outdoor air intake areaways or plenums. While this is clearly an important area, there are numerous other locations where access for routine inspection is desirable. For example, areas around turning vanes, 90° turns, and duct terminations are locations were dirt entrained in the airstream can accumulate because of impaction and/or settling. Periodic inspection of these locations can provide valuable information about the efficacy of the particulate matter filters and/or air cleaners. In addition, targeted maintenance/cleaning of these areas is greatly simplified by the installation of access panels or doors.

System Balancing and Monitoring Access
The location/placement of balancing and monitoring devices needs to be designed to ensure proper access and clearance. These devices are best installed either below the ceiling or in easily accessible above-ceiling locations (see Figure 4.3-F) whenever possible. It is wise to consider the future occupancy of the space and try to select locations that will not require the movement of furnishings or people in order to access these devices.

In the example shown in Figure 4.3-F, the floor-to-floor height is 20 ft (6.1 m) and a ceiling is installed 8 ft (2.4 m) above the finished floor. If the HVAC equipment, ductwork, and balancing devices are installed tight to the deck, they are nearly 12 ft (3.7 m) above the ceiling. There is no way to access this equipment once the ceiling is installed. It is critical to ensure that the devices that require access, including balancing dampers, controllers, etc., are located close enough to the ceiling so that a ladder can be used to reach the components through an access door or by removing one or two ceiling tiles.

As illustrated in Figure 4.3-G, the two balancing valves installed in this unit (factory installed) do not allow access to the test ports (circled) for flow measurement. The balancing valves could have been installed with the test ports facing out of the unit on the vertical piping to allow for insertion of the instrument test probes for flow measurement. If there is not enough clearance in the unit for the proper installation of the balancing valves, then the balancing valves need to be field-installed with proper access and clearance.

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STRATEGY OBJECTIVE 4.3

Using the Part II Detailed Guidance

Part II—Detailed Guidance
Whether you've already had projects with moisture problems and want guidance on how to avoid them, are doing your first brownfield project with the potential for vapor intrusion, have been asked to design a green building with low-emitting materials, want to do a better job of controlling outdoor pollutants in an urban location, or want to reduce the energy costs due to ventilation, the Part II detailed guidance will help.

The Part II detailed guidance provides information to use when working on a specific project, including detailed design, construction, and Cx recommendations; calculation procedures; additional case studies and sidebars; extensive references; and more. Part II is structured by Objectives and Strategies identical to the Part I summary guidance. Each Strategy in Part II concludes with its own references section so that the source information is close at hand when dealing with a particular issue.

Message to Building Owners

Indoor air quality (IAQ) is one of many issues that building owners and developers must address to provide buildings that meet their needs and the needs of the building occupants. While building occupants do sometimes complain about poor IAQ, it is not always on the top of their list of concerns. So why should you worry about IAQ when you have so much else to worry about?

- First, better IAQ leads to more productive and happier occupants. In commercial real estate, satisfied occupants are tied directly to return on investment and bottom-line economics, while in schools and institutional buildings they are tied to learning outcomes and organizational missions. While it is hard to put firm numbers on these benefits, there is increasing evidence of measurable productivity increases and reduced absentee rates in spaces with better IAQ.[1] In considering the economics of IAQ, it is important to note that the salaries of building occupants are the largest cost associated with building operation, dwarfing energy by a factor of 50 or even 100.

- Second, IAQ problems that get out of hand can be quite costly in terms of lost work time, lost use of buildings, expensive building or mechanical system repairs, legal costs, and bad publicity. While extreme IAQ problems are rare, they do occur, and the consequences can be dramatic. Less severe problems are more common and can erode occupant productivity, affect occupancy and/or rent levels, and lead to costs for smaller legal disputes or repairs.

This document presents a wealth of practical information on how to design and construct buildings with better IAQ without large financial investments or untested technologies. While the Guide is full of information on design and construction to control moisture, reduce contaminant entry, and provide effective ventilation, probably the most important message for the owner/developer is to put IAQ on the table at the very beginning of the development and design processes. Including IAQ in the earliest discussions with the architect and the rest of the project team will make it easier and more effective to provide good IAQ at lower or even no added cost.

By the time a building's schematic design is complete, many opportunities to achieve good IAQ have been foreclosed, which can easily result in unintended consequences or expensive and inadequate "force fitting" of solutions. When IAQ, energy efficiency, and other project objectives are considered together at the initial design phases, design elements for each objective can be mutually reinforcing rather than at odds with one another.

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[1] For a good overview of research quantifying IAQ health and productivity impacts, visit the IAQ Scientific Findings Resource Bank at http://eetd.lbl.gov/ied/sfrb/sfrb.html. The IAQ-SFRB is jointly administered by the U.S. Environmental Protection Agency and Lawrence Berkeley National Laboratories.

Appendix A

Environmental Monitoring

A wide variety of environmental monitoring methods are available to evaluate the quality and/or acceptability of the indoor environment. However, conducting such monitoring is not always needed or even advisable and is extremely challenging for a variety of reasons. This appendix is intended to provide design professionals with an understanding of these complexities in order to better appreciate these challenges. Factors to keep in mind when considering environmental monitoring include

- the selection of the contaminants to be measured;
- the selection of testing equipment and protocols;
- the location, timing, duration, and accuracy of the tests;
- the training, bias, and competency of the investigator;
- appropriate controls or reference values to which the results can be compared; and ultimately
- the purpose of the evaluation.

Misunderstanding of these factors occurs even by experienced professionals, resulting in the monitoring contributing little useful information—or worse, leading to erroneous conclusions and ill-advised actions.

Key Points Regarding Environmental Monitoring of IAQ

- Never measure anything unless the purpose of environmental monitoring has been clearly established and you know what you are going to do with the results. The specific target pollutants that will be measured and the reference concentrations that will be used for interpreting the results need to be defined before the monitoring and must fulfill the intended purpose for the monitoring effort.
- Short-term, localized measurements represent the conditions only at the place and time the sample is collected and cannot be assumed to represent the building more generally. Monitoring needs to cover a range of times and building operational and use conditions to enable a meaningful characterization of IAQ.
- Airborne concentrations of indoor-source pollutants are strongly dependent on concurrent outdoor air ventilation rates. Only by simultaneously measuring ventilation can concentration results be interpreted correctly, particularly variations over time.
- While it would be ideal to have a simple and easily used metric to quickly and inexpensively establish the acceptability of the IAQ, no such metric exists due to the wide range of pollutants in indoor air and the lack of knowledge regarding human responses to most pollutants and pollutant mixtures.

Indoor Air Characteristics

Many of the challenges associated with indoor air sampling are due to the characteristics of indoor air pollution. This section briefly describes some of these characteristics.

Indoor Air is a Complex Mixture

The chemicals that are commonly present in indoor air generally include scores or even hundreds of compounds at widely varying concentrations from parts per trillion to parts per thousands. The two main constituents of air at sea level are nitrogen (about 78%) and oxygen (about 21%), along with 0.038% carbon dioxide (CO_2), trace amounts of other gases, and a variable amount (around 1%) of water vapor. The compounds present in air that are of interest to IAQ include chemicals, particles, and microbial components, as shown in Table A-1.

Appendix A

Table A-1 Broad Categories of Indoor Air Pollutants

Constituent	Detailed Categories
Chemicals*	Organic • Volatile • Semi-volatile Inorganic
Particles—defined by size	Total suspended particles <100 µm mass median aerodynamic diameter Respirable suspended particles <10 µm mass median aerodynamic diameter Fine particles <2.5 µm mass median aerodynamic diameter
Biological aerosols (Bioaerosols)**	Fungi, mold Bacteria Viruses Pollen

* Chemicals may be in the solid (condensed) phase or the gaseous phase. Gases can be molecules in the air or on surfaces, including the surfaces of airborne or settled dust and other particles.

** Bioaerosols may be viable or nonviable.

Most Indoor Air Pollutants are Present at Very Low Concentrations

Even chemicals that are commonly considered to be important indoor air pollutants, such as formaldehyde and carbon monoxide, are not usually found at concentrations greater than 10 ppm or 0.0001%. Most common volatile organic compounds (VOCs) found indoors are typically at levels less than 10 ppb or 0.000001%. Because of these low concentrations, very sensitive measurement methods are required to detect these pollutants. Traditional "industrial hygiene" methods, intended for industrial workplaces, where pollutants are typically at much higher concentrations, are not generally appropriate for nonoccupational spaces such as offices, schools, and residences.

Pollutant Concentrations Vary Greatly Within and Between Buildings

An individual building's air quality can vary greatly from one space to another and from one time point to another both in the pollutants present and in their concentrations. These variations can be as large as 1000- to 10,000-fold. Concentration variations occur due to differences in pollutant emission rates in different building locations as well as differences in air distribution. The contaminants found and their concentrations can also vary greatly between buildings. There are substances that will be found only rarely in any building and others that will be found commonly but not in all buildings.

Humans Can Sense Chemicals that Cannot be Detected by Environmental Monitoring

There are pollutants and odors that can be detected by humans or that will affect human health that cannot be detected by any but the most sensitive air sampling methods. There are also short-lived, reactive pollutants that may affect occupants but escape detection by available measurement methods. It is therefore common for monitoring efforts to conclude that there are no IAQ problems despite the fact that occupants are experiencing symptoms.

Measurement Cautions

Based on the challenges described in the previous paragraphs and many years of experience in studying building IAQ, the following guidance is presented to help practitioners understand if, when, and how to conduct IAQ measurements.

Use Environmental Monitoring Sparingly

Most experts agree that when investigating IAQ problems, environmental monitoring should only be employed late in the process. Interviews, building walk-throughs, and establishing the history of the problem(s) are the first steps. If necessary, follow-up steps include review and evaluation of building plans and specifications, review of operational logs, and establishment of initial hypotheses regarding the potential causes of the problem. The hypotheses can point toward specific pollutants that could or should be measured. Finally, monitoring of ventilation system performance, outdoor air delivery rates, thermal conditions, and a set of target pollutants may be warranted.

Carefully Consider Where Samples are Taken

Given the variation in concentrations typically seen in buildings, it is important to be careful in selecting air sample locations. Some factors to consider include building layout in terms of activities and occupancy patterns, HVAC system zoning, and locations of complaint and non-complaint areas.

Indoor air sampling presents challenges in terms of obtaining samples that represent occupant exposures. Sample collection too close to the occupants will be influenced by the occupants' activities and metabolic products. On the other hand, sample collection too far from the occupants will not capture the occupants' actual pollutant exposures, particularly those that are dominated by the occupants' own activities.

Consider Source Strength and Ventilation when Interpreting Results

As noted previously, indoor concentrations are strongly dependent on outdoor air ventilation rates and source strengths. This relationship is defined by the following equation, which describes how the indoor concentration is impacted by ventilation and source strength at steady-state and zero outdoor concentration:

$$C = EF/Q$$

where

C = pollutant concentration
EF = pollutant source strength (amount of pollutant emitted per unit time, in some cases also per unit of area of the source)
Q = outdoor air ventilation rate of the space

Figure A-1 contains plots of this relationship for three different source strengths, demonstrating the importance of source strength and ventilation in determining concentrations. While low ventilation rates can lead to very high concentrations, note that once the ventilation is high enough to reduce the concentration, further increases in ventilation have little impact on absolute concentration. On the other hand, reducing the source strength can achieve significant concentration decreases at the lower end of typical building ventilation rates.

Only by simultaneously measuring ventilation can concentration results be interpreted, particularly variations over time in these concentrations. If the monitoring effort is to be used to calculate source strengths, then ventilation rate measurements are essential.

Time Period of Monitoring

For long-term sampling—hours to days—results are usually given in time-weighted averages that represent time-integrated (average) exposure over the total duration of the monitoring. These results are useful for assessing average or cumulative exposure. However, they fail to capture variations in concentrations or source strengths during the time covered.

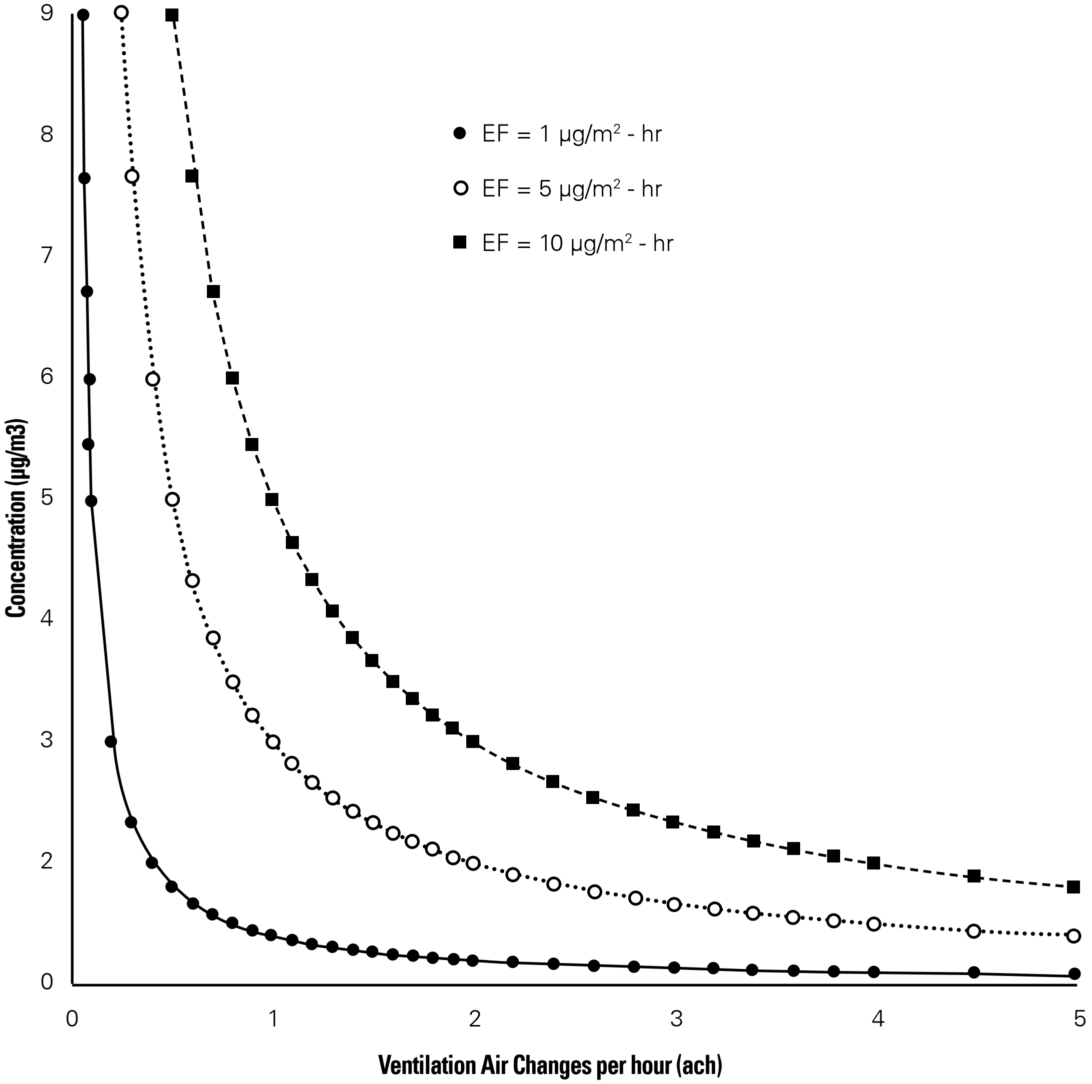

Figure A-1 Relationship of Source Strength, Ventilation, and Pollutant Concentration

Short-term samples such as "grab samples" collect air over a very short period of time and can capture a peak exposure if the time the sample was taken is coincident with peak concentrations. However, since source strengths and ventilation vary over time and space, a grab sample may not provide an indication of average, long-term concentration.

Sampling Methods Determine and Limit What can be Measured

Sampling and analysis can only detect what the method is capable of detecting. Most methods are relatively limited and have interferences and biases that must be considered when interpreting results. For example, the results of all VOC samplings are dependent on the methods used, and the results obtained with different methods should not be compared without abundant caution. Even the very best sampling technology is incapable of detecting all organic compounds of interest. Noteworthy for their usual absence from indoor air sampling and their potential health impact are the semi-volatile organic compounds (SVOCs) including pesticides, plasticizers, and fire retardants.

Appendix A

Some sampling methods that are more general than specific in terms of what they measure can be useful for comparisons where the measurement objective is to determine whether conditions in the building have changed. The most common general methods are the measurement of total volatile organic compounds (TVOCs) and the measurement of total colony-forming units, which are both the sum of those compounds or organisms, respectively, that the method used is capable of detecting. However, no methods are capable of collecting all TVOCs or colony-forming units. Furthermore, the lack of information about the species of organic compounds or microorganisms prevents the results from being useful for understanding potential health or comfort implications of exposure and can even result in erroneous interpretations and inappropriate actions. Only by identification and quantification of specific compounds or organisms can there be any health or comfort assessment of the monitoring results.

Particle measurements are also commonly reported as the sum of all sampled particles or of those in a particular size range, e.g., total suspended particles, particles less than 10 μm in diameter (PM10), and particles less than 2.5 μm in diameter (PM2.5). Even within a particular size range, particles can be widely varying in important, health-effects-relevant characteristics including their chemical compositions, their sizes and shapes, and the chemicals that may be adsorbed to their surfaces.

Pollutants with Outdoor Sources

Some indoor pollutants have primarily or only outdoor sources, some have only or predominantly indoor sources, and most have both indoor and outdoor sources. For those that have both indoor and outdoor sources, simultaneous measurements need to be made both indoors and outdoors in order to understand the results.

Knowing What to Do with Results

Monitoring should never be done unless there is knowledge about what will be done with the results. This presents challenges for indoor environmental monitoring because of the lack of sufficient information about the health impacts of most indoor pollutants. There is an important deficiency in terms of standards and guidelines regarding safe or acceptable concentrations of indoor air pollutants. Several available guidelines and standards are documented in Appendix B of *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007).

An alternative to comparing concentrations to health and safety regulations, guidelines, or standards is to compare them to what is commonly found in similar buildings. Two databases of indoor pollutant measurements include the U.S. Environmental Protection Agency (EPA) BASE study (EPA 2006) and Hodgson and Levin (2003).

Measurement of Specific Pollutants

Standardized methods for measuring indoor air pollutants are limited in the pollutants covered, but many are available from several sources, such as the following.

- ASTM Subcommittee D22.05 on Indoor Air Quality— www.astm.org/COMMIT/SUBCOMMIT/D2205.htm
- *ASTM Standards on Indoor Air Quality*, Third Ed.—www.astm.org/BOOKSTORE/COMPS/179.htm
- National Institute of Occupational Safety and Health (NIOSH)— www.cdc.gov/niosh
- EPA Indoor Air Quality Publications and Resources—www.epa.gov/iaq/pubs/
- *Recognition, Evaluation and Control of Indoor Mold*, American Industrial Hygiene Association (AIHA)— www.aiha.org
- American Conference of Governmental Industrial Hygienists (ACGIH)—www.acgih.org

Appendix A

Carbon Dioxide—The Most Measured Gas in Indoor Air

Carbon dioxide (CO_2) is not a pollutant per se when measured at typical indoor concentrations. It is usually used as a surrogate for the adequacy of ventilation in relation to human occupancy. While the relationship between building ventilation rates and indoor CO_2 is well understood (Persily 1997; ASTM 2007a; Mudarri 1997), measurements of CO_2 in indoor air are commonly misapplied and misinterpreted. These references need to be consulted before conducting such measurements.

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