Indoor Air Quality Guide

Best Practices for Design, Construction, and Commissioning

Developed by:

American Society of Heating, Refrigerating and Air-Conditioning Engineers
The American Institute of Architects
Building Owners and Managers Association International
Sheet Metal and Air Conditioning Contractors' National Association
U.S. Environmental Protection Agency
U.S. Green Building Council

Indoor Air Quality Guide

This is an ASHRAE Design Guide. Design Guides are developed under ASHRAE's Special Publication procedures and are not consensus documents. This document is an application manual that provides voluntary recommendations for consideration in achieving improved indoor air quality. This publication was developed under the auspices of ASHRAE Special Project 200.

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The PC's efforts were guided by a steering committee (SC) made up of members from all of the cooperating organizations: American Institute of Architects (AIA), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Building Owners and Managers Association (BOMA) International, U.S. Environmental Protection Agency (EPA), Sheet Metal and Air-Conditioning Contractors' National Association (SMACNA), and U.S. Green Building Council (USGBC). The SC assembled an expert team of authors and defined a project scope that kept the PC's task manageable and focused. The representatives from these organizations brought a collegial and constructive spirit to the task of setting policy for the Guide.

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Martha J. Hewett
Chair, Special Project 200

Andrew Persily
Chair, IAQ Guide Steering Committee

October 2009

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

Foreword: Why this Guide Was Written

Buildings are expected to fulfill a variety of requirements related to their function, applicable codes and standards, and environmental and community impacts. Among these requirements, indoor air quality (IAQ) is typically addressed through compliance with only minimum code requirements, which are based on industry consensus standards such as *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007a). Yet IAQ affects occupant health, comfort, and productivity, and in some cases even building usability, all of which can have significant economic impacts for building owners and occupants.

While building owners and building professionals may recognize the importance of IAQ, they often do not appreciate how routine design and construction decisions can result in IAQ problems. In addition, they may assume that achieving a high level of IAQ is associated with premium costs and novel or even risky technical solutions. In other cases, they may employ individual measures thought to provide good IAQ, such as increased outdoor air ventilation rates or specification of lower emitting materials, without a sound understanding of the project-specific impacts of these measures or a systematic assessment of IAQ priorities.

Information exists to achieve good IAQ without incurring excessive costs or employing practices that are beyond the current capabilities of the building professions and trades. This Guide, resulting from a collaborative effort of six leading organizations in the building community[1] and written by a committee of some of the most experienced individuals in the field of IAQ, presents best practices for design, construction, and commissioning (Cx) that have proven successful in other building projects. It provides information and tools architects and design engineers can use to achieve an IAQ-sensitive building that integrates IAQ into the design and construction process along with other design goals, budget constraints, and functional requirements. While some key issues in the field of IAQ remain unresolved, this document presents the best available information to allow practitioners to make informed decisions for their building projects.

The Guide addresses the commercial and institutional buildings covered by ASHRAE Standard 62.1 and was written with the following audiences in mind:

- Architects, design engineers, and construction contractors who can apply the recommended practices during design and construction processes.
- Building owners, developers, and other decision makers who can use this Guide to direct the work of these professionals.
- Commissioning authorities (CxAs) who can ensure that design elements, construction schedules, construction observation, and functional testing are appropriate to meet IAQ-related goals and requirements.
- Product and material specifiers for both new and existing buildings who can choose materials and products with lower IAQ impact.
- Organizations that provide sustainable building rating programs and/or that conduct training for these programs.
- Facility managers and building operators who may use the Guide to understand the IAQ implications of existing systems and operations and maintenance practices.

[1] The six organizations contributing to the creation of this Guide are American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); American Institute of Architects (AIA); Building Owners and Managers Association (BOMA) International; U.S. Environmental Protection Agency (EPA); Sheet Metal and Air Conditioning Contractors' National Association (SMACNA); and U.S. Green Building Council (USGBC).

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.

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.

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.

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.

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

[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.

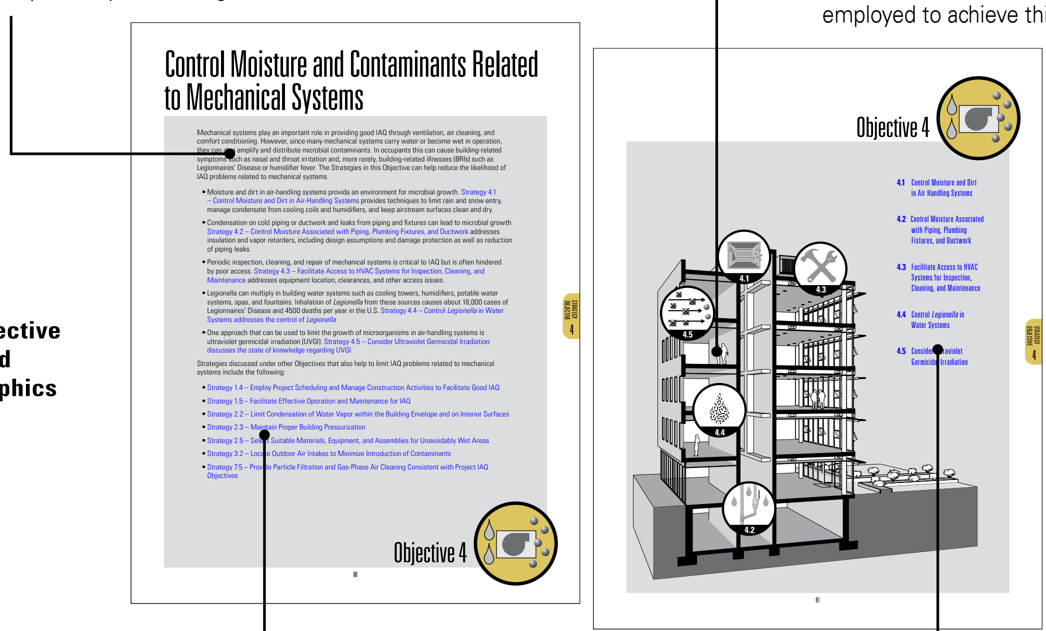
Part I—Summary Guidance

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.

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.

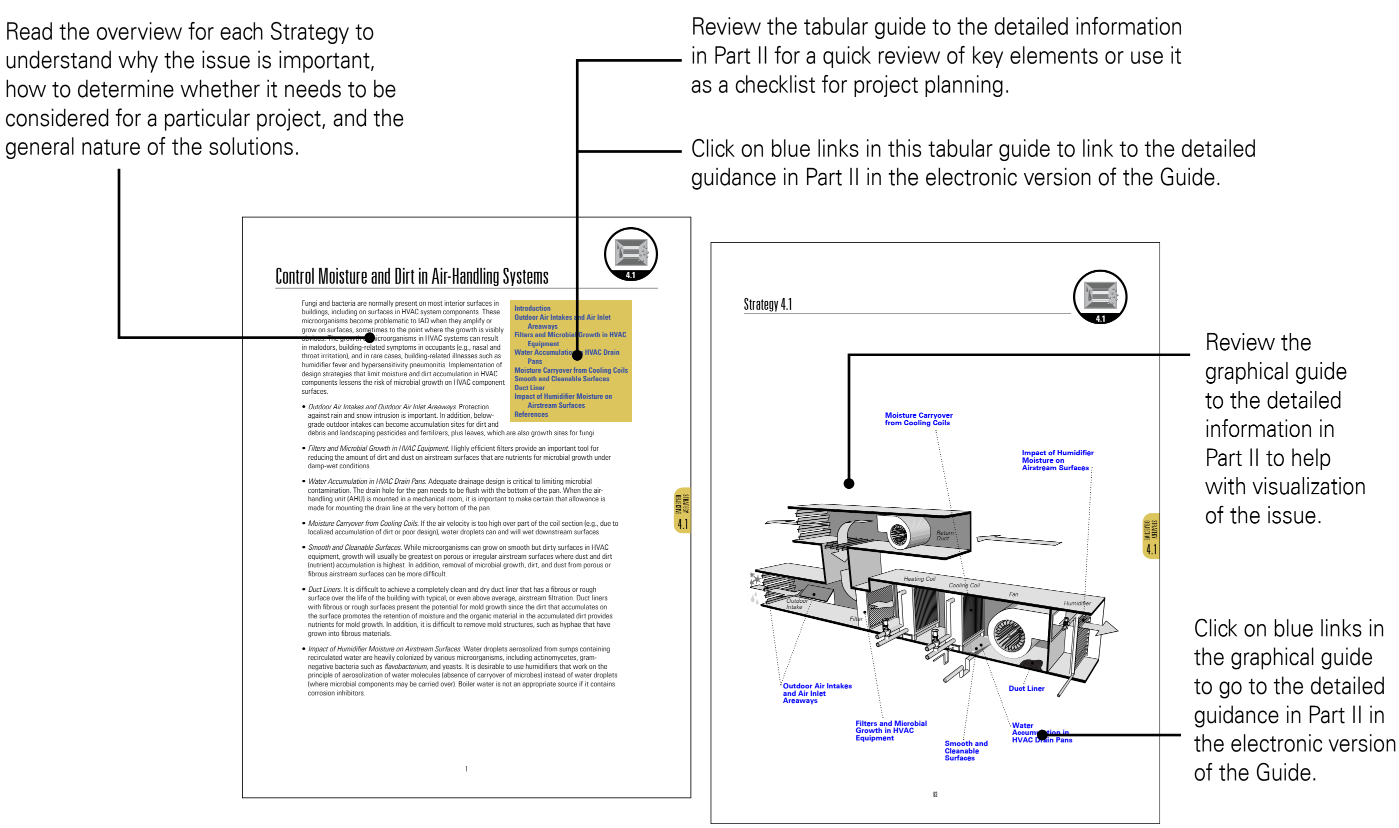
Using the Objective Overviews and Objective Graphics



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.



Using the Strategy Overviews and Tabular and Graphical Guides


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.

Check out the case studies for insights from other projects.

Using the Case Studies

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.

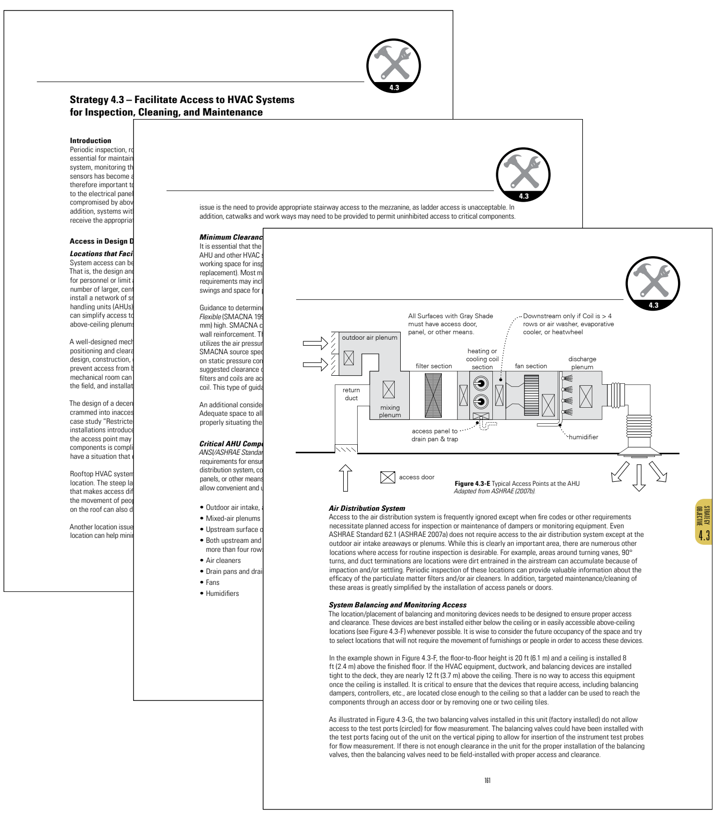

Strategy 4.3 – Facilitate Access to HVAC Systems for Inspection, Cleaning, and Maintenance

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

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.

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:

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.

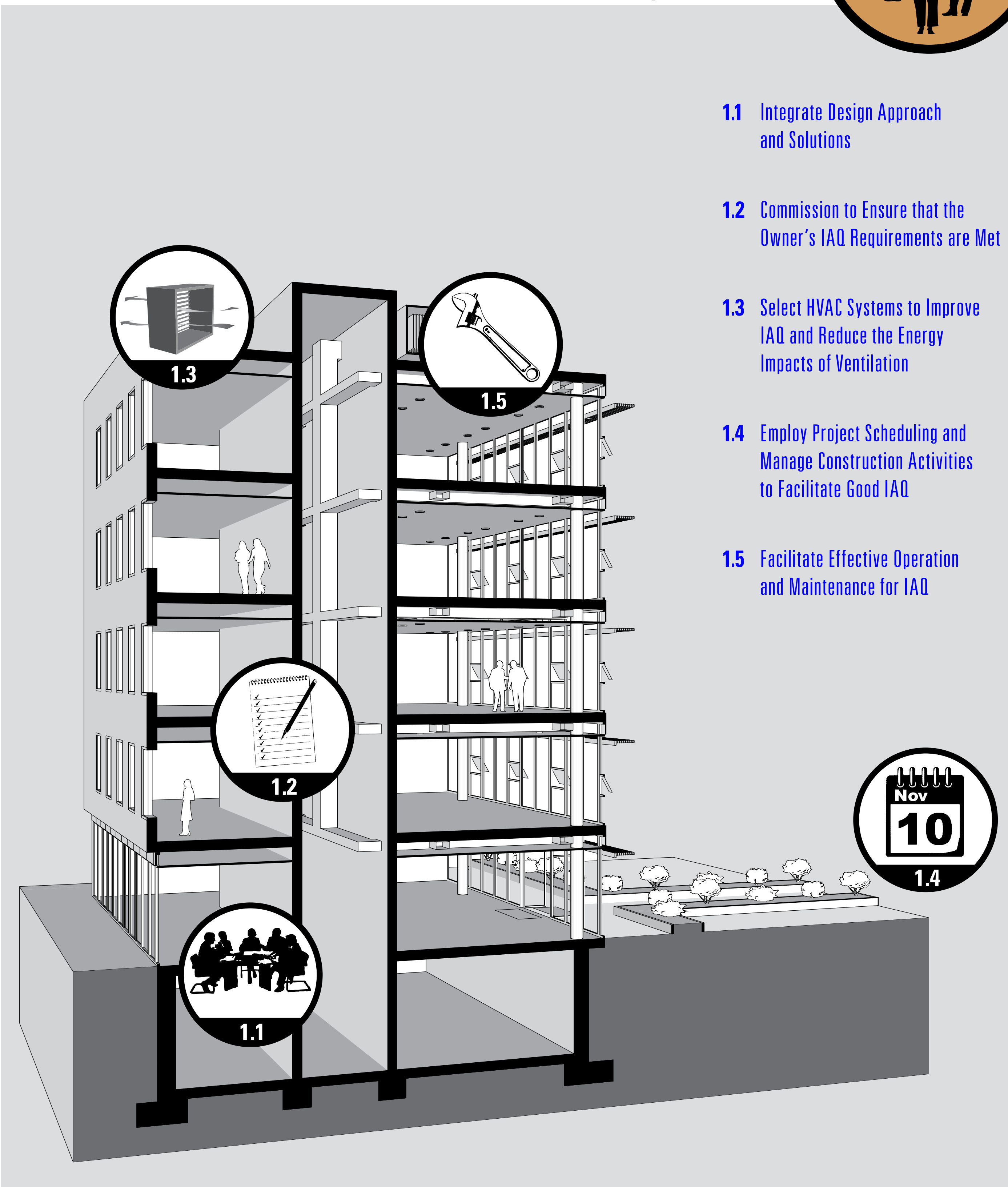
Manage the Design and Construction Process to Achieve Good IAQ

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.

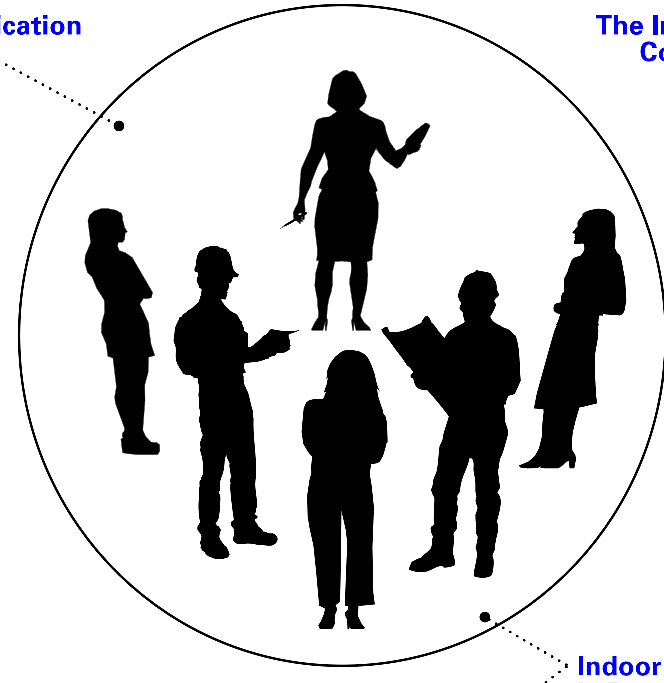
In typical design processes, lacking such a collaborative effort to produce an overall design concept, the building's basic concept ends up reflecting only some of the important considerations. Then the remainder of the design process looks more like an effort to retrofit the design concept to accommodate 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.

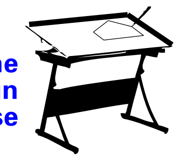
Strategy 1.1

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

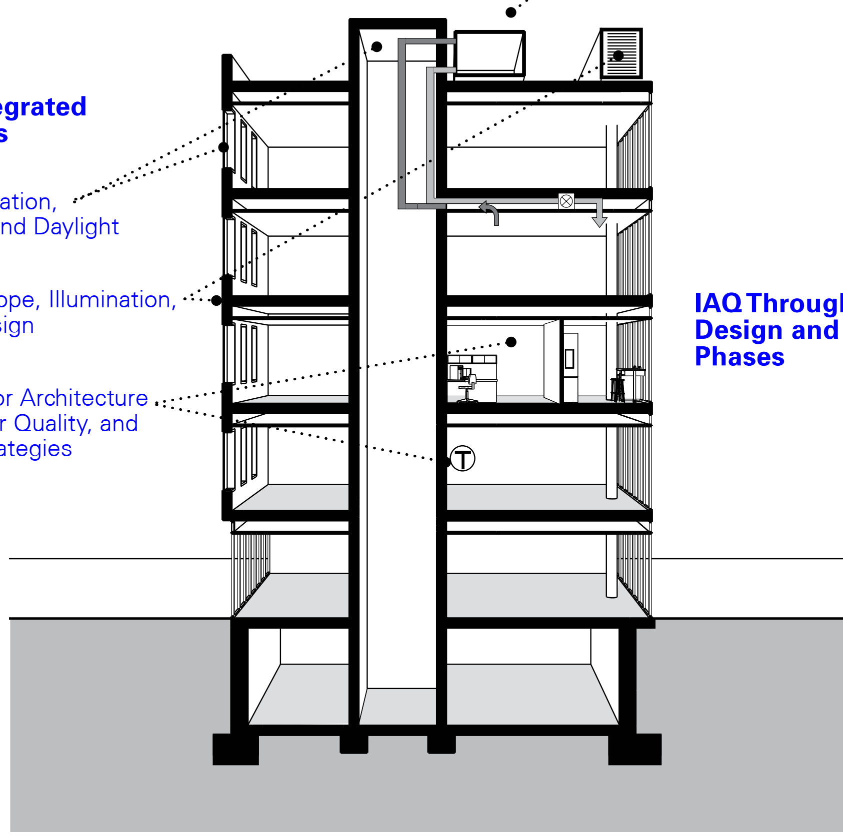
Indoor Environmental Quality is Best Served by Integrated Design

Examples of Integrated Design Solutions

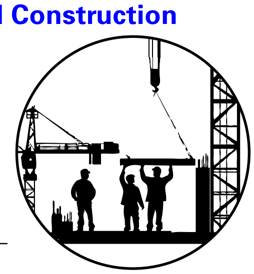
Use of Hybrid Ventilation, Occupant Control, and Daylight

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

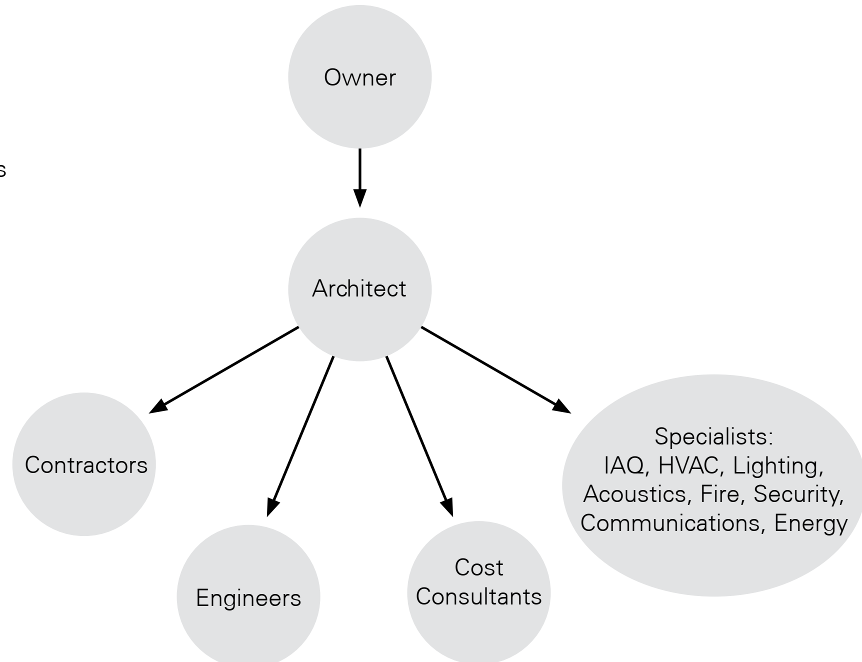


Figure 1.1-A Traditional Design Team

Integrated

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

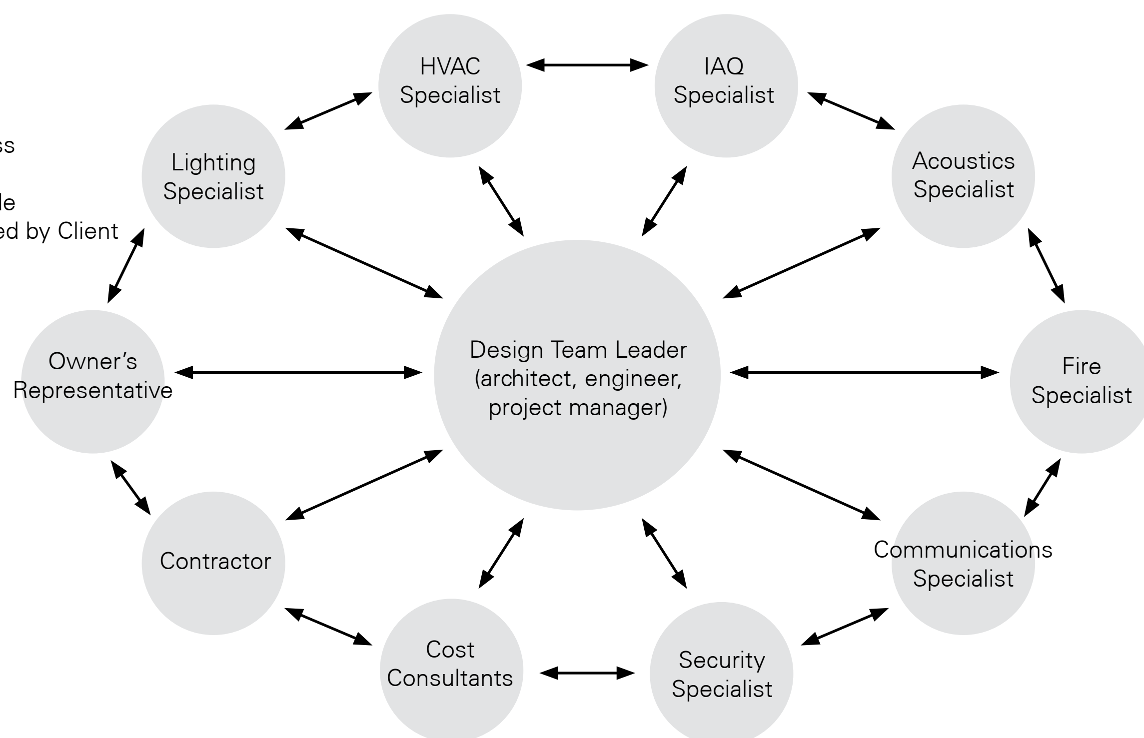


Figure 1.1-B Integrated Design Team

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

1.2

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.

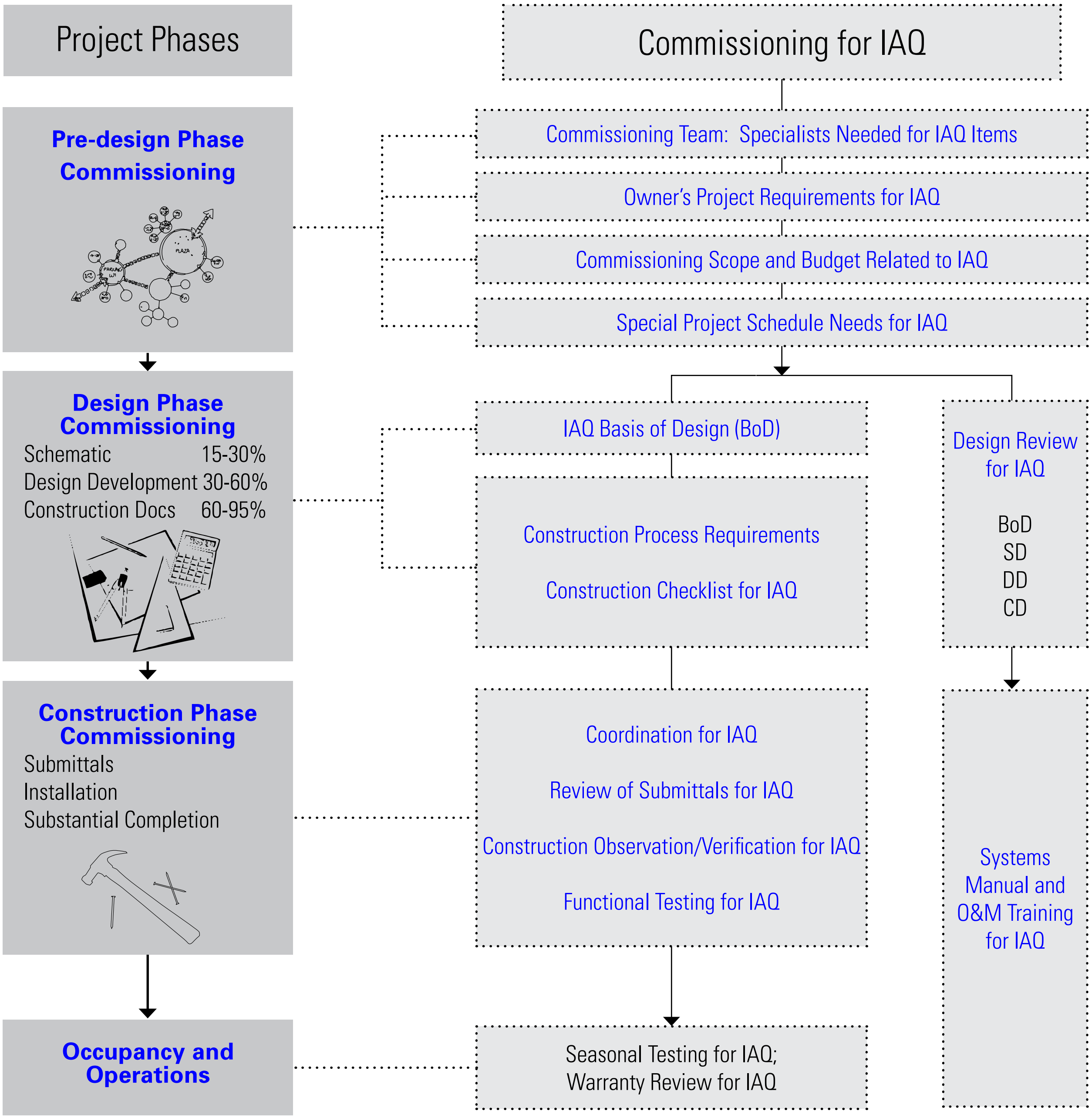
Commissioning the Design
It is much easier and cheaper to correct deficiencies on paper during design than in the finished building after construction.

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
Commissioning for IAQ
Pre-design Phase Commissioning
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
Design Phase Commissioning
Schematic 15-30%
Design Development 30-60%
Construction Docs 60-95%
IAQ Basis of Design (BoD)
Construction Process Requirements
Construction Checklist for IAQ
Design Review for IAQ
BoD
SD
DD
CD
Construction Phase Commissioning
Submittals
Installation
Substantial Completion
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
Occupancy and Operations
Seasonal Testing for IAQ; Warranty Review for IAQ

Strategy 1.2

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

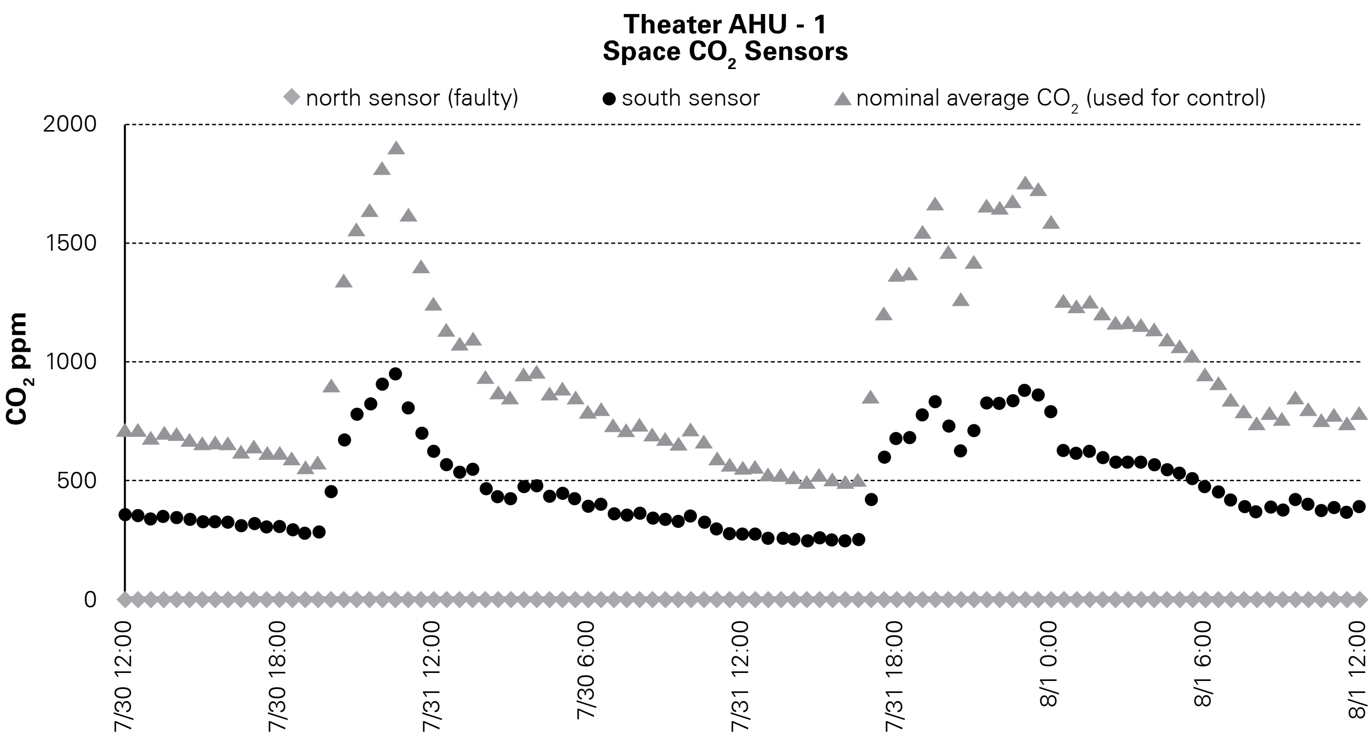


Figure 1.2-A Space CO_2 Sensor Graph

Strategy 1.2

900 ppm (1600 mg/m³). The programming as implemented actually reset the minimum OA between 2000 cfm (940 L/s) at 1000 ppm (1800 mg/m³) CO_2 and 3000 cfm (1400 L/s) at 1500 ppm (2700 mg/m³) 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/m³). 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/m³), the average value passed to the control loop was (1900 + 4)/2 = 952 ppm [(3400 + 7)/2 = 1703 mg/m³], 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.

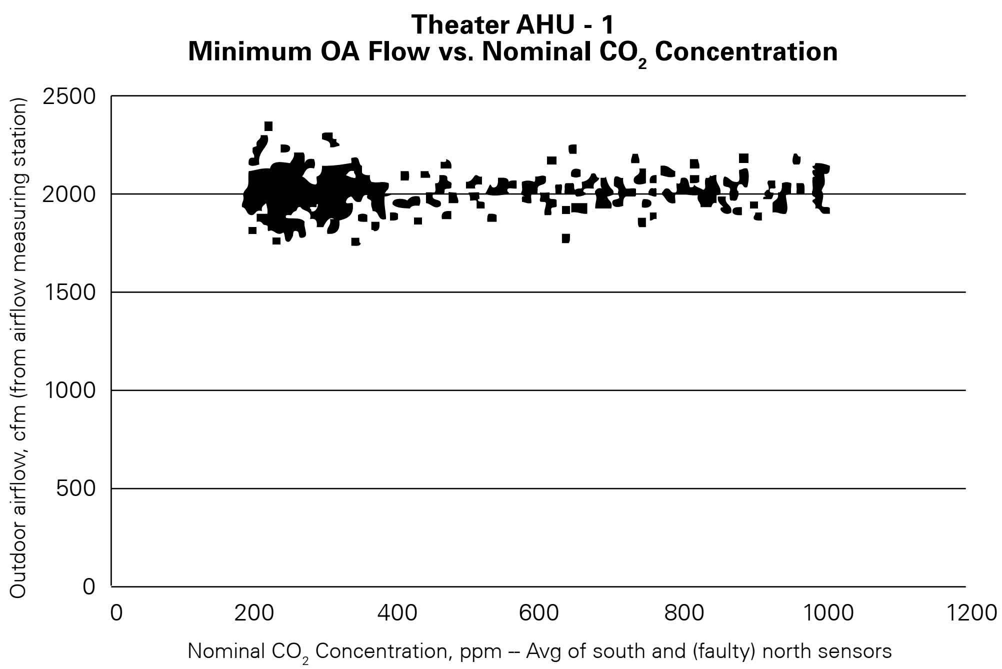


Figure 1.2-B Minimum OA Flow vs Nominal CO_2 Concentration

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

Prior to the invention of electrical power and mechanical cooling, buildings were designed to take full advantage of the prevailing natural forces such as wind, outdoor temperature, sunlight, and thermal mass to ventilate and cool occupied spaces. After the invention of mechanical air conditioning, buildings could be designed with little concern for the building configuration, solar gains, or outdoor conditions. Today, due to concerns about global warming, there is a worldwide movement toward buildings that employ sustainable strategies. Building owners, architects, and engineers are designing buildings that are more sympathetic with their surrounding environment and using natural features and forces to reduce a building's "environmental footprint." This emerging trend is forcing designers to look at energy in a different way, giving consideration to the quantity of energy used in buildings and also the quality of the energy used. An example of this type of design is using passive/natural or low-grade energy/waste/renewable energy in lieu of fossil fuel/electrical power (Willmert 2001).

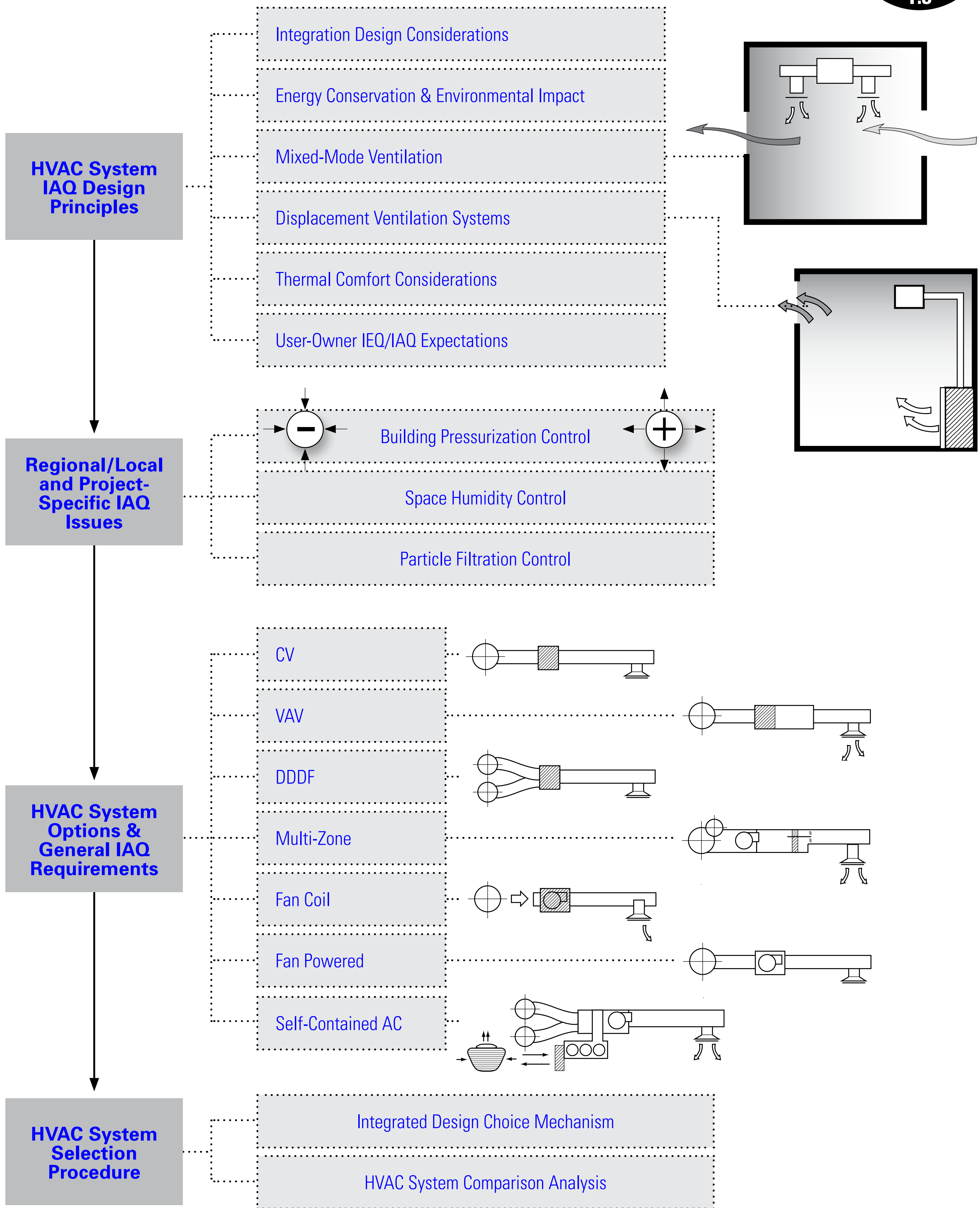
The primary difference between present-day conventional design and this emerging approach is in the design process. Designing a building with a reduced environmental footprint requires a fully integrated design process in which all members of the design team work in an integrated framework, thinking 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. A key example of this is the use of displacement ventilation. If displacement ventilation is going to be used effectively in a building, the design team must factor solar gains and thermal envelope loads into the discussion about the ventilation strategy.

Despite these trends, HVAC system designers are still often required, for numerous reasons, to use conventional HVAC systems such as variable-air-volume (VAV) with reheat, constant volume (CV) with reheat, fan-coil (FC), or packaged HVAC equipment to condition institutional, commercial, and residential building air. Clearly these conventional systems have their place, and those designers using them can apply low-energy and improved IAQ principles within their design, effectively moving away from inefficient non-integrated design practice.

It is well understood that in mechanically ventilated buildings, HVAC systems can have a significant effect on IAQ, energy use, and occupants' well-being. Studies have shown that poor IAQ can be directly linked to insufficient ventilation rates and inappropriate HVAC system design or operation (Seppanen and Fisk 2004). Also, Mendell and Heath (2005) found evidence that certain conditions commonly found in U.S. schools, such as low ventilation rates, have adverse effects on the health and the academic performance of many of the more than 50 million U.S. schoolchildren.

In addition to the measurable IEQ factors such as temperature, humidity, CO_2, and air speed, the HVAC system design should also consider human factors such as personal control over the environment. It has been suggested in a number of studies (e.g., Wyon [1996]) that ventilated buildings with enhanced occupant control of the indoor environment have lower reported rates of sick building syndrome symptoms.

Strategy 1.3


HVAC System IAQ Design Principles
Integration Design Considerations
Energy Conservation & Environmental Impact
Mixed-Mode Ventilation
Displacement Ventilation Systems
Thermal Comfort Considerations
User-Owner IEQ/IAQ Expectations
Regional/Local and Project-Specific IAQ Issues
Building Pressurization Control
Space Humidity Control
Particle Filtration Control
HVAC System Options & General IAQ Requirements
CV
VAV
DDDF
Multi-Zone
Fan Coil
Fan Powered
Self-Contained AC
HVAC System Selection Procedure
Integrated Design Choice Mechanism
HVAC System Comparison Analysis

Gulf Islands National Park Reserve Operations Centre —Sidney, British Columbia, Canada

Figure 1.3-A GINPR Operations Centre
Photograph copyright Stantec Consulting Ltd. Architect McFarland Maceau Architects Ltd.

Figure 1.3-B Interior View, GINPR Operations Centre
Photograph copyright Stantec Consulting Ltd. Architect McFarland Maceau Architects Ltd.

The Gulf Islands National Park Reserve (GINPR) Operations Centre (Figures 1.3-A and 1.3-B), designed by McFarland Marceau Architects Ltd., project architects, and Stantec Consulting Ltd., project mechanical engineers, is 11300 ft2 (1050 m^2) and the first project in Canada to achieve the Leadership in Energy and Environmental Design (LEED) Platinum certification. The redevelopment is designed to accommodate Parks Canada and other associated user group vessels. The GINPR operations building consists of office space, a small laboratory, a library, lockers, and two sleeping quarters. The project utilizes a mixed-mode ventilation system for energy efficiency and IAQ. An ocean-based heat pump system provides heating and domestic hot water, and a rainwater collection system is used for marine wash-water and sewage conveyance. For more information on the project's energy performance and sustainability features, visit www.pc.gc.ca/pn-np/bc/gulf/ne/ne5_e.asp.

STRATEGY OBJECTIVE 1.3

Philip Merrill Environmental Center—Annapolis, Maryland

Figure 1.3-C Philip Merrill Environmental Center
Photograph courtesy of NREL/DOE. Photographer Rob Williamson.

As the first Leadership in Energy and Environmental Design (LEED) Platinum building in the United States, the Philip Merrill Environmental Center (Figure 1.3-C) is at the leading edge of sustainability practices. The building was designed by the architect Smith Group and was one of the 2007 winners of the Livable Buildings Awards from the Center for the Built Environment (CBE 2007).

The building, which is 32,000 ft^2 (2973 m^2), is described as a combination of space-age technology and age-old techniques. It has a large number of enhanced IEQ features, including high levels of occupant control, abundant natural lighting, and low-VOC-emission material usage.

The occupants of the Philip Merrill Environmental Center were surveyed and interviewed about the IEQ and its effect on psychosocial and productivity-related factors. Key positive findings of this survey showed that occupants were highly satisfied with the building as a whole and that intangibles such as pride in the building and aesthetics contributed to high levels of morale, well-being, and a sense of belonging at work. Acoustical conditions were the most negatively rated, primarily due to distractions from people talking and loss of speech privacy associated with the highly open environment.

Figure 1.3-D shows an overall summary of survey responses regarding the Philip Merrill Environmental Center. The mean score on all of these categories was at or above 2.0 on a seven-point scale ranging from –3 to +3.

For more information on the building details of the Philip Merrill Environmental Center, visit www.archiplanet.org/wiki/Philip_Merrill_Environmental_Center.

Source: Heerwagen and Zagrreus (2005).

Figure 1.3-D Survey Summary
Image copyright Judith Heerwagon. Publisher: Center for the Built Environment, UC Berkley.

Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ

Nov 10 1.4

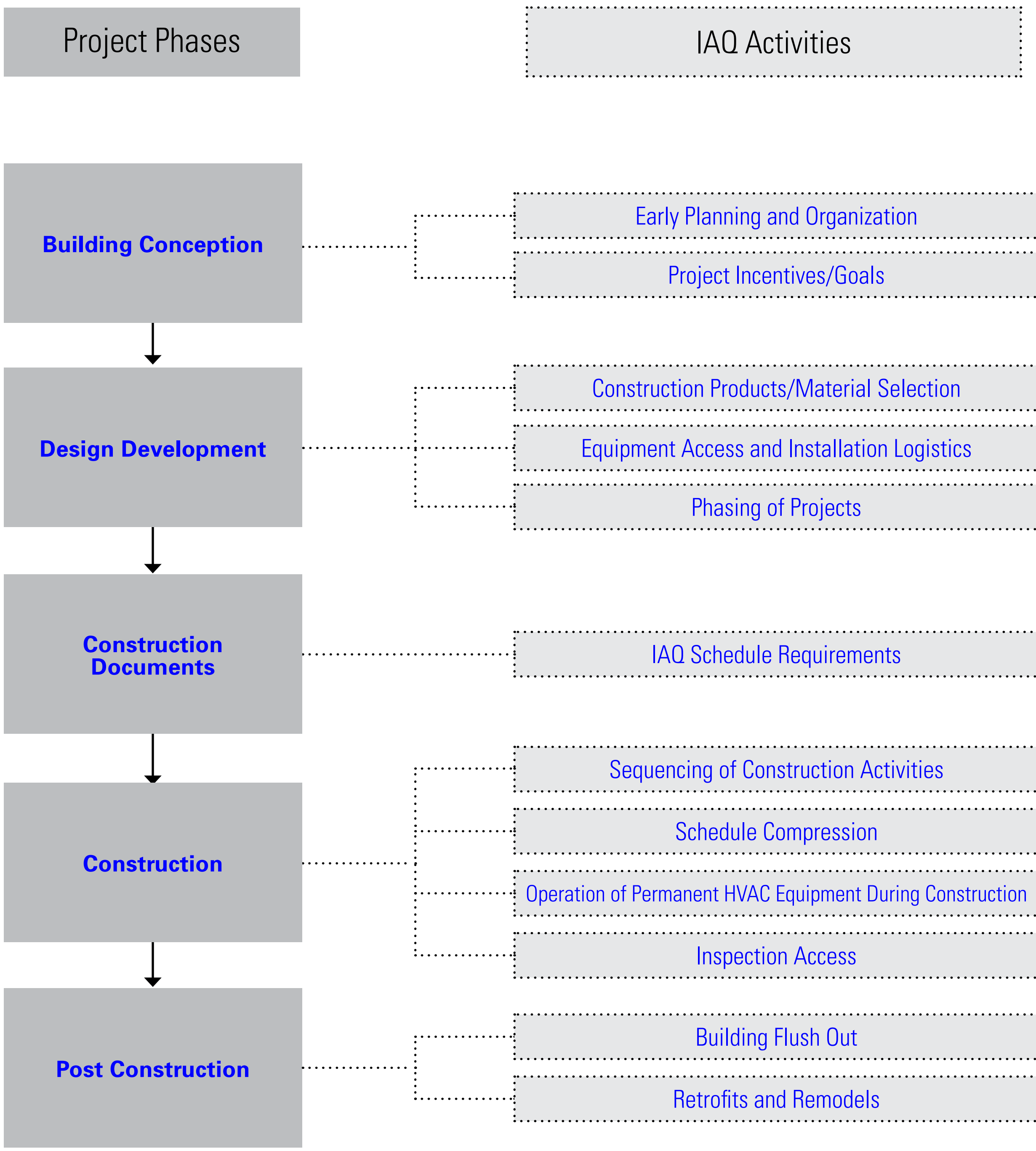
Establishing a comprehensive and realistic project construction schedule and using sound management of construction activities will help ensure the achievement of good IAQ for a building project. A building owner can have the best intentions, the design team can provide a great building design, and the contractors can achieve their best execution, but if the schedule is too compressed or has sequencing issues or if construction activities are not well managed, the IAQ of the finished project will be compromised.

All phases of the construction project need to be identified and evaluated for scheduling purposes and construction management. In particular, a Cx schedule covering each phase of the project needs to be developed, and part of the Cx work needs to include checking to insure that IAQ-related project scheduling activities are properly implemented.

Scheduling issues can be critical to achieving good IAQ. For example, installing construction materials that can absorb moisture before the building is closed in, storing construction materials in or exposing construction materials to the weather prior to installation, and starting and operating HVAC equipment for temporary heating or cooling during construction are just a few project-schedule-related items that could jeopardize the IAQ of the final building project. A sound IAQ plan coupled with proper scheduling and sequencing of the construction project will help ensure achievement of good IAQ.

The schedule needs to allow for adequate time to complete the construction activities and properly sequence them. It is best to involve the design and construction team early in the scheduling process. This could include gathering input from the construction team during the design phase to help with sequencing and planning the duration of construction activities. The schedule needs to be reviewed on a regular basis throughout the project and be maintained and updated as necessary. In addition, proper construction material selection could be evaluated to match the sequencing and scheduling of the construction activities. An accelerated project schedule can seriously undermine the achievement of good project IAQ.

Strategy 1.4


Project Phases
IAQ Activities
Building Conception
Early Planning and Organization
Project Incentives/Goals
Design Development
Construction Products/Material Selection
Equipment Access and Installation Logistics
Phasing of Projects
Construction Documents
IAQ Schedule Requirements
Construction
Sequencing of Construction Activities
Schedule Compression
Operation of Permanent HVAC Equipment During Construction
Inspection Access
Post Construction
Building Flush Out
Retrofits and Remodels

Nov 10 1.4

Strategy 1.4

Improper Storage and Installation of Construction Materials

STRATEGY OBJECTIVE 1.4

Figures 1.4-A through 1.4-D illustrate a case of improperly storing and installing water-sensitive construction materials. The drywall in this project was installed after exposure to the elements. Before installation, the drywall had been stored outside and exposed to the weather and not properly protected. This allowed for moisture to invade the drywall and create an opportunity for microbial growth.

Figure 1.4-A Unprotected Storage of Water-Sensitive Materials

Figure 1.4-B Installation of Water-Sensitive Materials in an Exposed/Unprotected Structure

Figure 1.4-C Mold Growth from Wetting of Exposed Water-Sensitive Materials—Example 1

Figure 1.4-D Mold Growth from Wetting of Exposed Water-Sensitive Materials—Example 2

Photographs courtesy of George DuBose.

Facilitate Effective Operation and Maintenance for IAQ

1.5

Operation and maintenance (O&M) can have as great an effect on IAQ as design and construction. O&M itself is outside the scope of this Guide, but there are steps the project team can take that greatly enhance the potential for effective O&M after the building is turned over to the owner. Among the most important are the following:

- Consider the owner's expected level of O&M capability when selecting systems.
- Involve O&M staff during project planning, design, construction, and Cx whenever possible.
- Provide O&M documentation that explains the design intent of key systems and how they need to be operated and maintained to fulfill that intent.
- Provide truly substantive training of O&M staff, emphasizing how systems need to be operated and maintained to achieve their design intent.
- Prioritize IAQ-related O&M documentation and training to emphasize the issues most important to IAQ for a given project.

O&M staff size, skill level, and budget need to be considered in selecting and designing systems. When systems are too complex or require maintenance that is too frequent or requires more advanced skills than the resources available, they will not be properly operated and maintained. When O&M resources are limited, selecting systems that are simpler, more forgiving, less numerous, and less difficult or time consuming to access is an important aspect of design for IAQ.

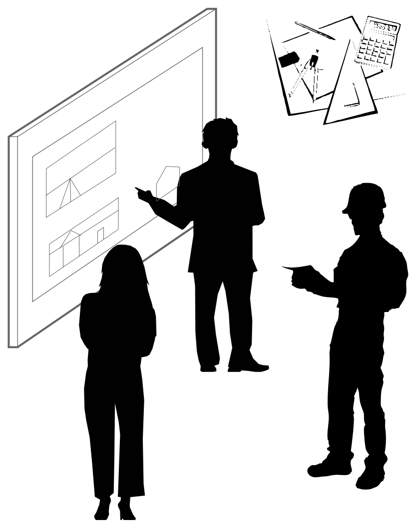
Involving O&M staff during planning, design, construction, and Cx facilitates effective O&M after turnover for two reasons. First, O&M staff can provide valuable input on issues that will affect operability and maintainability, such as standardization of equipment and components to reduce O&M costs, experience with product quality and vendor responsiveness, O&M training needs, and other issues. Second, staff can gain knowledge about the design and construction that will be useful in operating and maintaining the building.

Providing system-oriented O&M documentation, in addition to the customary component-oriented information, facilitates more effective O&M long after project completion. O&M documentation ought to explicitly communicate the purpose and intended performance of key IAQ-related building systems. If O&M staff do not understand the design intent of these systems, they will be much less able—or indeed motivated—to operate and maintain the systems to fulfill that intent. ASHRAE Standard 62.1 (ASHRAE 2007a), establishes minimum requirements for documentation of the design intent of ventilation systems that can serve as a starting point for compiling system-oriented O&M information. But design intent documentation also needs to cover other aspects of ventilation system design, other mechanical systems, and the building enclosure assemblies that can have a significant impact on IAQ. *ASHRAE Guideline 1.1-2007, HVAC&R Technical Requirements for The Commissioning Process* (ASHRAE 2007b), and *NIBS Guideline 3-2006, Exterior Enclosure Technical Requirements for the Commissioning Process* (NIBS 2006), provide useful guidance and examples of design intent documentation for HVAC systems and building exterior enclosures, respectively.

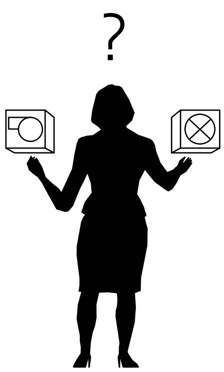
When projects are commissioned, the Cx reports need to be included in the O&M documentation. These reports document the conformance of systems and equipment to the design intent at turnover, providing a benchmark against which later performance can be compared. They also provide inspection checklists and test procedures that can be used as is or adapted for later inspection and testing.

Strategy 1.5

Involving O&M Staff in Planning, Design, Construction, and Commissioning



Considering O&M Capabilities in System Selection



Providing O&M Documentation that Facilitates Delivery of the Design Intent

Owner's Project Requirements and Basis of Design

Record Documents

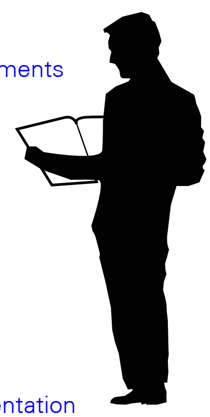
Commissioning Report

Operations Manual

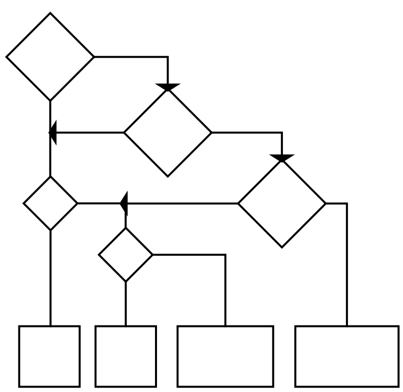
Training Manual

Maintenance Manual

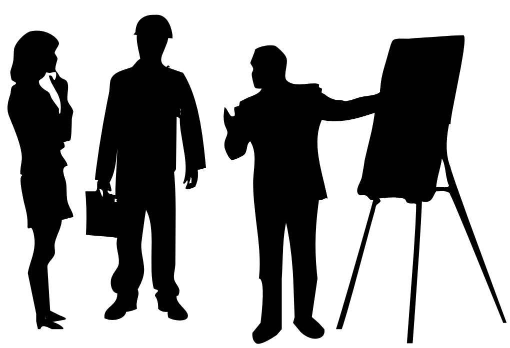
Format of O&M Documentation



Prioritizing O&M for IAQ



Providing O&M Training to Support Delivery of the Design Intent



Strategy 1.5

1.5

STRATEGY OBJECTIVE 1.5

The operations manual needs to include system-oriented information that can be used to proactively manage building operation. This includes standards of performance for relevant IAQ parameters such as space humidity and temperature, ventilation rate, and building pressurization, as well as log forms for recording periodic measurements of these parameters. Other useful elements include thorough system descriptions, operating routines and procedures, and seasonal start-up and shutdown procedures.

The maintenance manual needs to provide recommended maintenance activities and intervals for key IAQ-related systems. ASHRAE Standard 62.1 establishes minimum requirements for the maintenance of ventilation systems. *ANSI/ASHRAE/ACCA Standard 180, Standard Practice for Inspection and Maintenance of Commercial Building HVAC Systems* (ASHRAE 2008b) and the U.S. Environmental Protection Agency (EPA) *IAQ Building Education and Assessment Mode* (I-BEAM; EPA 2008a) and IAQ Tools for Schools Program (EPA 2007) provide additional guidance.

Providing O&M documentation in electronic as well as printed form makes it easier for staff to retain and update the information, make it available to multiple users, and search it for specific information.

O&M training needs to explain the design intent of key systems, their intended performance, and how they need to be operated and maintained to achieve that performance. Training materials need to be included in the O&M documentation and need to provide enough information so that a new operator using them for self-directed study can understand how to operate the systems properly. Recording O&M training sessions makes the training available for later reference by the same or new O&M staff.

Commissioning (see Strategy 1.2 – Commission to Ensure that the Owner's IAQ Requirements are Met) is an effective process to address O&M documentation and training needs. Other aspects of project design and execution also influence operability and maintainability for IAQ. These are discussed as separate Strategies, including, for example:

- Strategy 2.5 – Select Suitable Materials, Equipment, and Assemblies for Unavoidably Wet Areas
- Strategy 3.5 – Provide Effective Track-Off Systems at Entrances
- Strategy 3.6 – Design and Build to Exclude Pests
- Strategy 4.3 – Facilitate Access to HVAC Systems for Inspection, Cleaning, and Maintenance
- Strategy 4.4 – Control Legionella in Water Systems
- Strategy 5.3 – Minimize IAQ Impacts Associated with Cleaning and Maintenance

Including the Ventilation Design Intent in Project Drawings Facilitates Proper Building Operation

1.5

Figure 1.5-A Minnesota School Building
Photograph courtesy of Center for Energy and Environment.

A Minnesota elementary school (Figure 1.5-A) had many of its air handlers replaced to bring ventilation rates up to current standards. Figures 1.5-B and 1.5-C show a portion of the design intent documentation provided by the mechanical engineering firm. This firm includes these tables as part of the drawings, on a sheet immediately following the usual HVAC equipment schedules. Since plans are often the longest-lived part of the building documentation, putting these tables in the plans helps to ensure that the ventilation system design intent is available for O&M staff over the long term.

Including this information as part of the O&M documentation enables facility staff to understand the rationale for minimum outdoor airflow rates. The documentation and training also needs to describe how these flow rates are to be set or controlled for each air-handling system. The design intent data can be used to develop operating standards and logs for inclusion in the operations manual. This clearly communicates the owner's building performance standards to O&M staff and fosters accountability for building IAQ performance.

VUV - Typical Classroom (28 VUV's Total)

zone name	zone ceiling height	zone area A (z)	zone people P (z)	oa rate/ person R (p)	oa rate/ area R (a)	zone cfm V (pz)	cfm per sq ft	a/ch per hour	breathing zone oa V (bz)	air dist. zone eff. E (z)	design zone oa V (oz)
classroom	9	1,000	30	10	0.12	1,250	1.25	8.3	420	0.8	525
totals		1,000	30			1,250			420		525
design results											
system total supply cfm		1,250									
system total OA cfm V (ot)		525	42%								

Figure 1.5-B Ventilation Design Intent Data for Vertical Unit Ventilators Serving Classrooms
Adapted from Hallberg Engineering, Inc.

RTU - 3 Design Intent Schedule

zone name	zone ceiling height	zone area a (z)	zone people p (z)	oa rate/ person r (p)	oa rate/ area r (a)	zone cfm v (pz)	cfm per sq ft	a/ch per hour	breathing zone oa v (bz)	air dist. zone eff. e (z)	design zone oa v (oz)
1301 computer lab	9	940	20	10	0.12	1,950	2.07	13.8	313	0.8	391
1301b computer lab	9	385	10	10	0.12	840	2.18	14.5	146	0.8	183
1301a office	9	150	1	5	0.06	210	1.40	9.3	14	0.8	18
totals		1,475	31			3,000			473		591
design results											
system total supply cfm		3,000									
system total oa cfm v (ot)		591	20%								

Figure 1.5-C Ventilation Design Intent Data for a Rooftop Unit Serving Computer Labs
Adapted from Hallberg Engineering, Inc.

STRATEGY OBJECTIVE 1.5

Control Moisture in Building Assemblies

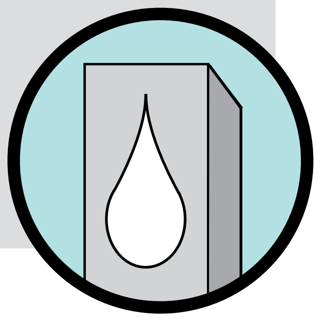
Moisture is one of the most common causes of IAQ problems in buildings and has been responsible for some of the most costly IAQ litigation and remediation. Moisture enables growth of microorganisms, production of microbial VOCs and allergens, deterioration of materials, and other processes detrimental 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.

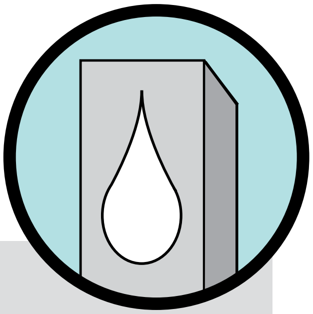
Other important moisture control issues are discussed in the following sections:

- 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

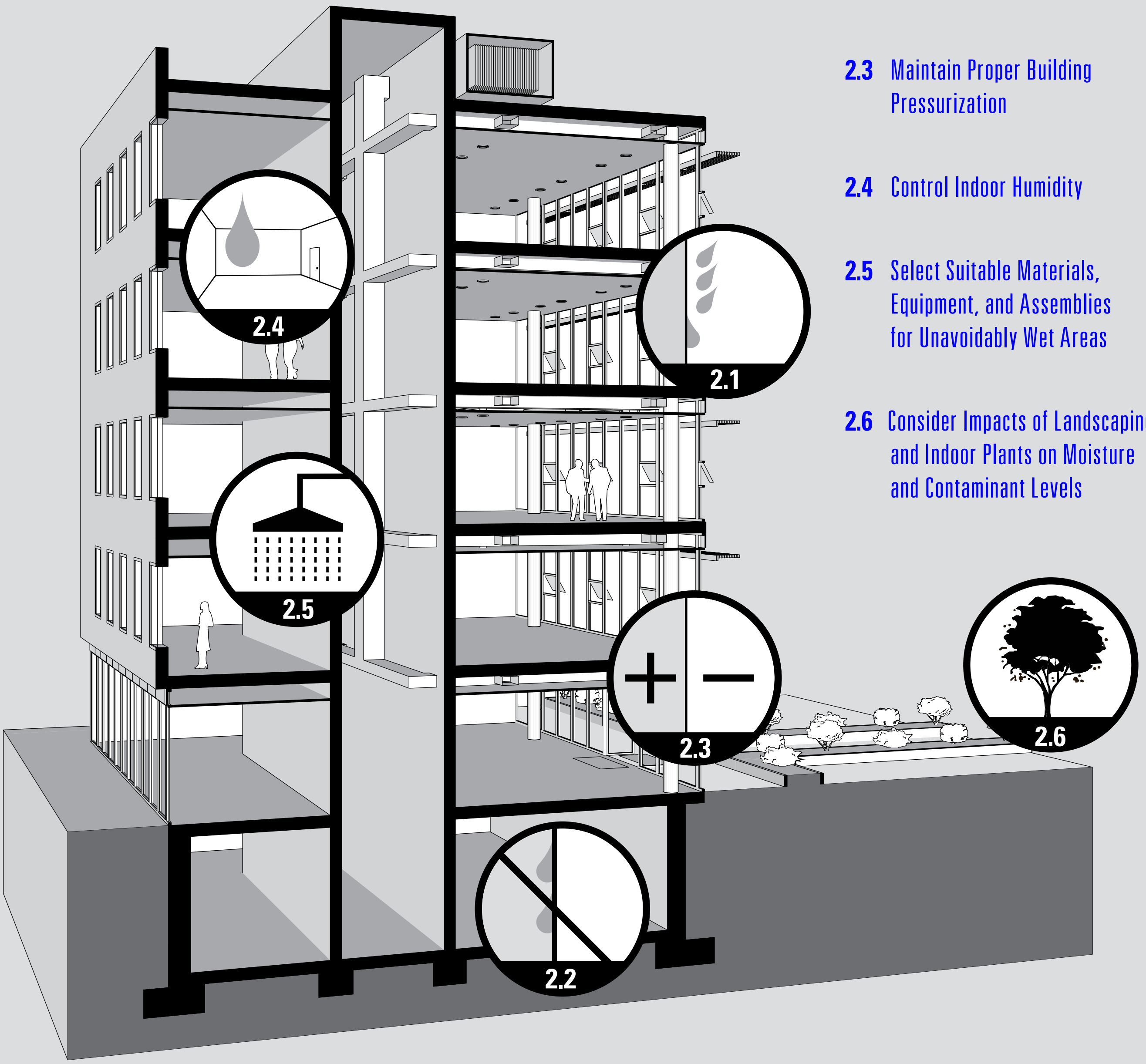
2.2 Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces

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.

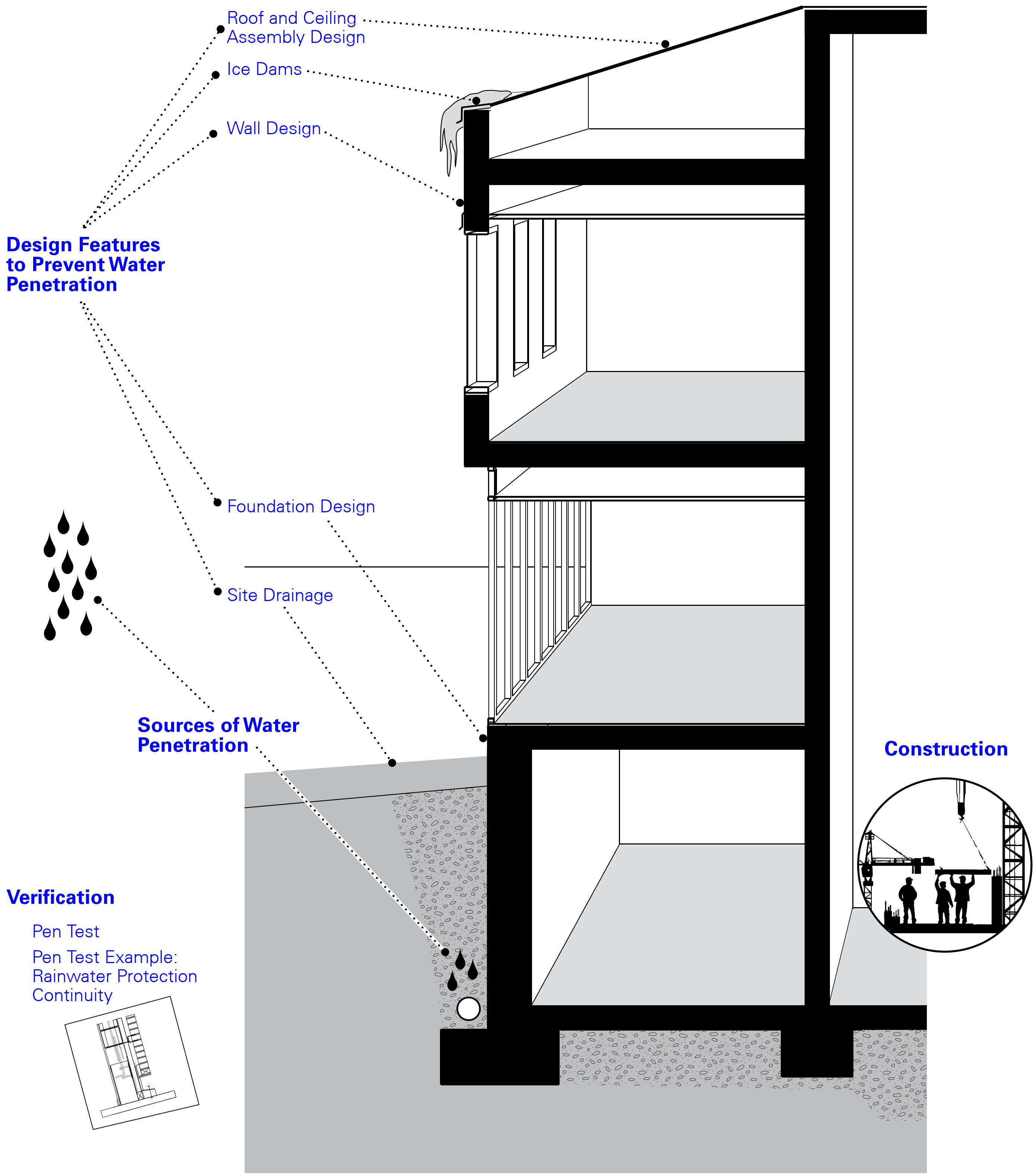
Once the site is designed properly to drain water away from the building, the building needs a storm water runoff system to divert precipitation from the roof into the site drainage system. This component of moisture control is called *storm water runoff management*.

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



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

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.

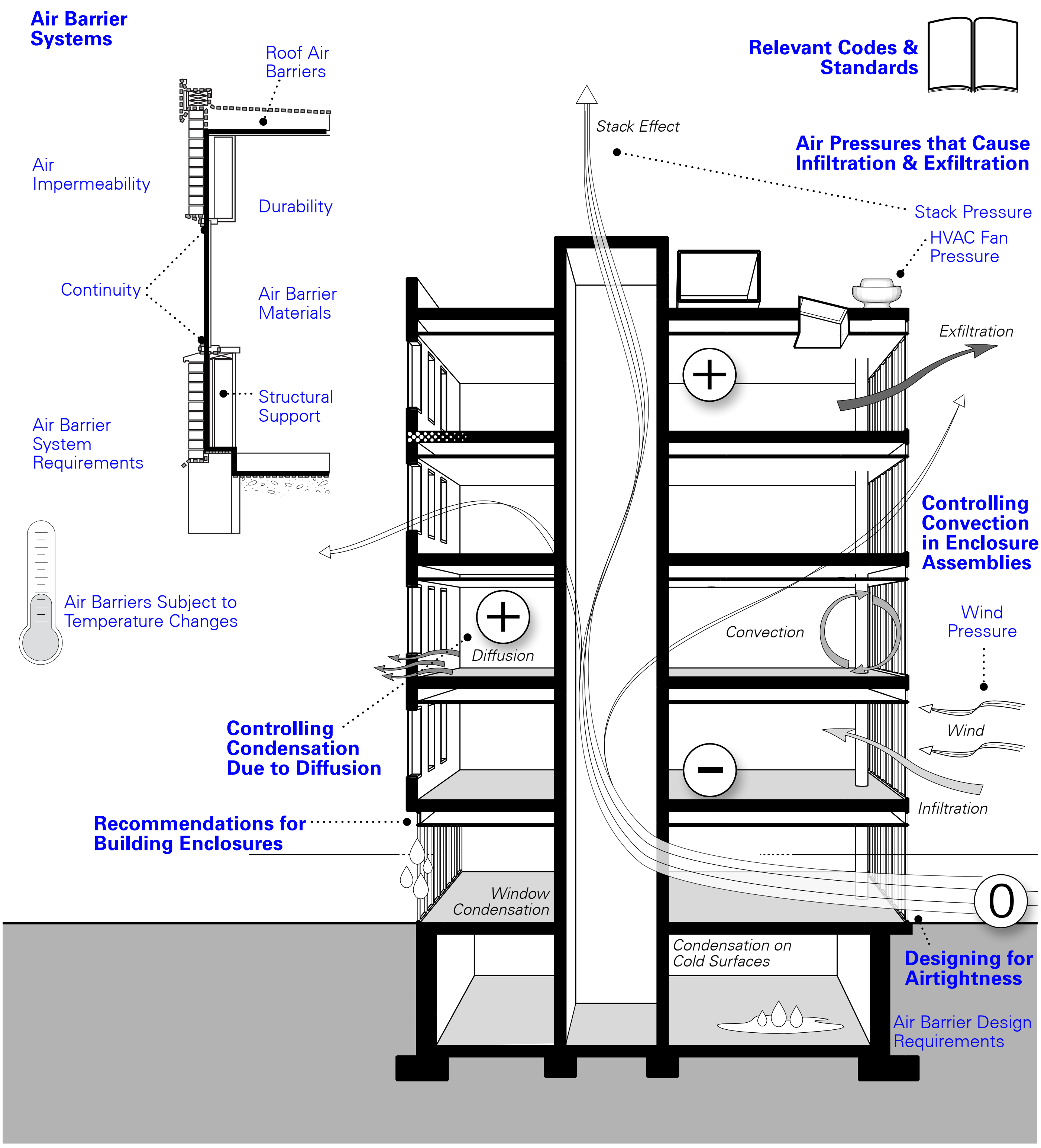
Building enclosures need to be designed by a knowledgeable design professional using design tools referenced in *ASHRAE Handbook—Fundamentals* (ASHRAE 2009) in order to avoid the likelihood of moisture-related problems.

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


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
Relevant Codes & Standards
Stack Effect
Air Pressures that Cause Infiltration & Exfiltration
Stack Pressure
HVAC Fan Pressure
Exfiltration
Controlling Convection in Enclosure Assemblies
Wind Pressure
Wind
Convection
Diffusion
Infiltration
Controlling Condensation Due to Diffusion
Recommendations for Building Enclosures
Window Condensation
Condensation on Cold Surfaces
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.

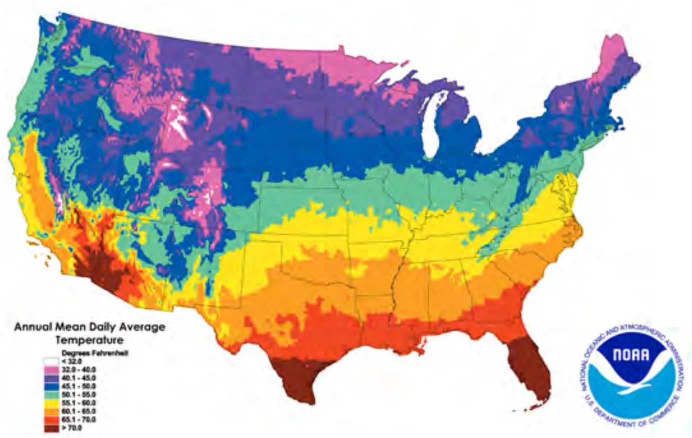


Figure 2.2-A Average Mean Daily Temperatures
Image courtesy of National Climatic Data Center.

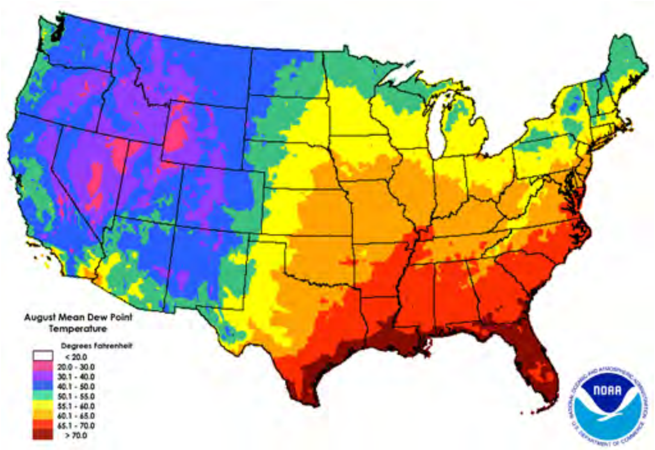


Figure 2.2-B Mean Dew-Point Temperatures for August
Image courtesy of National Climatic Data Center.

Thermal Bridging

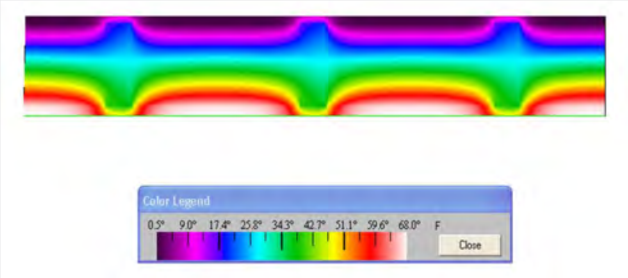


Figure 2.2-C THERM Study Showing Temperature of Studs

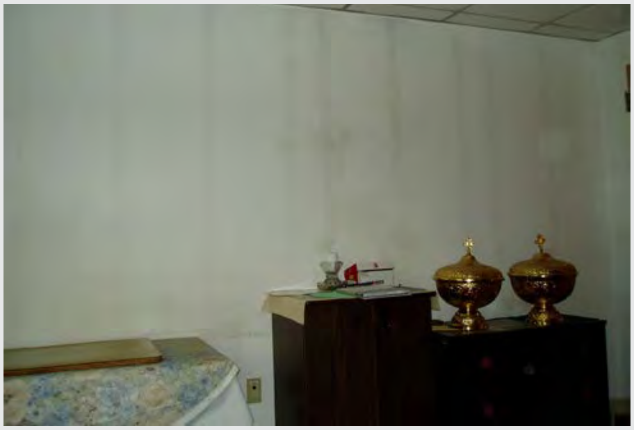


Figure 2.2-D Ghosting of Steel Studs on Walls
Photograph copyright Wiss, Janney, Elstner and Associates, Inc.

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.

2.3

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.

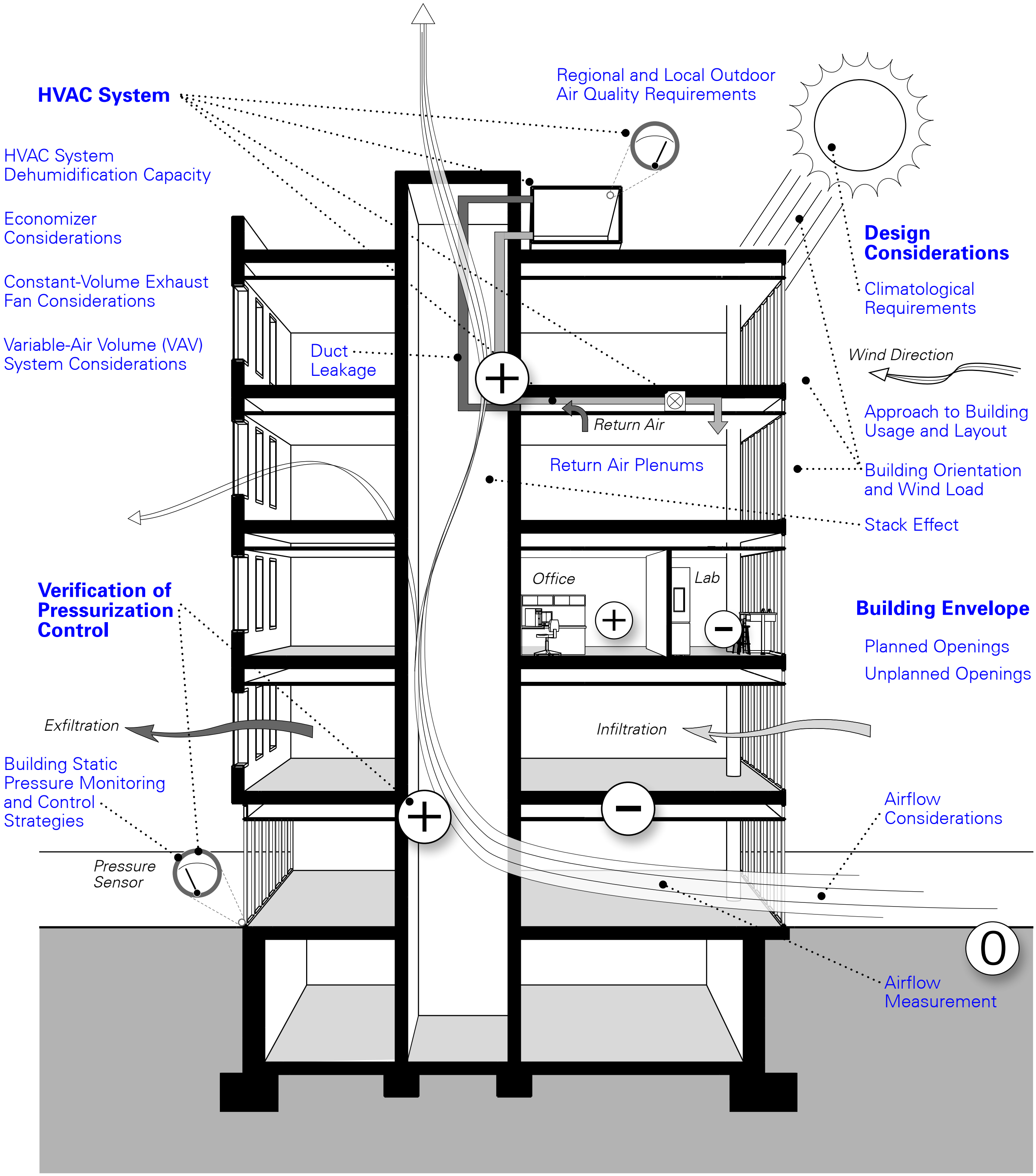
Positive building pressure is particularly important to maintain in the following situations: mechanically cooled buildings in hot and humid climates for reduced infiltration and control of condensation and mold growth, buildings maintained at low temperatures relative to outdoor temperatures (refrigerated 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
Return Air
Return Air Plenums
Building Orientation and Wind Load
Stack Effect
Office
Lab
Building Envelope
Planned Openings
Unplanned Openings
Verification of Pressurization Control
Exfiltration
Infiltration
Building Static Pressure Monitoring and Control Strategies
Airflow Considerations
Pressure Sensor
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.

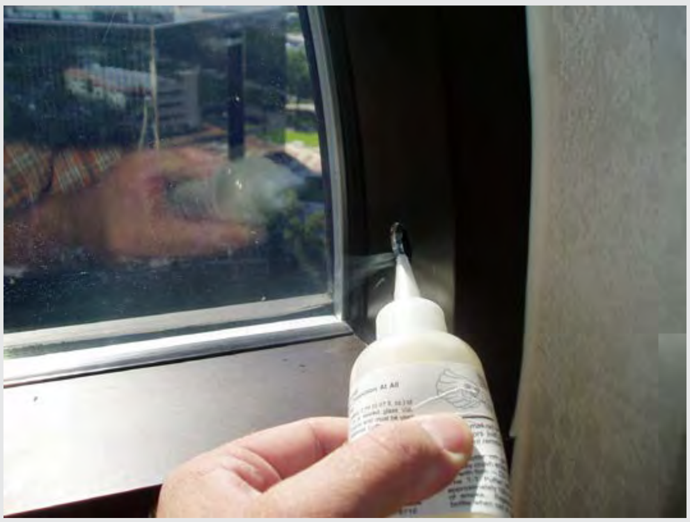


Figure 2.3-A "Smoke" Test Demonstrating the Building was Negatively Pressurized in Reference to the Exterior

Figure 2.3-B Mold Growth due to Negative Pressure

Photographs copyright Liberty Building Forensics Group®.

2.4

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

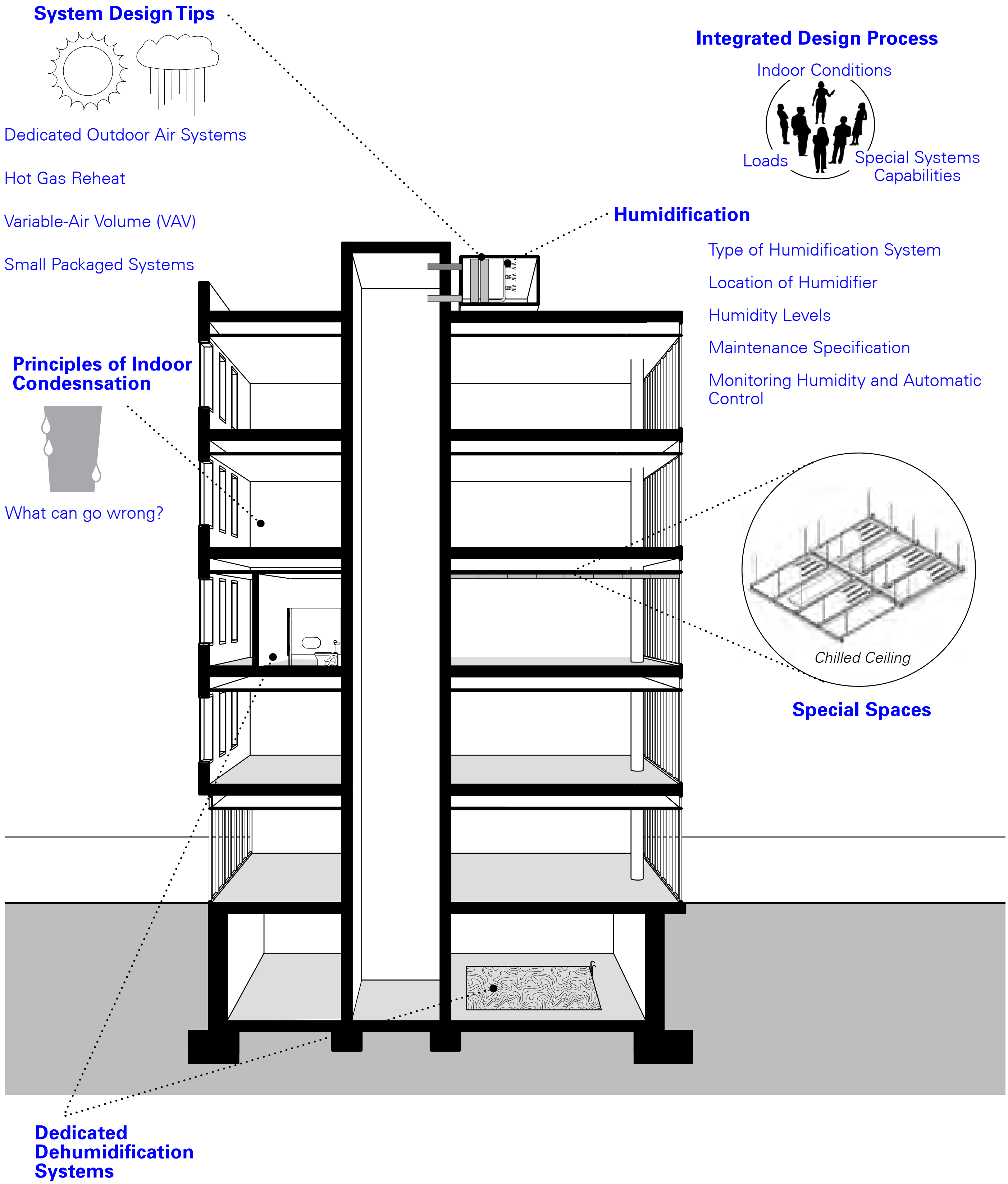
As air is cooled, its capacity to hold moisture diminishes. When air cools enough that it becomes saturated (100% RH) so it can no longer hold all its water vapor, the vapor turns back into a liquid (condenses). The temperature at which this happens is a called the *dew point* and typically occurs on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

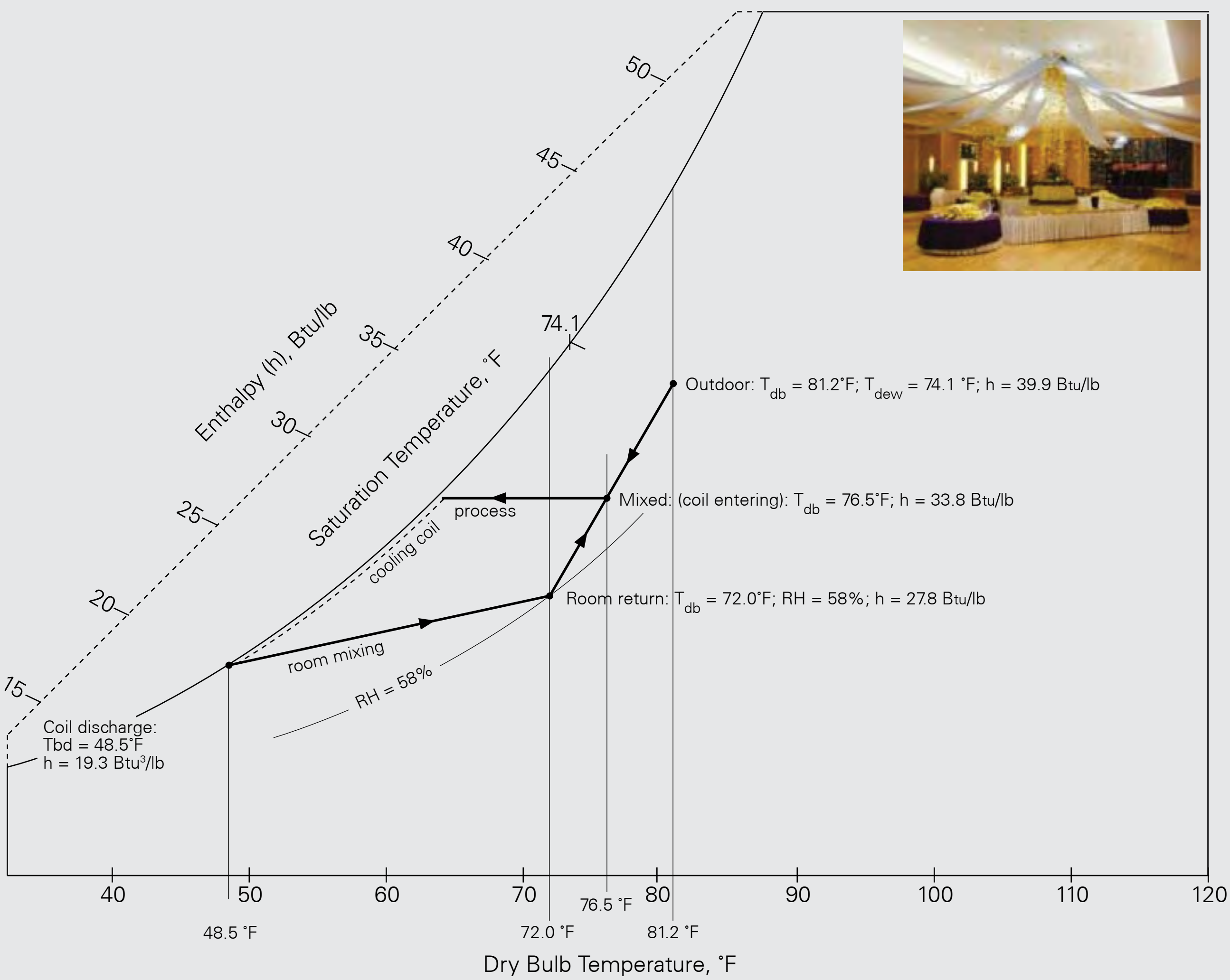


Figure 2.4-A Assembly Room Psychometric Chart
Inset photograph courtesy of Larry Schoen.

Strategy 2.4

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

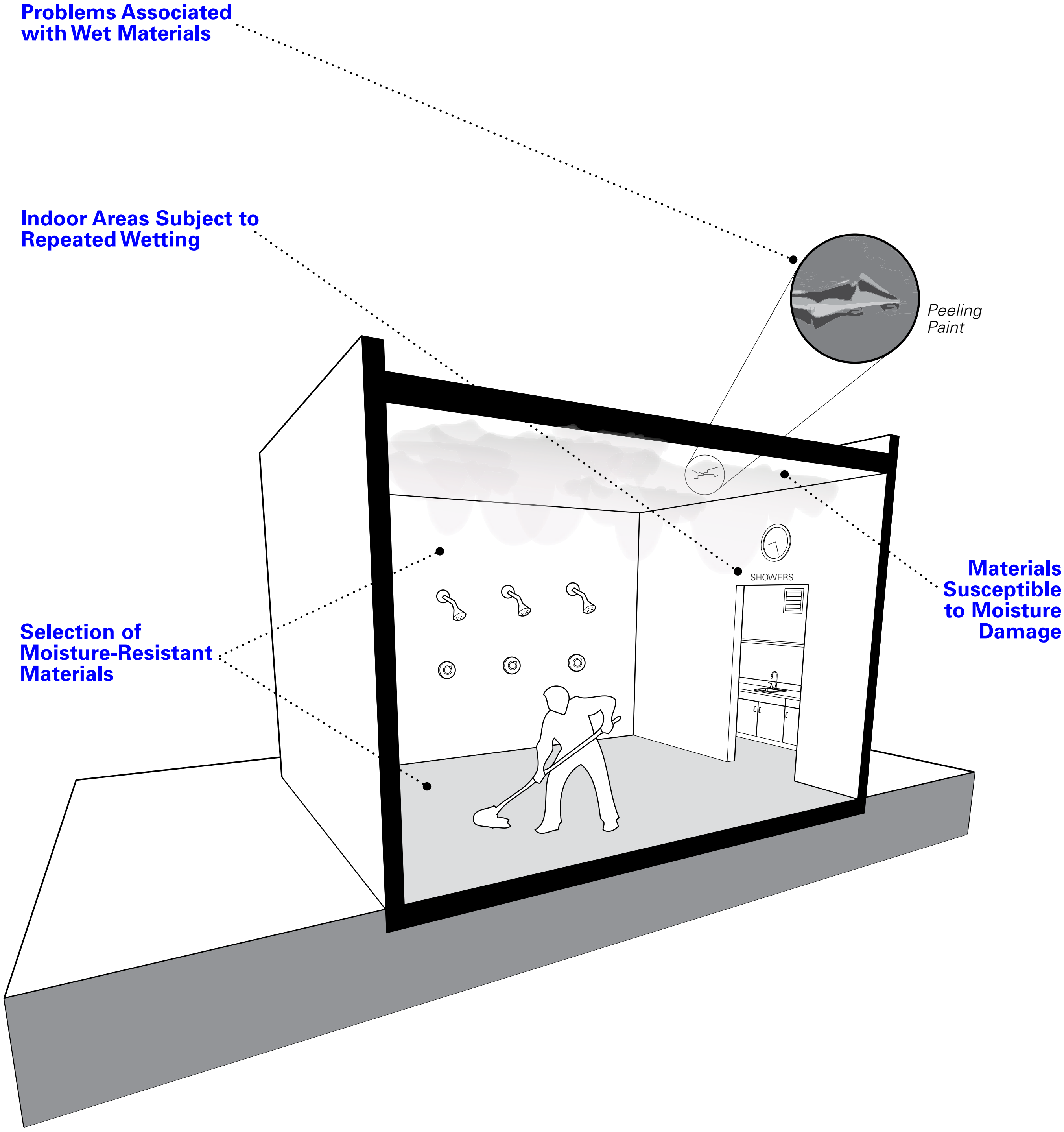
2.5

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

2.5

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

2.6

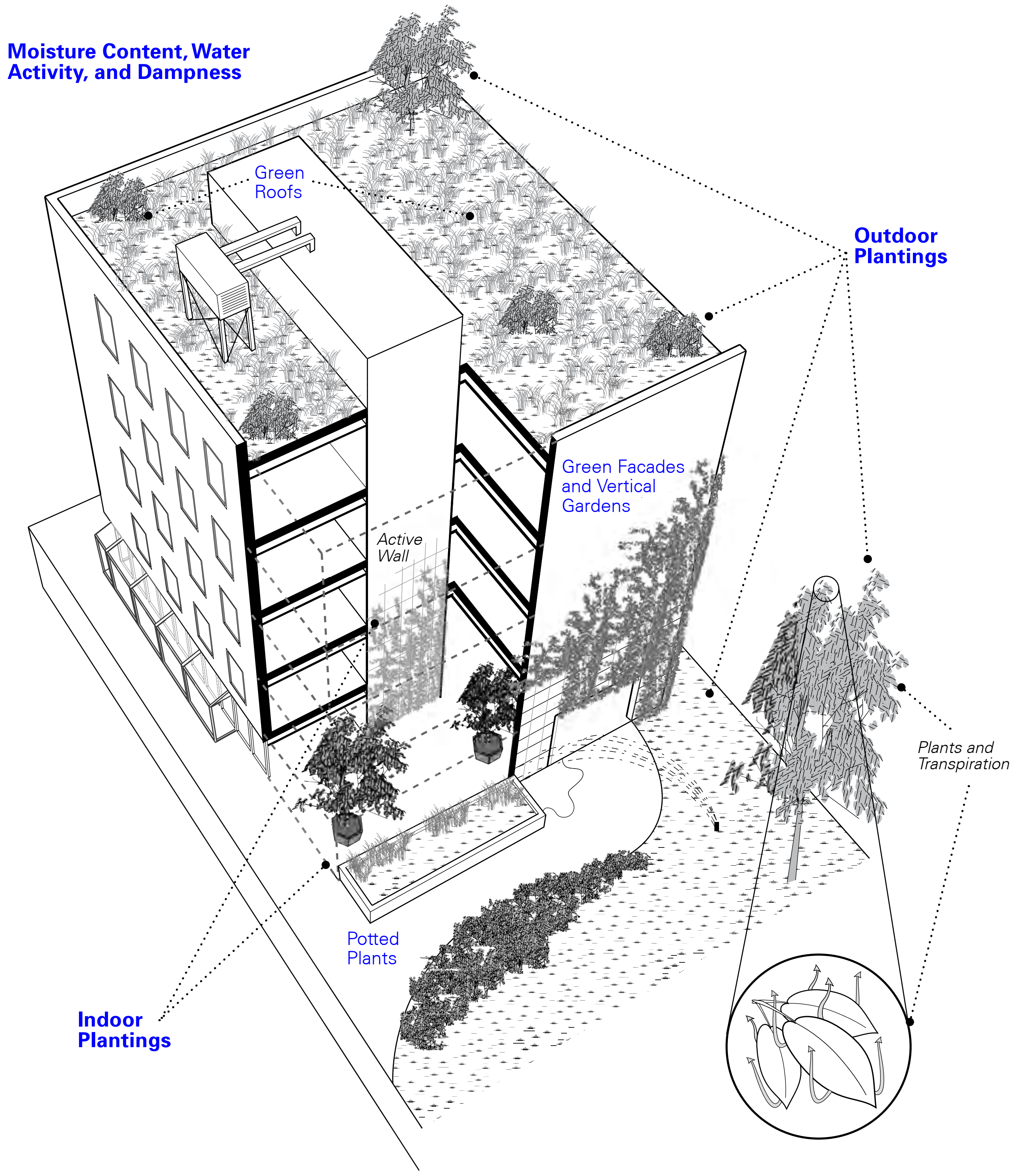
There are potential advantages and disadvantages associated with the presence of plants as a component of the building envelope (e.g., green roofs or roof gardens, living facades, or vertical gardens) or on walls or other locations in the interior space (e.g., atrium gardens, living walls, vertical gardens, 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.

Strategy 2.6



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 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.

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

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.

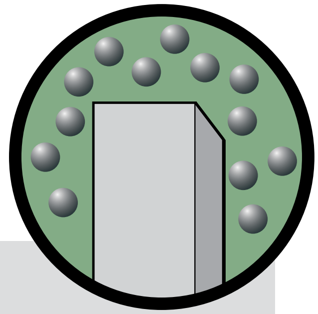
- Strategy 3.1 – Investigate Regional and Local Outdoor Air Quality describes assessment of outdoor air pollution levels and control measures to limit the entry of these contaminants.
- Strategy 3.2 – Locate Outdoor Air Intakes to Minimize Introduction of Contaminants addresses separation of air intakes 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

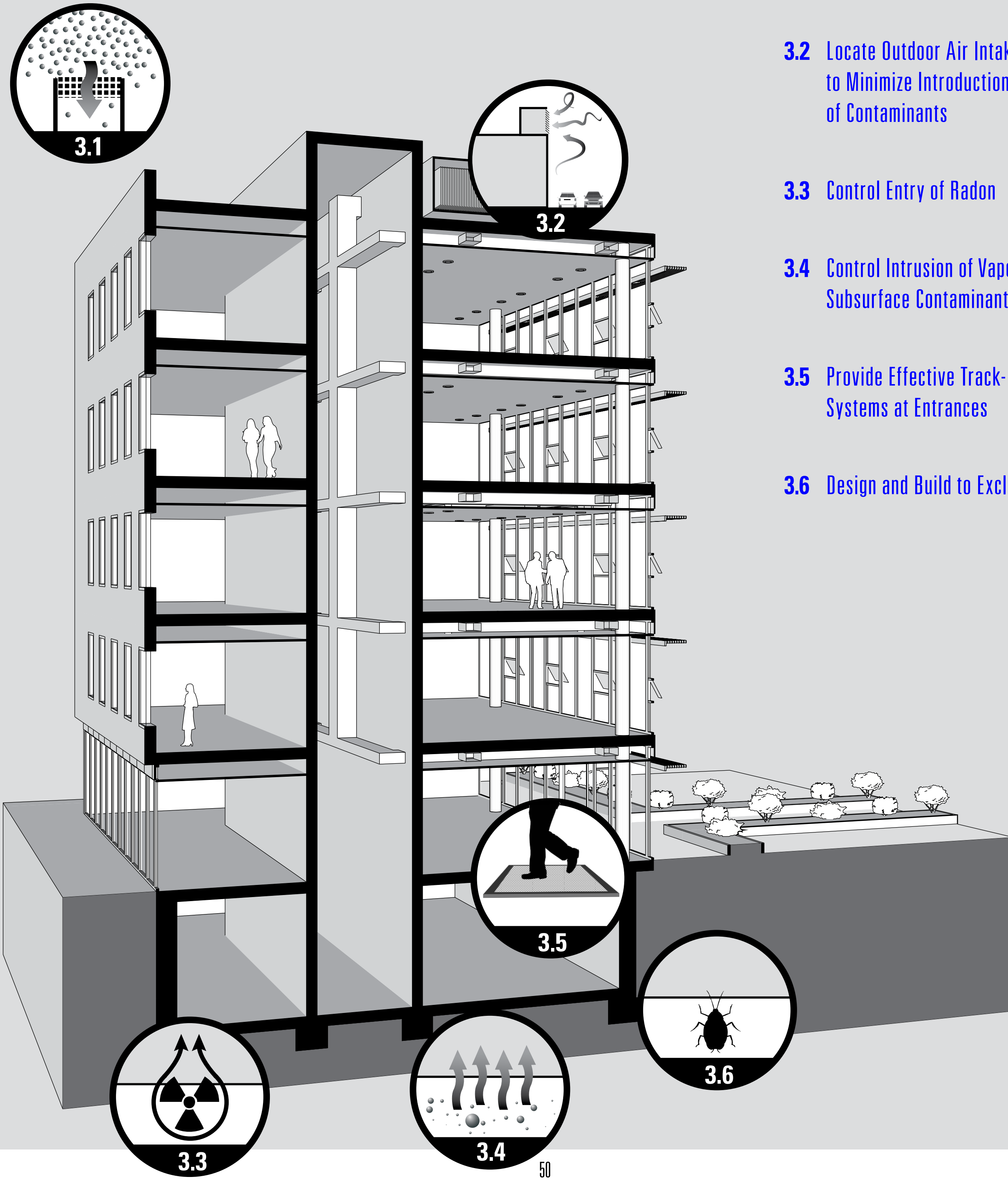
3.2 Locate Outdoor Air Intakes to Minimize Introduction of Contaminants

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

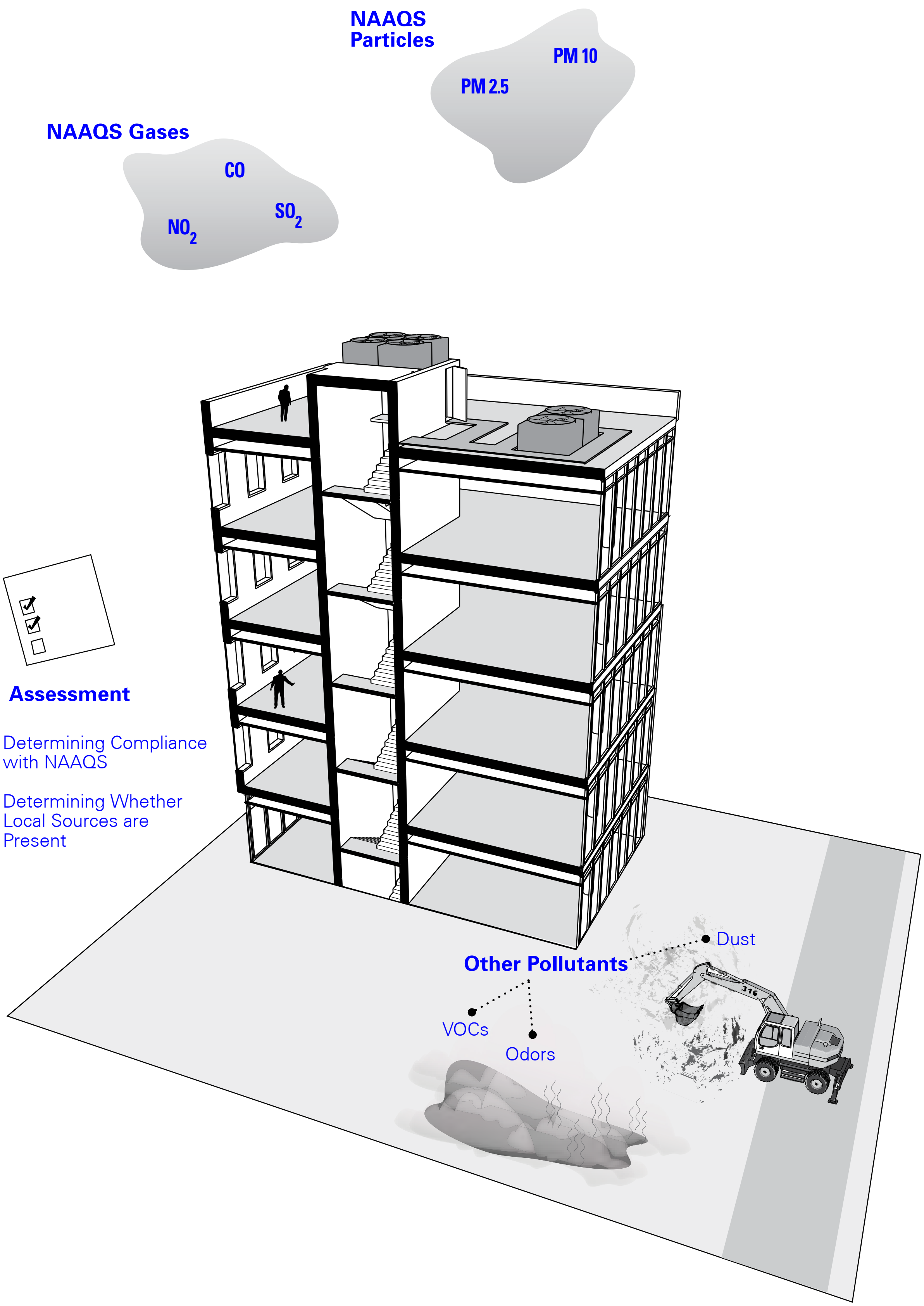
- Ozone is formed in the atmosphere by a photochemical reaction under sunlight. Therefore, ozone is not generated on cloudy or cold days. Ozone air treatment is provided by carbon or other sorbent filters that cause the ozone to react on the surface. Table 3.1-A illustrates the air quality index for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

Strategy 3.1

3.1



NAAQS Particles
PM 10
PM 2.5
NAAQS Gases
CO
SO2
NO2
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

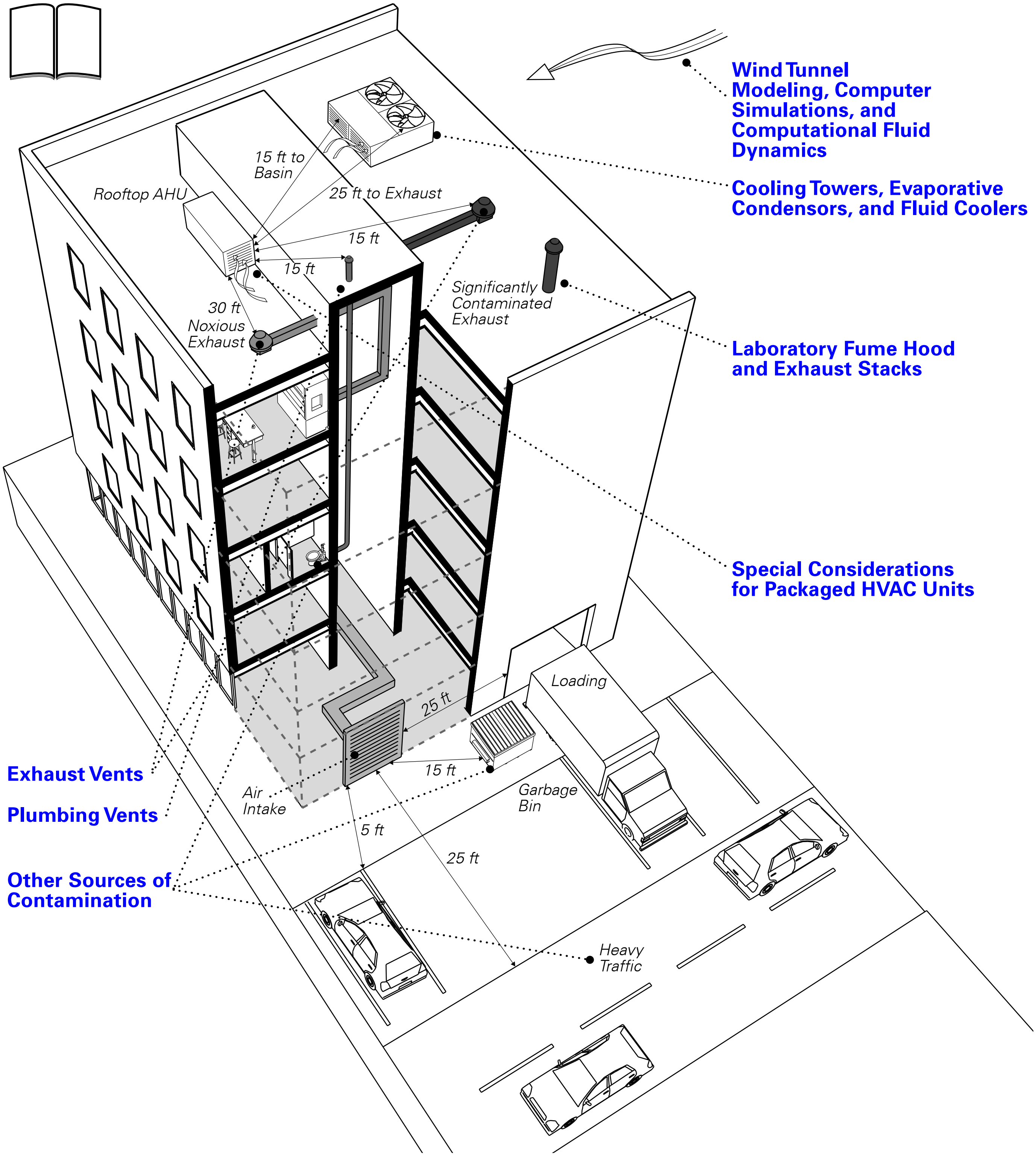
According to Table 5.1 of ASHRAE Standard 62.1, outdoor air intakes need to be located at least 25 ft (7.6 m) from plume discharges and upwind (prevailing wind) of cooling towers, evaporative condensers, and fluid coolers. In addition, outdoor air intakes need to be located at least 15 ft (4.6 m) away 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

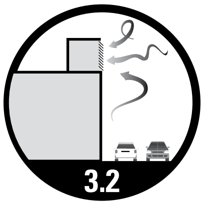
All nearby potential odor or contaminant sources (such as restaurant exhausts, emergency generators, etc.) and prevailing wind conditions need to be evaluated. Locations of plumbing vents in relationship to outdoor air intakes in high-rise buildings may require additional analysis. Model codes such as *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.

Strategy 3.2

Applicable Codes, Standards, and Other Guidance



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.

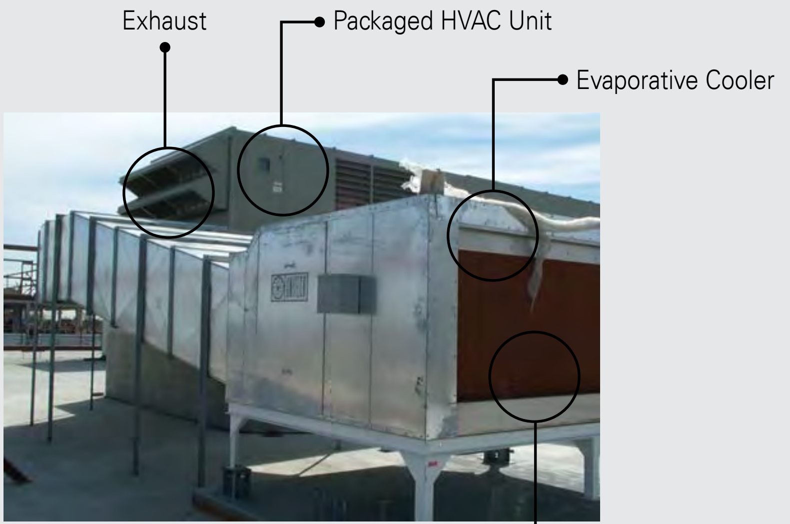


Figure 3.2-A Large Packaged HVAC Unit with Relocated Outdoor Air Intake to Reduce Exhaust Air Re-entrainment (Shown is a Closeup of the Indirect Evaporative Cooler at the Outdoor Air Intake)
Photograph courtesy of Leon Alevantis.

3.3

Control Entry of Radon

Radon is a radioactive gas formed from the decay of uranium in rock, soil, and groundwater. Exposure to radon is the second leading cause of lung cancer in the U.S. after cigarette smoking and is responsible for about 10% to 14% of lung cancer deaths (NAS 1999).

Radon most commonly enters buildings in soil gas that is drawn in through joints, cracks, or penetrations or through pores in concrete masonry units (CMUs) when the building is at negative pressure relative to the ground. The potential for high radon levels varies regionally, with additional variation from building to building in the same region and even from room to room in the same building.

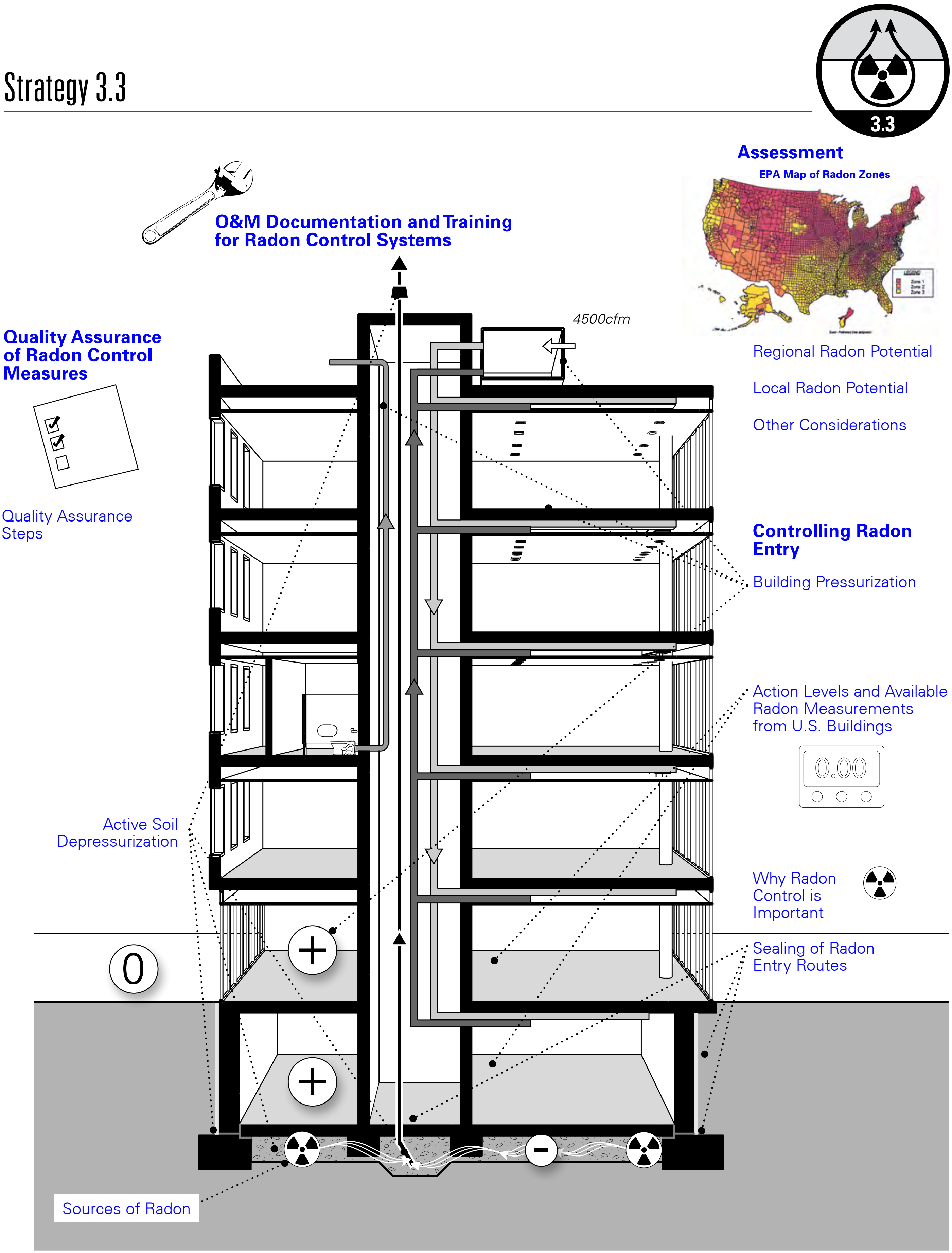
Design for control of radon entry includes three components, as follows:

- Active soil depressurization (ASD), which uses one or more suction fans to draw radon from the area below the building slab and discharge it where it can be harmlessly diluted to background levels. By keeping the sub-slab area at a lower pressure than the building, the ASD system greatly reduces the amount of radon-bearing soil gas entering the building. A permeable sub-slab layer (e.g., aggregate) allows the negative pressure field created by a given radon fan to extend over a greater sub-slab area.
- Sealing of radon entry routes, including ground-contact joints, cracks, and penetrations and below-grade CMU walls.
- Use of HVAC systems to maintain positive building pressure in ground-contact rooms and to provide dilution ventilation, as an adjunct to ASD and sealing of radon entry routes.

An ASD system and sealing of radon entry routes are easier and cheaper to implement during construction than they are as a retrofit. In addition, many elements of a radon control system are also useful for reducing the intrusion of vapors from brownfield sites and for reducing the penetration of liquid water and water vapor into below-grade building assemblies. For these reasons, it may be preferable to address radon during initial design and construction rather than after the building is built.

The design team needs to review with the owner the radon potential, the synergies of radon control techniques with design for other IAQ issues, and the new construction vs. retrofit costs to determine whether to implement radon control measures.

Strategy 3.3


3.3
Assessment
EPA Map of Radon Zones
Regional Radon Potential
Local Radon Potential
Other Considerations
O&M Documentation and Training for Radon Control Systems
4500cfm
Quality Assurance of Radon Control Measures
Quality Assurance Steps
Controlling Radon Entry
Building Pressurization
Action Levels and Available Radon Measurements from U.S. Buildings
0.00
Why Radon Control is Important
Active Soil Depressurization
Sealing of Radon Entry Routes
0
+
+
−
Sources of Radon

Strategy 3.3

How Complaints of Headache and Nausea led to Discovery of High Radon Levels

Figure 3.3-A Office Building with Elevated Radon Levels, Identified During an Investigation of Occupant Complaints Related to Another Contaminant

Photograph courtesy of H.E. Burroughs.

A four-story owner-occupied office building in the Southeastern U.S. (Figure 3.3-A) is located on a site with shallow topsoil over granite in an identified radon region. At the time of the investigation, the building was eight years old. It has an open atrium lobby that penetrates all floors. Each floor is served by a separate air handler, and ventilation and makeup air are introduced from the roof through a common shaft to each mechanical room. The return air on each floor flows to the lobby atrium, entering each floor's mechanical room through transfer grilles from the lobby wall. The lower floors are open-plan office space, and the upper floor is devoted to the company cafeteria and the executive dining room. The lobby is decorated with architectural plantings including a large and valuable ficus tree several stories tall.

An investigation was undertaken in response to complaints of regular, repeated occurrences of headaches and nausea reported by over 50% of the occupant population every other Friday afternoon after 2:00 p.m. Air testing conducted on a "problem" Friday revealed elevated VOC levels (above 5000 μg/m^3) and high fungal counts (greater than three times the outdoor levels). To the surprise of the investigators, radon levels were also elevated to over three times the level at which EPA recommends action be taken (EPA 2009). When the air testing was done, the investigation team reviewed the airflow data from specifications and the test and balance report but took no airflow measurements.

The report and findings were submitted by the investigation team two weeks later, on another "problem" Friday afternoon. At this time, it was obvious that fish was being served in the cafeteria because the distinctive odor was present on all floors of the building, clearly migrating from the fourth-floor kitchen. Based on this obvious evidence of contamination crossover between floors, the kitchen area and operating practices were investigated. It was found that the kitchen closed at 2:00 p.m. on Friday afternoons, and on every other Friday pesticide treatment was applied. The pesticide aerosol quickly migrated throughout the building because of the lobby atrium's negative pressurization and was drawn onto all floors in the return air. The negative atrium pressure was also depressurizing the soil in which the ficus tree was planted. The team learned that the root system penetrated the concrete slab because of the size of the tree. Thus, there was no air barrier between the soil and the space, which allowed the depressurization to draw radon into the building. The soil was also the source of the high fungal counts.

Strategy 3.3

Once the causes of these problems were determined, they were easily solved, through:

- the addition of localized exhaust in the kitchen with integral makeup air,
- rescheduling of pesticide application to off-hours,
- provision of additional fan-powered outdoor air delivered directly to each floor's mechanical room, and
- balancing of outdoor air quantities to deliver a larger quantity to the ground-floor zone.

The atrium lobby pressure relative to the outdoors was about –0.2 to –0.24 in. w.g. (–50 to –60 Pa) before the modifications and increased to 0 to 0.032 in. w.g. (0 to 8 Pa) after the modifications. This was sufficient to bring the level of radon right at the source (the ficus tree root area) to below the action level. The problem of headaches and nausea related to the pesticide application was resolved as well. Had the building not had an IAQ problem that was causing acute symptoms in the building occupants, the elevated radon levels likely would never have been detected or resolved.

Control Intrusion of Vapors from Subsurface Contaminants

3.4

What is Vapor Intrusion?

Vapor intrusion is "the migration of a [chemical of concern] vapor from a subsurface soil or groundwater source into the indoor environment of an existing or planned structure" (ASTM 2008, Section 3.2.53). Although vapors can intrude into buildings from naturally occurring subsurface gases, most guidance, standards, and regulations are specific to vapors from environmental contaminants. Contaminants can be present below ground due to accidental spills, improper disposal, leaking landfills, or leaking underground or aboveground storage tanks (Tillman and Weaver 2005). Some of the most widespread present and past land uses associated with chemicals of concern include gas stations, dry cleaners, former industrial sites that used vapor degreasers or other parts-cleaning chemicals, and manufactured gas plants (ASTM 2008). There are hundreds of thousands of contaminated or potentially contaminated sites in the U.S. (EPA 2002). Vapor intrusion can occur even though a site has undergone or is undergoing remediation. Moreover, the potential for vapor intrusion is not limited to the sites where contaminants were originally released, since contaminants reaching the water table can travel at least several miles in contaminated groundwater plumes, and contaminant vapor can travel shorter distances through the vadose zone above the water table.

Why Is Vapor Intrusion a Concern?

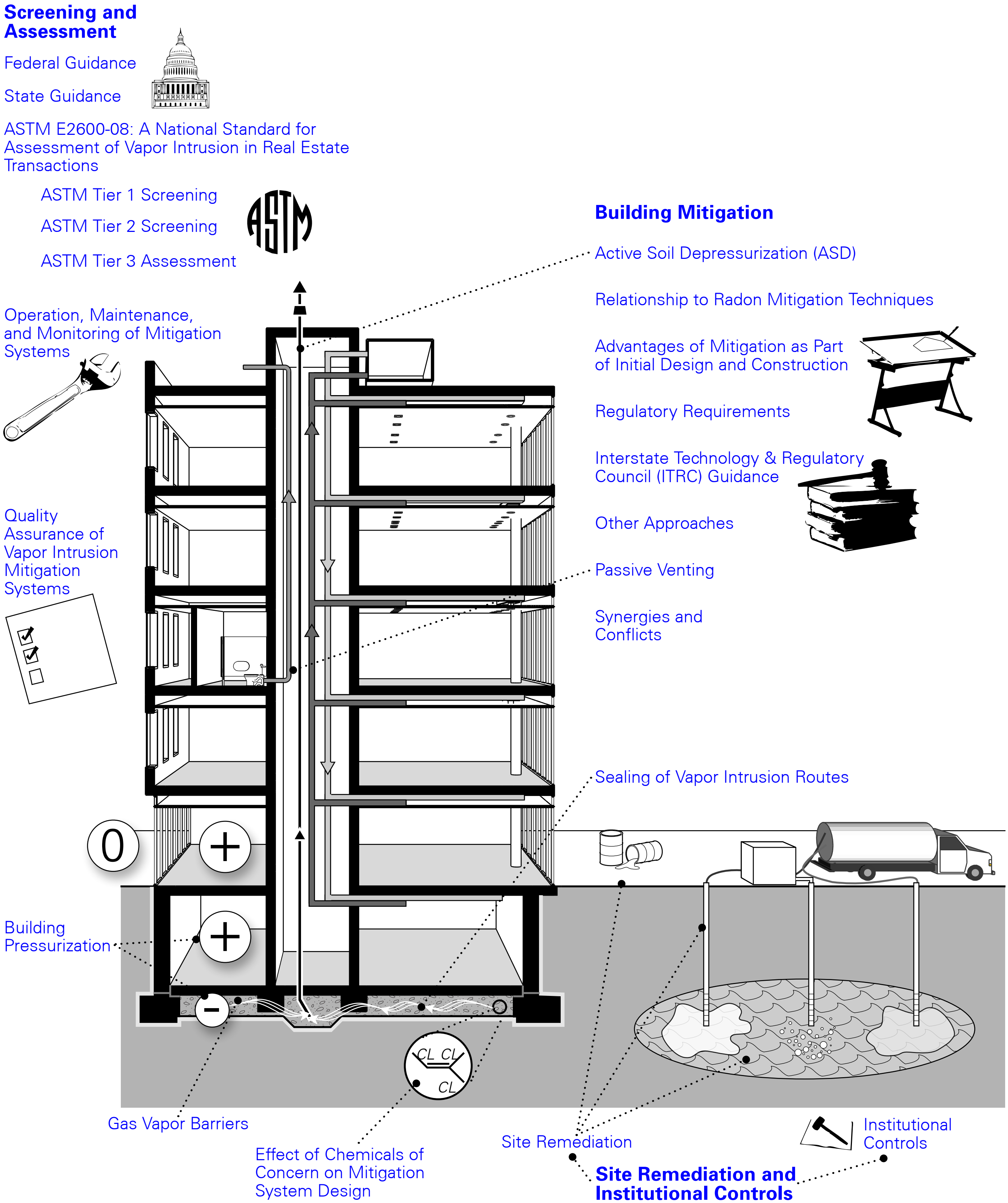
Vapor intrusion is a concern primarily because of the potential for chronic health effects from long-term exposure to low contaminant concentrations, although in extreme cases vapor concentrations can be high enough to cause acute health effects or explosion hazards (EPA 2002). The chemicals of concern for vapor intrusion are those that are sufficiently volatile to migrate through the soil as a vapor and sufficiently toxic that they may adversely affect human health (EPA 2002). These include many VOCs, some semi-volatile organic compounds (SVOCs), and some inorganic substances such as mercury.

Standards, Guidance, and Regulations

The potential for intrusion of vapors from these sites into buildings was not widely recognized by U.S. regulators until the 1990s (IRTC 2007), and both the science and the regulatory environment are still evolving. ASTM International (ASTM) recently developed a national standard for assessment of vapor intrusion on properties involved in real estate transactions (ASTM 2008). The standard uses a tiered approach to allow properties with a low risk of vapor intrusion to be screened out quickly and at relatively low cost. The Interstate Technology & Regulatory Council (ITRC) published guidance on both assessment and mitigation in 2007.

Screening and assessment of the potential for vapor intrusion must follow the regulations, policies, and guidance of the relevant jurisdiction and must be performed by a person meeting the qualifications required by that jurisdiction. In many cases this will be an environmental professional outside the primary design team. Obtaining guidance from the appropriate regulatory agency early in the process is the best way to avoid problems and ensure a successful project.

Strategy 3.4


Screening and Assessment
Federal Guidance
State Guidance
ASTM E2600-08: A National Standard for Assessment of Vapor Intrusion in Real Estate Transactions
ASTM Tier 1 Screening
ASTM Tier 2 Screening
ASTM Tier 3 Assessment
ASTM
Operation, Maintenance, and Monitoring of Mitigation Systems
Quality Assurance of Vapor Intrusion Mitigation Systems
Building Pressurization
0
+
+
−
Gas Vapor Barriers
CL CL
CL
Effect of Chemicals of Concern on Mitigation System Design
Building Mitigation
Active Soil Depressurization (ASD)
Relationship to Radon Mitigation Techniques
Advantages of Mitigation as Part of Initial Design and Construction
Regulatory Requirements
Interstate Technology & Regulatory Council (ITRC) Guidance
Other Approaches
Passive Venting
Synergies and Conflicts
Sealing of Vapor Intrusion Routes
Site Remediation
Institutional Controls
Site Remediation and Institutional Controls

Site Remediation

In the long term, the best remedy for contaminated sites is to remove the contaminant source or to perform treatments in place to reduce contaminant levels. Some remediation techniques may reduce or eliminate soil gas migration substantially in a relatively short time, rendering building mitigation measures unnecessary. Some other technologies are longer-term strategies that may take many years to reduce the contaminant source to a level where vapor intrusion is no longer a concern. In still other cases, cleanup may be on hold for various reasons. Where longer-term cleanup strategies are used or cleanup is on hold, institutional controls and/or building mitigation are necessary as interim strategies.

Institutional Controls

Institutional controls are "legally enforceable conditions placed on a property to reduce the likelihood of exposure to unacceptable levels of contaminants" (ASTM 2008, Section 11.3.1). They may include such measures as zoning restrictions, requirements that vapor intrusion mitigation systems be preemptively installed in new construction, requirements that source remediation systems or building mitigation systems be periodically inspected, or requirements that contaminant levels be periodically monitored (ITRC 2007).

Building Mitigation Systems

Building mitigation systems are systems that reduce intrusion of vapors into buildings.

- *Qualifications for Design and Installation.* These systems must be designed and installed by parties who meet the qualifications of the regulatory agency having jurisdiction and who have relevant expertise. Very few design teams or contractors have this expertise in-house, so most rely on specialized environmental consultants and mitigation contractors. Requirements for design, installation, and performance testing of vapor intrusion mitigation systems vary widely by jurisdiction, so it is important to involve the appropriate regulatory agency early in the design process.

- *When to Address Vapor Intrusion*. Where the need for mitigation is a possibility, it is cheaper and more effective to incorporate the system in the original design and construction rather than to retrofit it after the building is built and vapor concentrations are tested. The need for vapor intrusion control needs to be considered early in design, when other design elements may be modified to potentially eliminate the need or reduce the cost.

- *Comparison with Radon Control*. Vapor intrusion mitigation technologies are largely adapted from radon control strategies. Bringing indoor vapor concentrations below action levels commonly requires reductions of two or three orders of magnitude (and sometimes more), in contrast to the one to two orders of magnitude typically required to bring radon concentrations below action levels. To achieve these larger reductions, it may be necessary to combine several mitigation techniques or to design and install systems to exacting standards.

- *Active Soil Depressurization (ASD)*. ASD (sub-slab or sub-membrane) is generally the most reliable and most frequently employed vapor intrusion control technology. ASD systems use one or more suction fans to depressurize the soil in contact with the building. This ensures that the predominant direction of air leakage across those portions of the building envelope in contact with the ground is from the building into the soil rather than from the soil into the building. Soil gas is drawn through vent risers by the suction fan(s) and released above the building, where it can be diluted by ambient air. ASD systems need to be combined with sealing of joints, cracks, and penetrations and sealing of below-grade walls. In new construction, ASD is usually combined with two additional elements to enhance its effectiveness: 1) a "venting layer" of gas-permeable aggregate and/or a network of perforated pipe and 2) a gas vapor barrier above the venting layer. Where the amount of vapor intrusion that will occur is uncertain, it may make sense to install a passive venting system with a gas vapor barrier and add the fan(s) to convert to ASD if post-construction testing shows it to be necessary. Passive systems should always be designed to be readily converted to active systems. In general, use of gas vapor barriers alone without passive venting is not recommended.

Strategy 3.4

- *Building Pressurization*. Building pressurization can be the best choice for sites with wet or low-permeability soils where ASD is not effective. It can also be a viable alternative to ASD for other buildings if the HVAC system has the capability to reliably maintain positive pressures in all ground-contact rooms. However, pressurization for vapor intrusion control requires a level of quality assurance in design, construction, operation, and maintenance that goes beyond that associated with building pressurization control for most other purposes. It is also likely to increase energy use more than an ASD system. In cases where the building owner is not the party legally responsible for mitigation, the owner may be reluctant to employ the HVAC system for vapor intrusion mitigation control. For these reasons, building pressurization has not been widely used as a vapor intrusion mitigation strategy to date (Folkes 2008).
- *Other Techniques*. Positive sub-slab pressurization, indoor air treatment, and "intrinsically safe building design" may be viable alternatives or supplemental mitigation techniques in certain circumstances.

Strategy 3.4

Vapor Intrusion Mitigation to Accelerate Redevelopment of a Brownfield Site

Figure 3.4-A Gas Vapor Barrier Being Sprayed onto Geotextile Base Fabric (Additional photographs from this project are shown in Figures 3.4-D, 3.4-E, and 3.4-G.)

Photograph copyright CETCO.

A big-box retailer on the East Coast wanted to build a store on a brownfield site that had been occupied by a chemical manufacturing plant for more than 50 years. Both the soil and the groundwater were contaminated with a number of VOCs. The primary chemicals of concern for vapor intrusion were xylene, ethylbenzene, and chlorobenzene.

Site remediation included excavation and removal of source-zone soils and air sparging with soil vapor extraction for long-term in situ treatment of the shallow groundwater in the overburden and weathered upper bedrock. Institutional controls were established limiting the future use of the site and requiring site cover.

Air sparging with soil vapor extraction was expected to take several years to reduce concentrations to levels that would allow redevelopment without additional engineering controls for vapor intrusion. Further, the air sparging process promotes volatilization of the chemicals of concern and tends to pressurize the subsurface in the treatment area, so it can temporarily increase the risk of vapor intrusion. Several approaches were considered to mitigate this risk and enable earlier redevelopment. The approach ultimately selected combined a passive sub-slab venting system and spray-applied gas vapor barrier (Figures 3.4-A and 3.4-B) with ongoing monitoring and contingency plans that could be implemented if monitoring results exceeded regulatory action levels.

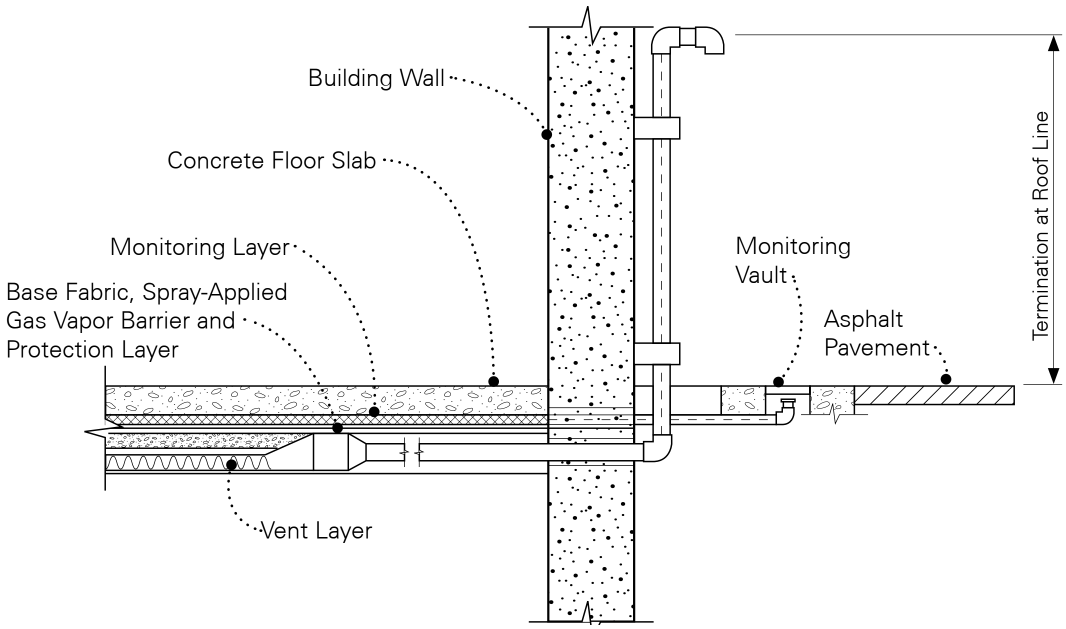


Figure 3.4-B Cross Section of Venting Layer, Gas Vapor Barrier, and Monitoring Layer

Adapted from an image copyright CH2M HILL and The Dow Chemical Company (Rohm and Haas is a wholly owned subsidiary of The Dow Chemical Company).

Strategy 3.4

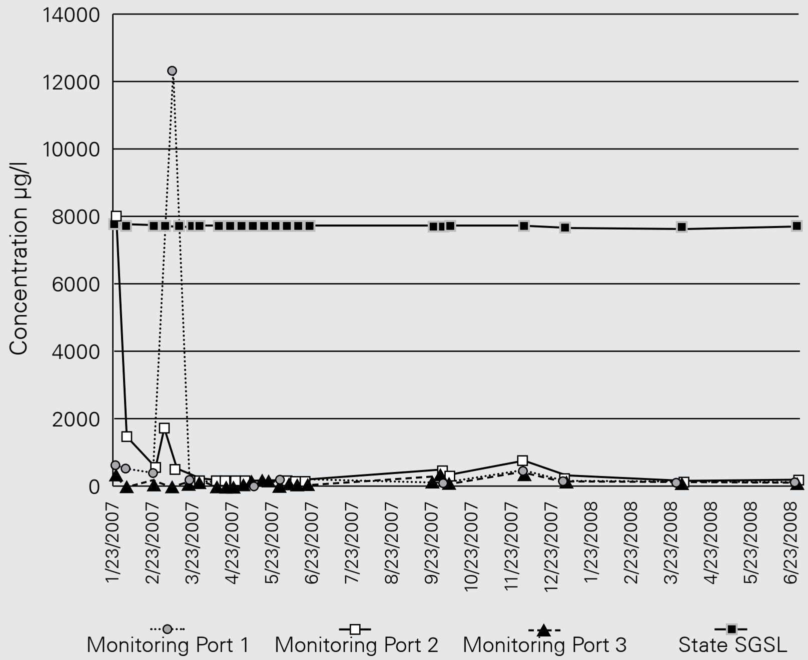


Figure 3.4-C Concentrations of Xylene in the Air Samples from the Monitoring Layer (The graph covers an 18-month period starting with the initial samples [Lowe et al. 2009].)

Adapted from an image copyright CH2M HILL and The Dow Chemical Company (Rohm and Haas is a wholly owned subsidiary of The Dow Chemical Company).

Case study courtesy of CH2M HILL (Lowe et al. 2009) and CETCO Liquid Boot Co.

For this project, monitoring of indoor air was deemed problematic since both the building finishes and some of the products sold by the retailer might emit VOCs, including some of the chemicals of concern. The regulatory agency agreed to allow the remediator to monitor concentrations in a permeable monitoring layer installed above the gas vapor barrier and beneath the concrete foundation (Figure 3.4-B). Concentrations exceeding the state's soil gas screening levels (SGSLs) would trigger confirmatory sampling followed by execution of contingency plans. These included conversion of the passive venting system to an active system, temporary discontinuation of air sparging (while continuing soil vapor extraction), and more frequent sampling. Further contingency plans were available if the more frequent samples remained above screening levels.

Initial vapor concentrations in the monitoring layer were above the state's SGSLs for some compounds (Figure 3.4-C). In response, the monitoring layer was purged to remove any construction-related residuals, the air sparging system was temporarily turned off, soil vapor extraction was enhanced, and the venting layer was converted from passive to active operation by connecting it to the soil vapor extraction system. The frequency of monitoring was increased, and concentrations were observed to fall rapidly to well below screening levels. Since that time, the sampling interval has been gradually increased as concentrations have remained far below action levels.

The vapor intrusion mitigation system was successful in enabling redevelopment of this brownfield site well ahead of the schedule that would have been permitted with soil and groundwater remediation alone.

Provide Effective Track-Off Systems at Entrances

Dirt and moisture transported into a building on the footwear of its occupants can be a significant source of indoor pollutants because the dirt carries a variety of contaminants and, combined with the moisture, may foster the indoor growth of biocontaminants. Various contaminants of concern (CoC) have been identified in tracked-in dirt (including pesticides). Tracked in dirt and moisture also increases the need for indoor cleaning and thus indirectly degrades IAQ through the unnecessary release of contaminants associated with cleaning activities (see Strategy 5.3 – Minimize IAQ Impacts Associated with Cleaning and Maintenance). The best way to reduce the IAQ impact of these tracked-in pollutants is to develop effective barrier systems. Note that entranceways are also major pathways for outdoor airborne contaminants (including moisture) to reach building interiors and are thus critical zones for building pressurization strategies (see Strategy 2.3 – Maintain Proper Building Pressurization). As part of total entranceway design, track-off systems need to consider and accommodate pressurization strategies, including the use of revolving doors or two-door vestibules.

Barriers to tracked-in dirt begin with the approaches to the building itself and include appropriate selection of landscaping materials and plants. Since pesticides applied outdoors can be readily carried into the building on footwear, well-considered pest control strategies are also important (see Strategy 3.6 – Design and Build to Exclude Pests). To prevent dirt accumulation on footwear, well-designed and well-laid-out walkways using textured paving materials need to be selected. An effective building maintenance and cleaning strategy also needs to be included in the O&M documentation and training (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ) to ensure that building entranceways are kept clean and, to the extent possible, dry. Any landscaping materials that drop flowers or berries that can be tracked into the building need to be avoided near walkways.

Installation of effective dirt track-off (or walk-off) systems at all entranceways is an essential component of a building's IAQ strategy. Zones such as loading docks, receiving areas, and garage entrances may not have the traffic density of main entrances but can be dominant contributors to tracked-in contaminants within the building and therefore need to be carefully considered.

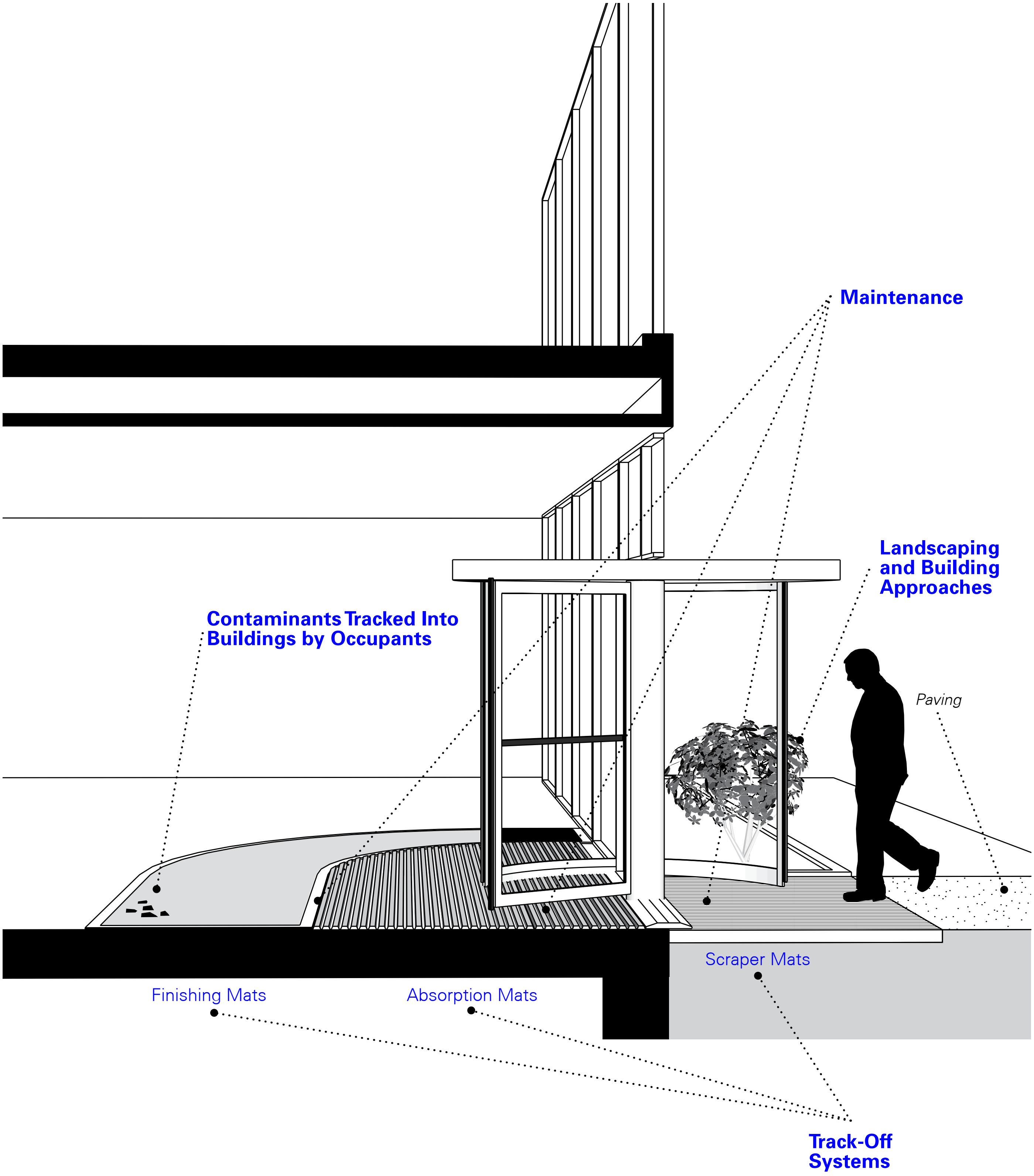
Proper design of dirt track-off/entry mat systems needs to include specific combinations of mat materials, textures, and lengths. A three-part system is generally recommended: an initial scraper section installed outside building entrances serves to remove loose dirt and water (or snow), stiff-bristled adsorption mats located immediately within the building (also called *trapper* or *wiper* sections) remove additional dirt and moisture via brushing/scrubbing action, and final finishing (or *duster*) mats complete the process by removing particles left after the scraper and adsorption mats.

Final design of the track-off system needs to consider traffic loads and aesthetics as well as local environmental/climate conditions. Systems installed in snowy climates typically require greater lengths of scraper mat, while in rainy locations longer adsorption portions are needed. Muddy locations mandate the need for extended lengths of all three track-off zones.

In addition to decreasing the amount of outdoor contaminants brought into the building, track-off systems also provide the additional economic benefit of increased life expectancy for flooring materials by reducing dirt abrasion of flooring materials.

Strategy 3.5


3.5


Maintenance
Landscaping and Building Approaches
Contaminants Tracked Into Buildings by Occupants
Paving
Scraper Mats
Finishing Mats
Absorption Mats
Track-Off Systems

Strategy 3.5

Design Elements Lead to Effective Track-Off System

In the fall of 1996, The H.L.Turner Group Inc. embarked on the design and construction of its new corporate offices in Concord, NH. The intent of the design included many features to enhance IAQ and energy efficiency. Site constraints dictated that the main entrance to the facility (Figure 3.5-A) be located in a predominantly northeastern exposure. Given the normal New England winters, the entrance and flooring system design became an important consideration for fostering good IAQ and ease of maintenance.

Key design elements evolved to include:

1. *Heated Walkway*. Thermostatically controlled heat, provided by means of a walkway heat loop supplied by the hydronic system, eliminates the use of sand and ice melting chemicals at the north entrance. Maximum efficiency is achieved by positioning this loop just before the heating water returns to the condensing boilers.
2. *Canopied Entrance*. There is a canopied entrance with the first aluminum track-off grating element located just outside the vestibule entrance.
3. *Vestibule Entrance*. The vestibule entrance has a hard surface surrounding the second track-off grating, this one with a rubber matting cover and a dirt catching pit below. The pit is exhaust-vented to the building exterior.
4. *Removable Track-Off Matting*. The third track-off element is located just inside the vestibule entrance. The length of this matting can be adjusted seasonally.
5. *Entrance Area Flooring*. Hard surface flooring is located in the gallery area between the third track-off mat and the primary flooring.

Figure 3.5-A Entrance Design with Effective Track-Off System Features
Photograph copyright The HL Turner Group, Inc.

The three track-off areas and hard surface gallery area provide a total of 30 ft (9 m) of walk-off distance before the primary flooring is reached. The soft non-flow-through textile primary flooring was selected to facilitate dirt removal and easy maintenance. Daily vacuuming includes a central vacuum system that is exhausted to the outdoors after the dust is removed from the airstream.

Results. Carpet dust sampling conducted a few years after occupancy revealed extremely low levels of extractable dust (less than 0.017 oz/ft2 [5 g/m^2]) except for the area immediately adjacent to the entryway, where it was 0.020 oz/ft^2 (6.1 g/m^2). Visible staining of the surface is minimal, requiring only annual extraction to remove surface staining in heavily trafficked corridors.

3.6

Design and Build to Exclude Pests

Buildings may experience infestations from a variety of creatures. These include an assortment of mammals, insects and arthropods, rodents, birds, and fungi. These creatures can bring about both infectious diseases and allergic reactions in occupants, produce unpleasant noise or odors, cause emotional distress to occupants, damage the building fabric, or bring about the use of pesticides, which results in pesticide exposure to building occupants. Preventing and controlling infestations is therefore of paramount importance.

"Architecture plays a key role [in infestation prevention and control] because design features alone may provide exterior shelter for and/or allow access by pests to interiors" (Franz 1988, p. 260). Building managers report that many new buildings with innovative, energy-efficient designs have pest problems that could have been reduced or avoided with better planning at the design and build stage (PCT 2008; Merchant 2009). In addition, landscape design, construction errors, and poor construction site management can increase the risk of pest colonization of a new building after infestation.

It is possible to design and construct buildings that are resistant to colonization by pests. All colonizing organisms need a point of entry to the building; sources of food and water within or near the building; protected locations where they can eat, rest, and find a mate (called harborage); and passages that allow them to safely move among entry, food, water, and *harborage* areas. Left to their own devices, a population of colonizing organisms will expand until it comes to equilibrium with the available food, water, and harborage. In ecological terms, this is referred to as the *carrying capacity* of the building.

To design a building resistant to colonization requires the following steps:

- *Identify Pests of Concern*. Identify the organisms likely to colonize the building based on its proposed location. For example, American cockroaches, German cockroaches, Norway or roof rats, and house mice are likely in many urban locations.

- *Block, Seal, or Eliminate Pest Entry Points*. In the proposed building design, identify the likely entry routes and seal the building enclosure to prevent pest entry. Examples include gaps around doors and windows, between the foundation and the upper portion of the building, or around utility pipes, conduits, or wires.

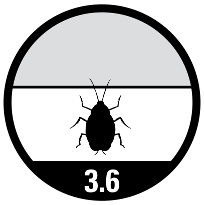
- *Reduce Risk of Pest Dispersal Throughout Building*. In the proposed building design, identify the likely passageways pests could use to move freely between food or water resources and harborage and eliminate, block, or seal off these routes. This includes gaps around floor and ceiling joists; penetrations in walls, floors, and ceilings; or openings around shafts and chutes.

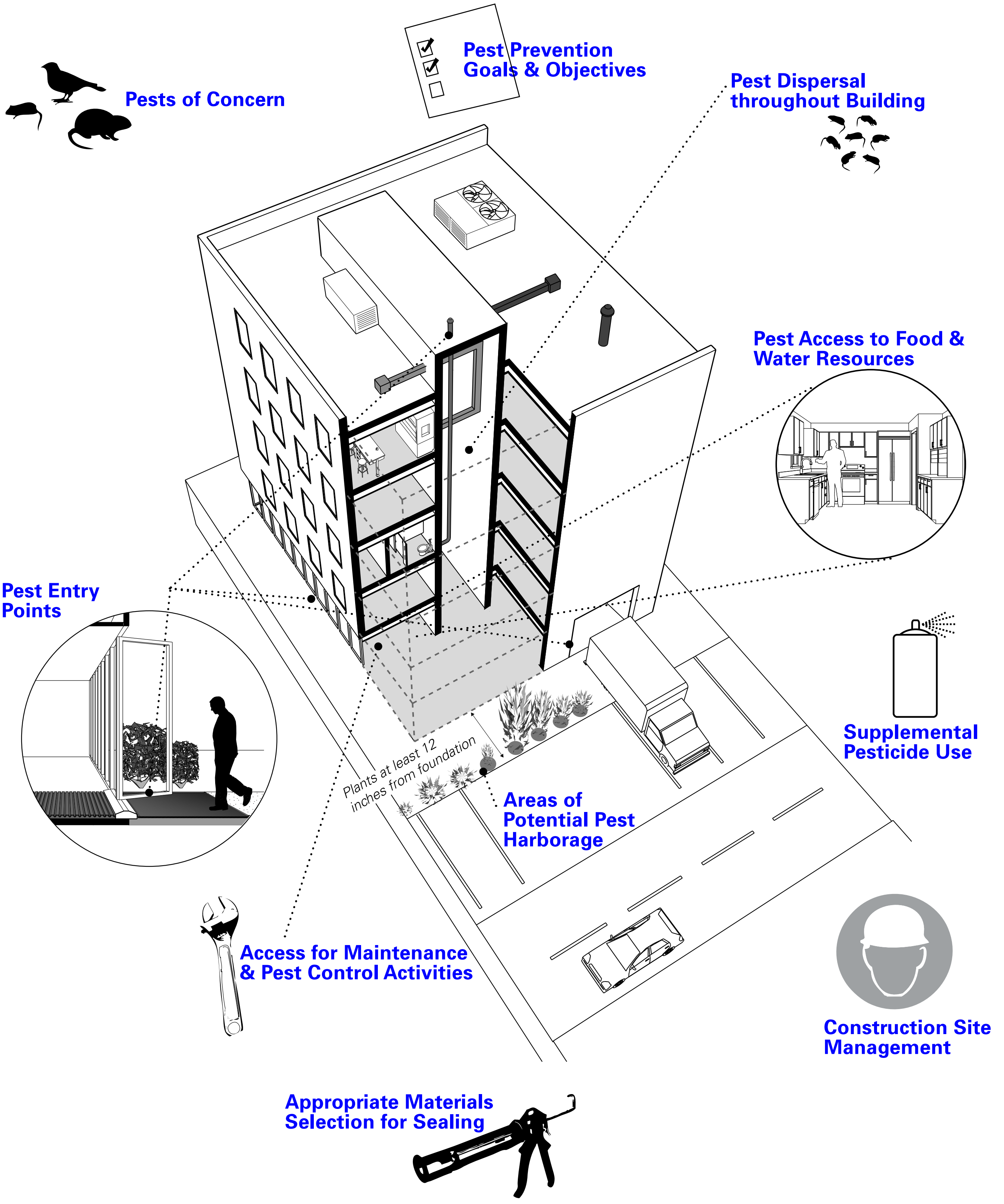
- *Reduce Pest Access to Food and Water Resources*. In the proposed building design, identify potential sources of food and water that pests might exploit and take steps to block access to these areas. For example, kitchens and garbage handling areas are likely to provide food for many different organisms.

- *Limit Areas of Potential Pest Harborage*. In the proposed building design, identify and eliminate or block access to areas where pests might find harborage. This includes spaces behind brick veneers or sidings; wall cavities, porches, attics, or crawlspaces; plants or trees planted near the building; and specific architectural features.

- *Provide Access for Maintenance and Pest Control Activities*. Since it may not be feasible to eliminate or seal all potential entry points, passageways, voids, and

Strategy 3.6


3.6


Pests of Concern
Pest Prevention Goals & Objectives
Pest Dispersal throughout Building
Pest Access to Food & Water Resources
Pest Entry Points
Supplemental Pesticide Use
Plants at least 12 inches from foundation
Areas of Potential Pest Harborage
Access for Maintenance & Pest Control Activities
Construction Site Management
Appropriate Materials Selection for Sealing

harborage sites within a structure, good building design must provide accessibility to such areas for maintenance, cleaning, and possible pest control activities.

- *Appropriate Materials Selection for Sealing*. Sealing or blocking pest access to potential entry points, food and water resources, and harborage sites must be done using materials and methods that are appropriate for the organisms identified as likely colonizers in the neighborhood of the building site.

- *Supplemental Pesticide Use*. It may be necessary to consider the use of pesticides as part of building construction. For example, in some areas of the country, a termiticide or bait system may be needed (or required by law) in order to prevent termite colonization.

- *Construction Site Management.* Since pest infestations can begin as a new building is being erected, pest control needs to be integrated into construction site management to reduce the potential for pest colonization.

Adding Pest Control Features to Building Design without Adding Cost

Early in the design phase of a housing complex built in New York City from 2004–2006, an IAQ expert recommended incorporating pest control (in addition to other IAQ improvements) into the design of four seven-story low-income multi-family buildings (Figure 3.6-A). Excited about the concept, architect Chris Benedict took on the task of convincing the buildings' owner to approve the plan, which was designed to target rodents, pigeons, and cockroaches.

Pest control features included:

- slab on grade, with all penetrations from below grade for services and plumbing sealed,
- boiler rooms and makeup air louvers placed on the roofs,
- pigeon-resistant lintels over windows,
- boric acid treatment in cavity walls surrounding plumbing chases,
- trash rooms on each floor with the trash chute separated from living space by air barrier construction, and
- floor drains with positive pitch to drains in mechanical rooms where the water could accumulate.

The design team was able to construct the buildings with the pest control features (and many other elements for good IAQ) for the same per-square-foot cost as a typical building without such features. They did this through innovative designs that reduced costs in other ways. For example, for the brick veneer the designers used stainless steel brick ties and created a novel type of window detail to accommodate expansion and contraction instead of installing very expensive steel relieving angles every couple of floors. The window design also eliminates the entry of rainwater without the use of exterior caulking, greatly saving on maintenance costs. The elimination of the relieving angles also means there are no thermal short-circuits in the insulation. Another cost-saving aspect of the buildings is the location of the boiler rooms on the top floor, which greatly reduced the expense of long chimneys and has the added benefits of eliminating potential pest passageways and freeing up area on the lower floors.

3.6

Strategy 3.6

The exterior walls of the building are made with concrete plank and CMU construction, making a durable structure that is relatively easy to seal for pest exclusion (Figure 3.6-B). The CMU makes a vapor barrier, drainage plane, and pest barrier. In addition, individual apartments were compartmentalized to reduce unit-to-unit pest migration. The buildings' manager reports that the pest control measures appear to be very successful, as they have had no pest infestations to date.

Figure 3.6-A Exterior of one of the buildings in the complex.

Figure 3.6-B Exterior Wall of Parged CMU

Photographs courtesy of Terry Brennan.

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.

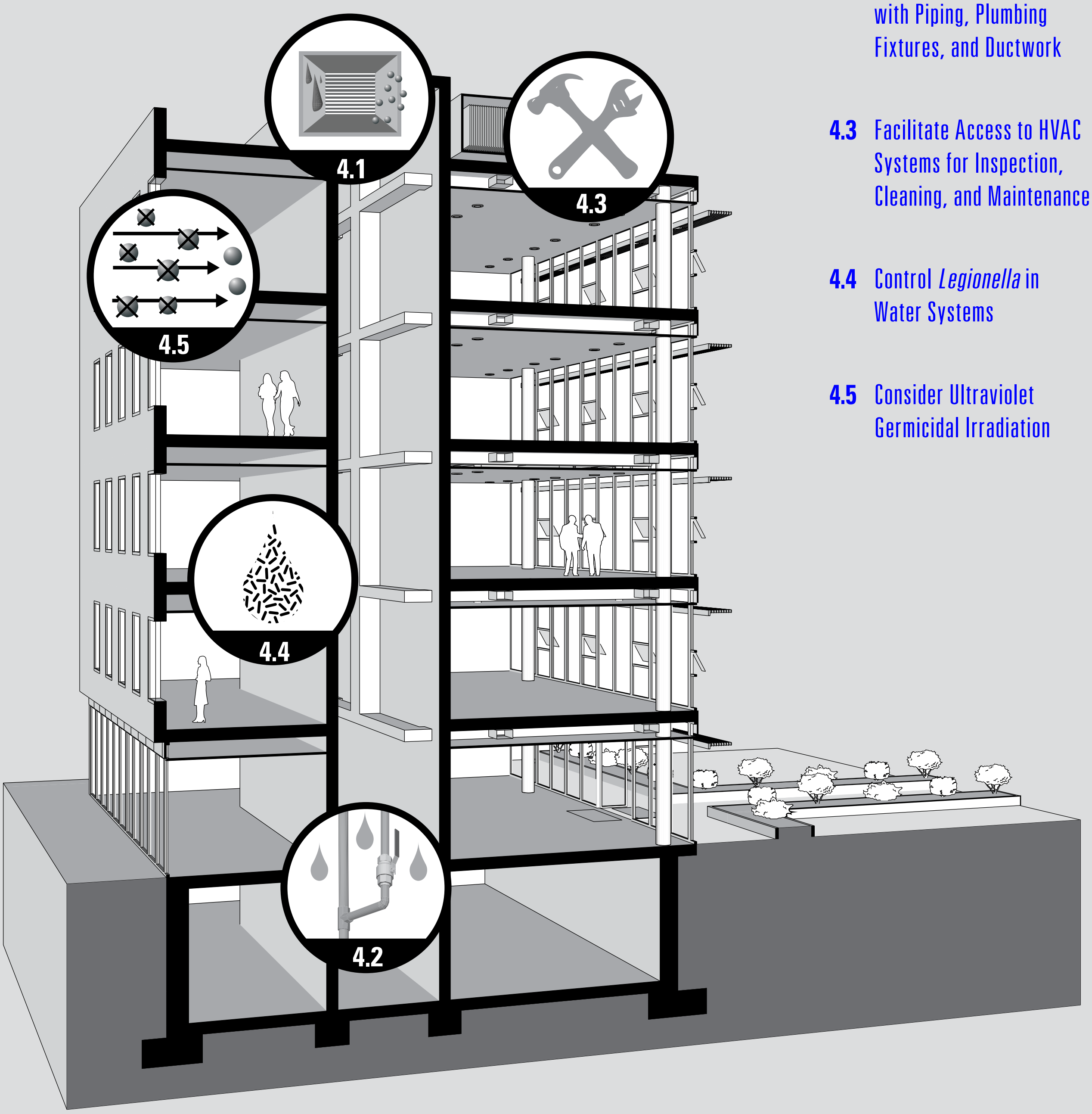
- Moisture and dirt in air-handling systems provide an environment for microbial growth. Strategy 4.1 – Control Moisture and Dirt in Air-Handling Systems provides techniques to limit rain and snow entry, manage condensate from cooling coils and humidifiers, and keep airstream surfaces clean and dry.
- 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

4.1

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.

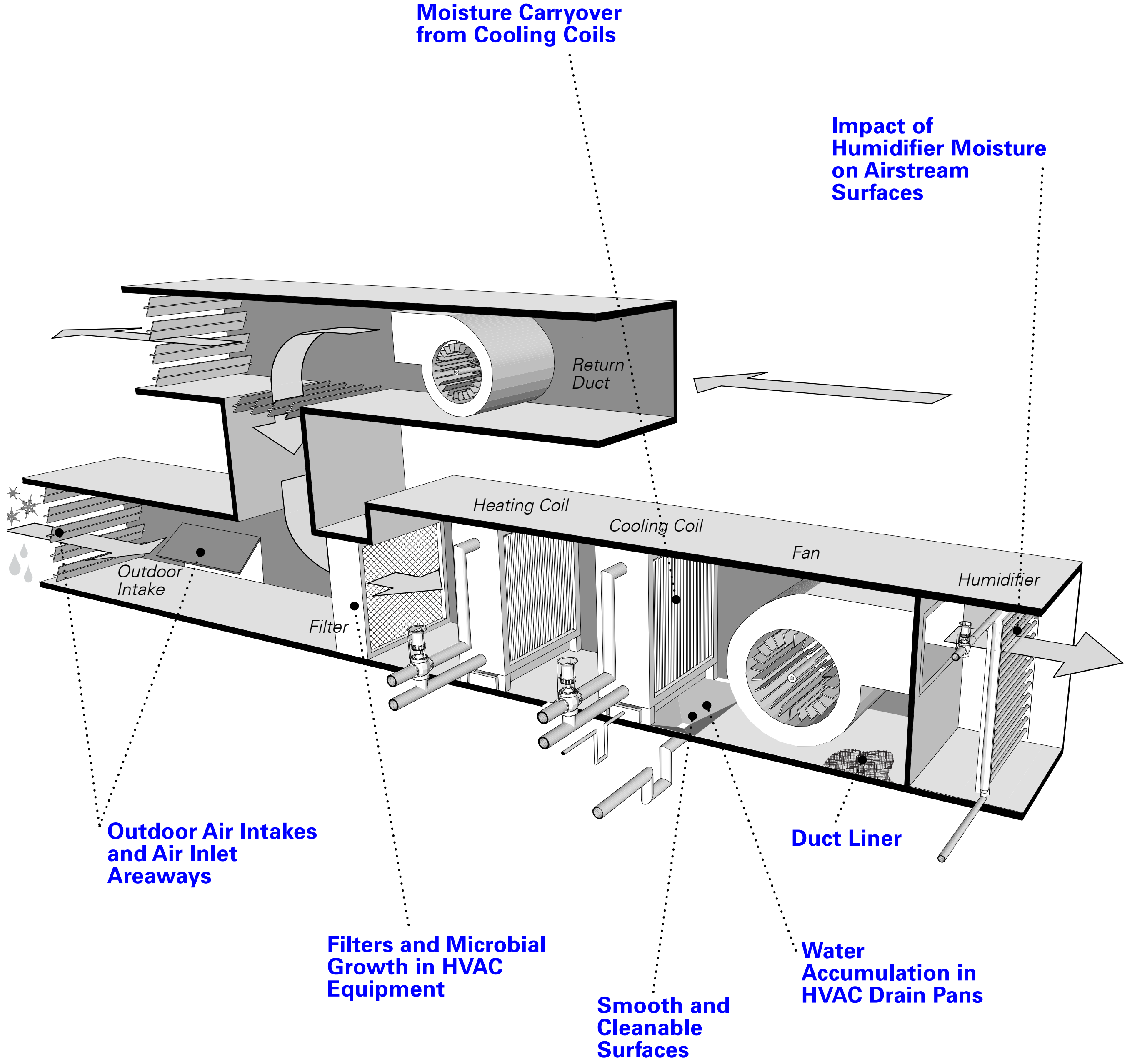
- *Moisture Carryover from Cooling Coils*. If the air velocity is too high over part of the coil section (e.g., due to localized accumulation of dirt or poor design), water droplets can and will wet downstream surfaces.

- *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.

Strategy 4.1



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

4.2

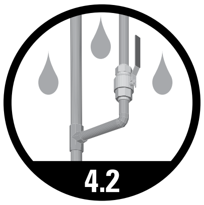
Mold growth can occur on cold water pipes or cold air supply ducts with inadequate thermal insulation or a failed vapor retarder and result in material damage or significant IAQ problems leading to potential adverse health impacts on occupants. Liquid water from condensation can damage materials nearby 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.

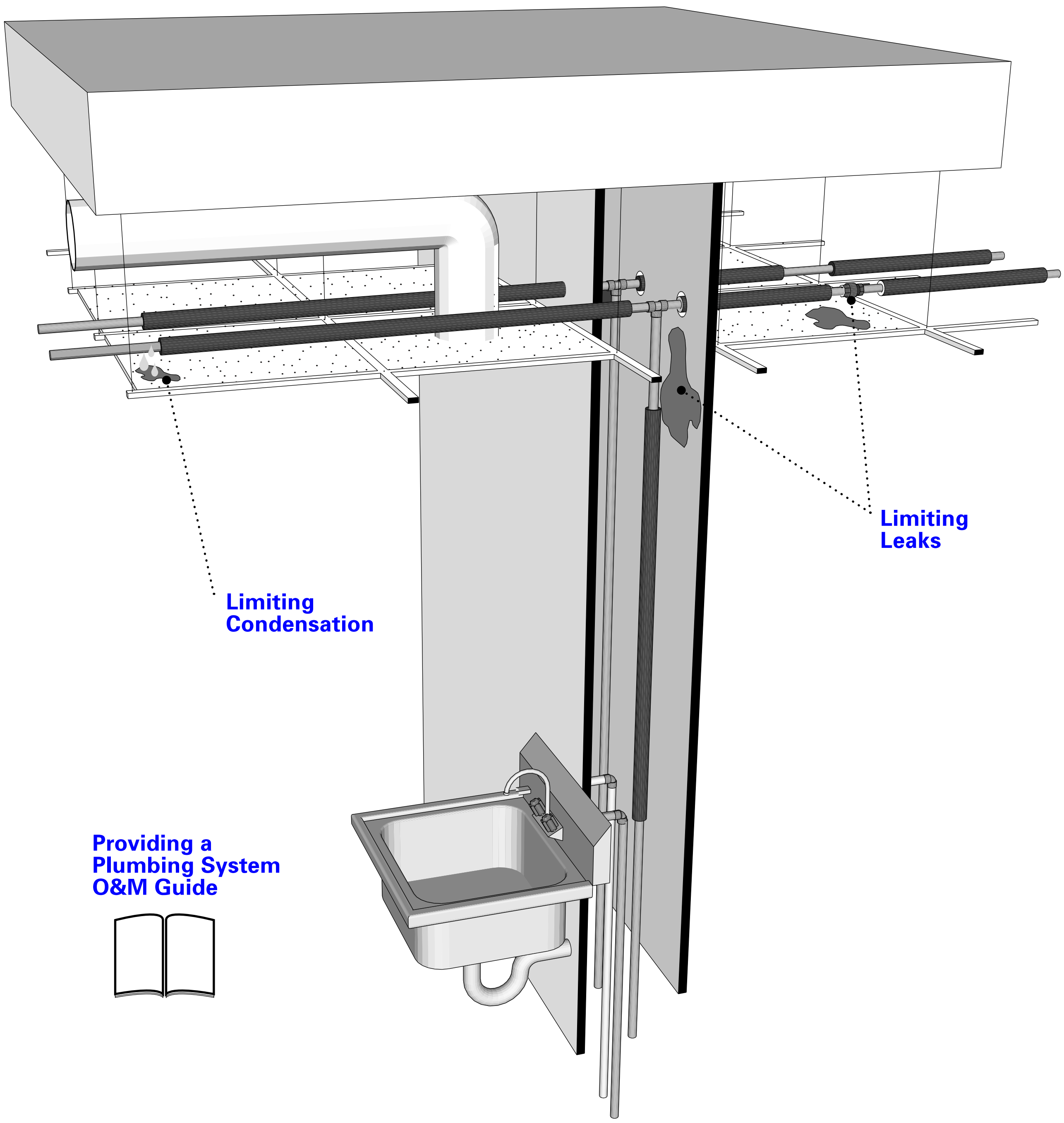
Condensation Associated with High Dew-Point Temperature around Chilled-Water Pipes

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.

Strategy 4.2




Limiting
Condensation
Limiting
Leaks
Providing a
Plumbing System
O&M Guide

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

4.3

Good maintenance of building systems, especially the HVAC system, is a foundation for good IAQ during occupancy. Therefore, during design and construction it is critical that access to the HVAC system for periodic inspection, routine maintenance, and cleaning of the air-handling systems is provided. As HVAC systems become more complex, the ability to access the system, monitor air cleaning, and validate monitor/sensor performance is an increasingly important aspect of building O&M.

Access in Design Documents

Initial design decisions regarding the type and location of the HVAC system can both limit access and increase maintenance problems. Centralized systems require fewer access points than a network of smaller units. Units installed in inaccessible spaces can provide significant barriers and encourage deferred or neglected inspection and maintenance. Wherever located, the space/room needs to be sized to not only accommodate the equipment but also provide adequate clearance distances that take into account door swings, space for personnel, and movement of tools and materials. Lastly, the design needs to allow adequate space for replacement of major equipment required over the life of the building.

Coordination with Trades

During construction, the installation of HVAC systems and components needs to be carefully monitored and managed to ensure that clear access is maintained. This includes coordinating with the installation of other building systems, reviewing subcontractor submittals, and assessing the impact of field changes.

Unanticipated Access Requirements

New situations arise over the life of a building that may require new access points. These points can be either one-time openings that can then be sealed or newly engineered openings that will allow for repeated access. The specific need should be evaluated before any new access points are established.

Strategy 4.3

Unanticipated Access Requirements

Compliance with SMACNA Standards

Repeated Access

Access in Design Documents

Locations that Facilitate Access

Minimum Clearance Distances

Critical AHU Components

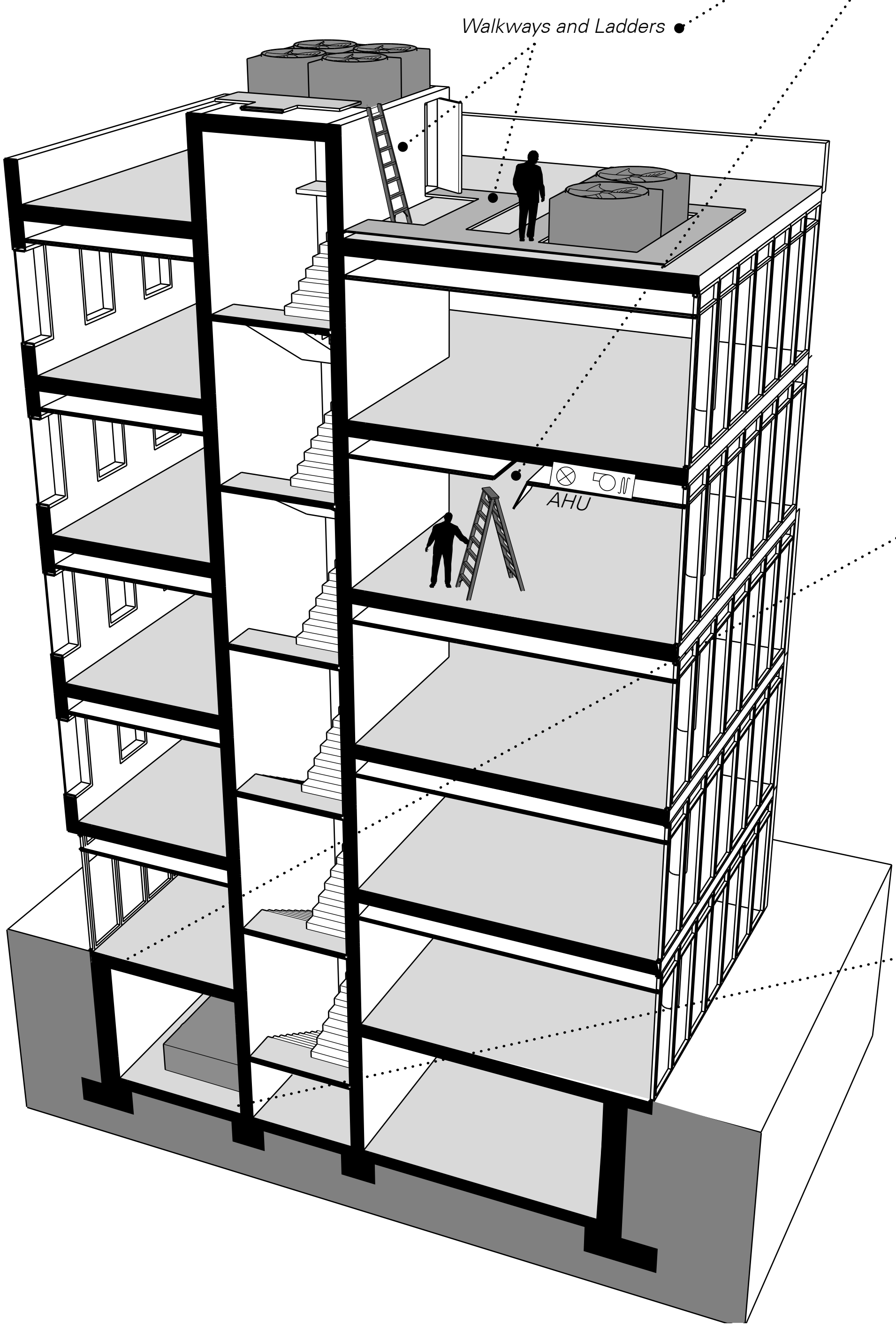
Air Distribution System

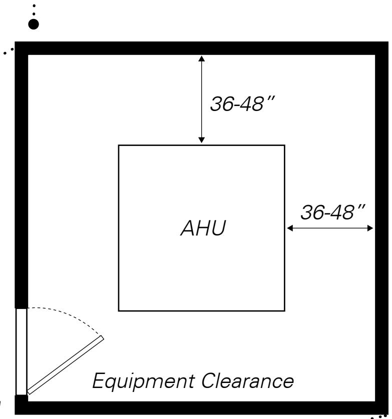
System Balancing and Monitoring Access

Terminal Equipment

Electrical Code Access Criteria

Access Door/Panel/View Port Requirements





Access During Construction

Coordination with Trades

Review of Submittals

Field Changes

Monitoring Installations

Strategy 4.3

Restricted Above-Ceiling Access Compromises Maintenance

Figure 4.3-A Access Door to Systems

Figure 4.3-B Above-Ceiling System

Figure 4.3-C System Location Limits Access

Figure 4.3-D All System Components not Readily Accessible

The photographs in this case study (Figures 4.3-A through 4.3-D) illustrate how an above-ceiling installation can significantly compromise access, impede maintenance, and compromise IAQ. In this installation, there were complaints of poor room temperature control and concerns about the rate of outdoor airflow being provided to the space by the fan-coil unit. First, a ladder is required simply to get into the space above the ceiling where the fan-coil unit is located. Notice in Figure 4.3-B that there is no plywood across the metal ceiling joists to support the weight of a technician. The technician had to procure a piece of plywood that would fit through the access door and lay it across the joists in order to access the outdoor air duct for flow measurement and access the unit to verify proper system and component operation. In addition, the narrow plenum space provides a very cramped work area that prevents reasonable access to key components of the system. It was found that the outdoor air damper was not actuating correctly. This allowed too much outdoor airflow to the unit, which did not have the capacity to handle the extreme summer heat and humidity or the extreme winter cold; this caused the space temperature control problems. The balancing dampers for the two outlets (visible in the ceiling near the glass block wall and door in Figure 4.3-A) could not be accessed, which prevented the proper proportioning of the airflow. Maintenance on such installations is frequently ignored or postponed, which can lead to significant operation and IAQ problems.

Photographs courtesy of Jim Hall.

4.4

Control *Legionella* in Water Systems

Legionella are bacteria normally present in aquatic environments such as rivers and lakes. These bacteria can also be present in man-made water systems, where they can multiply or grow and potentially cause illnesses known as Legionnaires' Disease and Pontiac Fever. Legionnaires' Disease is a lung infection caused by inhalation of mist or water droplets containing the bacteria. Legionnaires' Disease can be fatal. Approximately 18,000 cases of Legionnaires' Disease occur annually in the United States (Squier et al. 2005). Case fatality rates are approximately 20% for community-acquired Legionnaires' Disease and 20%–40% for hospital-acquired disease, which translates into an annual fatality total of 4,000 to 5,000 (Squier et al. 2005; Benin et al. 2002). *Legionella* can grow in most man-made aquatic environments such as cooling towers, potable water systems including showers and sinks, whirlpool spas, humidifiers, vegetable misters, and decorative water fountains.

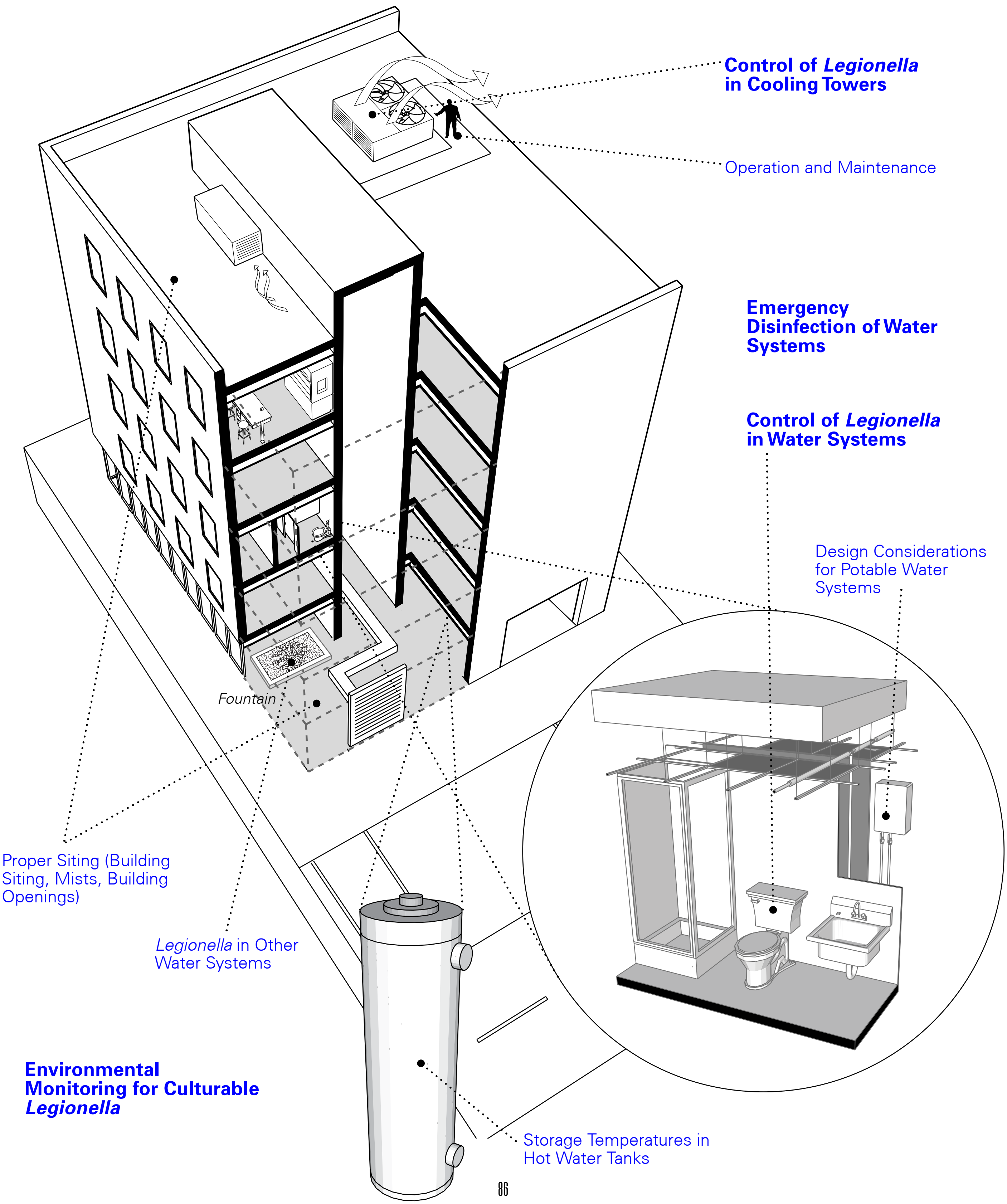
Drift from Cooling Tower Travels ~330 ft (~100 m)

Figure 4.4-A Cooling Tower Found to be the Source of Legionnaires' Disease in Nearby Building

Photograph copyright Janet Stout, Special Pathogens Laboratory.

The drift from the cooling tower shown in Figure 4.4-A travelled approximately 330 ft (100 m) and was implicated as the source of Legionnaires' Disease in three people at a nearby building. The water in the cooling tower basin, which had been treated with biocide and appeared quite clean, was heavily colonized by *Legionella pneumophila* serogroup 1.

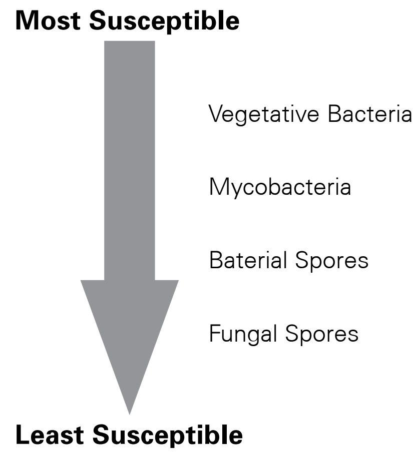
Strategy 4.4


Control of *Legionella* in Cooling Towers
Operation and Maintenance
Emergency Disinfection of Water Systems
Control of *Legionella* in Water Systems
Design Considerations for Potable Water Systems
Fountain
Proper Siting (Building Siting, Mists, Building Openings)
Legionella in Other Water Systems
Environmental Monitoring for Culturable *Legionella*
Storage Temperatures in Hot Water Tanks

Consider Ultraviolet Germicidal Irradiation

Ultraviolet germicidal irradiation (UVGI) has been used successfully for many years to control airborne infective microorganisms such as *Mycobacterium tuberculosis*, the bacterium that causes tuberculosis. Ultraviolet light at all wavelengths but especially at around 265 nanometers (NM) (modern ultraviolet lamps have an optimal discharge at 254 NM) damage the DNA of irradiated microorganisms (Martin et al. 2008). Ultraviolet light emitted and localized in the upper portion of room air (referred to as *upper-air UVGI*) has been used for controlling tuberculosis, especially in poorly ventilated or crowded indoor spaces where other interventions such as increasing HVAC outdoor air ventilation rates or raising filtration efficiency are not practical (Nardell 2002; Nardell et al. 2008). Droplet nuclei[1] from infected occupants in a room can migrate on air currents into the upper (room) air to be inactivated by UVGI from lamps along upper portions of walls. Inactivation of airborne microorganisms depends on both the intensity of the UVGI and the length of time that the particle containing the microbe is irradiated.

Figure 4.5-A Susceptibility of Microorganisms to UGVI
Adapted from ASHRAE (2008c), Chapter 11, Figure 2.



STRATEGY OBJECTIVE 4.5

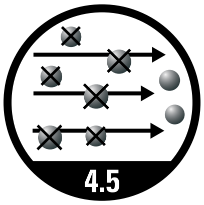
In addition to inactivating airborne microorganisms, UVGI directed at environmental surfaces can damage culturable microorganisms present or growing on the surface. Lower-intensity UVGI is effective for surface inactivation because irradiation is applied continuously. UVGI from lamps in AHU plenums has been used successfully to inactivate microorganisms present on airstream surfaces such as on cooling coils and drain pans (Menzies et al. 1999, 2003).

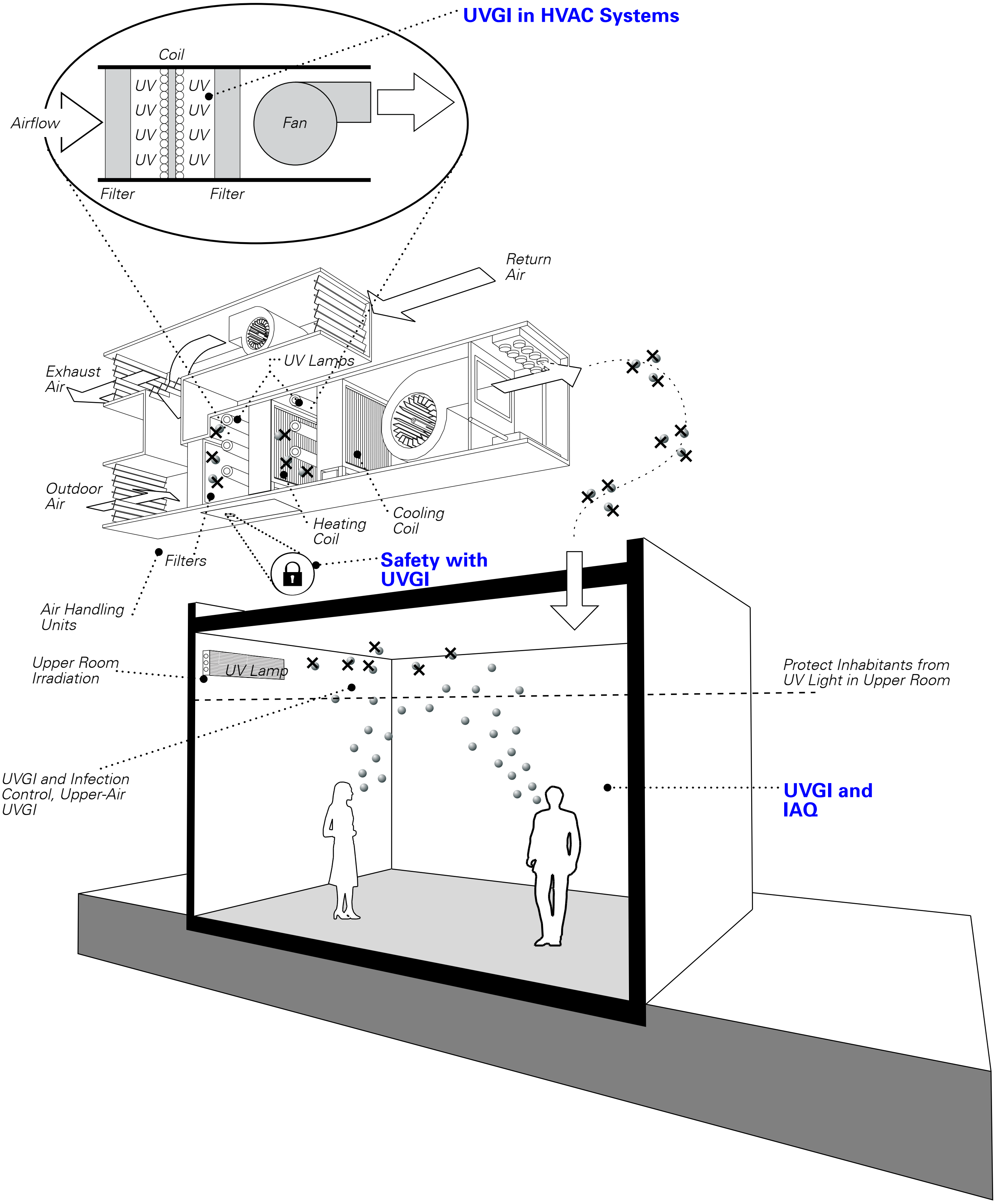
Vegetative bacteria including *Mycobacterium tuberculosis* are most susceptible to UVGI. Fungal and bacterial spores are more resistant to UVGI inactivation (see Figure 4.5-A). It needs to also be noted that viruses are among the most susceptible microorganisms to UVGI (Wells 1943; Perkins et al. 1947).

Studies by Menzies et al. (1999, 2003) have shown that occupants in several office buildings in Montreal reported a reduction in building-related symptoms when UVGI lamps in AHUs were turned on (as compared to time periods when the lamps in the same AHUs were deactivated.) Environmental microbiology tests in buildings studied by Menzies et al. determined that there was a significant decline in culturable bacteria and fungi on irradiated surfaces on cooling coils and in drain pans. However, these intervention studies did not find any decline in culturable fungi or endotoxins in workplace (office) air when UVGI lamps in AHUs were turned on. Air sampling in offices when UVGI lamps were turned on did show a slight, but not significant, decline in culturable bacteria on blood agar medium (not optimal for environmental bacteria). Thus, while Menzies et al. did find a significant decline in building-related symptoms associated with use of UVGI in

[1] Small particles originating from the human respiratory tract; as water evaporates, the particles become smaller and remain airborne because of their small aerodynamic size.

Strategy 4.5





STRATEGY OBJECTIVE 4.5

Strategy 4.5

AHUs, significant declines in airborne levels of culturable fungi and bacteria as well as endotoxins were not detected in the office workplace.

Studies by Bernstein et al. (2006) in Cincinnati homes with asthmatic children showed an association between decline in airway hyper-responsiveness and use of UVGI in home ventilation systems. However, significant declines in concentrations of airborne fungi and bacteria associated with UVGI intervention were not detected. Thus, while both Menzies et al. (1999, 2003) and Bernstein et al. did find positive benefits associated with use of UVGI in HVAC systems, the environmental cause(s) for the reduction in building-related symptoms remains obscure and a topic for future research.

The designer needs to be aware that the use of UVGI lamps in AHUs, ductwork, and upper air requires careful attention to safety considerations to prevent inadvertent exposure of people to ultraviolet light. For example, lockout/tagout procedures are necessary to prevent accidental turning on of UVGI lamps when facility maintenance personnel are working in AHUs. Refer to Chapter 16 of the *ASHRAE Handbook—HVAC Systems and Equipment* (ASHRAE 2008c) for a comprehensive review of safety considerations associated with the use of UVGI in buildings. Well designed upper-air UVGI systems have been used safely for many years (Nardell et al. 2008).

Limit Contaminants from Indoor Sources

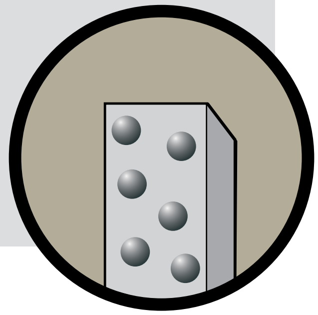
Many building materials, finishes, and furnishings emit compounds that can cause discomfort, irritation, or other more serious health impacts. These include organic compounds that can cause health effects ranging from eye, nose, and throat irritation to headaches and allergic reactions to organ damage 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.

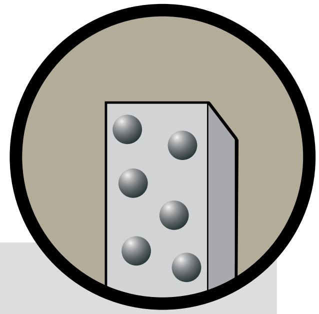
This Objective focuses on Strategies to reduce indoor contaminant sources. Additional Strategies to deal with contaminants generated indoors include capture and exhaust, filtration and air cleaning, and dilution ventilation. These are discussed under the following:

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

Objective 5



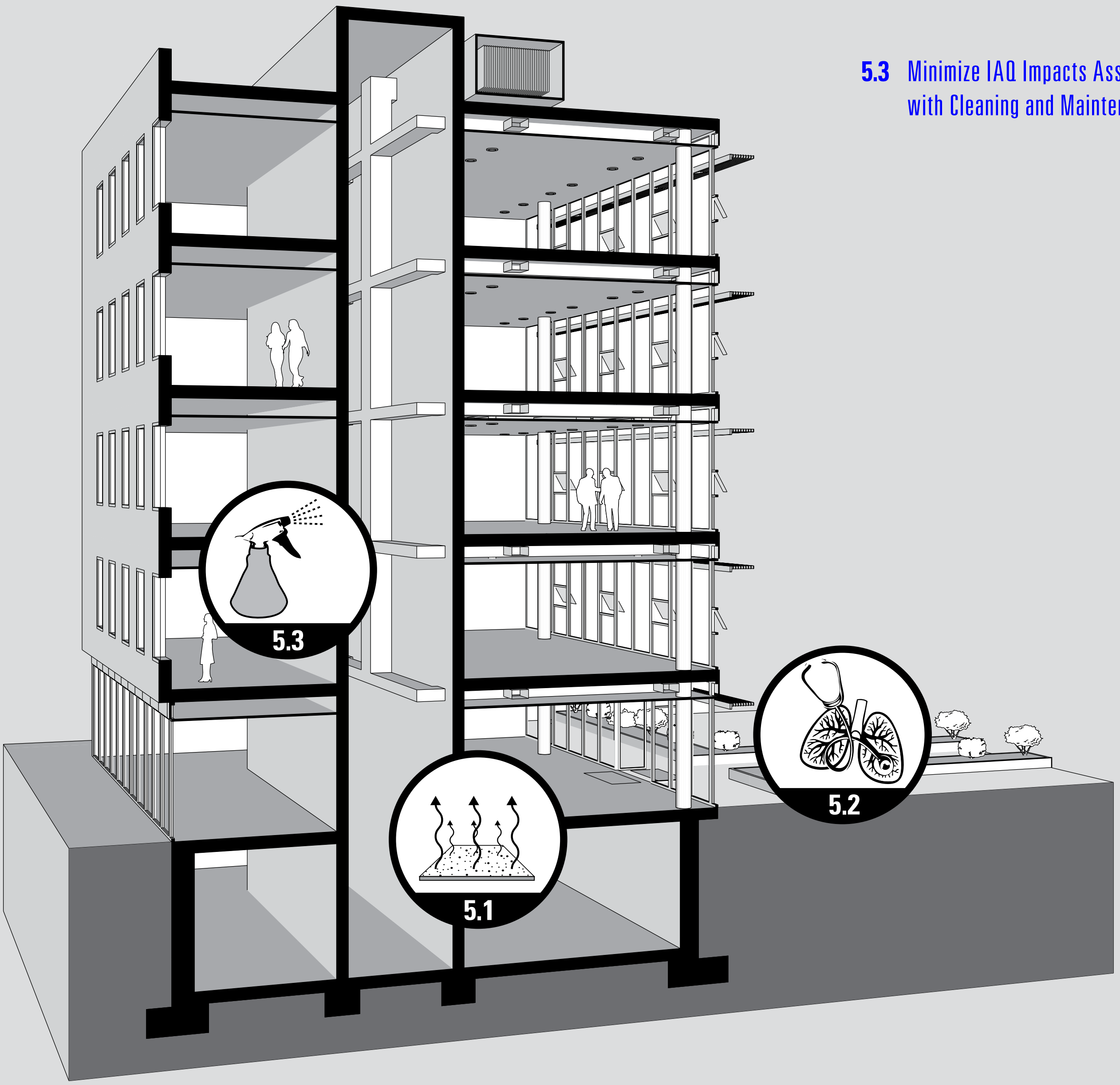
Objective 5



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

5.1

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

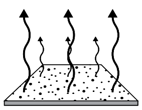
IAQ Guidelines, Standards and Specifications

Shades of Green - Environmentally Preferred Products

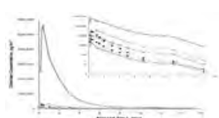
Product Information - Composition vs. Emissions

Emissions Behavior

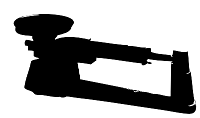
Emissions Data: Available Information



Emissions Testing



Emissions Databases



Manufacturer Supplied Information: MSDSs

Labels: Emissions-Based

Labels: Content-Based

Priority Materials/ Finishes/Furnishings

Architectural Coatings

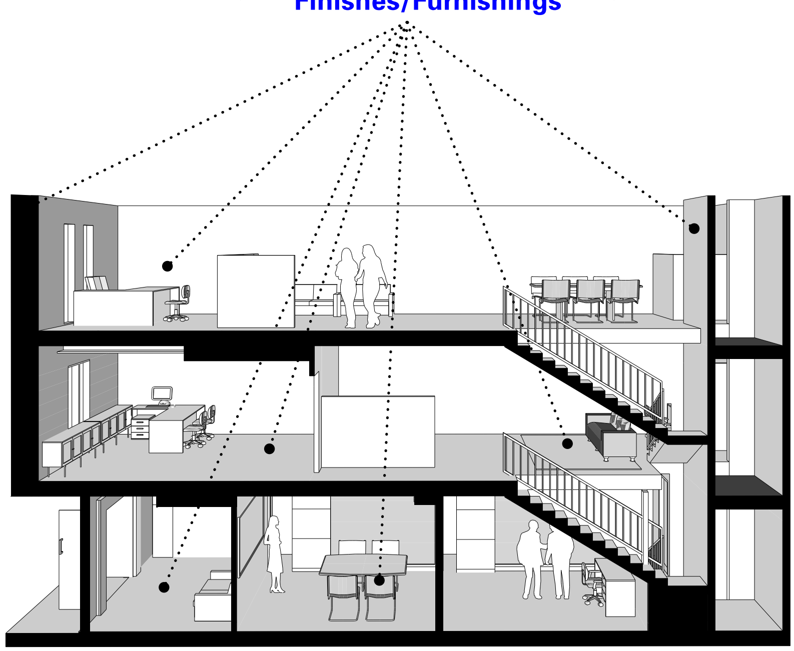
Flooring Materials

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

Strategy 5.1

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.

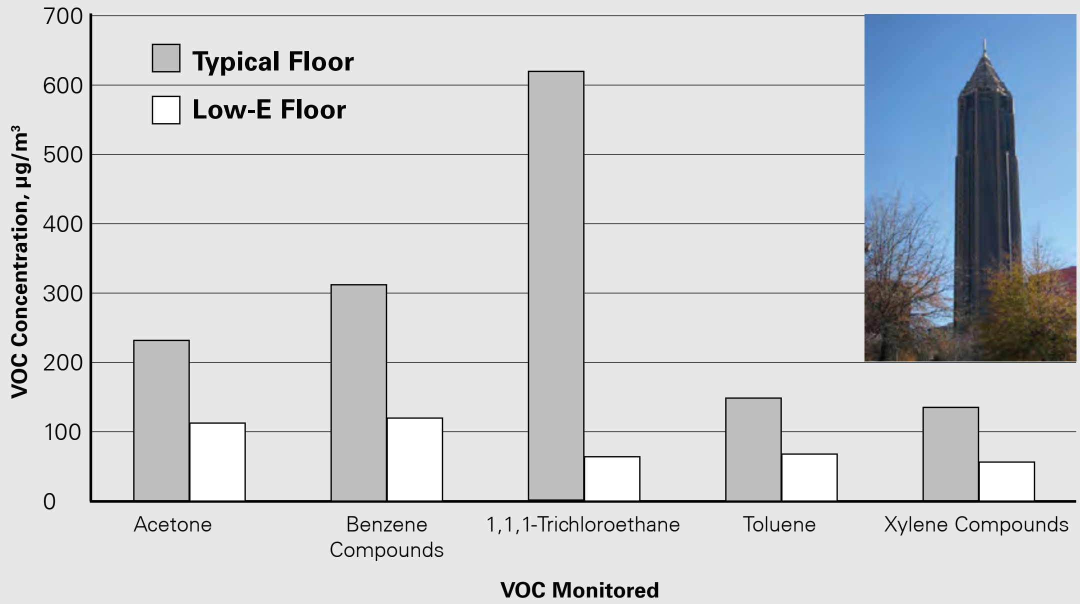


Figure 5.1-A Monitored VOC Levels
Data source: Milam (1994). Inset photograph courtesy of H.E. Burroughs.

Strategy 5.1

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.

Employ Strategies to Limit the Impact of Emissions

The first and most effective means to reduce the impact of material emissions is to employ selection strategies that limit the entry of high-emitting materials into the building (i.e., source control; see Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection). The products used in building construction and furnishing will still emit some level of contaminants, and certain materials with relatively high emissions may be unavoidable due to a lack of alternative products or due to emission-generating activities. To reduce the negative impact of these materials/activities on the indoor environment, the building design team needs to consider a variety of alternative strategies.

Control of Emissions through Use of VOC Barriers

Various coatings can be used to reduce or eliminate the emissions from underlying materials. These include laminates, veneers, and liquid-applied or dry powder coatings. Their effectiveness as barriers has been most extensively measured for reducing formaldehyde emissions and, to a lesser extent, controlling general VOC emissions. Emissions barriers for "hidden" surfaces and for exposed material edges can be particularly effective in controlling contaminant release.

Material Conditioning and In-Place Curing

Airing new materials in a well-ventilated, clean space prior to installation in a building can be an effective means of reducing the typically high emissions that characterize new materials. Off-site opening of wrapped or tightly packaged materials to facilitate this "conditioning" phase is an important aspect of this simple strategy. Products that have been formulated to undergo a curing process that will result in reduced contaminant emissions can be sought during material selection. This is particularly relevant for products such as caulks, sealants, and adhesives that must be applied in wet form and for which effective in-place curing can have greatest benefit.

Local Exhaust of Unavoidable Emissions

Where contaminant-generating equipment or activities can be localized in a specific area (such as with certain types of office equipment, kitchen/cafeteria operations, etc.), an effective strategy to limit the impact on IAQ is to provide local exhaust systems. Also see Strategy 6.2 – Provide Local Capture and Exhaust for Point Sources of Contaminants.

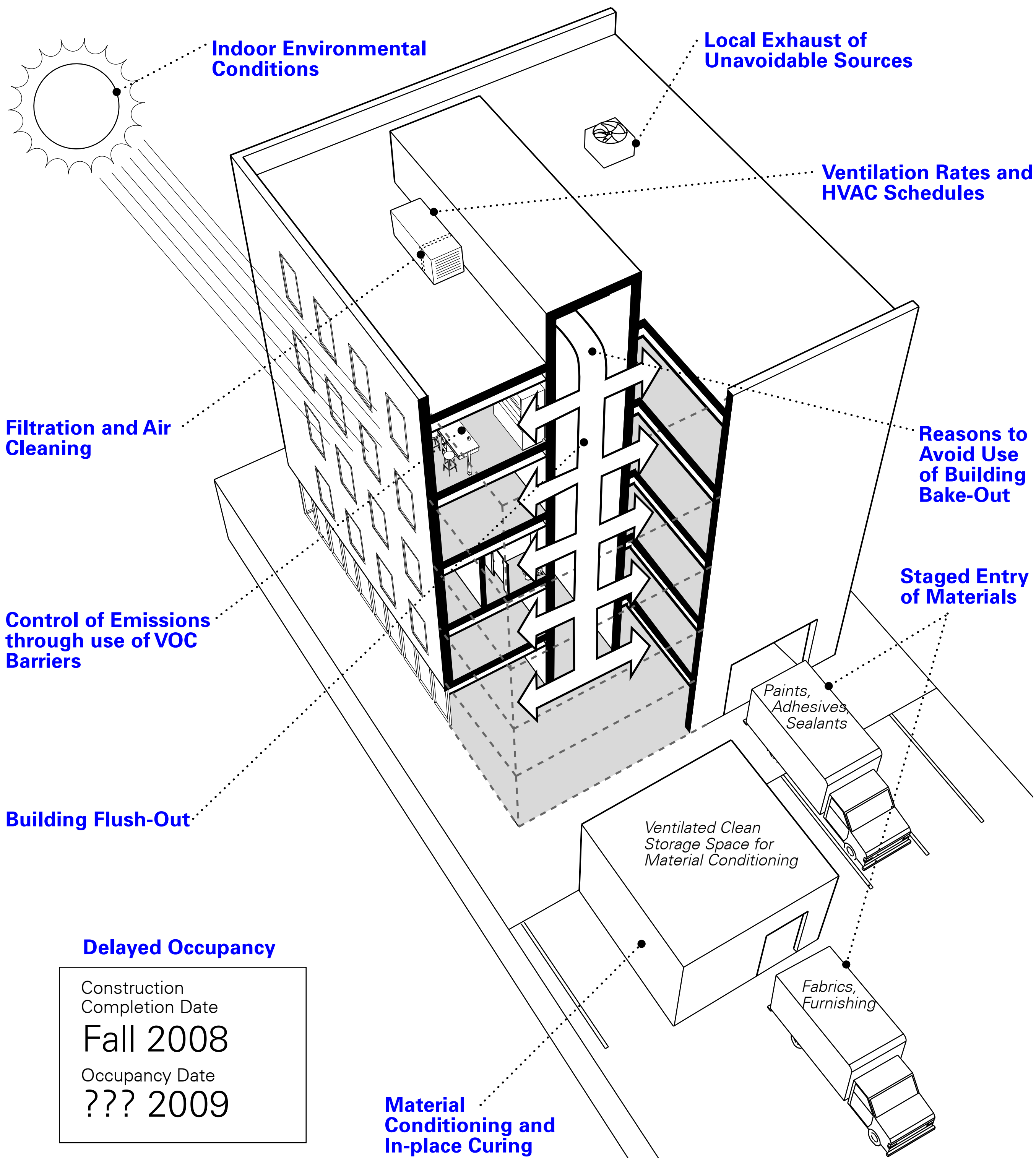
Staged Entry of Materials

To the extent practical, materials that by their nature are highly absorptive (or "fleecy") need to be installed after completion of construction activities that release high levels of VOC contaminants (e.g., painting/staining and application of caulks, adhesives, and sealants). These absorptive materials include textiles, carpets/underlayments, acoustical ceiling tiles, open-plan office partition panels, and insulation materials. Without careful staging of their installation and storing prior to their installation, they can act as contaminant reservoirs (sinks), leading to long-term re-emission into the indoor air.

Delayed Occupancy

It is important to delay building occupancy until a reasonable flush-out operation to reduce contaminant levels from early-phase product emissions has been completed. Building bake-out, in which the interior space is heated to between 95°F and 102°F (35°C and 39°C) in an attempt to speed emissions from materials and finishes, is discouraged because the effect has been shown to be temporary, tends to merely redistribute contaminant sources, and may damage building materials.

Strategy 5.2



Indoor Environmental Conditions
Local Exhaust of Unavoidable Sources
Ventilation Rates and HVAC Schedules
Filtration and Air Cleaning
Reasons to Avoid Use of Building Bake-Out
Staged Entry of Materials
Control of Emissions through use of VOC Barriers
Paints, Adhesives, Sealants
Building Flush-Out
Ventilated Clean Storage Space for Material Conditioning
Delayed Occupancy
Construction Completion Date
Fall 2008
Occupancy Date
??? 2009
Fabrics, Furnishing
Material Conditioning and In-place Curing

Strategy 5.2

5.2

Building Flush-Out

At completion of a new building, contaminant emissions from building materials and interior surfaces are typically at their highest. It is useful, therefore, to operate the building HVAC systems at a higher than normal ventilation rate for a period of time to help flush the building of these contaminants prior to occupancy and even during initial occupancy. The specific flush-out procedure employed must be adapted to local climatic/seasonal conditions.

Ventilation Rates and HVAC Schedules

Guidance and training to operation personnel (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ) related to HVAC operation schedules needs to also consider provision of adequate ventilation during cleaning activities (see Strategy 5.3 – Minimize IAQ Impacts Associated with Cleaning and Maintenance) and any other activity where high emissions might be expected (e.g., painting, caulking, applying adhesives).

Indoor Environmental Conditions

In addition to considerations for areas that need to be able to withstand repeated wettings (Strategy 2.5 – Select Suitable Materials, Equipment, and Assemblies for Unavoidably Wet Areas), which can affect the emissions from building materials, temperature-induced increases in emissions can result from solar gains or from the use of radiant flooring. Special selection of materials is required in such situations, while general management of building temperature and humidity remains an assumed element of material emissions control.

Filtration and Air Cleaning

Gas-phase or particle-phase filtration can, if applied to HVAC system return airstreams, assist with the removal of IAQ contaminants. Ozone filtration of outdoor air can reduce the formation of ultrafine particulates and gaseous irritants formed through reaction with IAQ contaminants. Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives provides additional guidance on this method to limit the impact of indoor material emissions.

Strategy 5.2

Impact of Flush-Out on Similar Floors in New Office Building

As part of the Cx process for a new office building, the building's AHUs, toilet exhaust, and outdoor air systems were specified to run continuously during the last month of construction and for the first few weeks of occupancy. Air sampling conducted during this flush-out period revealed a significant difference in the VOC levels on two similarly designed and furnished floors (Figure 5.2-A). An investigation of the cause of this unexpected result revealed a malfunction in the outdoor air system for Floor A. Air change measurements revealed that while Floor B was ventilated at 0.76 ach, the ventilation rate of Floor A was essentially zero. Comparing VOC levels, it was found that the levels on Floor B were 64% to 92% lower than the corresponding levels on Floor A. This gave a clear indication of the effectiveness of flush-out in reducing contaminant levels in a newly furnished office space.

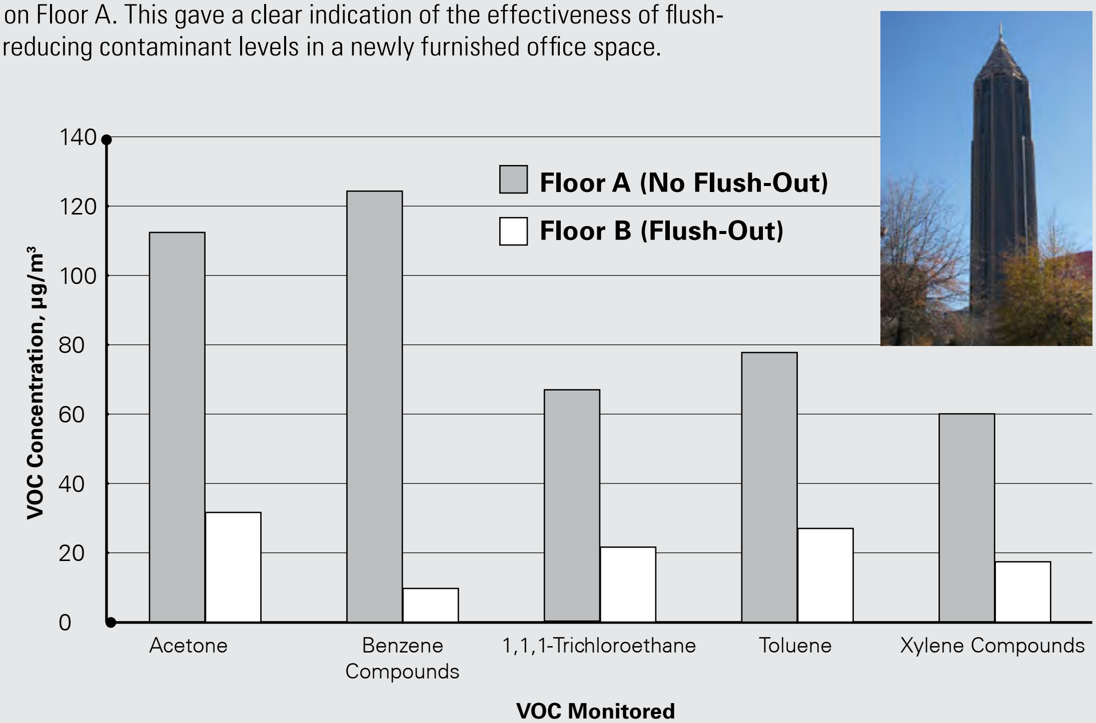


Figure 5.2-A Indoor VOC Concentrations on Two Typical Office Floors: Impact of Flush-Out
Data source: Milam (1993). Inset photograph courtesy of H.E. Burroughs.

Minimize IAQ Impacts Associated with Cleaning and Maintenance

A clean indoor environment is generally considered an essential requisite for good IAQ. There is growing recognition, however, that if chosen poorly, cleaning agents and/or practices can have detrimental effects on indoor air. Designs that minimize the need for cleaning and that facilitate cleaning with non-toxic and non-corrosive agents and that provide good O&M documentation for proper cleaning methods can go a long way toward ensuring a clean and healthy indoor environment.

A preferred initial strategy is to prevent dirt from entering the building in the first place, thus reducing the need for cleaning. This strategy pays additional dividends by lowering operating costs (cleaning is expensive) and can be achieved through effective design of building approaches and dirt track-off systems (see Strategy 3.5 – Provide Effective Track-Off Systems at Entrances) and through improved HVAC filtration system design and maintenance (see Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives).

Select Durable Materials and Finishes that are Simple to Clean and Maintain

As part of the design of the building, selecting interior materials and finishes that have surfaces that can be easily cleaned without strong chemical agents is also an important aspect of the overall strategy for controlling cleaning-associated IAQ impacts. Ensuring that these surfaces are also durable will reduce maintenance requirements as well as the IAQ impacts associated with replacement or refinishing. Particular attention should be paid to appropriate selection of flooring materials and surfaces used in restrooms.

Recommend Cleaning Products with Minimal Emissions

Cleaning will be an ongoing and essential requirement of building operation. This is why cleaning protocols and guidance need to be included in the O&M documentation (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ). Cleaning products are diverse in function and chemical composition and may contain ingredients that are irritating or harmful to building occupants and cleaning staff. Formation of highly irritating secondary byproducts in the presence of indoor oxidants has been associated with certain cleaning products. Careful selection of cleaning products to avoid these potential problems is thus an important component of the O&M documentation.

Provide Appropriate Storage for Cleaning Products

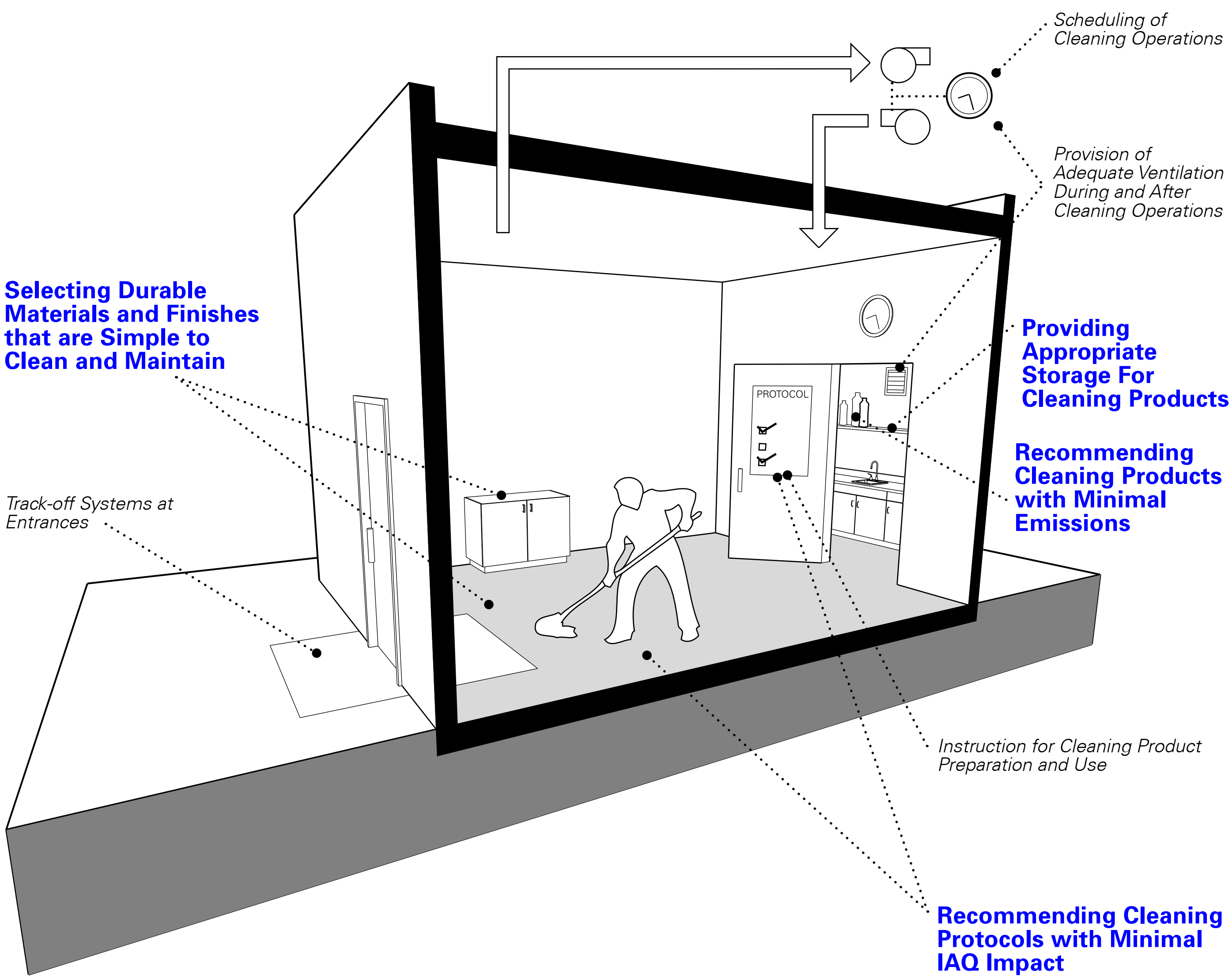
Storage and handling of cleaning products in well-designed and ventilated janitorial closets is an important aspect of an overall strategy to minimize IAQ impacts associated with cleaning and maintenance. Provision of hot water taps and adequate mop sinks, proper dispensing systems for stock cleaning agents, moisture-resistant flooring materials, posted instructions for preparation of cleaning agents, and protocols in well-located closets will assist in the delivery of improved cleaning services.

Recommend Cleaning Protocols that Will Have Minimal IAQ Impact

Protocols for effective cleaning need to be included in O&M documentation and training. These ought to include the equipment employed in cleaning operations, the timing of cleaning activities, and provision of adequate building ventilation during and immediately following cleaning operations as well as the effective training of cleaning personnel in all these issues.

Strategy 5.3

5.3



Strategy 5.3

“Green Housekeeping” Program at Brooklyn Public Library

- *Reduction of Toxins*. Over 16 hazardous substances have been eliminated from Brooklyn Public Library’s cleaning operations (including butoxyethanol, diacetone alcohol, dipropylene glycol, petroleum distillates, ethanolamine, ethyl ether, isobutane, isopropanol, methyl ether, naptha, and nonyl phenolethoxylate).

- *Reduction of Cleaning Products*. Staff estimates a reduction of approximately 50% in the amount of cleaning products used, primarily the result of using a proportioning chemical dispenser, which premixes cleaners and disinfectants for accurate dilution.

- *Packaging Waste Reduction*. Staff eliminated the use of 55 gal storage drums, which, in addition to being bulky and wasteful, were difficult and dangerous to handle.

- *Improved Efficiency*. The use of the proportioning dispenser was shown to save time. Staff believe the Green Housekeeping initiative boosted the morale of the custodial staff, increasing productivity as a result.

Data source: NY (1999).

Capture and Exhaust Contaminants from Building Equipment and Activities

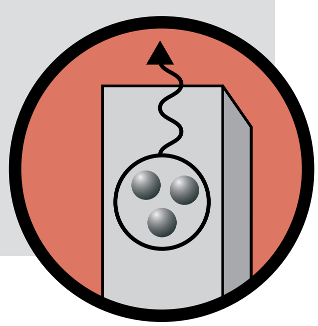
Building equipment and activities can be significant sources of indoor air contaminants. Among these are combustion products from fuel-burning equipment; exhaust from vehicles in enclosed parking garages; hazardous air pollutants from dry cleaners and nail and hair salons; particles and fumes from school 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.

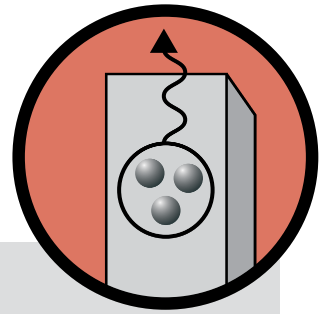
Other Strategies that can affect or be affected by exhaust and space depressurization include the following:

- 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

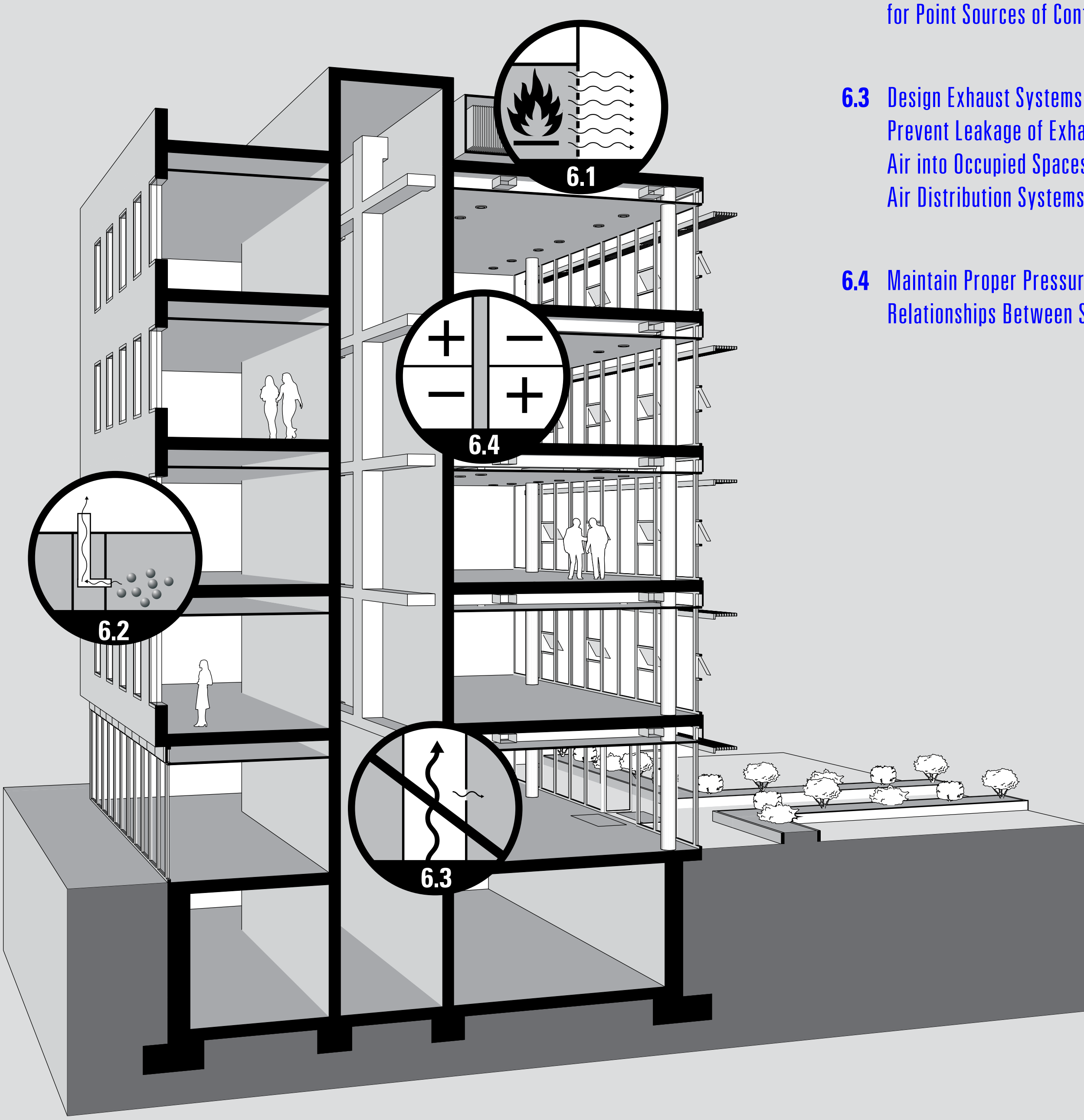


6.1 Properly Vent Combustion Equipment

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.

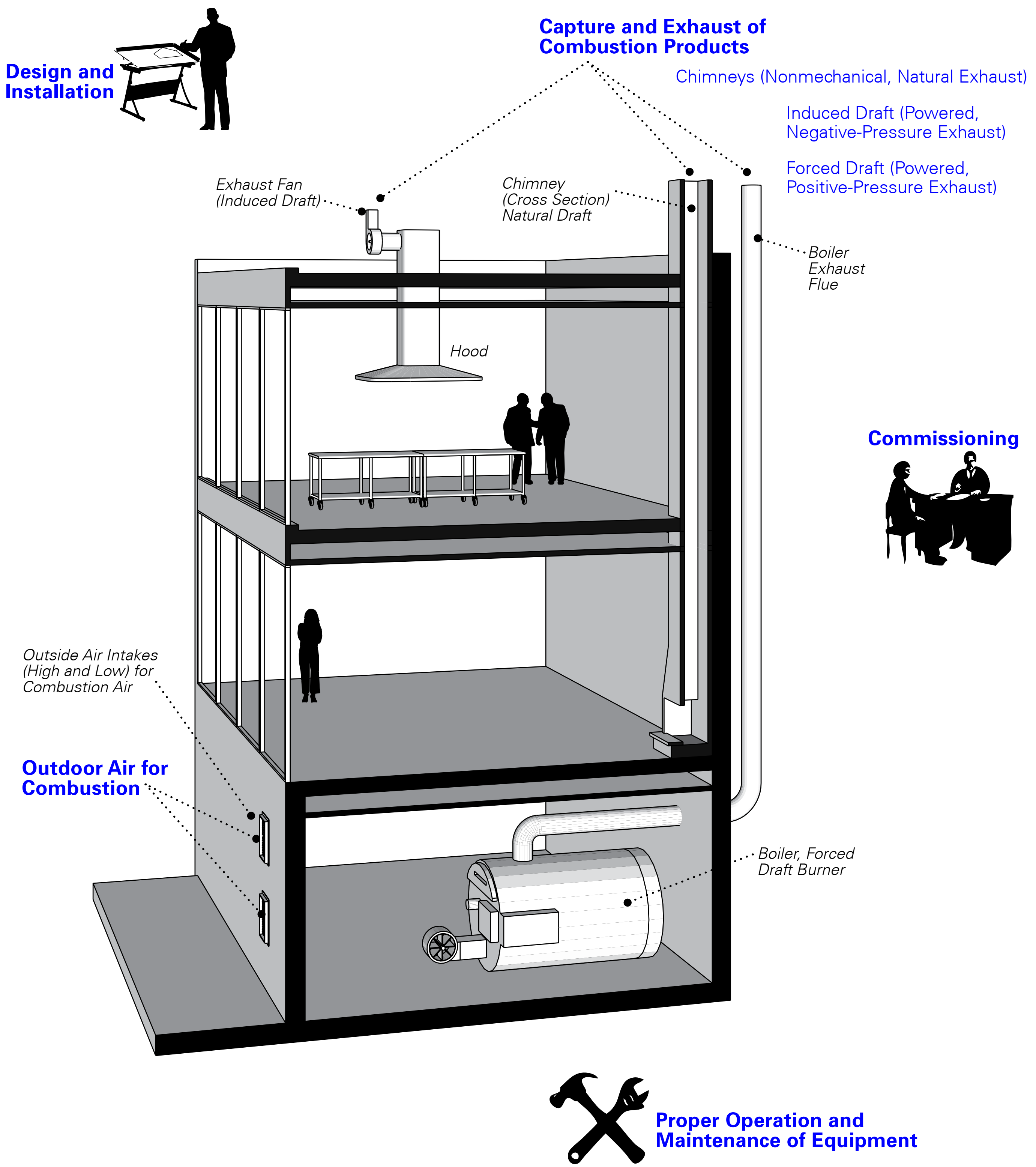
Operation and Maintenance

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.

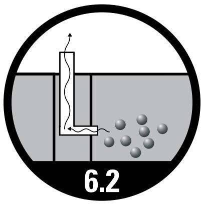
Exhausting directly to the outdoors removes the contaminants from the building. The location and height of the exhaust discharge outside the building is important to prevent re-entrainment of the contaminants into the building or surrounding buildings.

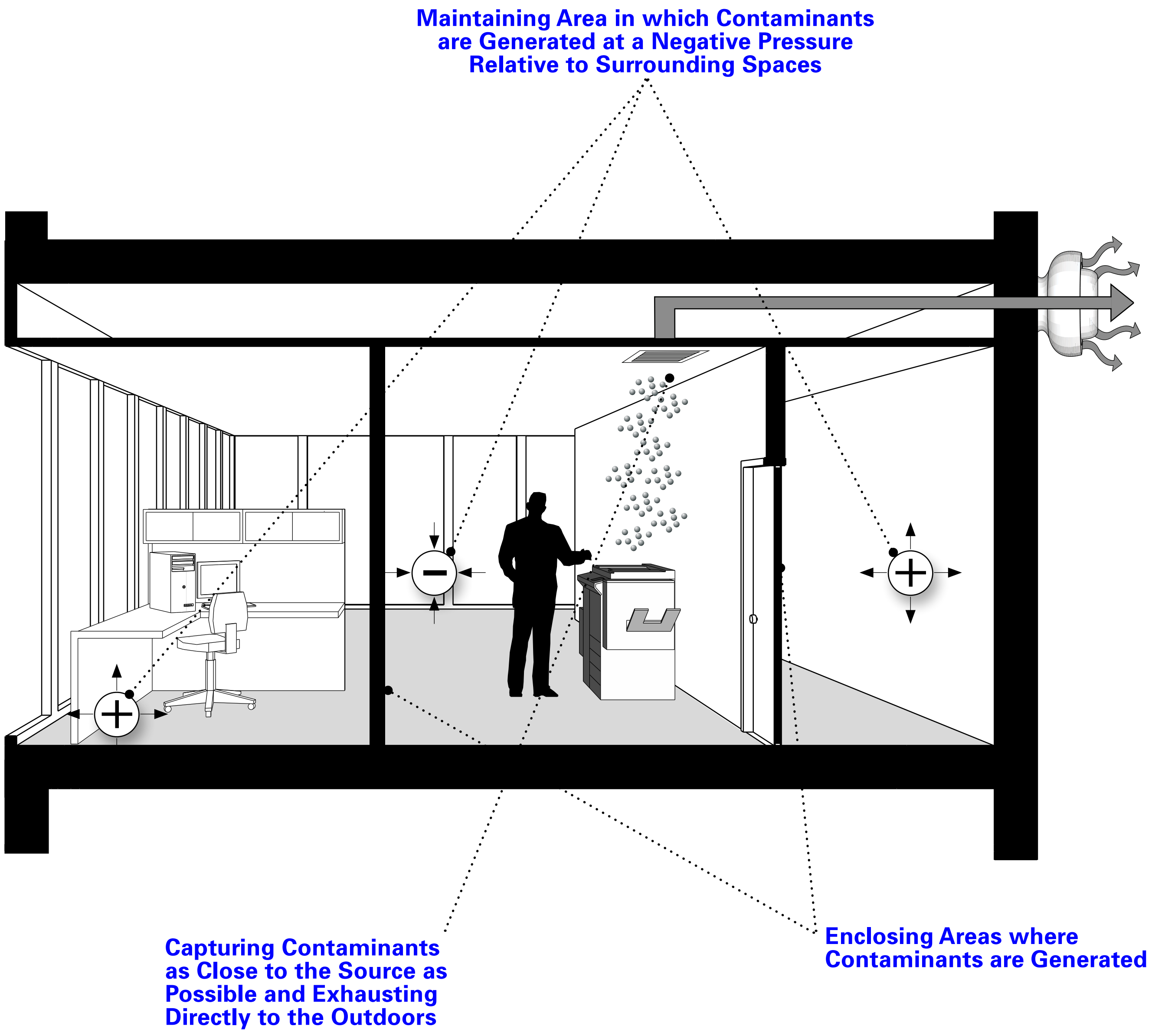
Maintaining the area in which these contaminants are generated at a negative pressure relative to the surrounding space reduces the potential migration of contaminated air into adjacent occupied spaces.

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.

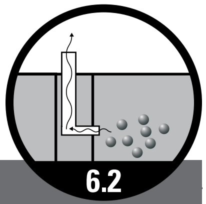
The principles of capturing contaminants close to the source and exhausting to the outdoors, maintaining the area under negative pressure, and enclosing the area are part of a contaminant control system and are meant to be used in concert with one another and not as substitutes for each other.

Strategy 6.2


6.2


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

Strategy 6.2



Lack of Exhaust—Indoor Swimming Pool

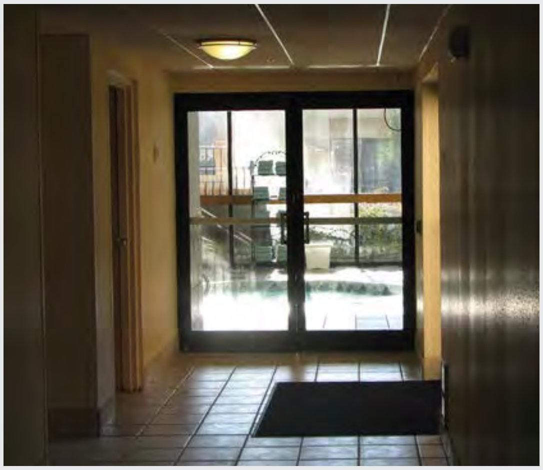


Figure 6.2-A Corridor to Indoor Swimming Pool
Photograph courtesy of H.E. Burroughs.

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.

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

Exhaust systems are required to remove odors and contaminants from the indoor environment. Areas that require exhaust include toilet rooms, soiled laundry storage rooms, pet shops (animal areas), areas where chemicals may be utilized extensively (such as natatoriums, photographic material facilities, and hair salons), and spaces where contaminants are generated as a 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. 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. 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.

In order to reduce the potential impact on the occupants in spaces outside of the area of the odor or contaminant, air must be effectively exhausted directly from the space. This topic is covered in Strategy 6.2 – Provide Local Capture and Exhaust for Point Sources of Contaminants.

In addition to effectively exhausting the area of odors or contaminants, it is critical that the exhaust air be conveyed to the outdoors and discharged in a manner to reduce leakage of the exhaust air into surrounding occupied spaces or into air distribution systems.

Effectively Seal Ductwork to Limit Leakage from the Duct System

Sealing of exhaust ductwork is paramount in order to reduce the potential for leakage of contaminants into plenum spaces or adjacent areas. Leakage rates vary significantly based on the method of duct fabrication, the assembly methods, and the quality of workmanship in the installation. There are various classes of sealing recognized by ASHRAE (ASHRAE 2009) and SMACNA (SMACNA 2005), depending on the specific application.

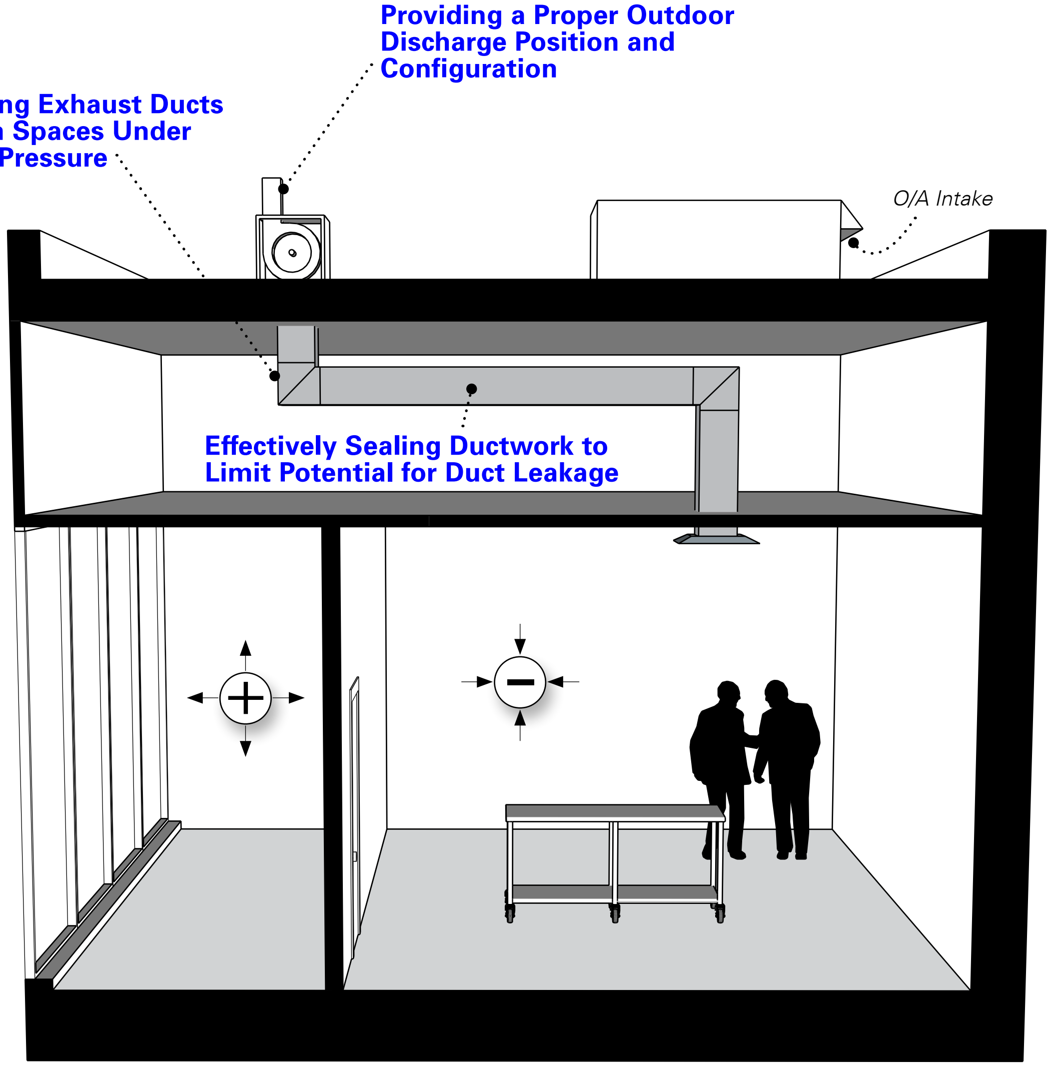
Provide Outdoor Discharge Position and Configuration to Limit Entrainment of Exhaust Air into Fresh Air Ventilation Systems or Adjacent Buildings

The location of the exhaust discharge and configuration is a critical component in reducing the potential for an exhaust system to have an impact on outdoor air ventilation systems and/or adjacent facilities or buildings. The analysis must not only consider the exhaust system composition, equipment, and installation but also take into account the effects of architectural screen walls/enclosures, prevailing wind patterns, and height and proximity of adjacent buildings.

Maintain Exhaust Ducts in Plenum Spaces under a Negative Pressure

To assist in reducing the potential impact of exhaust systems on adjacent spaces, the duct must be maintained at a negative pressure as it passes through any plenum spaces. This is a specific requirement in the *International Mechanical Code* (*IMC*; ICC 2006a) and results in defining the potential location for fans utilized with the exhaust system.

Strategy 6.3


Providing a Proper Outdoor Discharge Position and Configuration
Maintaining Exhaust Ducts in Plenum Spaces Under Negative Pressure
O/A Intake
Effectively Sealing Ductwork to Limit Potential for Duct Leakage

Strategy 6.3

Improper Separation between Exhaust and Intake Airstreams

Figure 6.3-A Location of Exhaust Fan

Figure 6.3-B Relative Location of Exhaust Fan to Intake Louvers

Figures 6.3-A and 6.3-B show an office building in California and reflect the roof installation of a mechanical exhaust system (toilet exhaust fan shown with dome on top) in close proximity to and upwind of the air intake location for one of the largest air-handling systems for the building. The problem was remedied, post-construction, by installing a sheet metal surround to raise the height of the air discharge above the height of the intake louver, allowing the exhaust plume to dissipate without entering the air intake.

Photographs courtesy of Hal Levin.

Maintain Proper Pressure Relationships Between Spaces

6.4

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
To determine the described pressure relationship between spaces, the usage of building spaces, along with their moisture and contaminant sources or conditions, need to be identified. Decisions then need to be made about which will be positively or negatively pressurized.

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 locations 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 outdoors.

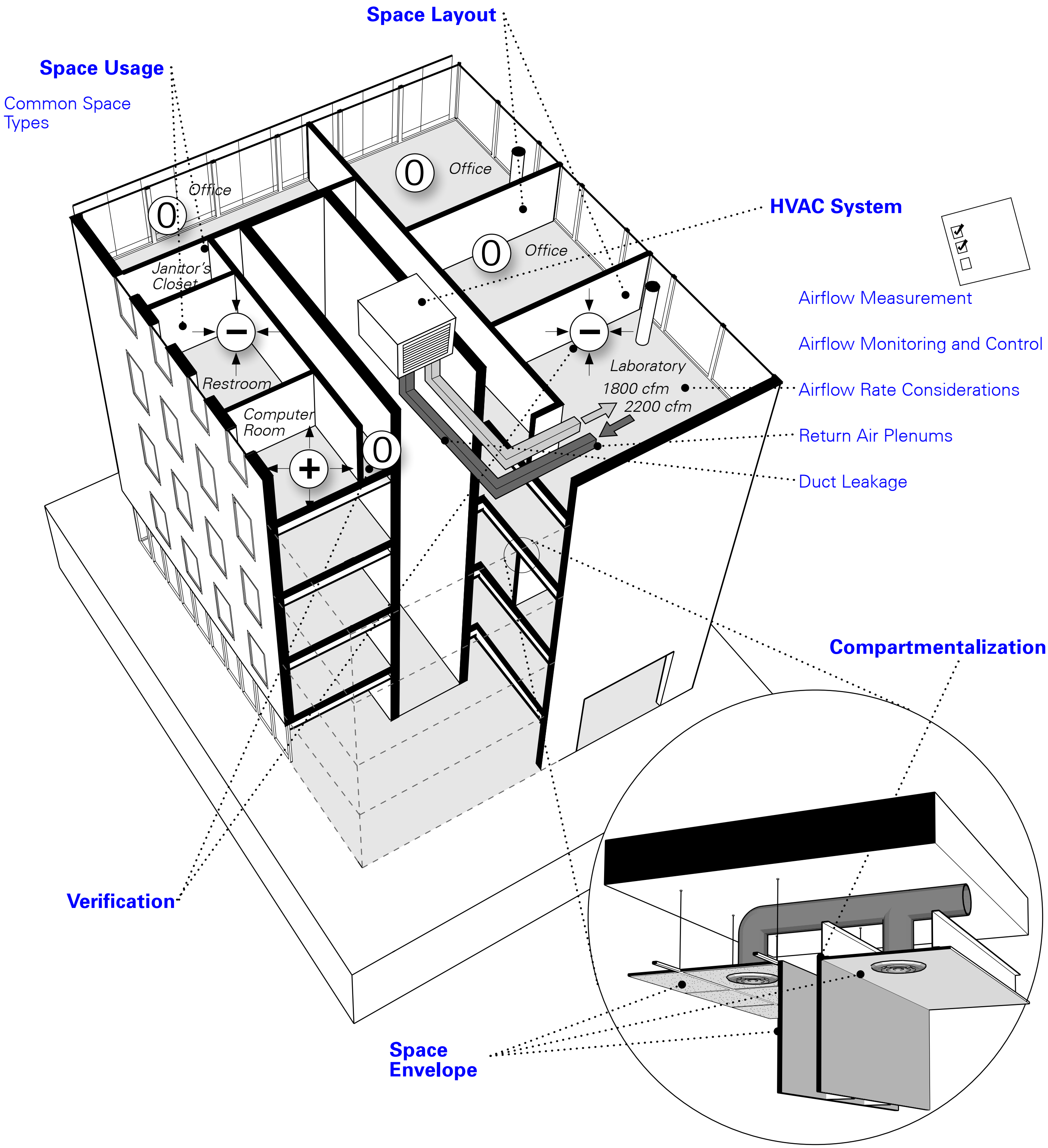
Space Envelope
The effectiveness of the space pressurization is reduced by the leakiness of the space envelope. Therefore, the space envelope needs to be designed to limit exfiltration, infiltration, and leakage. Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces provides information on the design and construction of the space envelope.

Compartmentalization
If space pressurization is not an option, sealing and other construction techniques can be used to compartmentalize spaces to contain contaminants and moisture.

HVAC System
A variety of issues need to be addressed to ensure appropriate space-to-space pressure control. These include design airflow rates, airflow measurements and monitoring control, negative relative pressures in return air plenums, and duct leakages that can compromise pressurization control and contaminate spaces with both pollutants and moisture.

Verification
A number of steps can be taken to ensure that desired space pressurization is attained. These include verifying proper construction of space envelopes, including design information on contract documents; performing testing and balancing to verify all airflows; and performing pressure differential mapping.

Strategy 6.4



Space Layout
Space Usage
Common Space Types
Office
0
Office
0
Office
0
Janitor's Closet
Restroom
Computer Room
0
Laboratory
1800 cfm
2200 cfm
HVAC System
Airflow Measurement
Airflow Monitoring and Control
Airflow Rate Considerations
Return Air Plenums
Duct Leakage
Compartmentalization
Verification
Space Envelope

Strategy 6.4

Noxious Spa Odors Invade a Hotel

Figure 6.4-A Jacuzzi/Pool Area Emitting Odors

Figure 6.4-B Ill-Fitting Double Glass Doors

Photographs courtesy of H. E. Burroughs.

In this low-rise hotel facility, the guest exercise room and spa is located in a separate structure that also contains a large multi-person heated jacuzzi/pool (Figure 6.4-A). Access to the facility from the main guest room wing is through ill-fitting double glass doors at the end of the guest wing corridor (Figure 6.4-B). As guests and visitors to the facility approach the spa entrance, the odor of chlorine from the pool area is noticeable halfway down the building wing. It becomes increasingly noxious closer to the entrance doors. To users of the facility, as well as to guests in nearby rooms, it is obvious that the odors from the water treatment chemicals are migrating into the corridor and sleeping rooms, even though the spa facility is in a separate building pod.

The corridor leading to the spa area is continuous and open to the hotel lobby and breakfast/kitchen area. What appears to be happening is that the breakfast/kitchen area exhaust system is depressurizing the hotel corridor, making the corridor negatively pressurized relative to the spa. The spa odors are thus drawn into the corridor. In addition, individual room exhausts exacerbate the problem by inducing the contaminant from the corridor into individual rooms. An unseen and less obvious problem is that the same odorous airstream is also inducing steam and high humidity from the spa into the conditioned space of the guest rooms.

This demonstrates how important it is to be diligent to establish proper pressure relationships within the building so that air does not flow from contaminated or moisture-laden areas into clean occupied spaces. Specifically in this case, the design properly incorporated an exhaust system in the breakfast/kitchen area but did not account for its impact on the corridor and spa. Similar problems can occur in other types of buildings.

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.

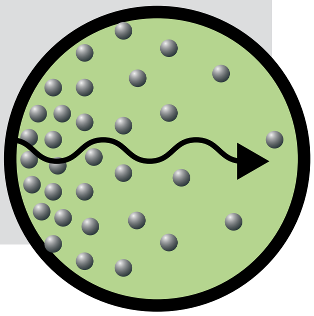
- Minimum ventilation requirements are described in Strategy 7.1 – Provide Appropriate Outdoor Air Quantities for Each Room or Zone.
- Poor control of minimum outdoor air delivery can waste energy if the flow is too high and degrade IAQ if the flow is too low. Strategy 7.2 – Continuously Monitor and 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:

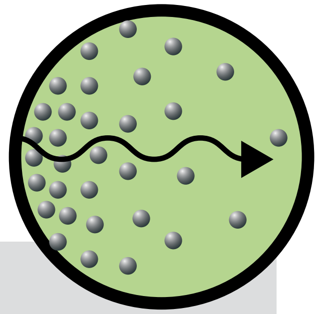
- Strategy 1.1 – Integrate Design Approach and Solutions
- Strategy 1.3 – Select HVAC Systems to Improve IAQ and Reduce the Energy Impacts of Ventilation
- Strategy 3.2 – Locate Outdoor Air Intakes to Minimize Introduction of Contaminants

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

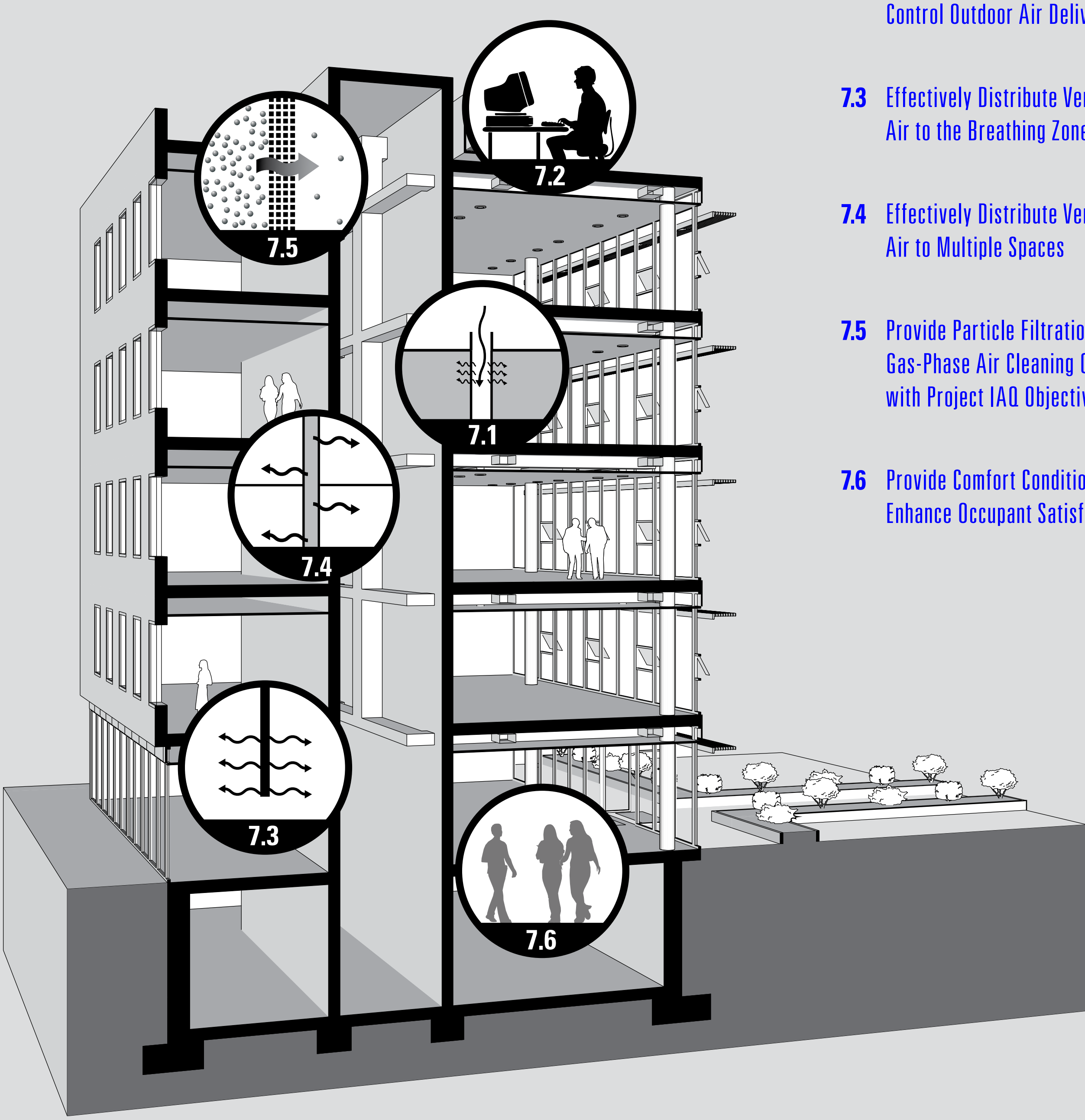
7.2 Continuously Monitor and Control Outdoor Air Delivery

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

7.1

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.

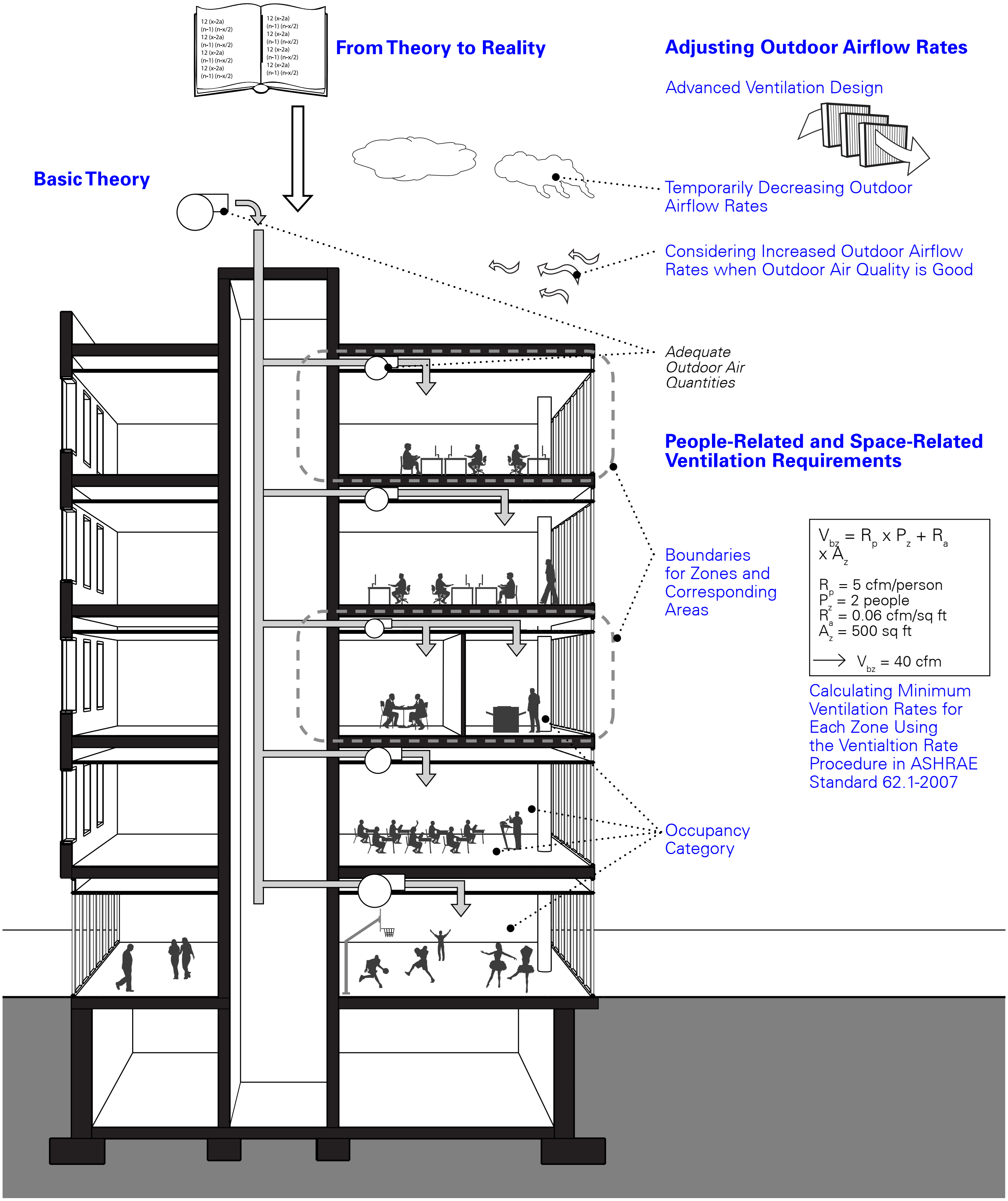
ASHRAE Standard 62.1-2007 specifies two distinct ventilation rate requirements. The first is a per-person requirement to dilute pollutant sources associated with human activity that are considered to be proportional to the number of occupants. The second is a per-unit-area requirement designed to dilute 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



STRATEGY OBJECTIVE 7.1

Strategy 7.1

Ventilation and Performance

Figure 7.1-A Measuring Student 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).

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).

STRATEGY OBJECTIVE 7.1

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

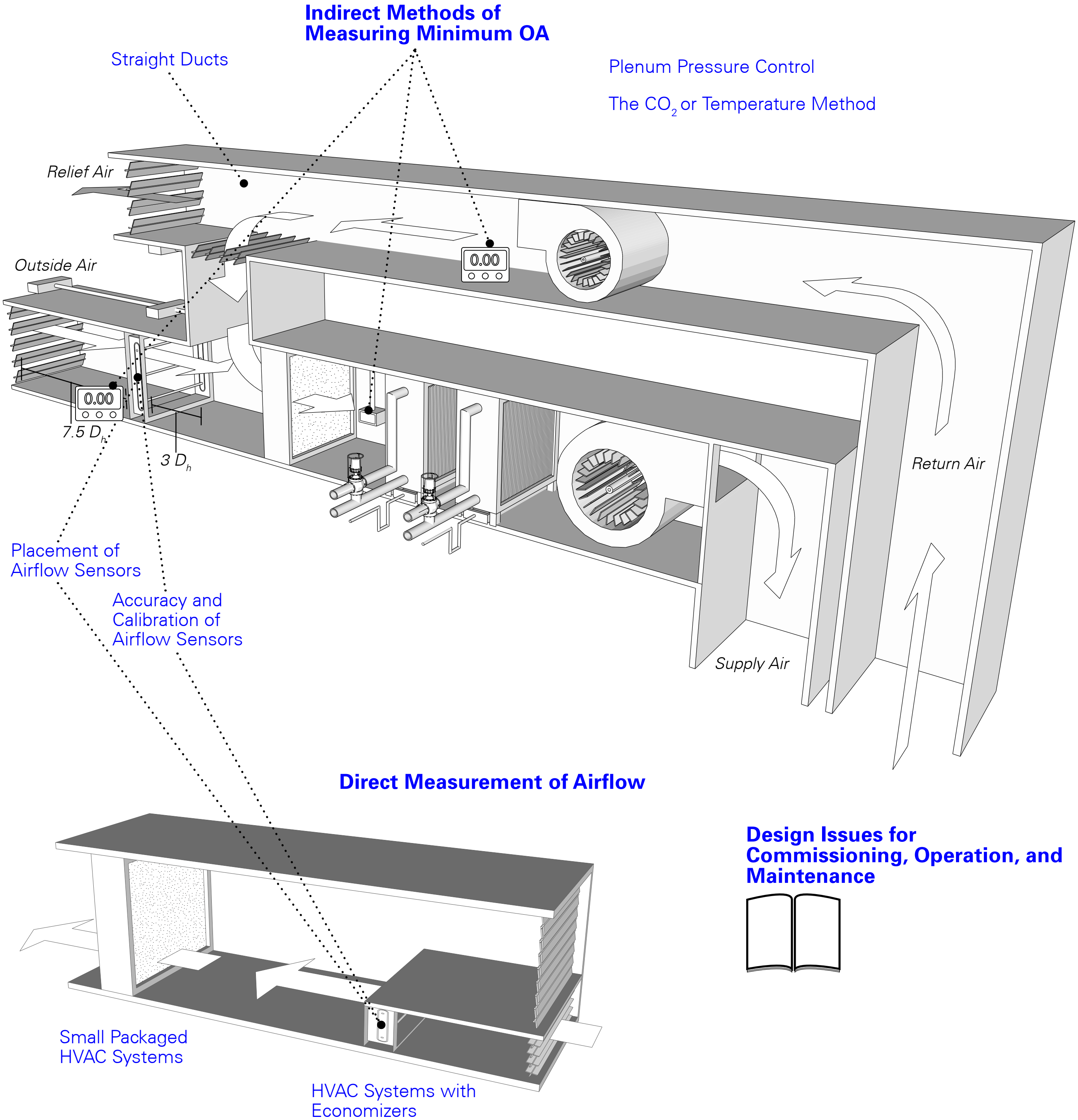
- *Straight Ducts.* Accurate airflow measurements require long, straight duct runs. This presents a challenge to the designer because space and architectural constraints often limit achieving sufficient straight duct lengths.

- *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



Design Issues for Commissioning, Operation, and Maintenance

STRATEGY OBJECTIVE 7.2

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.

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.

STRATEGY OBJECTIVE 7.2

Effectively Distribute Ventilation Air to the Breathing Zone

7.3

Ventilation only works when the air is delivered to the breathing zone. Different methods of distribution have different efficiencies. For an inefficient system, the quantity of outdoor air at the air handler needs to be increased in order to provide the required minimum quantities in the breathing zone that are required by code and by ASHRAE Standard 62.1.

Zone Air Distribution Effectiveness

The airflow rate that needs to be distributed to a zone varies by the effectiveness of the distribution within the room. The ventilation airflow rate provided to the zone needs to be sufficient to provide the required ventilation air to the breathing zone.

The zone outdoor airflow is given by Equation 6.2 in ASHRAE Standard 62.1, as follows:

$V_{oz} = V_{bz} / E_z$

where

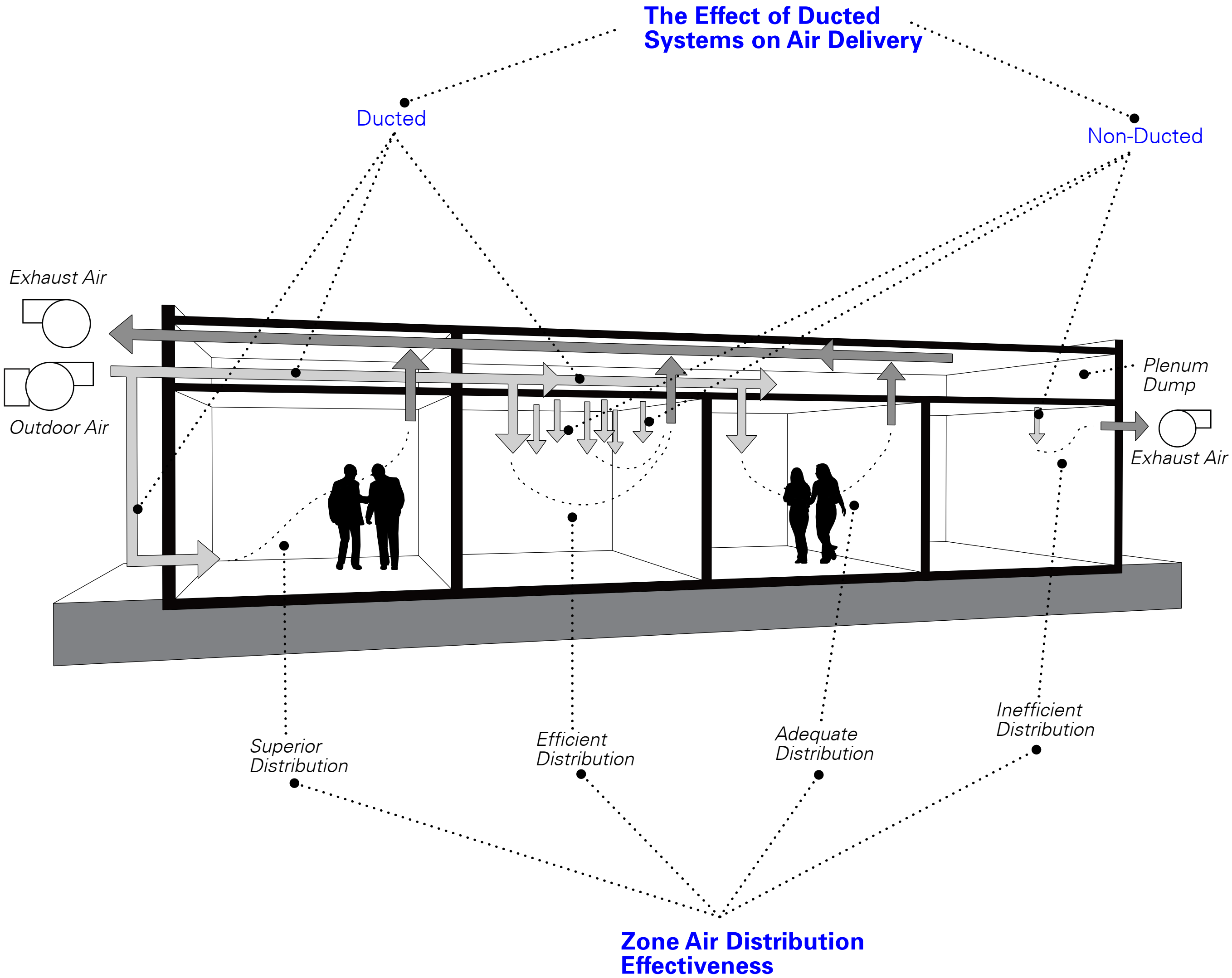
V_{oz} = quantity of ventilation air delivered to the occupied zone, cfm (L/s)

V_{bz} = quantity of ventilation air delivered to the breathing zone, cfm (L/s)

E_z = zone air distribution effectiveness

Thus, the less efficient an air distribution system is within a zone, the greater will be the required flow of outdoor air to the zone. Choosing air distribution configurations that improve effectiveness, or at least don't decrease it, is therefore an important design decision.

Strategy 7.3


The Effect of Ducted Systems on Air Delivery
Ducted
Non-Ducted
Exhaust Air
Outdoor Air
Plenum Dump
Exhaust Air
Superior Distribution
Efficient Distribution
Adequate Distribution
Inefficient Distribution
Zone Air Distribution Effectiveness

Strategy 7.3

Zone Air Distribution Effectiveness

Zone Air Distribution Effectiveness E_z = 1.0

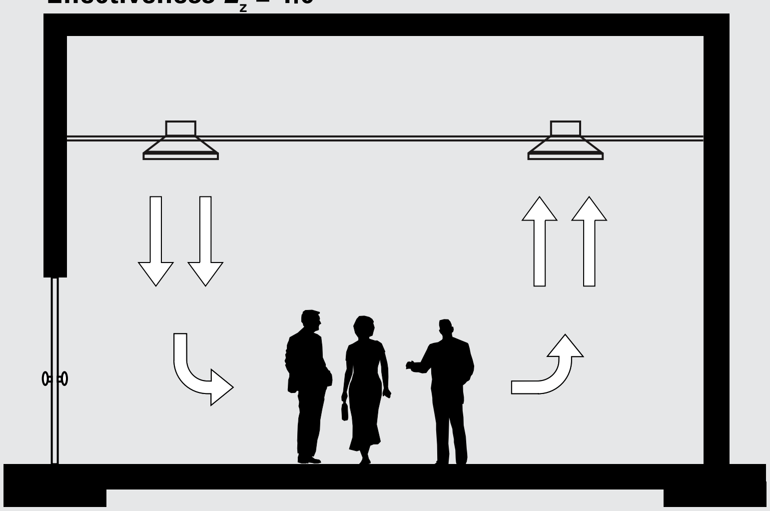


Figure 7.3-A Cold Air Falls and is Well Mixed

Zone Air Distribution Effectiveness E_z = 0.8

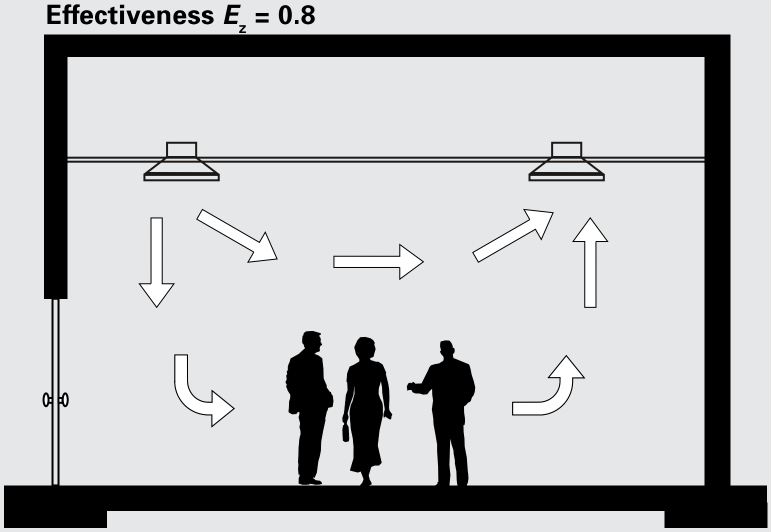


Figure 7.3-B Some Hot Air Stays at the Ceiling so Only 80% of the Air Gets to the Breathing Zone

Research in the 1970s revealed that overhead heating with temperatures greater than 15°F (8°C) above ambient resulted in excessive stratification (Int-Hout 2007). Other air distribution configurations can result in varying levels of zone air distribution effectiveness (Figures 7.3-A and 7.3-B). Zone air distribution effectiveness values for varying zone distribution configurations is provided in Table 6.2 of ASHRAE Standard 62.1.

The following are examples of the effect of zone distribution configurations. The effectiveness is categorized here as superior, effective, adequate, and ineffective for presentation clarity.

Superior Distribution: E_z = 1.2

- Floor supply of cool air and ceiling return, provided when low-velocity displacement ventilation achieves unidirectional flow and thermal stratification

Effective Distribution: E_z = 1.0

- Ceiling supply of cool air
- Ceiling supply of warm air and floor return
- 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.
- 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
- Floor supply of warm air and floor return

Adequate Distribution: E_z = 0.8.

- Ceiling supply of warm air 15°F (8°C) or more above space temperature and ceiling return
- Makeup supply drawn in on the opposite side of the room from the exhaust and/or return

Ineffective Distribution: E_z < 0.8

- Floor supply of warm air and ceiling return
- Makeup supply drawn in near the exhaust and/or return location

Effectively Distribute Ventilation Air to Multiple Spaces

Ventilation only works when the air is delivered to the breathing zone. Different methods of distribution have different efficiencies. For an inefficient system, the outdoor airflow rate at the air handler must be increased in order to provide the required minimum outdoor airflow rate to the breathing zone. For multiple-zone recirculating systems, the system will have an efficiency (E_v) that needs to be calculated to determine the outdoor airflow rate required at the air handler. This efficiency is for the system and needs to be used in addition to the corrections for effectiveness of distributing air within the zone (E_z). The values for system efficiency can range from 1.0 to 0.3 or lower, with higher values being more efficient (better).

System Ventilation Efficiency

Figure 7.4-A Building where Multiple-Space Equations Were Tested
Photograph courtesy of Yuill et al. (2007).

System Ventilation Efficiency

For a single-zone system or a DOAS, the airflow rate at the outdoor air intake (V_{ot}) is equal to the air required for the zone(s). The numbered equations are taken from ASHRAE Standard 62.1-2007, including Appendix A of that standard.

$$V_{ot} = V_{oz} \tag{6-3}$$

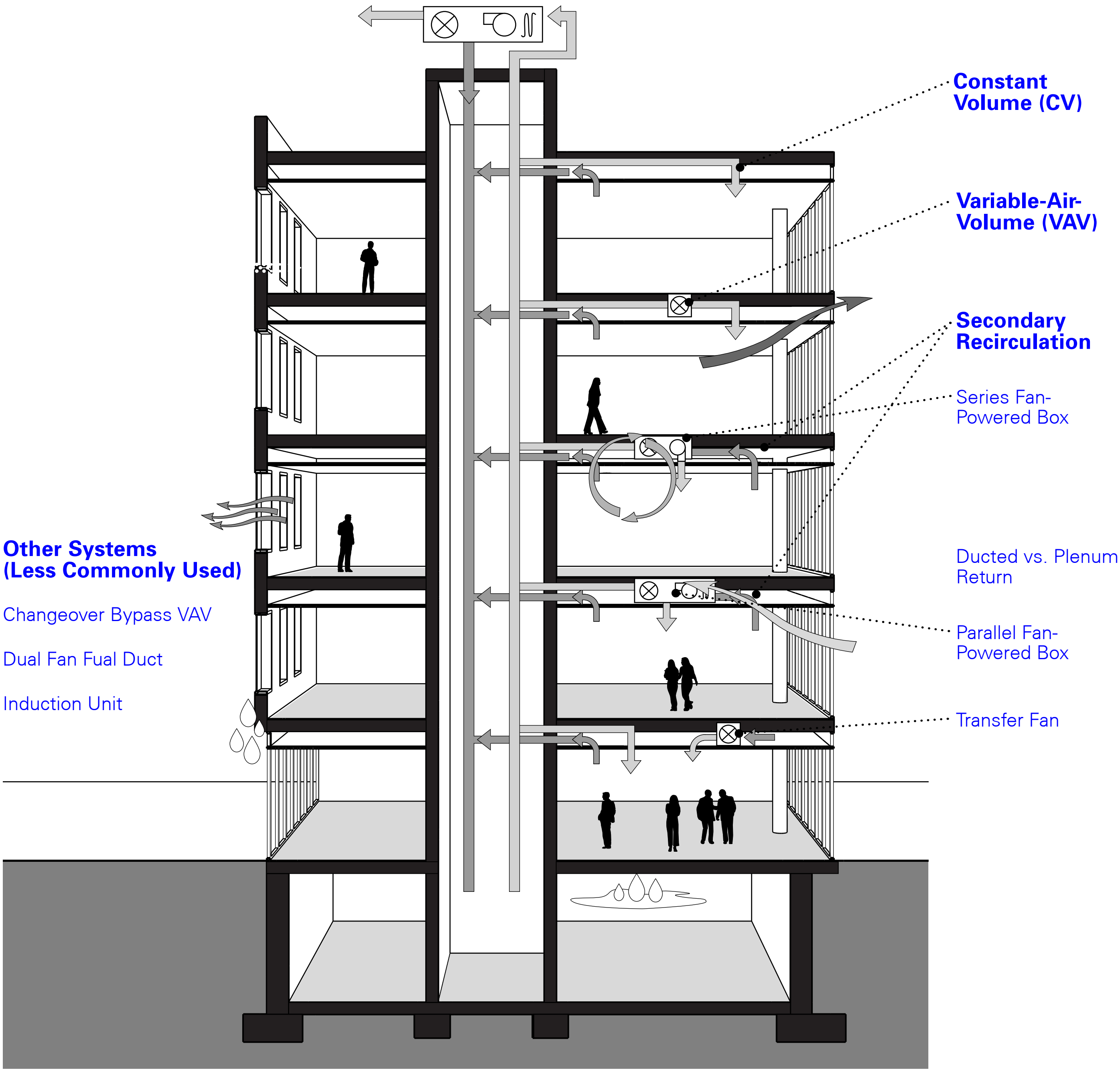
$$V_{ot} = \sum_{all\ zones} V_{oz} \tag{6-4}$$

For systems that supply multiple zones, the calculations are more complex. The airflow rate required at the outdoor air intake is driven by the critical zone. However, the percent outdoor air required at the system intake (X_s) can be less than the percent outdoor air required at the critical zone (Z_d critical). The system ventilation efficiency is given by the following equation:

Single Supply Systems $$E_{vz} = 1 + X_s - Z_d \tag{A-1}$$

The multiple-space equations were tested in the building illustrated in Figure 7.4-A, and a research project confirmed that the system intake air fraction does not have to be as large as the fraction of outdoor air at the critical zone in order to deliver the proper outdoor airflow rate (V_{oz}) to the zone (Yuill et al. 2007).

Strategy 7.4


Constant Volume (CV)
Variable-Air-Volume (VAV)
Secondary Recirculation
Series Fan-Powered Box
Ducted vs. Plenum Return
Parallel Fan-Powered Box
Transfer Fan
Other Systems (Less Commonly Used)
Changeover Bypass VAV
Dual Fan Fual Duct
Induction Unit

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

Filtration and gas-phase air cleaning (FAC) strategies are important because they can provide a more effective means of removing contaminants than source control or ventilation in some cases. In this way, filtration and air cleaning can help reduce occupant exposure to a variety of contaminants and thus improve occupant health, comfort, and productivity.

The technologies of enhanced particulate FAC are well developed, with a history of over half a century of application in industrial process control, cleanrooms, health care and pharmaceuticals, and special usage buildings such as museums and laboratories. However, filtration systems have not been widely applied in general commercial buildings. This Strategy provides a broad understanding and appreciation of the potential of FAC as a tool for attaining enhanced levels of IAQ. Both particulate and gas-phase control are discussed together in this Strategy because much of the design consideration and mechanical application technology is concurrent and co-mingled.

A full range of particulate FAC equipment is available from a wide selection of manufacturers. The filter cartridges vary widely in frame methodology and seal mechanisms, filter/sorption media, cartridge depth and size, loading characteristics and capacity, surface area configurations, airflow and pressure drop, and cost. The efficiency or removal performance is a critical component of the selection of FAC equipment. However, other factors also influence the overall performance and total value of the FAC system and, thus, should be included in the selection and specification process.

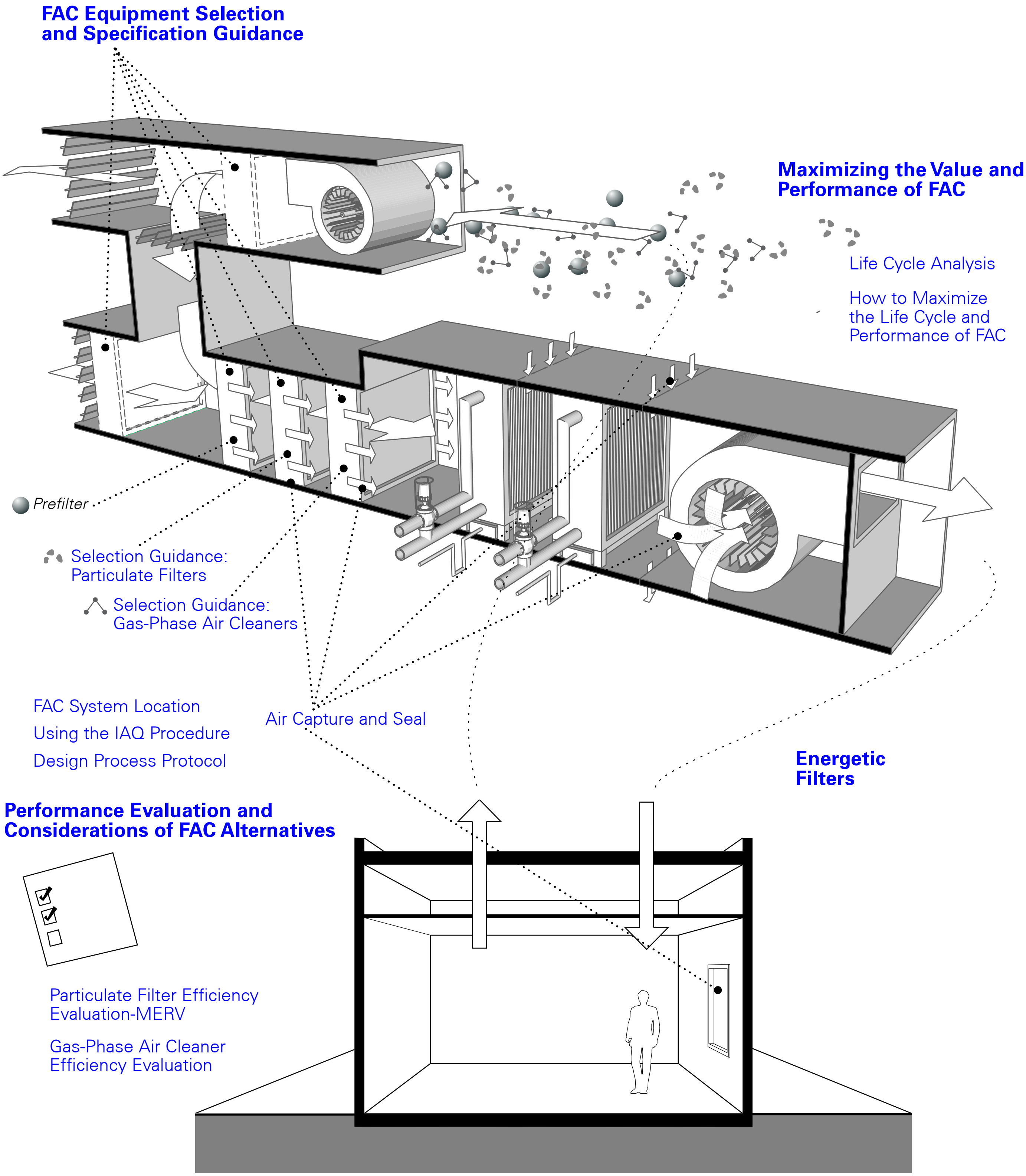
The application of FAC is a balance of:

- the control and extraction requirements,
- the physical/mechanical limitations of the air-handling system,
- the characteristics of the CoC, and
- the features of the FAC equipment.

Generally, the space requirements, energy, and O&M costs increase with higher efficiency requirements. Because of cost and space constraints, the final selection of equipment should go beyond removal efficiency to include capacity and life cycle, maintenance requirements, and lifelong pressure drop factors. Because of these factors, life-cycle cost, including energy requirements, should drive the selection of FAC rather than just first cost. The supportive discussion in the Part II detailed guidance to this Strategy in the electronic version of this Guide provides rationale for the selection of specific extraction efficiencies and specific FAC equipment along with specific recommendations.

Early consideration should be devoted to FAC in a number of overall building design aspects. This early consideration is necessary because the function of FAC equipment is similar to ventilation systems except the FAC system employs extraction rather than dilution to lessen the concentration of unwanted contaminants in the conditioned space. Thus, it can be applied in conjunction with ventilation to aid and improve the quality of the ventilation air or as an alternative or adjunct to ventilation air for economic reasons. Because of these factors, FAC has interactivity features that are similar to ventilation, including the evaluation of the outdoor air quality, an understanding of internal sources, knowledge of occupant density and activity, concern for air capture and recirculation efficacy, selection of HVAC equipment, and concern for energy management issues.

Strategy 7.5


FAC Equipment Selection
and Specification Guidance
Maximizing the Value and
Performance of FAC
Life Cycle Analysis
How to Maximize
the Life Cycle and
Performance of FAC
Prefilter
Selection Guidance:
Particulate Filters
Selection Guidance:
Gas-Phase Air Cleaners
FAC System Location
Using the IAQ Procedure
Design Process Protocol
Air Capture and Seal
Energetic
Filters
Performance Evaluation and
Considerations of FAC Alternatives
Particulate Filter Efficiency
Evaluation-MERV
Gas-Phase Air Cleaner
Efficiency Evaluation

Strategy 7.5

The following are typical interrelated areas that trigger early consideration of FAC by the design team:

- *When outdoor ventilation air is unreliable* for delivering dependable and effective dilution of indoor contaminants because of preexisting pollutant content, such as ozone or ultrafine particulate matter, or when other odor or pollutant generating sources are nearby.
- *When outdoor ventilation air is either consistently or seasonally burdened with high heat and latent loads* demanding additional and excessive HVAC equipment capacity and operating energy consumption.
- *When source control tactics, such as material selection and localized exhaust, are insufficient* for adequately lowering concentrations of CoC.
- *When occupant function or activity generates elevated levels of CoC* that cannot be adequately controlled by routine levels of dilution ventilation.
- *When internal occupancy patterns include high density and/or wide diversity of space usage* requiring high peak ventilation levels with related capacity and energy load.
- *When the owner or tenant needs or expectations require higher levels of contaminant control* to provide enhanced levels of indoor environmental acceptability and conditions.
- *When occupants, occupant activities, or contents of the building require enhanced levels of protection* from the deleterious effects of airborne contaminants, whether the CoC are microbiological, chemical, or particulate in nature.
- *When exhaust systems contain CoC that have the potential for re-entrainment* or contribution of potential risk to the ambient air.

Strategy 7.5

Improved IAQ and Protected Objects in Specialty City Museum

The low-rise building shown in Figure 7.5-A serves the archival offices and laboratories of a museum complex located in a major Southeastern city. The building is less than ten years old and is used for preservation and restoration of historically significant photos, documents, and objects d'art that are mostly cellulosic and/or organic-based in content. Thus, there are a number of odorous, noxious, and potentially hazardous chemicals used in the various preservation processes employed by the museum professionals. These normally require a high level of ventilation and dilution to maintain acceptable IAQ. However, the same historical documents are highly susceptible to the gaseous contaminants of ambient outdoor urban air. Thus, the facility HVAC system operates with reduced outdoor air, and both the outdoor air and return airstreams are treated with filtration and gaseous air cleaning to remove the chemical contaminants from both the outdoor air and the return air. This results in acceptable indoor environmental conditions for both the occupants and the valuable stored materials while reducing both the risk and the cost of introducing excessive quantities of outdoor air.

Figure 7.5-A Museum Archival Offices
Photograph courtesy of H.E. Burroughs.

The special FAC equipment consists of MERV 6 prefilters and 12 in. deep medium efficiency matrix media imbedded gas-phase filter cartridges and is located in the mixed air plenum to treat both return and outdoor air sources. On-site performance testing conducted in 2007 revealed that the system efficiency for particulate reduction was 94.6% at 0.5 μm size particles and the TVOC levels were maintained below 70 $\mu g/m^3$.

STRATEGY OBJECTIVE 7.5

Provide Comfort Conditions that Enhance Occupant Satisfaction

7.6

Thermal conditions indoors, combined with occupant activity and clothing, determine occupant thermal comfort, which in turn impacts occupant productivity and perceptions of air quality. Dry-bulb temperature is only one physical parameter out of many that interact in a complex manner to produce occupant satisfaction.

Thermal conditions affect chemical and biological contaminant levels and/or the intensity of occupants' reactions to these contaminants, but our knowledge of these effects and their mechanisms is very limited. Despite this limited knowledge, achieving high performance in thermal comfort is likely to result in lower contaminant levels and better occupant perceptions of IAQ.

Tools exist for calculating the proportion of people likely to be satisfied by the combination of comfort factors that include dry-bulb temperature, humidity, air velocity, and radiant temperature. The most commonly known tool in the U.S. is *ASHRAE Thermal Comfort Tool* (ASHRAE 1997), a computer program that is part of *ANSI/ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2004).[1] In order to use this tool, the amount of clothing worn by occupants and their levels of metabolic (or physical) activity must be provided, in units of clo (clothing level) and met (metabolic rate), respectively.

In traditional designs, the HVAC designer's role in achieving comfort conditions often begins and ends at the selection of an indoor design condition and the sizing of the HVAC system to provide these conditions at peak load. The selection of a design dry-bulb condition involves both comfort and cost or energy considerations and can dictate critical design features of the system. For example, some designers may pick a relatively high design cooling condition such as 78°F (26°C) in order to conserve energy, while others may select one such as 72°F (22°C) in order to maximize the number of satisfied occupants. Selecting systems and controls that perform efficiently at part load can mitigate the energy downside of the latter.

Each person having control over his or her own environment, referred to as *personalized ventilation and conditioning* (as provided in many automobiles and airplanes, for example) is the ideal situation but is not easily attained in buildings. It is wise, therefore, to select zones carefully and consider using as many as is needed to create sufficient homogeneity within each zone to improve the ability to satisfy comfort needs of occupants in the zones. Rooms and areas having loads that vary over time in patterns that are significantly different from areas that surround them benefit from having their own conditioning control loops and thermostats.

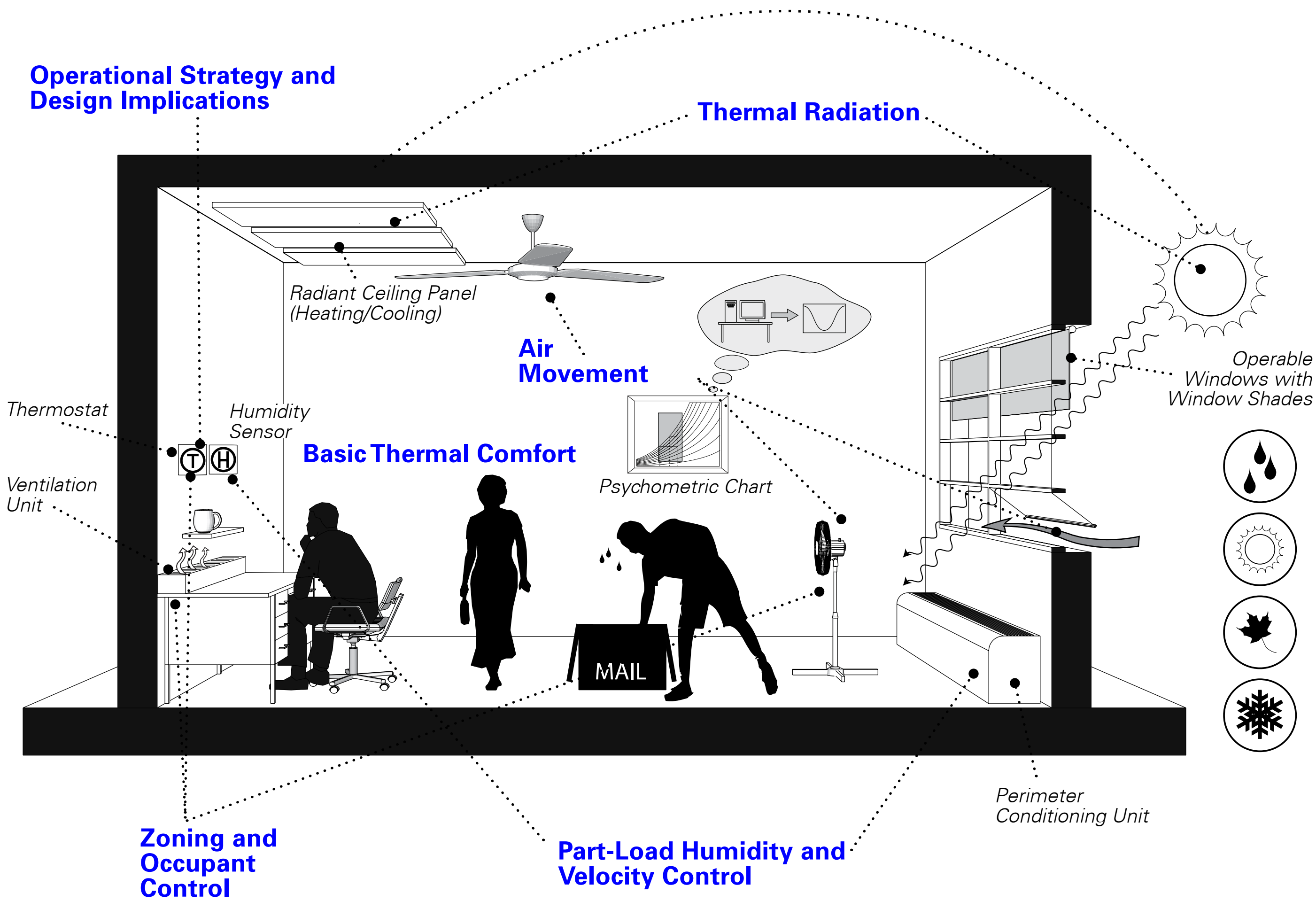
It is expected that individual occupants in the same temperature control zone will have different thermal comfort needs. They can be encouraged, therefore, to adjust their clothing to fit their own needs. However, if the occupants have an adjustable thermostat in the space, then so-called "thermostat wars" may occur, where occupants frequently readjust the thermostat that others have set. This situation can reduce both the efficiency and effectiveness of the comfort system. The solution in some cases may be either giving control to a neutral party, such as the building operator or office manager, or using thermostats for which the temperature adjustment range is limited.

The control of humidity at part load is a comfort goal that needs to be considered in the design of systems and their control sequences. Controlling moisture is also important to limit condensation and mold, as discussed in Strategy 2.4 – Control Indoor Humidity.

Air diffusion devices need be selected so that the required air velocity conditions in occupied zones are maintained at low airflow, as would occur in a VAV system. It is also important to choose thermostat locations that best represent the conditions that occupants will experience and that are not confounded by solar radiation or other heat sources.

1 The program code is published in Normative Appendix D of ASHRAE Standard 55-2004 in C++/BASIC. A user-friendly version on CD is available for purchase from ASHRAE.

Strategy 7.6


Operational Strategy and Design Implications
Thermal Radiation
Radiant Ceiling Panel (Heating/Cooling)
Air Movement
Thermostat
Humidity Sensor
Basic Thermal Comfort
Ventilation Unit
Psychometric Chart
Operable Windows with Window Shades
MAIL
Perimeter Conditioning Unit
Zoning and Occupant Control
Part-Load Humidity and Velocity Control

Strategy 7.6

Taking thermal radiation into account in system capacity can mitigate the negative effects of strong radiant sources while the comfort benefits—for instance, radiant heating—can be realized.

Drafts can occur under windows and other concentrated locations of heat loss. Overhead forced air for heating can be low in cost, but its effectiveness in avoiding drafts and comfort diminishes with increased height and temperature.

Layout of a Corridor with Large Amounts of Glazing

In order to achieve visual symmetry on the outside of the building, the corridor shown in Figure 7.6-A has 7 ft (2.1 m) high glazing. Because the building faces southeast, it requires massive amounts of air for cooling, which in turn increases both first costs and energy costs.

Discussions are under way with the design team to make one or several of the following improvements:

- reduce the amount of glazing,
- use glass with a heavy shading coefficient,
- install interior shading,
- use natural conditioning by making the windows operable and isolating the corridor from mechanically conditioned spaces, and/or
- relax the comfort criteria in the corridor since people pass through it quickly.

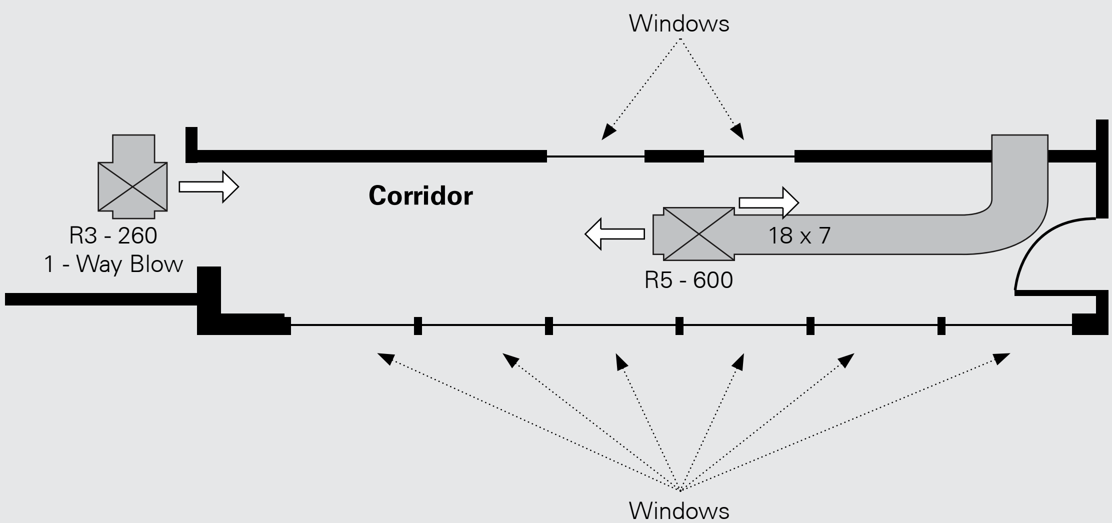


Figure 7.6-A Sample Corridor Layout

Apply More Advanced Ventilation Approaches

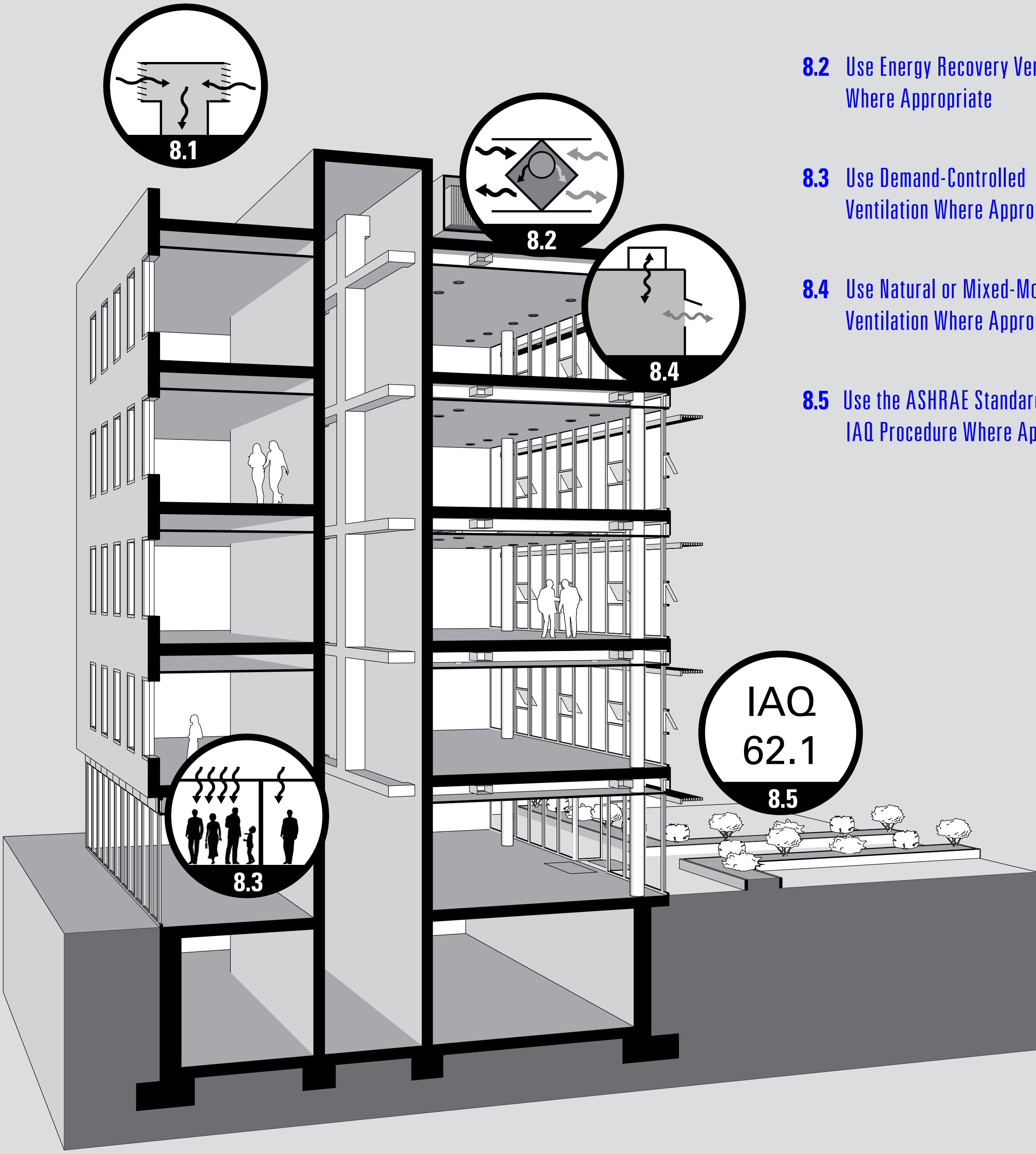
Conditioning and transporting ventilation air accounts for a significant fraction of building energy use. The Strategies presented in this Objective can help reduce the energy required to deliver good IAQ.

- 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

8.1

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.

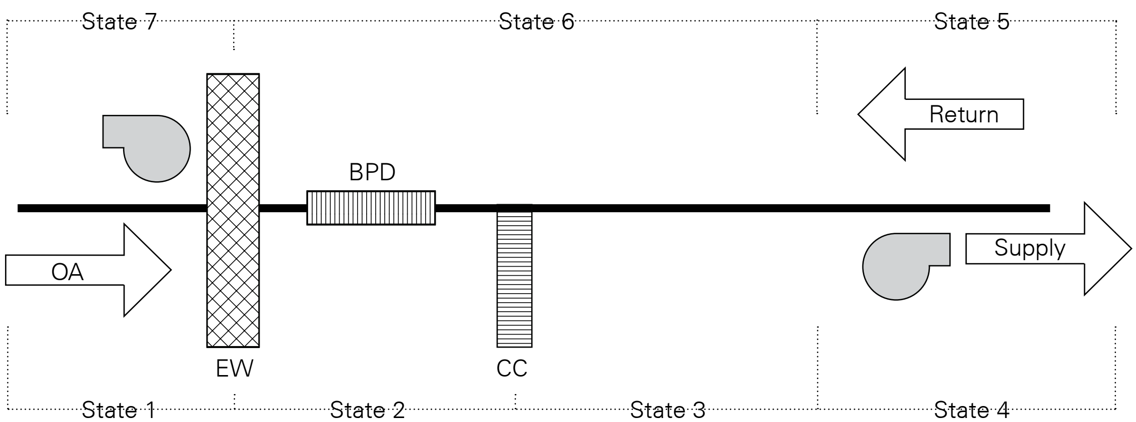
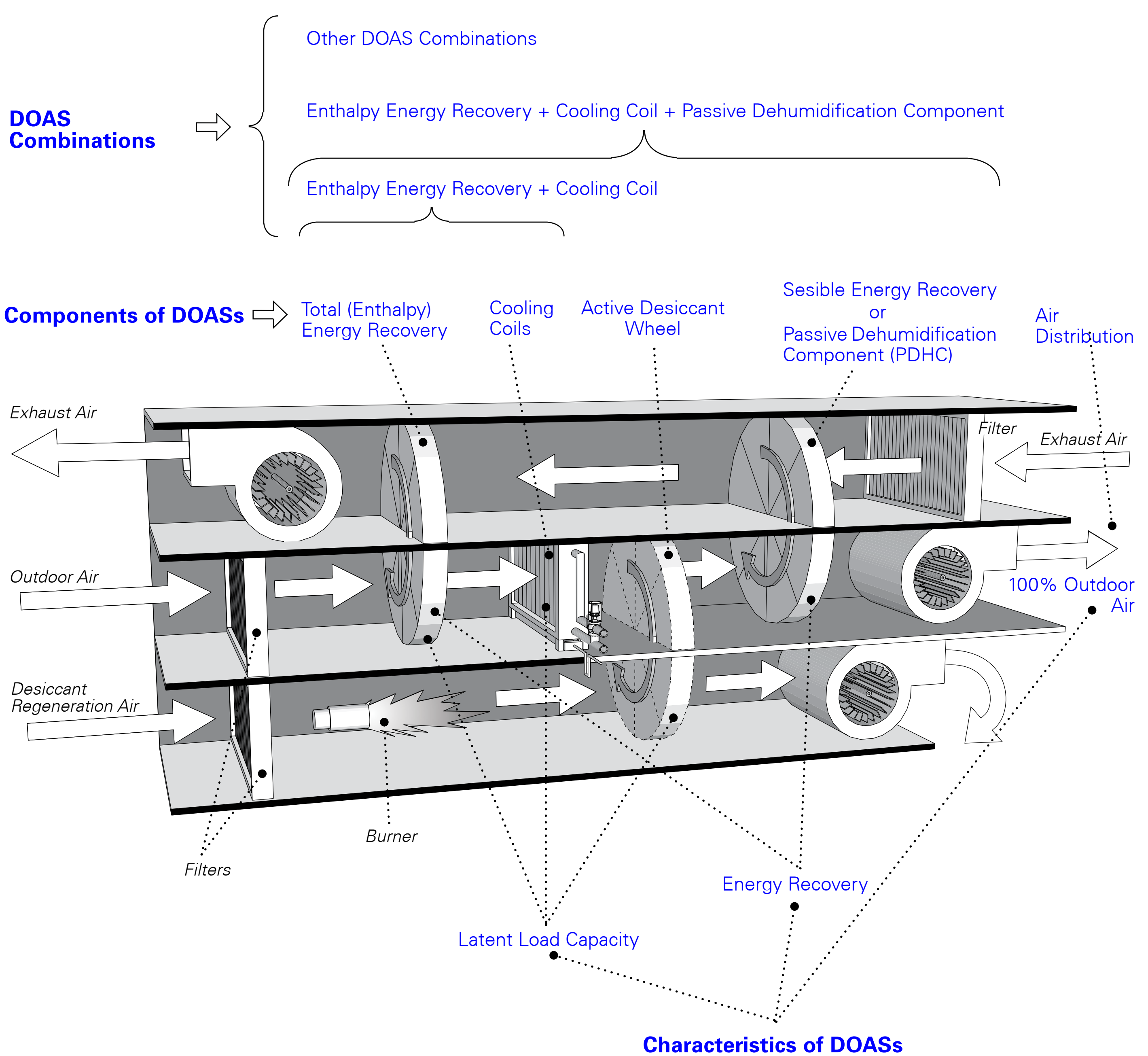


Figure 8.1-A Example of DOAS with enthalpy wheel (EW) and CC

Strategy 8.1


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.

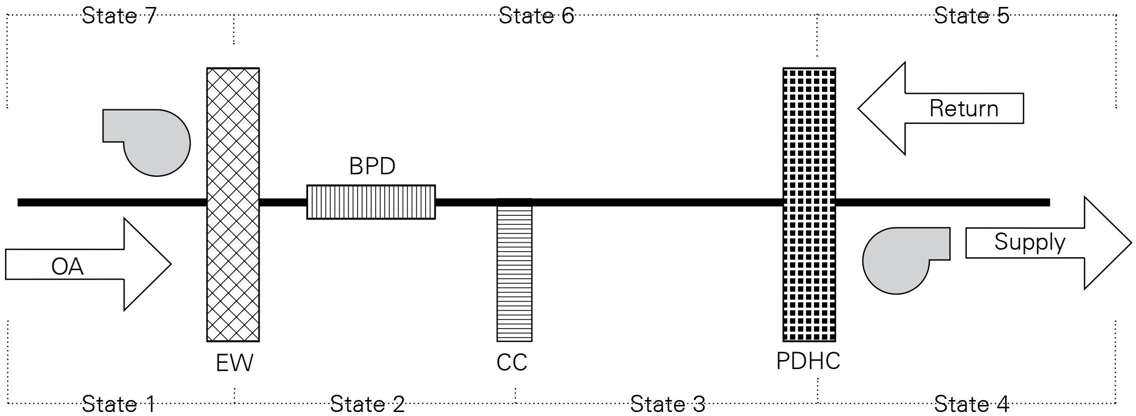


Figure 8.1-B Example of DOAS with EW, CC, and PDHC

Strategy 8.1

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.

8.2

Use Energy Recovery Ventilation Where Appropriate

Energy recovery ventilation is required for certain applications by energy standards such as *ANSI/ASHRAE/IESNA Standard 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings* (ASHRAE 2007e). In other cases, energy recovery systems provide such sufficient payback in overall system sizing and reduced operating costs over the life of the system that they are installed voluntarily. In the case of total energy recovery ventilators (ERVs), improved humidity control is an additional benefit, critical for controlling condensation and mold growth and for thermal comfort. In some cases an ERV is the critical component that allows the HVAC system to achieve moisture management objectives.

In general, there are two types of energy recovery ventilation devices: total ERVs that transfer heat and moisture between incoming and exhaust air and heat recovery ventilators (HRVs) that do not transfer moisture. Along with generic IAQ concerns about keeping mechanical air delivery equipment clean, proper application of equipment needs to address correct selection, sizing, application, Cx, and maintenance. Because this equipment needs to perform correctly under all outdoor weather conditions, it is essential that the system containing the energy recovery devices be properly commissioned for the specific application.

Types of energy recovery systems include an energy recovery wheel and fixed plate with latent transfer, fixed plate, heat pipe, and runaround loop systems.

General design considerations include those associated with filtration, controls, sizing, condensation, and sensible heat ratio.

Warning: Air-to-air energy recovery equipment needs to have airstreams filtered and/or cleaned for efficient, reliable operation. Like any other equipment, the system needs to be properly maintained.

Using Energy Recovery System to Control Humidity

In humid climates, there is a challenge in properly ventilating schools and also controlling indoor humidity. ASHRAE Standard 62.1-2007 requires that relative humidity in a space be limited to less than 65% during cooling conditions. Using packaged equipment for air conditioning and ventilation often cannot provide humidity control under part-load conditions. This is because a typical packaged equipment sensible heat ratio is 0.67 when the part-load sensible heat ratio in a classroom is closer to 0.40 (Fischer and Bayer 2003). Using an energy recovery system with latent transfer capability can provide improved humidity control while saving energy. A recent study of an energy recovery system documented reductions in space humidity with corresponding energy savings at schools in the Atlanta area (Fischer and Bayer 2003).

Figure 8.2-A shows sensible and latent loads for a typical classroom in Atlanta, GA.

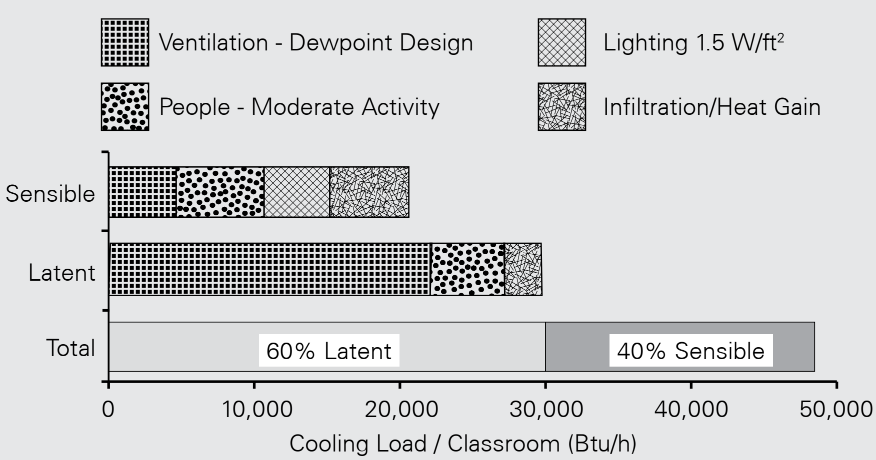
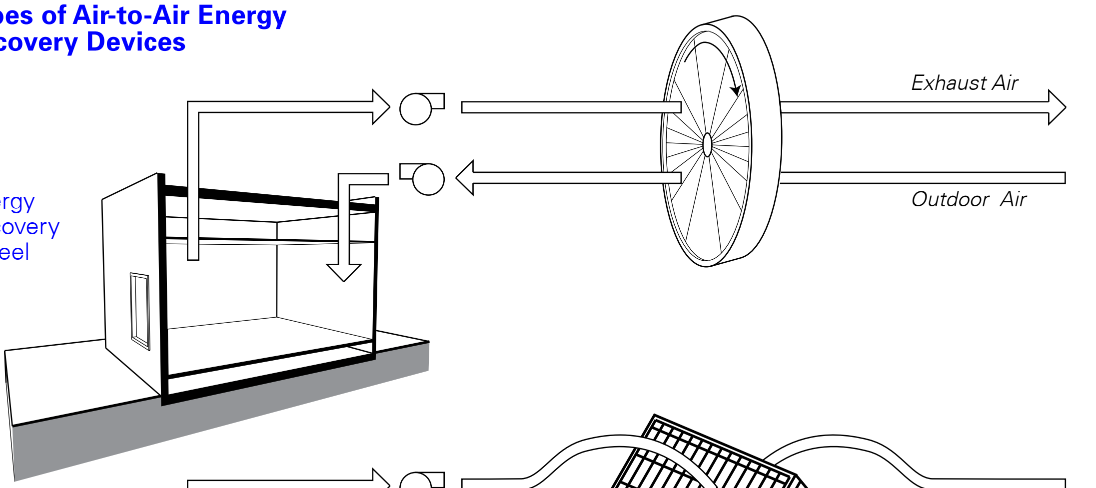


Figure 8.2-A Sensible and Latent Loads for a Typical Classroom in Atlanta

Strategy 8.2

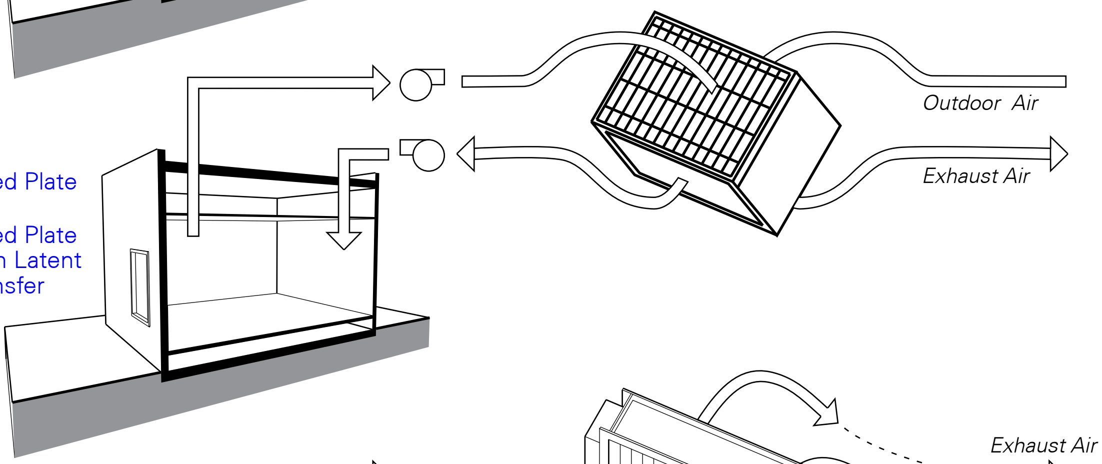
Types of Air-to-Air Energy Recovery Devices

Energy Recovery Wheel

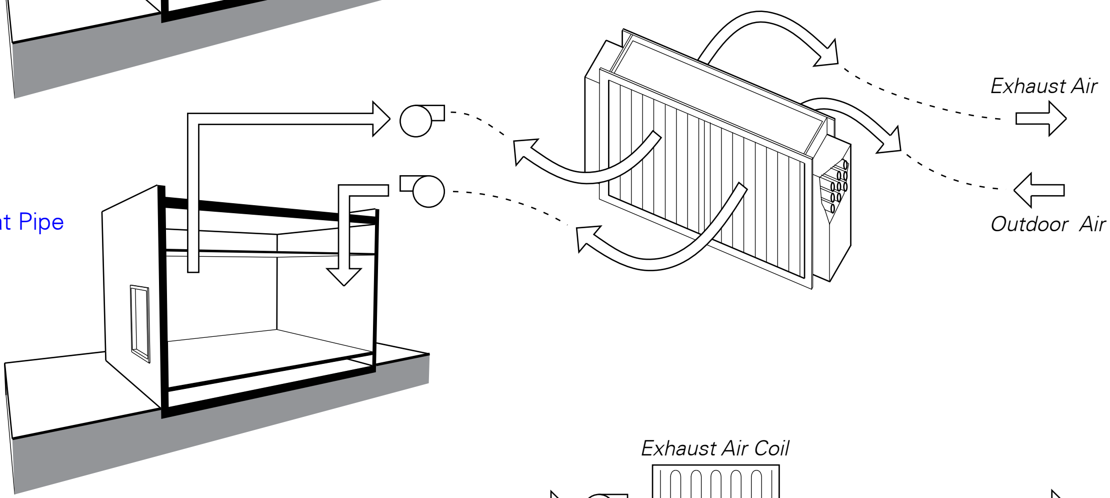


Fixed Plate

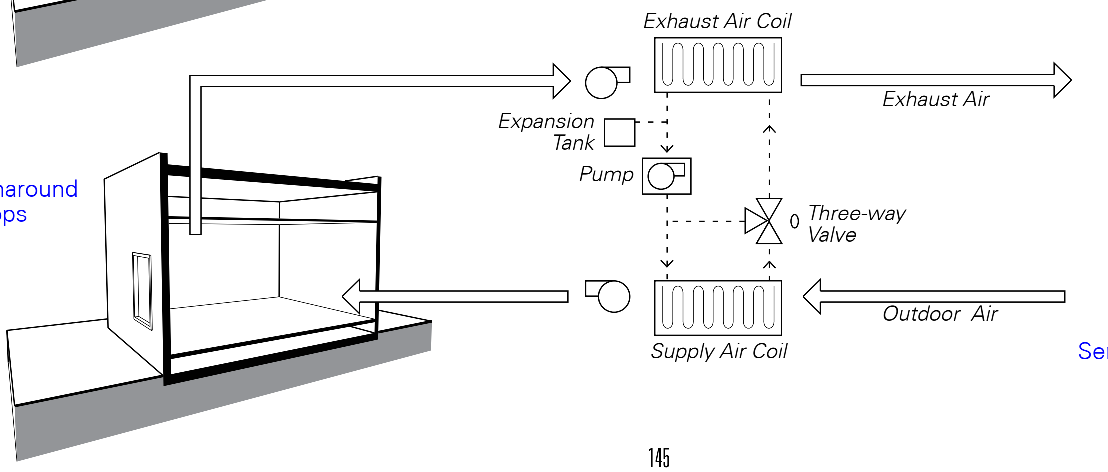
Fixed Plate with Latent Transfer



Heat Pipe



Runaround Loops



General Design Considerations

Appropriate Filtration

Controls

Sizing of Equipment

Condensation

Fouling and Corrosion

Sensible Heat Ratio (SHR)

Use Demand-Controlled Ventilation Where Appropriate

8.3

Demand-controlled ventilation (DCV) is a control strategy that varies the amount of ventilation by resetting the outdoor air intake flow setpoints to an occupied space based on the changing number of occupants. The goal is to avoid underventilation (increasing the potential for poor IAQ) as well as overventilation (wasted energy). 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% or from \$0.05/ft² (\$0.54/m²) to more than \$1/ft² (\$11/m²) annually. 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.

The simplest approach to DCV is control of the outdoor air rate in an on-off manner based on signals 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.

Appropriate Application of DCV

DCV is most appropriate in densely occupied spaces 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 appropriate for DCV include theaters, auditoriums/public assembly spaces, gyms, some classrooms, 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 less appropriate for DCV despite their intermittent or variable population. Densely and continuously occupied office spaces, such as call centers, are less likely to see the benefits of DCV given the lack of variability in occupancy.

Although the energy-conserving benefits of DCV may be small in general office buildings, making DCV a not-very-cost-effective energy-saving strategy in such applications, certain aspects of DCV controls may be beneficial to such a building in ensuring that the design ventilation rates are supplied under all operating conditions. For example, continuous measurement of outdoor airflow rates and indoor CO_2 levels can help building personnel find ventilation system faults or make adjustments to the HVAC system setpoints, thus avoiding overventilation or underventilation relative to the design or code requirements.

DCV in Multiple-Zone Systems

Application of DCV in single-zone systems is fairly straightforward. However, neither ASHRAE Standard 62.1-2007 nor its associated user's manual address the design and operation of DCV for systems that serve multiple spaces. There is currently no published guidance for DCV in multiple-zone systems.

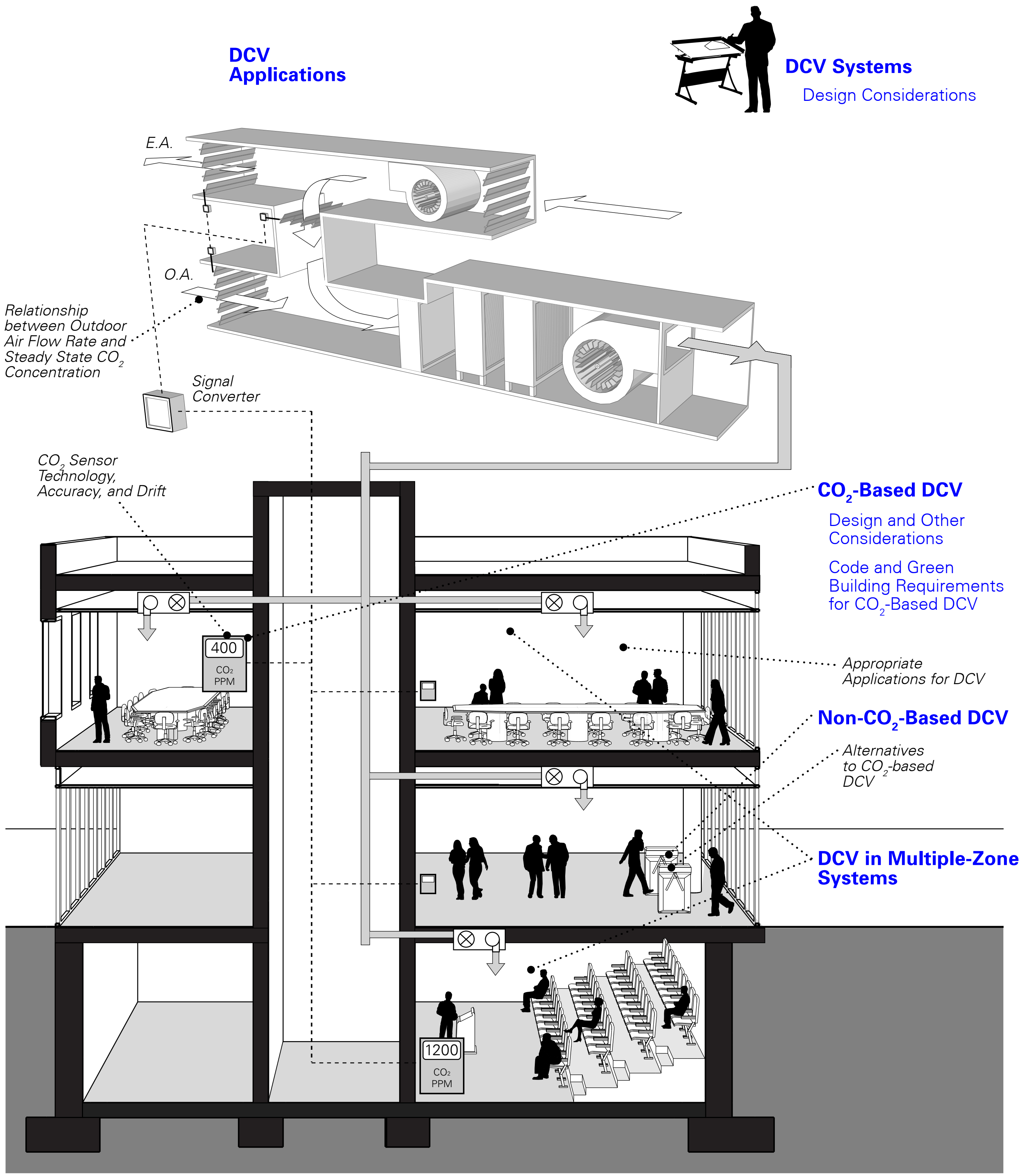
CO_2-Based DCV

Measurement and control of indoor CO_2 concentrations has been the most popular DCV method because CO_2 sensors and associated controllers are relatively inexpensive and, in controlled environments, have been shown to correlate well with people-related contaminant levels (Persily 1997). A number of packaged HVAC equipment manufacturers now offer CO_2 sensors and controllers as an option for their equipment. This method is based on the fact that the rate of CO_2 generation indoors by occupants is proportional to the number of occupants and their activity levels. Other indoor sources of CO_2 and removal mechanisms may exist in some buildings, and in some cases they may be significant enough to compromise the viability of a CO_2-based DCV.

Design Considerations for CO_2-Based DCV. CO_2-based DCV is required by some building codes. However, despite its relatively low cost and short payback, the CO_2-based DCV market has grown slowly since 1990 and has not necessarily reached its peak potential. This is partially due to the limited data on the long-term performance of

STRATEGY OBJECTIVE 8.3

Strategy 8.3



DCV
Applications
DCV Systems
Design Considerations
E.A.
O.A.
Relationship between Outdoor Air Flow Rate and Steady State CO_2 Concentration
Signal Converter
CO_2 Sensor Technology, Accuracy, and Drift
400
CO_2 PPM
1200
CO_2 PPM
CO_2-Based DCV
Design and Other Considerations
Code and Green Building Requirements for CO_2-Based DCV
Appropriate Applications for DCV
Non-CO_2-Based DCV
Alternatives to CO_2-based DCV
DCV in Multiple-Zone Systems

these sensors. Limited studies have indicated that there are numerous issues that need to be addressed by 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 sensor lag times (Shrestha and Maxwell 2009a, 2009b, 2010; Emmerich and Persily 2001; Fisk et al. 2007). Also, the CO_2 generation rates measured and reported for sedentary adults (1.2 met units) need to be adjusted for other situations, such as children in classrooms.

The following considerations should be made during the design of a CO_2-based DCV system:

- In HVAC systems with open plenum returns, CO_2 sensors should be located in the room so that the average concentrations at breathing level can be obtained. 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.
- In HVAC systems with ducted returns, CO_2 sensors may be placed in the return air duct from a zone if the designer can relate the CO_2 measurement in the return duct to breathing-level average measurements provided that same occupancy types and space usage are serviced by the return duct in that zone.
- 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.
- 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 offsetting potential errors such as the tendency to overventilate at higher densities and underventilate at lower densities.
- CO_2 sensors should be specified by the manufacturer to have an uncertainty no greater than ±50 ppm for concentration ranges typically found in HVAC applications (e.g., 400 to 2000 ppm), 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 indicates that field-based calibration should be performed once every one to two years [Fisk 2008]).
- 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; it allows review of CO_2 trend data in part to ensure that the CO_2 sensors and controls are operating as intended.

Alternatives to CO_2-Based DCV

In certain limited applications, such as classrooms, where occupancy is either zero or nearly 100%, the control of outdoor air rates in an on-off manner based on signals from a room occupancy sensor, time clock, or light switch is a practical and energy-saving solution. Other forms of DCV are based on technologies that can count the number of persons entering and exiting a space and adjust ventilation accordingly. In its simplest form this is done by estimating the number of persons during certain time periods and programming the ventilation supply accordingly. However, new advances in sensing and microcomputing technologies may automate this task. Dynamic infrared imaging hardware and software are now used for marketing and security purposes, and research proposals have been submitted to evaluate these technologies with DCV. New technologies have reduced signal delays and calibration drifts when compared to chemical-sensor-based DCV.

Strategy 8.3

CO_2-Based DCV Sensors

This case study illustrates some of the hardware used in applications of CO_2-based DCV. Figure 8.3-A shows a controller that can be used in single-zone constant-volume rooftop units. Figure 8.3-B depicts a conference room, which is a prime candidate for CO_2-based DCV given that the occupancy is variable and generally unpredictable. Figure 8.3-C shows how unobtrusive a wall-mounted CO_2 sensor can be.

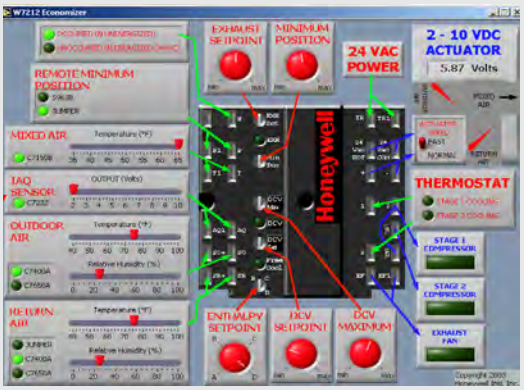


Figure 8.3-A Economizer Controller that Can Accept Reset Signal from a CO_2 Sensor
Photograph copyright Honeywell International, Inc.

Figure 8.3-B Wall-Mounted Sensor in Conference Room
Photograph copyright GE Sensing & Inspection Technologies.

Figure 8.3-C Wall-Mounted Sensor
Photograph copyright Trane.

8.4

Use Natural or Mixed-Mode Ventilation Where Appropriate

Natural ventilation has been used for thousands of years to ventilate and cool spaces. Many examples can be found in ancient building structures from the Pantheon in Rome, where the "Great Eye" at the dome's apex is the primary source of ventilation as well as daylight, to Persian building structures, which use wind scoops called *malqafs* and water features designed to take advantage of the wind, evaporative cooling, and natural buoyancy effects to passively ventilate and cool the building (Walker 2008).

Naturally ventilated buildings do not aim to achieve constant environmental conditions but do take advantage of, and adapt to, dynamic ambient conditions to provide a controllable, comfortable indoor environment for the occupants.

Clearly there are locations in North America that are not suitable for natural ventilation/natural cooling—especially where tight temperature and humidity control is required or in locations that experience prolonged periods of high outdoor temperature, high humidity, chronic outdoor air pollution, or other severe outside weather conditions. On the other hand, there are large portions of North America that can take advantage of natural ventilation strategies for the whole of the year or a significant portion of the year.

When considering the use of natural ventilation, early consideration/analysis of the appropriateness of the prevailing climate must be evaluated in some detail. Climatic issues such as the ambient air temperatures, humidity, and cleanliness of the outdoor air and wind airflow patterns need to be considered.

Natural ventilation and cooling generally works well with other sustainable strategies; for instance, energy-efficient design typically requires the reduction/control of thermal gains and losses, which in turn is an essential design component for natural ventilation. Daylit buildings with narrow floor plates and high floor-to-ceiling areas work well for natural ventilation. Also, naturally ventilated buildings often take advantage of thermally massive elements such as concrete/masonry structures to provide a more stable mean radiant temperature by absorbing and releasing heat slowly. Mass can also be used to temper incoming air, especially when using night flushing, and can moderate mean radiant temperature, which improves comfort. Mass provides a thermal damper, so the building requires less overall energy to heat and cool (Willmert 2001). Displacement ventilation and decoupled DOAS strategies can work well with natural ventilation, as well.

Natural/mixed-mode ventilation systems are now more common in large buildings, especially in the Pacific North West, Japan, and Europe. With mixed-mode systems, natural ventilation is commonly used for ventilating/cooling for most of the year and mechanical ventilation/cooling systems are used for peak cooling and when natural ventilation is not available.

Also, pressure sensors and motor-driven dampers are being used to control pressures in various parts of buildings and to take advantage of stack effect or wind pressure to deliver ventilation where and when it is needed. These sophisticated ventilation control systems need considerable care in design and operation as well as end-user education.

Key issues for consideration in selecting and designing natural ventilation systems include:

- delivering sufficient outdoor air to dilute indoor pollutants and maintain the required thermal comfort (in accordance with ASHRAE Standard 62.1 [ASHRAE 2007a] and ASHRAE Standard 55 [ASHRAE 2004]);

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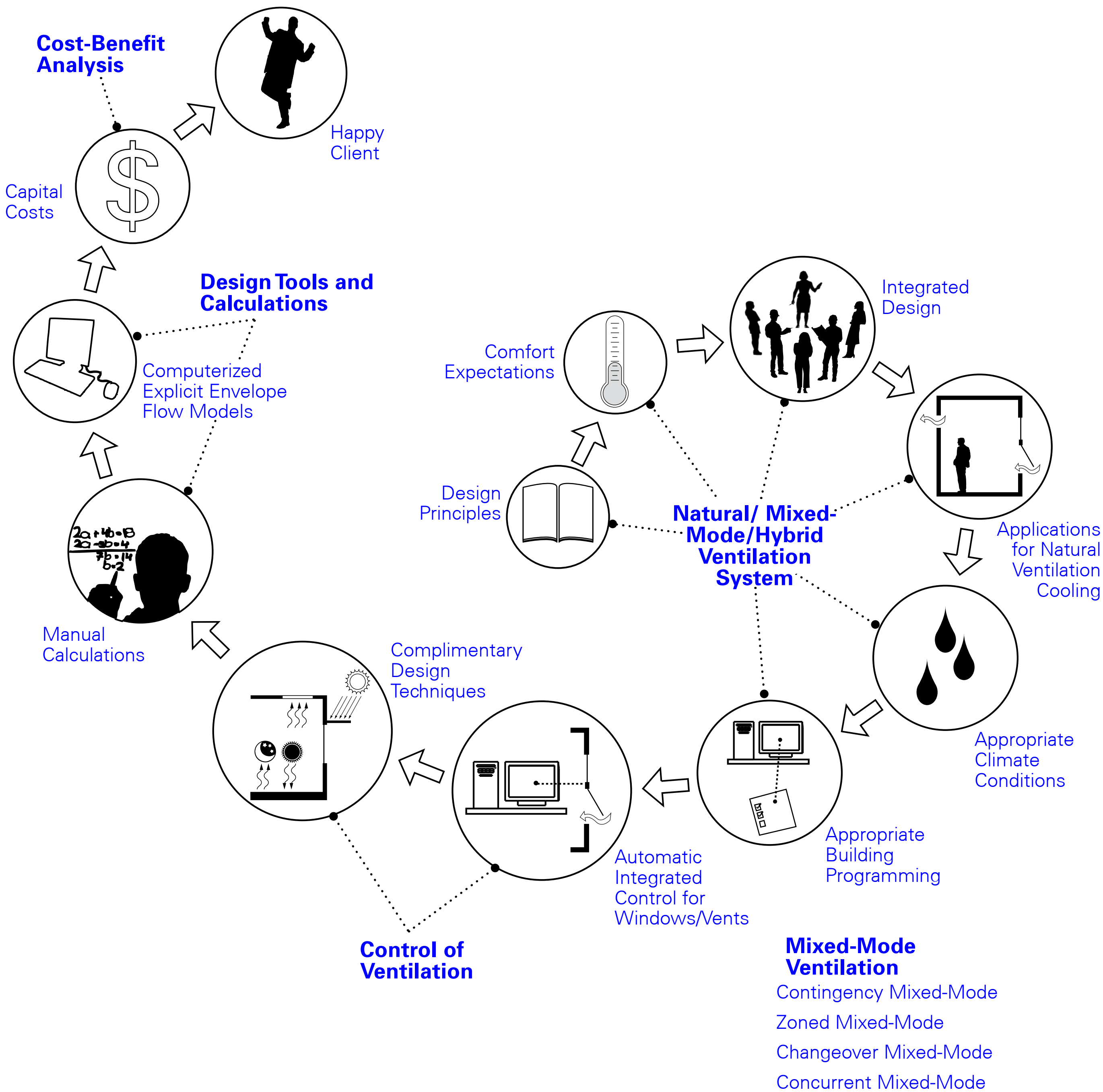

Cost-Benefit Analysis
Happy Client
Capital Costs
Design Tools and Calculations
Computerized Explicit Envelope Flow Models
Manual Calculations
Complimentary Design Techniques
Control of Ventilation
Automatic Integrated Control for Windows/Vents
Appropriate Building Programming
Appropriate Climate Conditions
Applications for Natural Ventilation Cooling
Integrated Design
Comfort Expectations
Design Principles
Natural/ Mixed-Mode/Hybrid Ventilation System
Mixed-Mode Ventilation
Contingency Mixed-Mode
Zoned Mixed-Mode
Changeover Mixed-Mode
Concurrent Mixed-Mode

Strategy 8.4

- reducing the entry of undesirable constituents in polluted outdoor air;
- good solar control and modest internal gains plus an acceptance that the internal temperature will exceed 77°F (25°C) for some period of time (CIBSE 2005);
- controlling airflow through passive or active means, which requires well-designed systems with thorough consideration of airflows under the wide range of outdoor weather conditions to which the building will be subjected;
- a satisfactory acoustic environment (natural ventilation openings provide a noise transmission path from outside to inside, which may be a determining factor in some building locations; in addition, naturally ventilated buildings often include large areas of exposed concrete in order to increase the thermal capacity of the space, and such large areas of hard surface require careful attention to achieve a satisfactory acoustic environment for the occupants);
- smoke control (since smoke can follow natural ventilation paths, the integration of the fire safety strategy must be integrated with the natural ventilation design); and
- health and safety (many natural ventilation openings will be at significant heights above floor level, so safe/easy access to these openings/control devices is required to be considered in the design).

The Carnegie Institute for Global Ecology

Figure 8.4-A Carnegie Institute for Global Ecology

Photograph courtesy of Paul Sterbentz, Carnegie Institution of Washington.

The Carnegie Institute for Global Ecology is an airy, daylit 11,000 ft2 (1022 m2) building on the Stanford University campus (Figure 8.4-A). The building was completed in 2004 by a project team including members from the architect firm Esherick Homsey Dodge and Davis (EHDD) and Rumsey Engineers and Engineering Enterprise. The designers predicted that the building would use 45% less energy and 40% less water than a code-compliant equivalent building. AIA recognized this extremely low-energy laboratory and office building as one of the Top Ten Green Projects of 2007. To control temperature, the building uses radiant cooling and operable windows in the upstairs office levels; only the laboratories are mechanically ventilated. An occupant survey conducted in the building indicated satisfaction from the users of the building in part due to the natural ventilation used in the design (Figure 8.4-B).

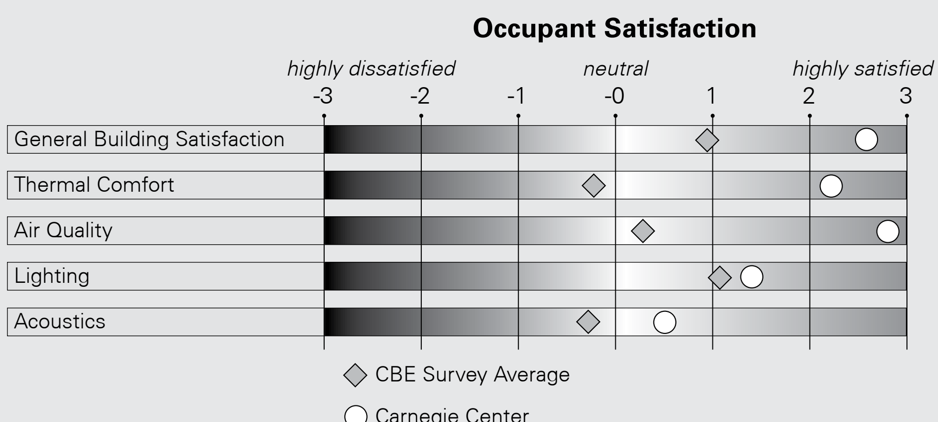


Figure 8.4-B Occupant Satisfaction Chart
Adapted from CBE (2005).

Case study source: Weeks et al. (2007) and CBE (2005).

STRATEGY OBJECTIVE 8.4

Strategy 8.4

Liberty Tower of Meiji University

Figure 8.4-C Liberty Tower
Photograph courtesy of Kato and Chikamoto (2002).

Liberty Tower, the high-rise school building of Meiji University in Japan (Figure 8.4-C), is 570,506 ft^2 (53,000 m^2) and has 23 floors above grade. It was completed by a project team including members from Nikken Sekkei Ltd. and Toshiharu IKAGA. The building shape and design (Figure 8.4-D) were determined to maximize natural ventilation, with controlled windows and a wind floor (Figure 8.4-E) automatically controlling the building pressure and airflow. The building optimizes the use of natural lighting and incorporated a number of energy savings measures. The decrease in primary energy consumption is shown in Figure 8.4-F.

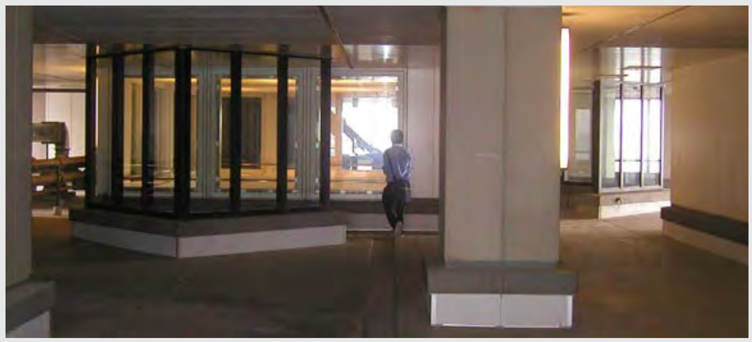


Figure 8.4-E Wind Floor
Photograph courtesy of Kato and Chikamoto (2002).

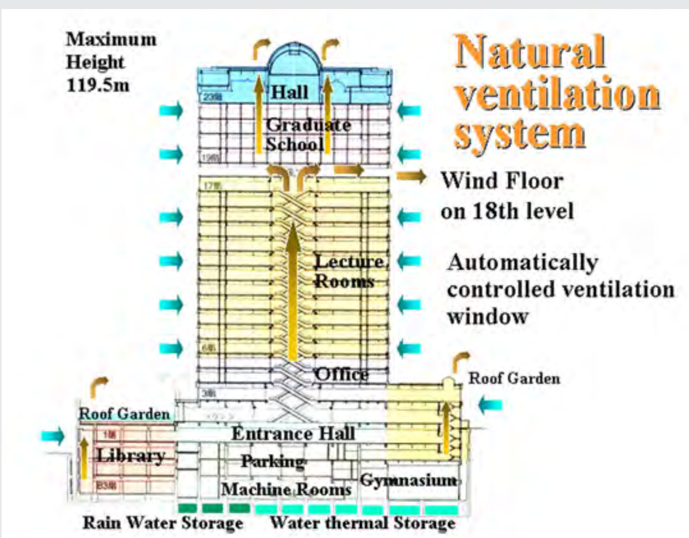


Figure 8.4-D Airflow Schematic for the Natural Ventilation System
Image courtesy of Kato and Chikamoto (2002).

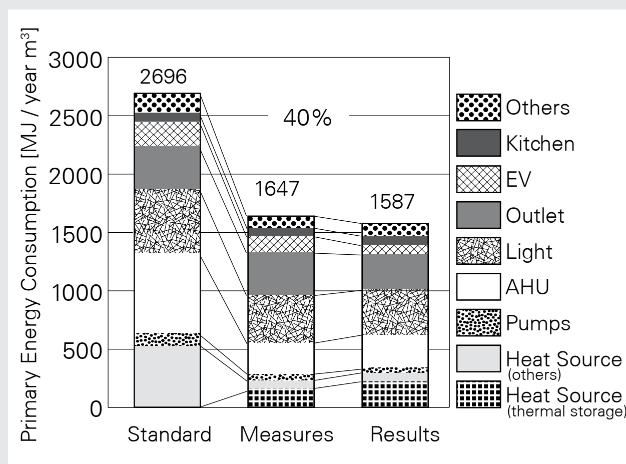


Figure 8.4-F Measured Energy Consumption
Adapted from Kato and Chikamoto (2002).

Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate

IAQ 62.1 8.5

The IAQ Procedure (IAQP) provides designers with an important option or adjunct to the prescriptive Ventilation Rate Procedure (VRP) in ASHRAE Standard 62.1 (ASHRAE 2007a), thereby increasing the potential for good IAQ control.

In general, the attainment of good IAQ can be achieved through the removal or control of irritating, harmful, and unpleasant constituents in the indoor environment. The established methods for contaminant control are source control, ventilation, and filtration and air cleaning. Source control approaches should always be explored and applied first because they are usually more cost-effective than either ventilation (dilution) or FAC (extraction). Other Strategies in this Guide discuss various aspects of ventilation for attainment of acceptable IAQ as presented by ASHRAE Standard 62.1-2007. However, the main focus of ASHRAE Standard 62.1 is the VRP, which specifies minimum outdoor air ventilation rates to dilute indoor contaminants.

This discussion focuses on an alternative compliance pathway to the VRP that is referred to in the standard as the *IAQ Procedure*. The application of the IAQP typically employs a combination of source control and enhanced extraction through filtration and/or gas-phase chemical air cleaning, in some cases resulting in a reduction in the minimum outdoor air intake flow required, compared to the more commonly used prescriptive VRP. (See Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives).

The IAQP generally employs all three basic control methods—source control, ventilation, and FAC—allowing one to realize the combined strengths of each to yield the following potential benefits:

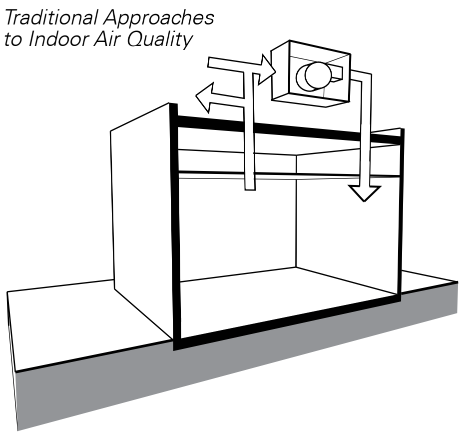
- A methodology for documenting and predicting the outcome of source control approaches and rewarding source reduction tactics by potentially lowering ventilation requirements.
- It can lower the heat, moisture, and pollutant burden of outdoor air by reducing the outdoor airflow rate to the conditioned space.
- The use of enhanced FAC lowers the constituent contaminant concentrations of CoC contained in the outdoor air.
- The use of enhanced FAC can lower the constituent concentration of CoC created and recirculated within the conditioned space.
- Enhanced FAC can result in cleaner heat exchange surfaces and more energy-efficient HVAC system operation.
- Lower outdoor air intake rates can lower system capacity and operating costs.

The IAQP (ASHRAE 2007a) was first introduced in the original ASHRAE Standard 62 in 1973, discussed in ASHRAE Standard 62-1981, and formalized in ASHRAE Standard 62-1989 as an alternate path of compliance to attain acceptable IAQ. However, the IAQP was not widely accepted by model code bodies, so approval by the authority having jurisdiction typically requires a code variance. For this reason, the procedure has not been widely used by designers, who are also reluctant to use it because of its complexity, the potential liability involved, and the additional engineering rigor required, including more calculations, analyses, and/or testing. The occasional use of the procedure has been predominately in areas having high outdoor humidity and heat loads; in buildings having high internal contaminant generation; and in buildings having high density and diversity, such as arenas, schools, auditoriums, theaters, convention centers, and hotels. In

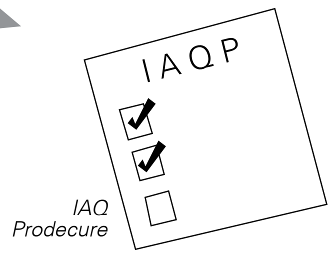
Strategy 8.5

IAQ
62.1
8.5

History of the IAQP



When to Use IAQP



Applying the IAQP

Mass Balance

Successful Buildings

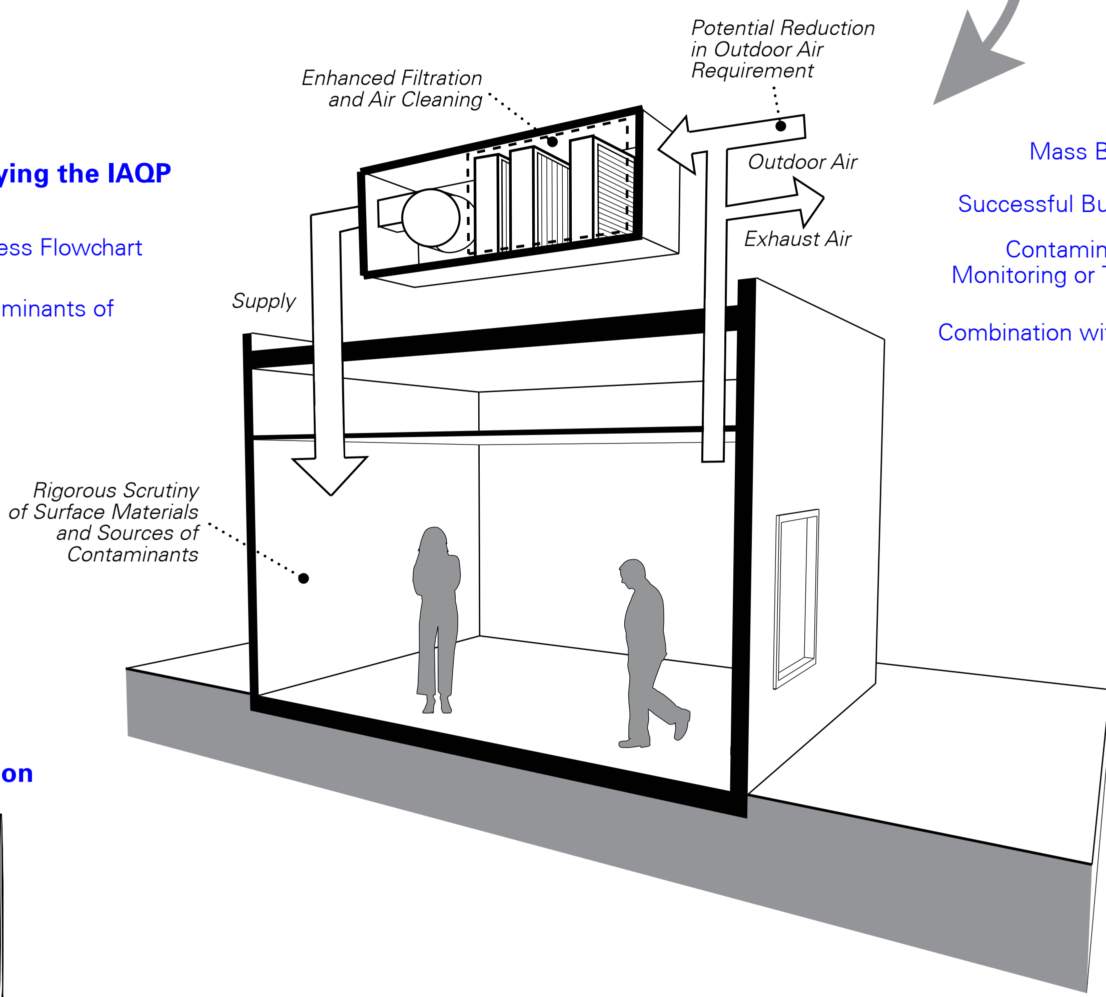
Contaminant Air Monitoring or Testing

Combination with VRP

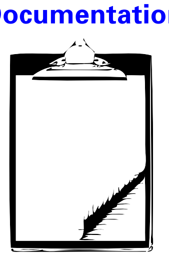
Process for Applying the IAQP

IAQP Design Process Flowchart

Selection of Contaminants of Concern (CoC)



Documentation



STRATEGY OBJECTIVE 8.5

these selected spaces, the economic advantages can provide compelling returns on the additional design and equipment investment, as illustrated by the case study titled "Using the IAQP in Building Design and Construction."

Related Strategies

There is considerable interaction of the application of the IAQP to other areas of the design process. These include the following:

- The evaluation of sources, components, and concentrations of CoC in the outdoor air. See the Strategies in Objective 3 – Limit Entry of Outdoor Contaminants.
- The selection and evaluation of the building component materials for their outgassing and contaminant source contributions. See the Strategies in Objective 5 – Limit Contaminants from Indoor Sources.
- The determination of filtration needs and the selection of the appropriate FAC efficacy and equipment type. See Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives.
- The evaluation and selection of the ventilation system. See the Strategies in Objective 7 – Reduce Contaminant Concentrations through Ventilation, Filtration, and Air Cleaning.
- The selection of HVAC systems and equipment so that enhanced filtration can be installed with adequate access, space, and fan horsepower. See Strategy 1.3 – Select HVAC Systems to Improve IAQ and Reduce the Energy Impacts of Ventilation.

Applying the IAQP

ASHRAE Standard 62.1-2007 allows several alternative approaches of applying the IAQP. They include a mass balance approach using steady-state calculations of CoC, a comparison with similar buildings approach to document successful usage elsewhere, and a contaminant monitoring approach where actual contaminant levels are monitored. By following a set of predefined steps, it is possible to both enhance the IAQ and substantially reduce the outdoor airflow requirements in some buildings. The steps include evaluation of CoC, target levels of acceptability, methods for determining acceptability, examination of ventilation requirements, material selection, FAC options, and implementation and documentation of the IAQP. (See the Part II detailed guidance on this Strategy for further details on applying the IAQP.)

IAQ
62.1
8.5

Strategy 8.5

Using the IAQP in Building Design and Construction

A large public assembly building located in a major Southeastern city (Figure 8.5-A) was constructed in 1991 using the IAQP of ASHRAE Standard 62-1989, which was part of the applicable Southern Building Code at the time. Enhanced filtration was included in the original design because the facility is located in an urban area near dense auto, truck, and train traffic. The facility features public events that generate high levels of internal dust and dirt loads, such as monster truck and tractor pulling, that led to the need for enhanced filtration. This filtration component enabled the use of the IAQP, which reduced the peak outdoor air requirement two thirds, from 15 to 5 cfm (7.5 to 2.5 L/s) per person (or over 750,000 cfm [375,000 L/s] total). This reduction yielded a reduction of 2350 tons (8260 kW) of chiller capacity and 2.5 million dollars of related construction costs. Reduced operating energy costs totaled 40 million Btu (42 million kJ), or $800,000 per year in 1991 dollars, which equals $1,256,000 per year in 2008 dollars. This highly successful installation currently services their MERV 13 bag filters annually. Staff estimate the total accumulated savings to date to be from $13,000,000 to $15,000,000, which is more than the original cost of the building.

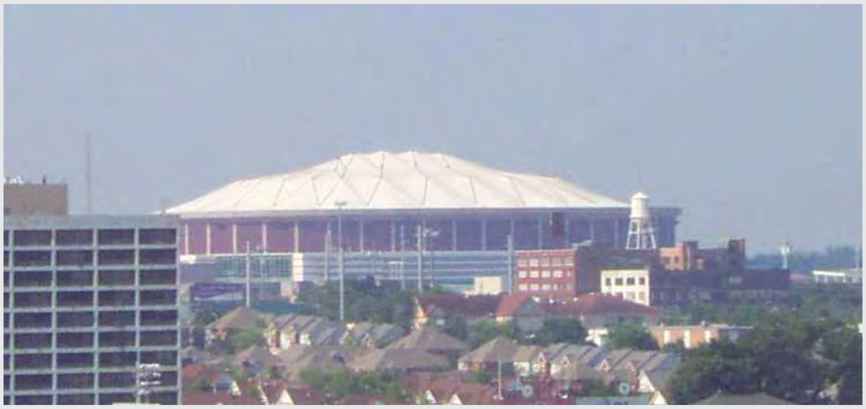


Figure 8.5-A Large Sports Arena in Southern United States
Photograph courtesy of H.E. Burroughs.

Performance verification conducted in 2006 revealed that the FAC system efficiency for particle reduction exceeded 90% at the 0.5 μm size. TVOC concentration of the supply air did not exceed 106 $\mu g/m^3$. No ozone was detectable downstream of the filter bank though outdoor challenge concentrations ranged from 11 to 48 ppb (22 to 94 $\mu g/m^3$).

STRATEGY OBJECTIVE 8.5

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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.

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.

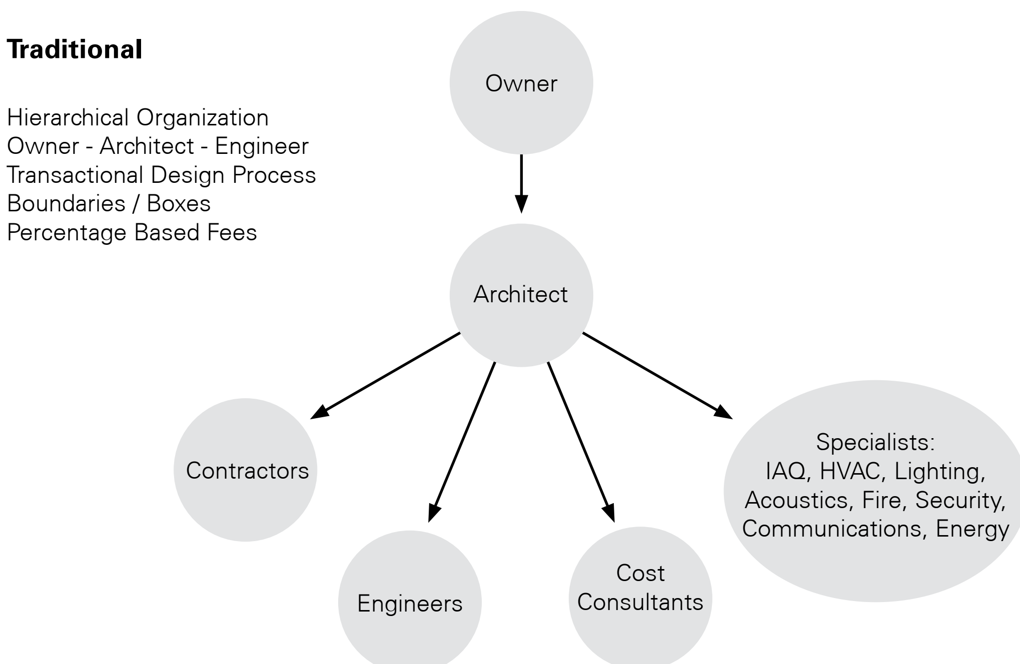

Figure 1.1-D Traditional Design Team

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

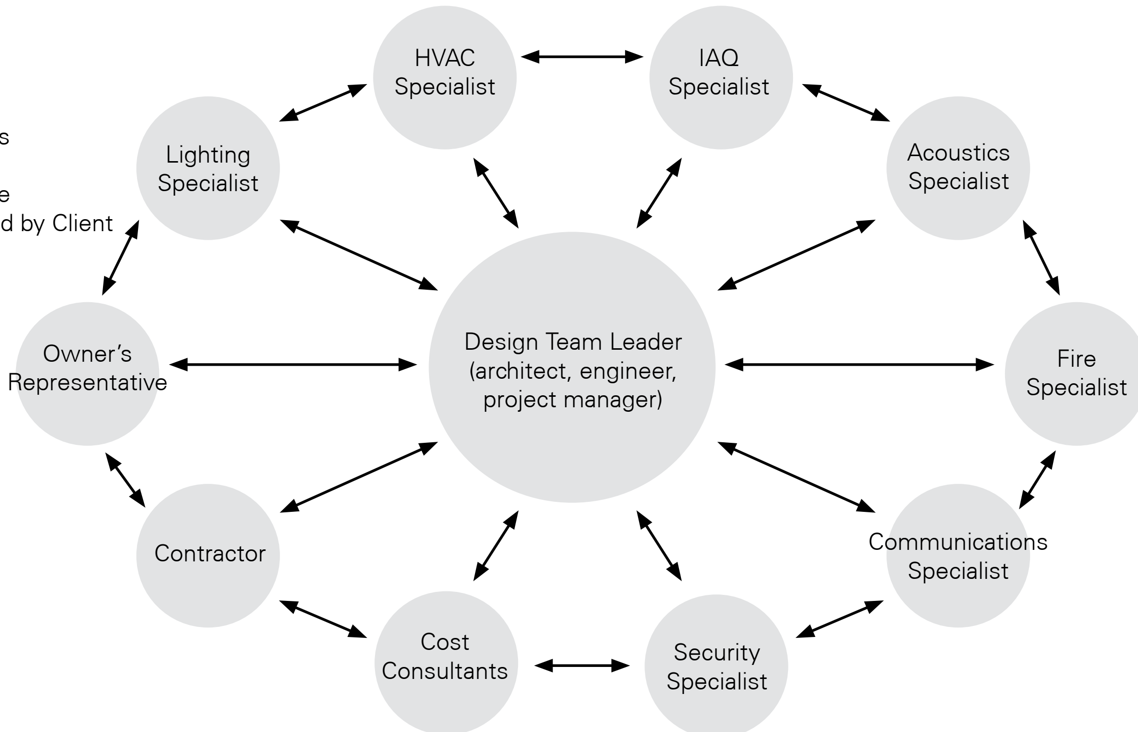

Figure 1.1-B Integrated Design Team

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

[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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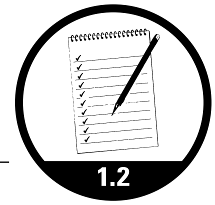
Strategy 1.2



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).

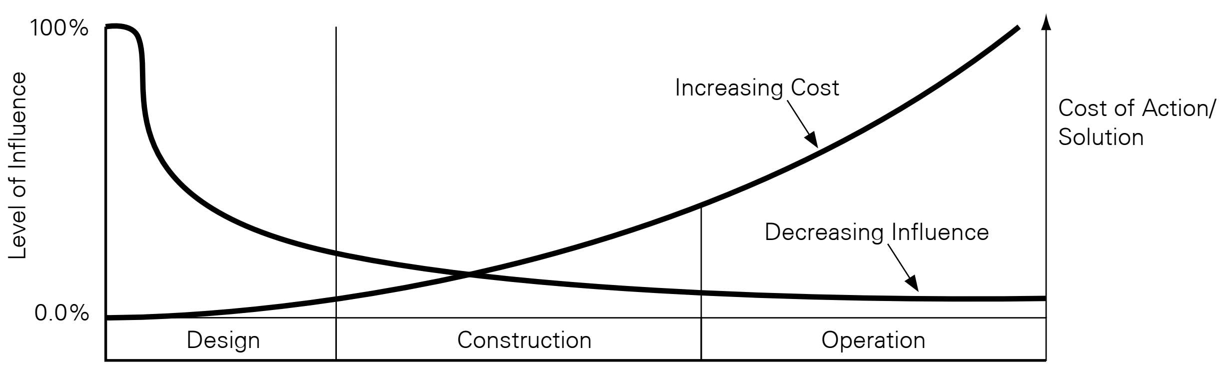


Figure 1.2-C Decreasing Ability to Influence Outcomes and Increasing Cost of Action as Project Proceeds
Adapted from a figure copyright CH2M HILL.

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).

Strategy 1.2

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.

Strategy 1.2

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.

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."

Strategy 1.2

1.2

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.

Strategy 1.2

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.

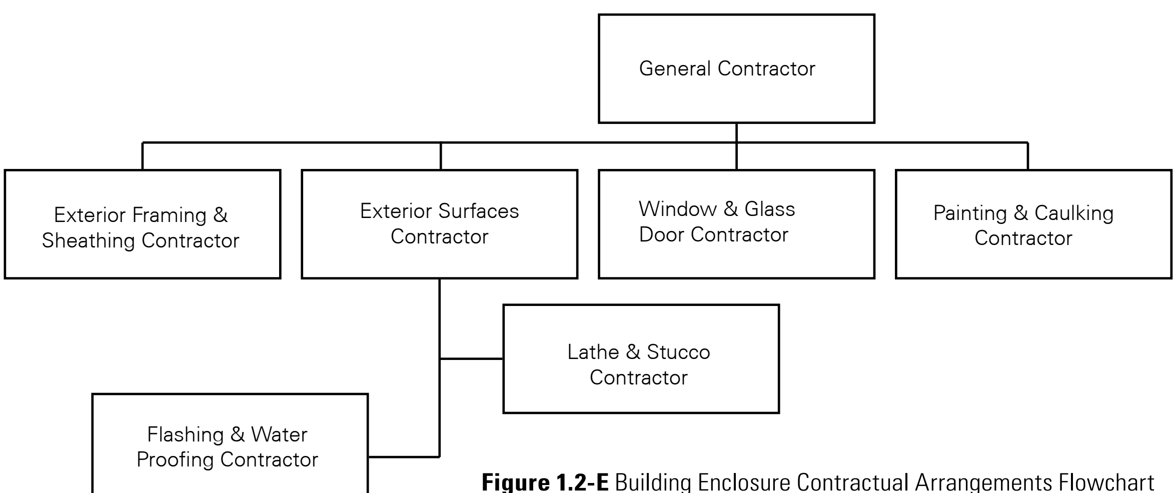


Figure 1.2-E Building Enclosure Contractual Arrangements Flowchart
Adapted from Parzych and MacPhaul (2005).

Strategy 1.2

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.

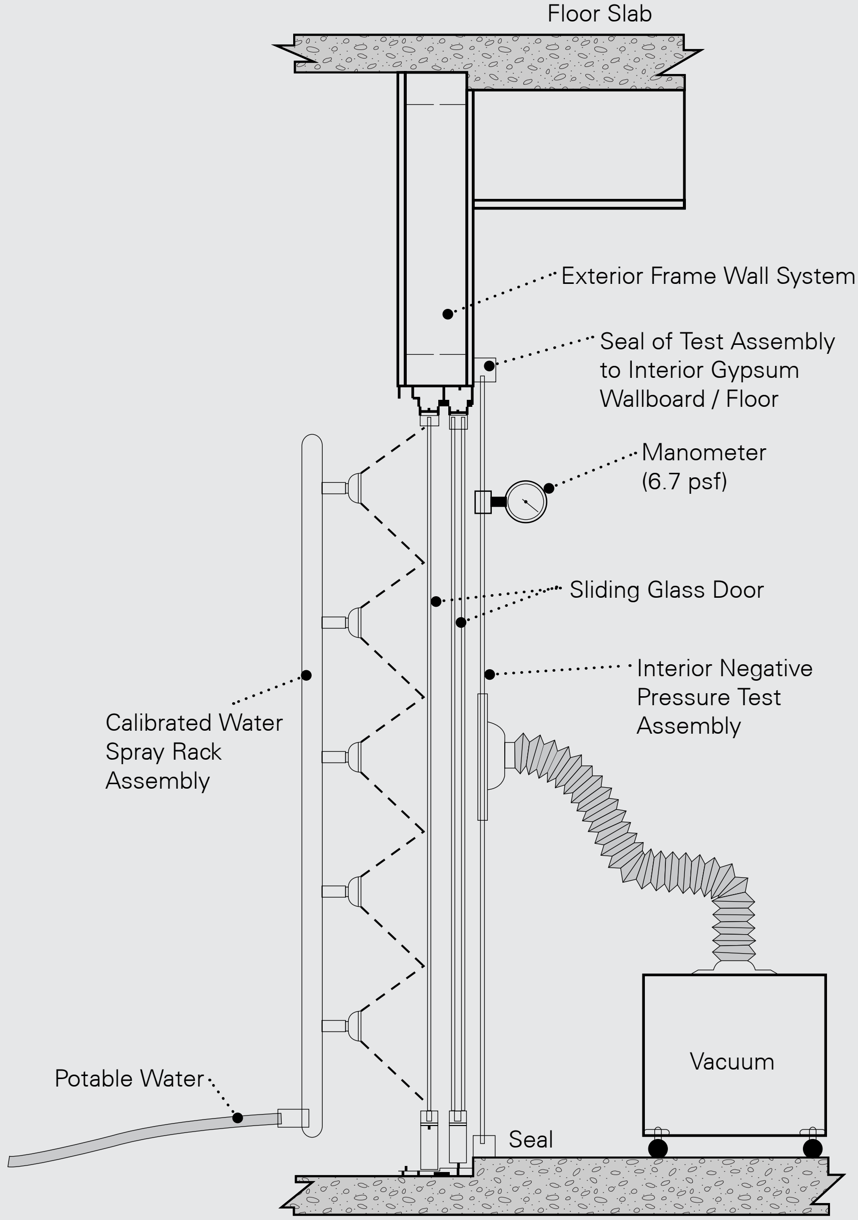


Figure 1.2-H Water Spray Test Assembly for Sliding Glass Doors
Adapted from Parzych and MacPhaul (2005).

Strategy 1.2

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 1.3

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

Introduction

The selection of HVAC systems to improve IAQ and reduce the energy impact of ventilation can be a complex process. HVAC systems need to be tailored to suit a building's use and location as well as to meet all applicable codes and standards. This Strategy is intended to help with this selection of the most appropriate HVAC system, based on an informed decision-making process.

HVAC System IAQ Design Principles

Decisions for the mechanical system design are central to the building's IAQ performance and will also have major impacts on thermal comfort and energy. As the design engineer considers these and other factors (e.g., space limitations, costs, robustness, controllability, redundancy, etc.), a few system options will likely emerge for detailed analysis. Such analysis and decision making is best accomplished through an integrated design process.

Integrated Design Considerations

In integrated building design, the design team works together on what at first sight appear to be unrelated design issues in a manner that allows synergistic benefits to be realized. The primary goal of integrated design is to achieve enhanced design and performance in a cost-effective, holistic manner. This process often includes integrating sustainable design principals and strategies in a multidisciplinary process, allowing for comprehensive consideration of IAQ- and energy-related issues with other project design goals in order to optimize the overall building design (FEMP 2001a, 2001b).

All of the project design specialists must be involved in the integrated design process, e.g., architecture, HVAC, structural, lighting and electrical, interior design, and landscape designers. Also, it is critical to engage the building owner and, where possible, the end user representatives in the process. By working together at key points in the design process, these participants can often identify highly attractive synergistic design solutions that otherwise might be overlooked.

Members of the integrated design team should be assigned to assess/analyze/champion the building's IAQ and energy performance. Such analysis should happen at a very early stage in the design process to proactively inform the other integrated design team members of the IAQ and energy-use implications of building design issues, such as building orientation, fenestration, and structural, mechanical and electrical system options, etc.

Finding the right building design recipe through an integrated design process can be challenging. At first, design teams often make initial changes that improve building performance along several dimensions while still controlling costs. The process need not stop there. Continuing to explore design integration opportunities has sometimes significantly improved performance even further. For example, building envelope and lighting design strategies that significantly reduce HVAC system requirements have produced remarkable results. Sometimes the most effective solutions also have the lowest construction costs, especially when they are part of an integrated design (see DOE 2005). More information on the integrated design process is provided in Strategy 1.1 – Integrate Design Approach and Solutions.

Indoor Environmental Quality and Operation and Maintenance. Improved indoor environmental quality/indoor air quality (IEQ/IAQ) have the potential to reduce building maintenance costs through a reduction in occupant complaints about IEQ-related issues. According to a study by Federspiel (2001) based on 575 buildings in the U.S., nearly one-fifth of complaints to facilities managers were related to indoor environment issues. More information on how commissioning (Cx) and ongoing operation and maintenance can affect IAQ is provided in Strategy 1.2 – Commission to Ensure that the Owner's IAQ Requirements are Met and Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ.

Linkages among Indoor Environmental Factors. The thermal, acoustic, and visual properties of the environment as well as the IAQ are intrinsically linked and should not be considered in isolation. For instance, higher temperatures can cause increased emissions of volatile organic compounds (VOCs). Higher air velocity can increase evaporation of volatile and semi-volatile chemicals from surfaces and disturb surface particles and make them airborne. Higher humidity increases the air concentration of water soluble chemicals such as formaldehyde and can increase the longevity of biological aerosols.

In a study of subjects in an environmental chamber exposed to combinations of controlled VOC concentrations and temperatures, Mølhave et al. (1993) found that

> temperature and pollutant exposures affected air quality, the need for more ventilation, skin humidity on the forehead, sweating, acute sensory irritation and possibly watering eyes in an additive way. Interactions were found for odor intensity ($p = 0.1$), perceived facial skin temperature and dryness, general well-being, tear film stability, and nasal cavity dimension. The presence of interactions implies that in the future guidelines for acceptable indoor air concentrations of VOC's should depend on room air temperature. (p. 155)

These findings illustrate the linkage between indoor contaminant concentrations and other environmental factors, particularly air temperature.

Most thermal control strategies are addressed, at least in part, by the designer of the ventilation system, which often supplies heating and cooling as well as the ventilation air into the occupied spaces. While these functions can and perhaps need to be separated, the design of the ventilation system needs to be done as an integrated effort that carefully considers all the interactions and trade-offs involved. "Optimizing" the design and benefits requires that the project architect, engineers, and owner address these issues early in the concept design phase and continually revise subsequent decisions throughout the design process.

The linkage among various indoor environmental factors points to the importance of integrated design (see also Strategy 1.1 – Integrate Design Approach and Solutions). Refer to Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection and Strategy 5.2 – Employ Strategies to Limit the Impact of Emissions for more information on material emissions.

Energy Conservation and Environmental Considerations

HVAC systems are typically used to deal with both the thermal comfort (temperature/humidity control) and the IAQ (pollutant control) goals within occupied spaces. Today, with rising energy costs and the worldwide movement toward buildings that employ "green" strategies, architects and engineers, mostly in Europe and Asia, are using advanced computerized modeling techniques to refine the physics of heating, cooling, ventilating, and IAQ. This emerging trend is also looking at energy in a different way, giving consideration to the quality and quantity of energy used in buildings, such as using passive/natural or low-grade energy or waste energy in lieu of fossil fuel/electrical power or using natural ventilation, free cooling, day lighting, mixed-mode ventilation, displacement ventilation, thermal mass, water/air economizers, etc. (Willmert 2001). For more information on energy recovery system options, refer to Strategy 8.2 – Use Energy Recovery Ventilation Where Appropriate.

The primary difference between present day-conventional design and this emerging approach is in the design process. In this new approach, 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. A key example of this is the use of natural and/or displacement ventilation. For natural and/or displacement ventilation to work, the building thermal solar gains and thermal losses have to be reduced to less than 13 Btu/ft^2 (40 W/m^2).

Also, there is compelling new research (Mendell and Mirer 2009) that examined data from 95 office buildings in the U.S. and found that in the buildings studied indoor temperatures were higher in winter and lower in summer than needed to maintain thermal comfort, thus potentially increasing the prevalence of building-related symptoms. The clear consequence of this research is that winter setpoints may be reduced and summer setpoints increased to reduce the building energy consumption as well as potentially decrease the occurrence of building-related symptoms.

Mixed-Mode Ventilation

In many parts of the world, designers are using natural ventilation or a combination of natural and mechanical ventilation systems to provide the required building IEQ. The combination of natural and mechanical ventilation is called *mixed-mode ventilation*. Mixed-mode ventilation recognizes that not all parts of a building have to be treated in exactly the same way; different strategies may be applied to different parts of a building or at different times. Mixed-mode ventilation is discussed in greater detail in CIBSE AM10 (CIBSE 2005). (See also Strategy 8.4 – Use Natural/Mixed-Mode Ventilation Where Appropriate.)

Displacement Ventilation Systems. Displacement ventilation systems use the natural buoyancy of warm air to move supply air slowly through the breathing zone from floor to ceiling rather than mixing it with all the air within the zone. This approach can "lift" contaminants out of the breathing zone. First developed for use in industrial buildings, displacement ventilation is now used for many applications throughout the world. Figure 1.3-E provides a visual representation of displacement ventilation. The graphic assumes that the air supplied into the occupied space is clean.

At the air handler, the displacement system is similar to the conventional system. There is, however, one important difference. The displacement system may require the use of a face and bypass or reheat configuration at the cooling coil if/when humidity control is required at the higher supply temperature, e.g., when necessary, a portion of the supply air is dehumidified then mixed with the bypass air to provide the required supply air temperature and humidity.

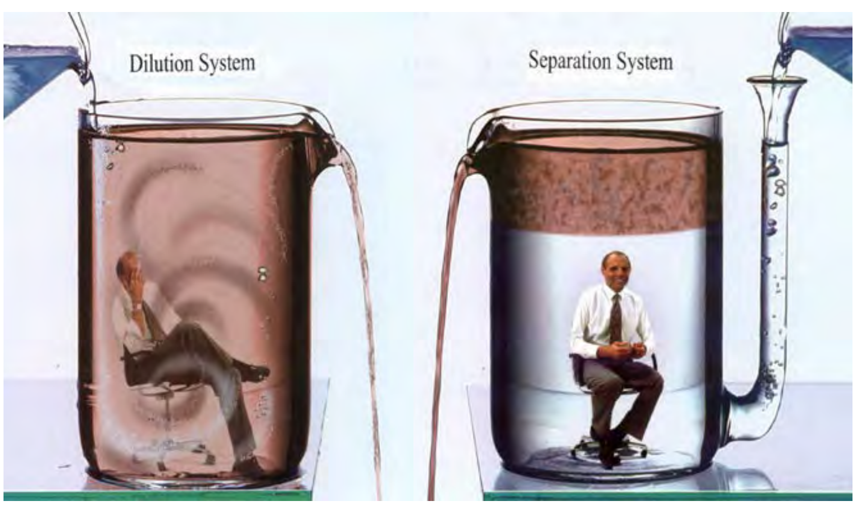

Figure 1.3-E Visual Representation of Displacement Ventilation
Graphic copyright Healthy Buildings International, Inc., used with permission.

Thermal Comfort Considerations

AM10: Natural Ventilation in Non-Domestic Buildings states "Thermal comfort is a complex mix of physiology, psychology and culture" (CIBSE 2005, p. 6). What is deemed acceptable will depend on activity and clothing level as well as surface and air temperatures, air speeds, and humidity. Occupants who have more control over these factors will find a broader range of temperature and relative humidity acceptable. This might involve, for example, using blinds or other moveable shading to cut out direct solar radiation or providing the opportunity to increase air movement by opening windows or using desk fans. Coupled with less formal dress codes, these opportunities allow occupants to adjust their environment to suit their own preferences, thus allowing greater freedom of choice than is usually practical in an air-conditioned environment. However, this approach does require careful design of the windows, their positions, and their opening mechanisms so that occupants can readily adapt their environments (CIBSE 2005).

Another important factor is that recent research has shown that in prolonged spells of warm weather, peoples' expectations of indoor thermal conditions change, suggesting that more careful fine tuning of thermal parameters with some occupant control can both improve occupant satisfaction and be more energy efficient.

In some locations with lower external nighttime temperatures, as long as outdoor humidity is not excessive, a night ventilation strategy can be used to pre-cool the building structure. This lowers the mean radiant surface temperatures as well as the indoor air temperature (because the cooler structure absorbs heat from the indoor air and warm surfaces). By lowering the mean radiant temperature, better comfort can be achieved although temperature in the space rises. Care must be taken to ensure that condensation does not form on the cold surfaces. More information on thermal comfort is provided in Strategy 7.6 – Provide Comfort Conditions that Enhance Occupant Satisfaction.

User-Owner IEQ/IAQ Expectations

Users and owners will have expectations for building function, performance, and cost that are brought to the table at the beginning of the project. It is highly preferable that these considerations be placed within the context of an integrated design process in which project goals are fully discussed and established as guideposts to the design, construction, documentation, and Cx processes. These should include specific IAQ goals and expectations and are critical factors that underlie all HVAC design decisions (see Strategy 1.1 – Integrate Design Approach and Solutions).

Despite trends toward integrated and more advanced HVAC system designs, HVAC system designers are still often required, for numerous reasons, to use conventional HVAC systems such as variable-air-volume (VAV) with reheat, constant volume (CV) with reheat, fan-coil (FC), and packaged HVAC equipment to air condition institutional, commercial, and residential buildings. Clearly these conventional systems have their place, but designers can still apply low-energy and improved IAQ principals within their designs.

Regional/Local and Project-Specific IAQ Issues

Regional prevailing conditions such as poor outdoor air quality, high/low humidity, cold/hot outdoor temperatures, snow drifting, winds, etc. should be considered as part of the HVAC selection process. Dealing with these conditions may require special design considerations such as building pressurization control, space humidity control, and particle filtration control—all of which are discussed in the following subsections.

Building Pressurization Control

Positive building pressurization is critical to IAQ in the following applications:

- Mechanically cooled buildings, particularly in warm, humid climates (Figure 1.3-F)—to reduce risk of condensation and mold growth in building cavities
- Refrigerated buildings (refrigerated warehouses, ice arenas) in most climates—to reduce risk of condensation and mold growth in building cavities (not covered in this Guide)
- Any building located in an area with poor outdoor air quality (Figure 1.3-G)—to reduce risk of infiltration of untreated air
- Regional locations with high outdoor humidity—to ensure outdoor air does not penetrate the building envelope

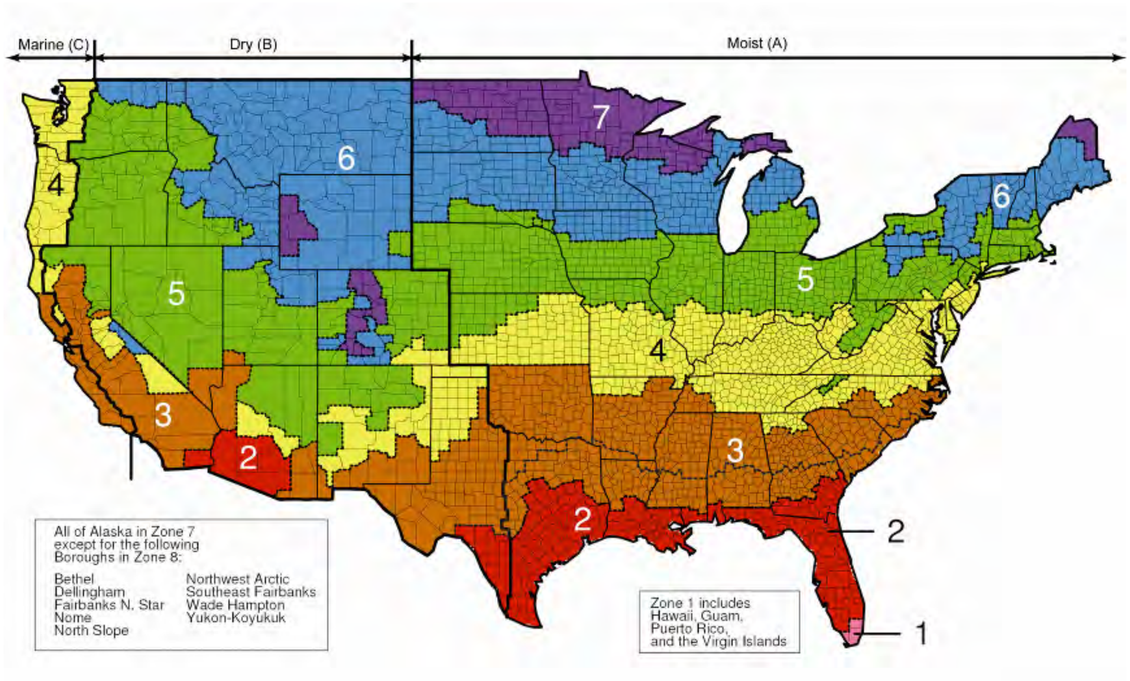

Figure 1.3-F U.S. Map Showing the DOE Climate Zones
Source: Briggs et al. (2003).

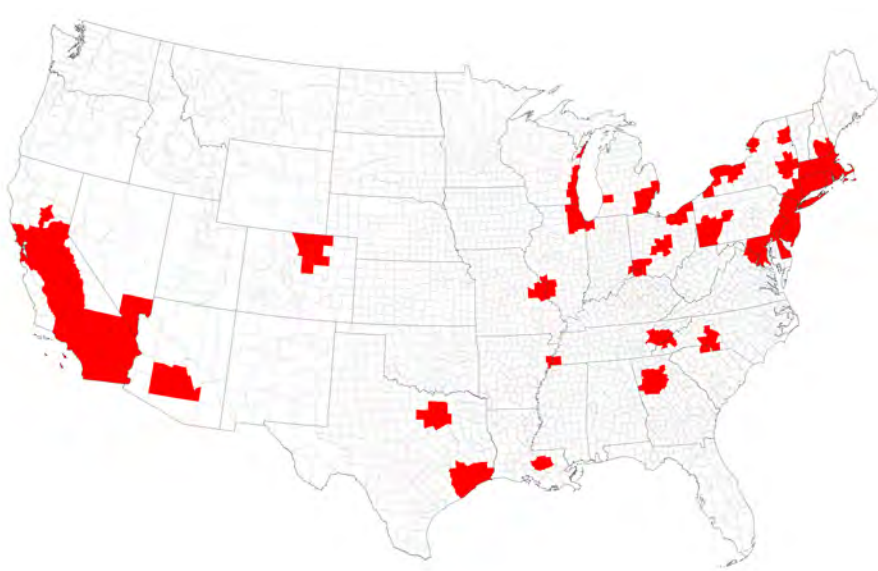

Figure 1.3-G U.S. Counties with 8-Hour Ozone Nonattainment Areas
Graph courtesy of EPA.

The map in Figure 1.3-F delineates the U.S. climate zones per the U.S. Department of Energy (DOE) (Briggs et al. 2003). Hot, moist climates in zones 1A, 1C, 2A, 2C, and parts of 3A and 3C are humid areas where buildings should have positive building pressurization to reduce the risk of mold growth in building cavities.

Areas with poor air quality should have positive building pressurization to reduce infiltration of untreated air. The map in Figure 1.3-G shows areas that do not attain National Ambient Air Quality Standards (NAAQS) for 8-hour ozone, which is one indicator of poor air quality. The highlighted areas are counties in the lower 48 states that contain nonattainment areas (with a snapshot of the nonattainment status as of

March 13, 2009); the entire county may not be nonattainment. Other locations may have other air quality issues and may have poor air quality in the immediate vicinity of a particular project. More information on regional air quality standards is provided in Strategy 3.1 – Investigate Regional and Local Outdoor Air Quality, and more information on building pressurization is provided in Strategy 2.3 – Maintain Proper Building Pressurization.

The types of HVAC systems shown in Table 1.3-A are less likely to provide positive building pressurization and therefore more likely to be unsuitable for applications requiring positive pressure unless the solutions listed in the table are implemented.

Table 1.3-A HVAC System Comparison Relating to Building Pressurization Control

System Type	Possible Causes of Poor Building Pressurization	Possible Solutions
PTACs PTHPs FCUs UVs	No outdoor air or lack of positive control of outdoor air volume.	Provide separate conditioned makeup air system ducted to each exterior space.
Systems relying on continuous exhaust to ventilate building by infiltration or through passive air inlets	Negative building pressure is intrinsic to design.	Provide separate conditioned makeup air system ducted to each exterior space and use intermittent exhaust.
Systems with plenum returns	Depressurization of building envelope in plenum area due to envelope leakage and building stack effects, etc. Undersized return air grilles and return air openings within return air plenums can result in significant depressurization of the plenum cavity. This depressurization can cause infiltration of uncontrolled outdoor air, which in turn can degrade the building IAQ, especially in humid and cold climates.	Use ducted returns. For buildings with return plenums, oversize return air openings and ductwork back to the AHU return air plenum to reduce the depressurization of the ceiling cavity. Seal building envelope and pressure test to limit air leakage.
Natural ventilation systems	Negative building pressure is required to draw ventilation air in.	Use systems in dry climates and in areas with good outdoor air quality. If used as part of a mixed-mode system in other areas, control natural ventilation openings to prevent opening at times of high humidity or low outdoor air quality.

Note: PTAC = packaged terminal air conditioner; PTHP = packaged terminal heat pump; FCU = fan-coil unit; UV = unit ventilator; AHU = air-handling unit.

Space Humidity Control

Space humidity control is critical to IAQ in the following applications:

- All buildings in climates with a significant amount of humid weather (Figure 1.3-G)
- Spaces with large latent loads relative to sensible loads, such as below-grade spaces, natatoriums, and shower rooms (not covered in this Guide)
- Buildings with chilled beams, chilled ceilings, or other sensible-only in-space cooling
- Buildings in cold climates with mechanical humidification

The types of systems shown in Table 1.3-B are less likely to provide proper humidity control and therefore more likely to be unsuitable for use in climates with a substantial number of humid days.

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Systems that do not provide separate humidity control are not appropriate in spaces with large latent loads and small sensible loads. Buildings with chilled beams, chilled ceilings, or other sensible-only in-space cooling systems need controls that keep the sensible cooling unit surface temperatures above the dew-point temperature of the room air. More information on control of indoor humidity is provided in Strategy 2.4 – Control Indoor Humidity. Also refer to Trane application manual SYS-APM004-EN, *Dehumidification in HVAC Systems* (Trane 2002) for information on dehumidification control.

Table 1.3-B HVAC System Comparison relating to Humidity Control

System Type	Possible Causes of Poor Building Humidity Control	Possible Solutions
PTACs PTHPs FCUs (DX)	Constant-volume operation satisfies space temperature by cycling cooling on and off or resetting discharge air temperature and does not provide adequate moisture removal at part-load conditions	Provide separate DOASs to condition the makeup air, ducted to each exterior space, and use these systems for space loads only.
UVs	As above, but more so because typically used in applications with high minimum outdoor airflow rates and high indoor latent loads	Provide separate DOASs to condition the makeup air, ducted to each exterior space, and use these systems for space loads only. Select UV with reheat (follow the requirements of ASHRAE/IESNA Standard 90.1 [ASHRAE 2007a]) and space relative humidity control.
Constant-volume remote terminal units, AHUs without reheat	As above	Provide remote terminal unit or AHU with reheat (follow the requirements of ASHRAE/IESNA Standard 90.1 [ASHRAE 2007a]) and space relative humidity control.
Natural ventilation systems	No ability to control humidity	Use systems in dry climates. If used as part of a mixed-mode system in other areas, control natural ventilation openings to prevent opening at times of high humidity.

Note: PTAC = packaged terminal air conditioner; PTHP = packaged terminal heat pump; FCU (DX) = direct-expansion fan-coil unit; UV = unit ventilator; DOAS = dedicated outdoor air system; AHU = air-handling unit.

Particle Filtration Control

Medium- to high-efficiency particle filtration may be an important IAQ consideration in the following applications:

- Buildings in areas with high levels of particulate matter in the outdoor air (Figures 1.3-H and 1.3-I)
- Buildings where control of airborne infectious agents is a concern (not covered in this Guide)
- Buildings or portions of a building requiring special control of the particulate matter
- Buildings where owners want to achieve enhanced particle control, such as allergy agent filtration

Areas with high levels of particulate matter in the outdoor air are shown in Figures 1.3-H and 1.3-I. The highlighted areas in the maps indicate counties that contain areas that do not attain NAAQS for PM10 (Figure 1.3-H) or PM2.5 (Figure 1.3-I) as of March 13, 2009; the entire county may not be nonattainment. Other locations may have poor air quality in the immediate vicinity of a particular project.

The types of systems shown in Table 1.3-C are less likely to be able to provide medium- to high-efficiency particle filtration and are therefore more likely to be unsuitable for use in areas with poor outdoor air quality or where enhanced IAQ is desired. More information about particle filtration and gas cleaning is provided in Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives.

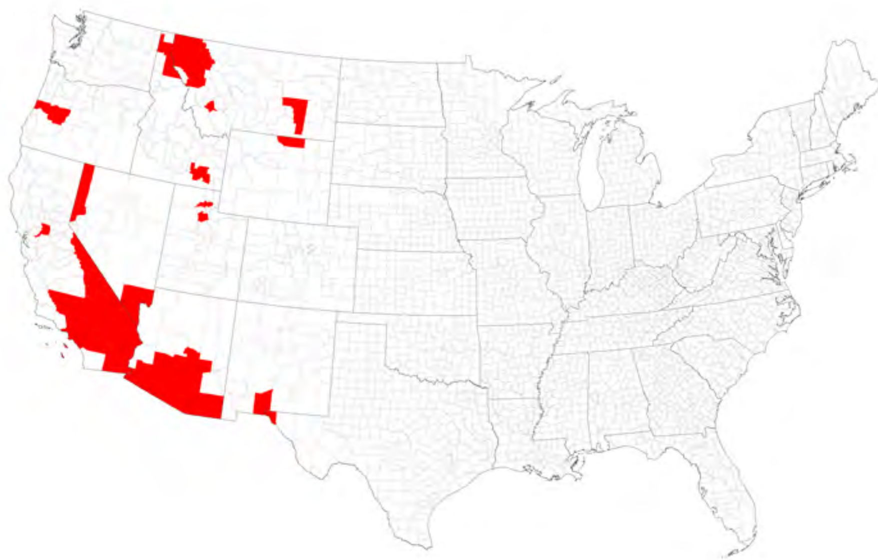

Figure 1.3-H U.S. Counties with PM10 Nonattainment Areas
Graph courtesy of EPA.

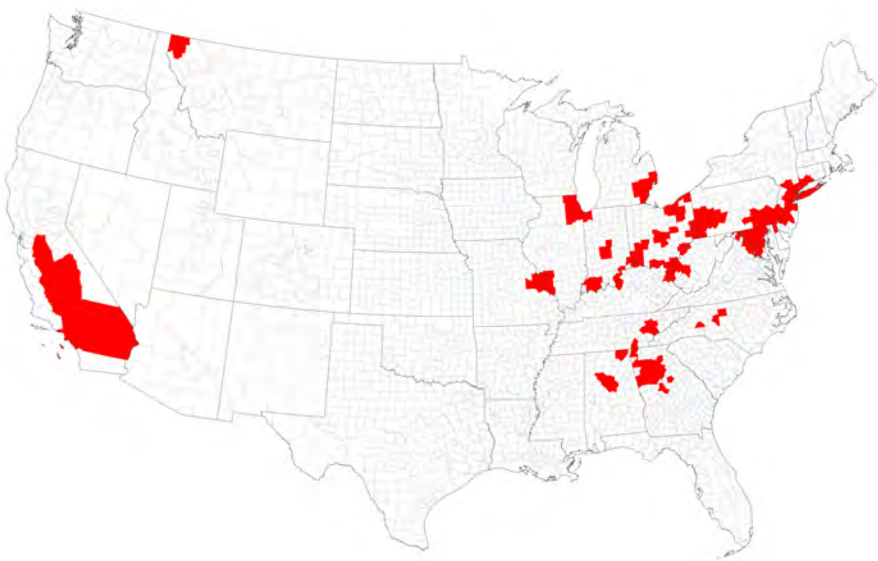

Figure 1.3-I U.S. Counties with PM2.5 Nonattainment Areas
Graph courtesy of EPA.

HVAC System Options and General IAQ Requirements

Up to this point, all of the factors discussed in this Strategy covering project goals and expectations; energy, IAQ, and other environmental considerations; owner-user requirements and expectations; and regional/local project-specific IAQ issues are processed as general requirements for the HVAC system. The design engineer must choose among available HVAC system choices and, with the design team, make decisions about the types of systems to employ and about the detailed design of those systems. The first step is to consider the advantages and disadvantages of different HVAC system options. Brief descriptions of some of the available HVAC systems are provided in the subsections that follow.

Constant-Air-Volume (CV) with or without Reheat

Constant-volume (CV) variable-temperature systems provide the area served (zone) with a fixed airflow rate. In most CV applications, the supply air volume is based on the zone design cooling load from equipment, lights, exterior conditions (solar, temperature, wind, etc.), and people. The air-handling unit (AHU) capacity is based on both zone cooling loads and outdoor air cooling load. The AHU supply air temperature is varied to match the sensible heating or cooling requirement of the zone.

Reheat coils are used in multiple-zone applications to supply warmer air to the zones not requiring maximum cooling.

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Since there is no diversity in supply air volume, significantly more air is circulated than required to meet the cooling load, even at design conditions. The energy used to reheat the air in this application is considered to be wasted energy. This system configuration does not meet most energy codes' minimum system operating efficiency requirements (McQuay 2006). (See Figure 1.3-J.)

Table 1.3-C HVAC System Comparison relating to Particle Filtration

System Type	Causes of Poor Particle Filtration	Possible Solutions
PTACs PTHPs UVs	These units have filter racks designed for filters 1 in. (25 mm) deep or less, and the unit fans have very limited capacity to overcome static pressures, so they are unable to accommodate filters with appropriate Minimum Efficiency Reporting Value (MERV) levels	Provide separate DOASs to condition the makeup air, ducted to each exterior space, and use these systems for space loads only. Select alternative system types.
Standard FCUs Standard (small) remote terminal units	These units have filter racks designed for filters 2 in. (51 mm) deep or less, and some unit fans have very limited capacity to overcome static pressures, so they are unable to accommodate filters with MERV levels beyond about 8	Select custom or specialized units designed for higher levels of filtration. Provide separate DOASs to condition the makeup air, ducted to each exterior space, and use these systems for space loads only.
Natural ventilation	Openings typically unfiltered; limited ability to overcome static pressure drop of medium- to high-efficiency filters	Use systems in areas with low levels of outdoor particulate matter.

Note: PTAC = packaged terminal air conditioner; PTHP = packaged terminal heat pump; UV = unit ventilator; FCU = fan-coil unit; DOAS = dedicated outdoor air system.

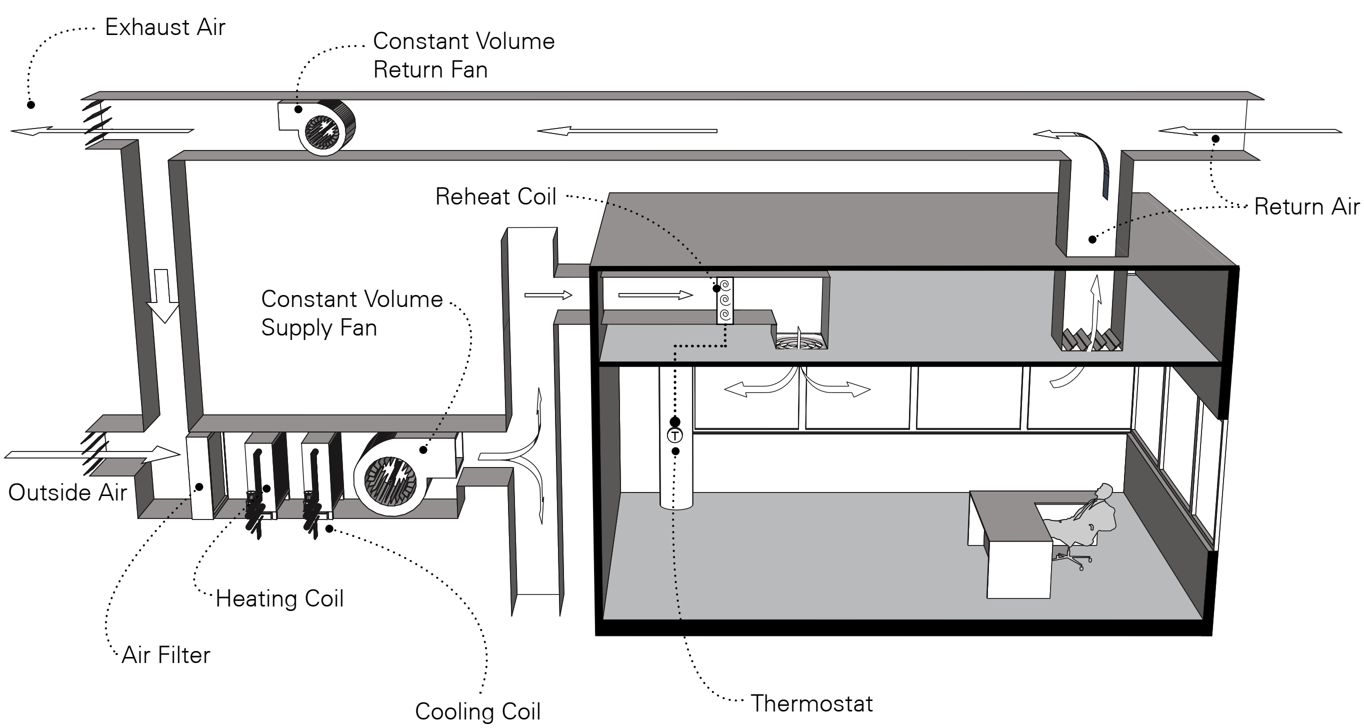


Figure 1.3-J CV Diagram
Adapted from McQuay (2006).

IAQ Considerations. Dehumidification can be a concern when using CV with or without reheat. Since the supply air temperature is modulated to meet the sensible cooling load only, humidity from ventilation air may not be removed, resulting in humid air being distributed throughout the building.

Advantages of CV with or without Reheat

- Constant-volume variable-temperature systems are good for maintaining the correct amount of outdoor air for each zone.
- Constant-air-volume to the space during heating and cooling ensures proper diffuser operation.
- Systems are very simple to understand and maintain.
- Systems have low first cost.
- Free cooling using outdoor air is available.

Disadvantages of CV with or without Reheat

- The operating energy cost of the CV reheat system is very high and does not meet most energy codes.
- During unoccupied hours, the main air-handling system needs to be started to heat and also sometimes cool a zone to maintain minimum and maximum allowable indoor air temperatures.
- Systems have large ductwork.

Variable-Air-Volume (VAV) with Reheat

Variable-air-volume (VAV) with reheat systems provide conditioned air to each zone at a constant temperature, typically 55°F. The amount of air varies to match the heat gain from equipment, lights, exterior conditions (solar, temperature, wind, etc.), and people. At part-load conditions, VAV systems supply only the necessary amount of conditioned air to each zone, saving significant fan energy when compared with CV reheat systems. A damper (such as a pre-manufactured VAV box) adjusts airflow at each zone. A temperature sensor located in the space adjusts the damper to maintain the room temperature setting. When more dampers close, the duct system static pressure increases. The primary supply fan adjusts to maintain duct static pressure using supply fan inlet vanes or variable-frequency drives (VFDs) (McQuay 2006).

In some VAV systems, supply air temperature reset is implemented to reduce overall system energy use. This requires considering the trade-off between compressor, reheat, and fan energy as well as the impact on space humidity levels. If supply air temperature reset is used in a humid climate, the reset can be disabled when it is humid outside (Trane 2002). (Also see the *Advanced Variable Air Volume System Design Guide* published by the California Energy Commission [CEC 2003]). (See Figure 1.3-K.)

IAQ Considerations. VAV systems present unique challenges in maintaining minimum outdoor air quantities. As the supply air volume decreases, the amount of outdoor air will decrease unless strategies are implemented to maintain the required minimum outdoor airflow under all operating conditions. Direct measurement of outdoor airflow and economizer damper reset strategies can help maintain minimum outdoor air quantities throughout the operating range of a VAV system (McQuay 2006).

Different zones need different amounts of outdoor air, but centralized AHUs provide only one outdoor air ratio. However, design procedures give credit for any unused outdoor air that recirculates. (See also Strategy 7.4 – Effectively Distribute Ventilation Air to Multiple Spaces.) At low cooling loads, and therefore low supply airflow, the AHU may be bringing in 100% outdoor air to satisfy the ventilation requirement, which during cold outdoor air conditions may present a pre-heat challenge.

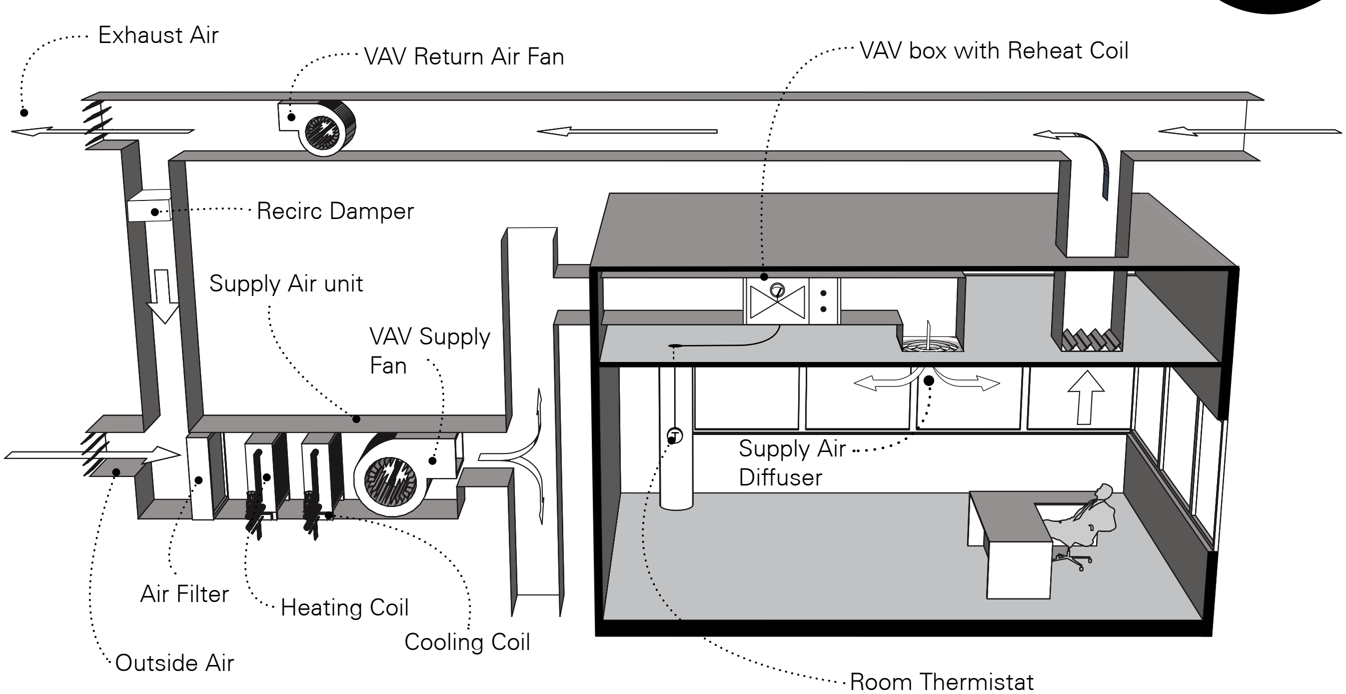


Figure 1.3-K VAV Diagram
Adapted from McQuay (2006).

Advantages of VAV with Reheat

- Systems are relatively simple to understand and maintain.
- Systems have low first cost.
- Free cooling using outdoor air is available.

Disadvantages of VAV with Reheat

- During unoccupied hours, the main air-handling system needs to be started to heat and possibly cool a zone.
- Water piping in the ceiling space is required to serve the reheat coils.
- Service access to reheat is required to control valves.

Dual Duct Dual Fan (DDDF) Systems

Dual duct dual fan (DDDF) systems are a variation of the more traditional dual-duct system. There is a dedicated cooling AHU and a dedicated heating AHU. Both units are normally VAV. Each unit is ducted to mixing boxes for each zone. The cooling AHU generally provides each zone mixing box with conditioned air at a constant temperature (typically 55°F). The amount of air is varied to match the heat gain from equipment, lights, exterior conditions (solar, temperature, wind, etc.), and people loads (McQuay 2006).

At part-load conditions, the mixing box supplies only the minimum amount of conditioned air necessary to each zone, resulting in significant fan energy savings. In heating mode, the mixing box reduces the cold air volume to the minimum and then modulates the hot air volume to meet the space conditions. As the mixing boxes modulate the hot and cold air, the duct system static pressures change. The supply fans are then

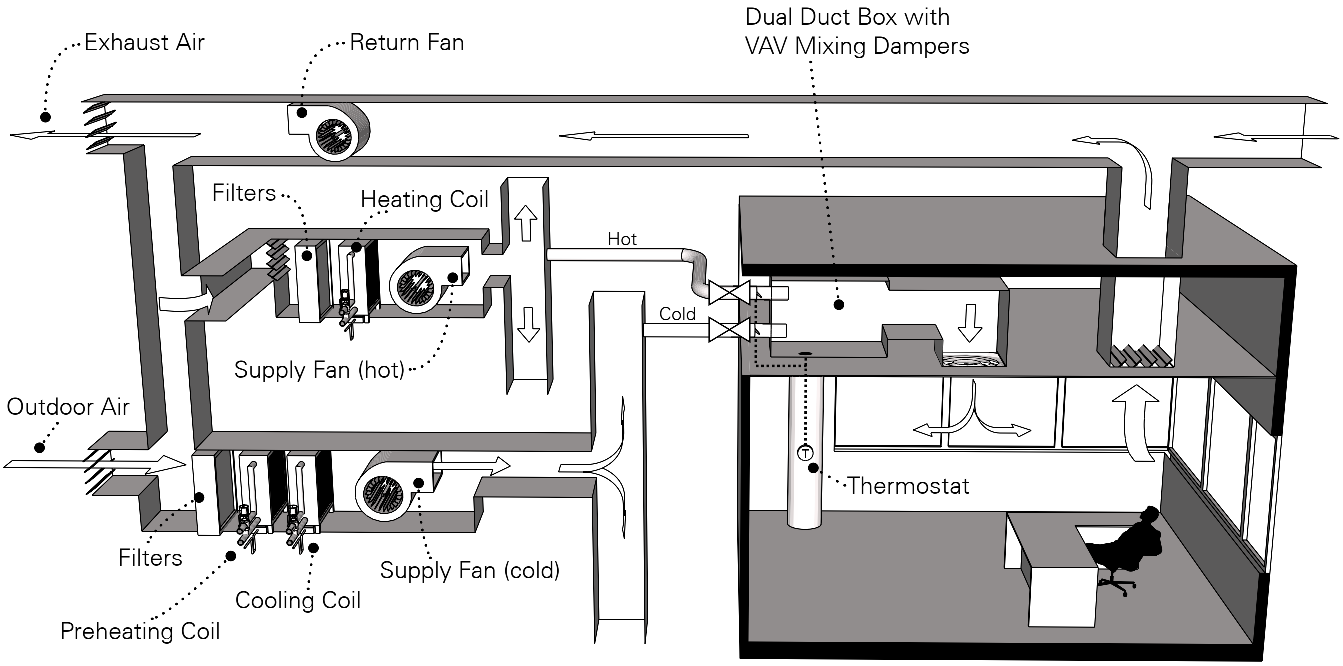


Figure 1.3-L DDDF Diagram
Adapted from McQuay (2006).

modulated to maintain duct static pressure either by discharge dampers, inlet guide vanes, or VFDs (McQuay 2006). (See Figure 13-L.)

IAQ Considerations. Ventilation air is introduced at the cooling AHU. The central air-handling system must be able to maintain a fixed amount of outdoor air while varying the supply air volume if IAQ ventilation requirements are to be met. This will not happen with an outdoor air damper in a fixed position and therefore requires alternative strategies.

Advantages of DDDF Systems

- Constant-air-volume to the space during heating ensures proper diffuser operation.
- No heating water piping is needed in ceiling spaces for terminal temperature control (all heating and cooling is typically done in the AHU).
- Systems have low operating energy costs due to the reduction/elimination of reheat.
- Utilizes free cooling using outdoor air when available.

Disadvantages of DDDF Systems

- System is relatively complex and requires special HVAC system training.
- System has higher capital first cost for the boxes and dual air-handling systems (partially offset by the elimination of the reheat piping).
- System requires more ceiling and equipment room space compared to most other HVAC systems.
- The maintenance costs are a little higher due to additional components such as the cold deck supply fan.

Strategy 1.3

Multi-Zone Systems

Two-deck multi-zone air-conditioning systems (AHUs with hot and cold decks) provide each zone with constant-volume variable-temperature air. From a ventilation viewpoint, they are similar to CV reheat systems, which also provide outdoor air to many zones from one central air handler. The air temperature is varied to meet the heat gain from equipment, lights, exterior conditions (solar, temperature, wind, etc.), and people loads. The zone space thermostats control their respective hot and cold deck dampers to maintain the required zone supply air temperature to satisfy the zone thermal loads (McQuay 2006). (See Figure 1.3-M.)

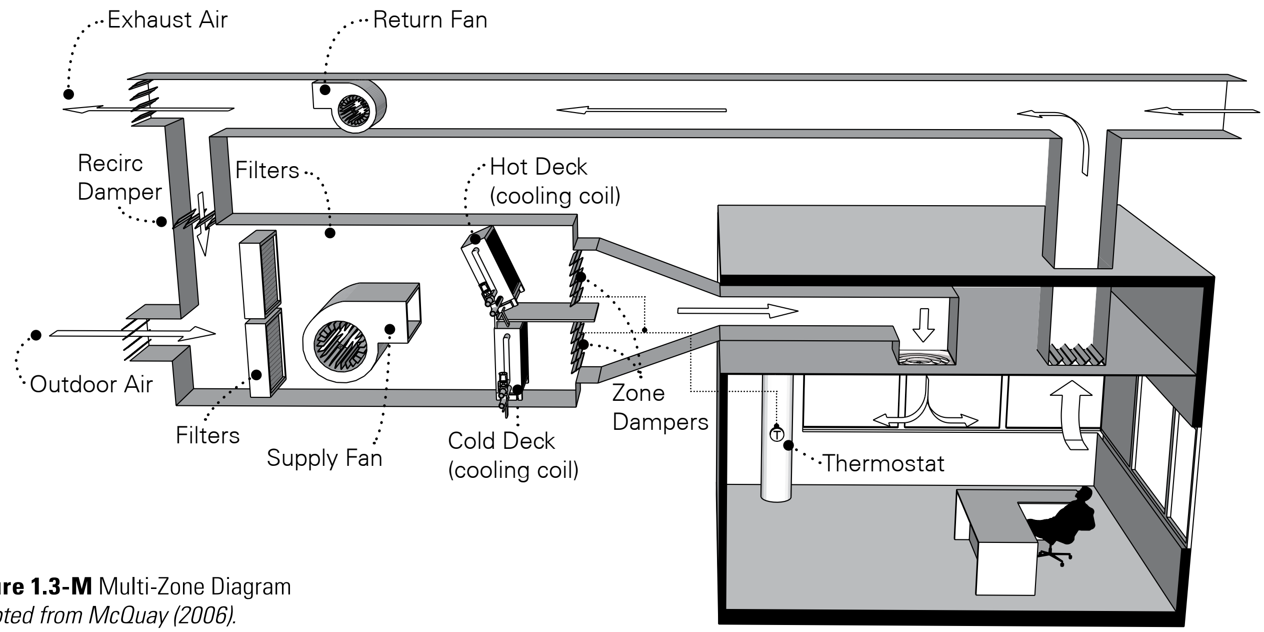


Figure 1.3-M Multi-Zone Diagram
Adapted from McQuay (2006).

A modification of the two-deck system is the three-deck system (AHU with hot, cold, and mixed-air decks), with the third deck being bypass air (return air with ventilation air introduced). The decks are arranged in such a way that when the zone calls for heating, bypass air and hot deck air are mixed to meet the zone requirements. In cooling, air from the cooling deck and bypass air mix to meet the cooling load. The result is the absence of simultaneous heating and cooling (McQuay 2006).

IAQ Considerations. Outdoor ventilation air is introduced at the AHU. Each zone receives constant airflow with a fixed percentage of outdoor air. Different zones require different percentages of outdoor air, but the centralized AHU can provide only one outdoor air ratio. Dehumidification can be a concern. Since the supply air temperature is normally modulated to meet the sensible cooling load only, humidity from ventilation air may not be removed, resulting in humid air being distributed throughout the building.

Advantages of Multi-Zone Air Conditioning

- Constant-air-volume to the space during heating and cooling ensures proper diffuser operation.
- Systems have low first cost.
- Systems have simple operation.
- There is no heating water piping in ceiling spaces for terminal temperature control (all heating and cooling is typically done in the AHU).
- The three-deck system is relatively efficient.

Disadvantages of Multi-Zone Air Conditioning

- The operating energy cost of the two-deck multi-zone air-conditioning system can be very high and does not meet most energy codes.
- During unoccupied hours, the main air-handling system needs to be started to heat and sometimes cool a zone.
- System has large ductwork.
- The maintenance cost of the AHU is high.

Fan-Coil (FC) Systems

Fan-coils have a fan and one coil (two-pipe) or two coils (four-pipe) in small units distributed throughout the building. Fan-coils are dedicated to each zone and are matched to the zone design load. Four-pipe FC systems allow some zones to be heated while other zones are being cooled (the fan-coil supply air temperature varies to meet the heating or cooling needs of the space) (McQuay 2006). A primary air-handling system typically supplies filtered and tempered 100% outdoor air to the back of the fan-coil units (FCUs). (See Figure 1.3-N.)

A further refinement of this system is sometimes referred to as a *dedicated outdoor air system* (*DOAS*). With a DOAS, the primary air can be further conditioned to deliver dehumidified (reheated to neutral) or humidified outdoor air directly to the back of the FCU (McQuay 2006). Refer to Strategy 8.1 – Use Dedicated Outdoor Air Systems for further information on this air-handling distribution system.

IAQ Considerations. FC systems usually have a dedicated ventilation system to supply each zone with outdoor air. FC systems and DOASs sometimes use ceiling or floor plenum air, which can contain particulate and gaseous matter, which in turn can be introduced into the occupied space.

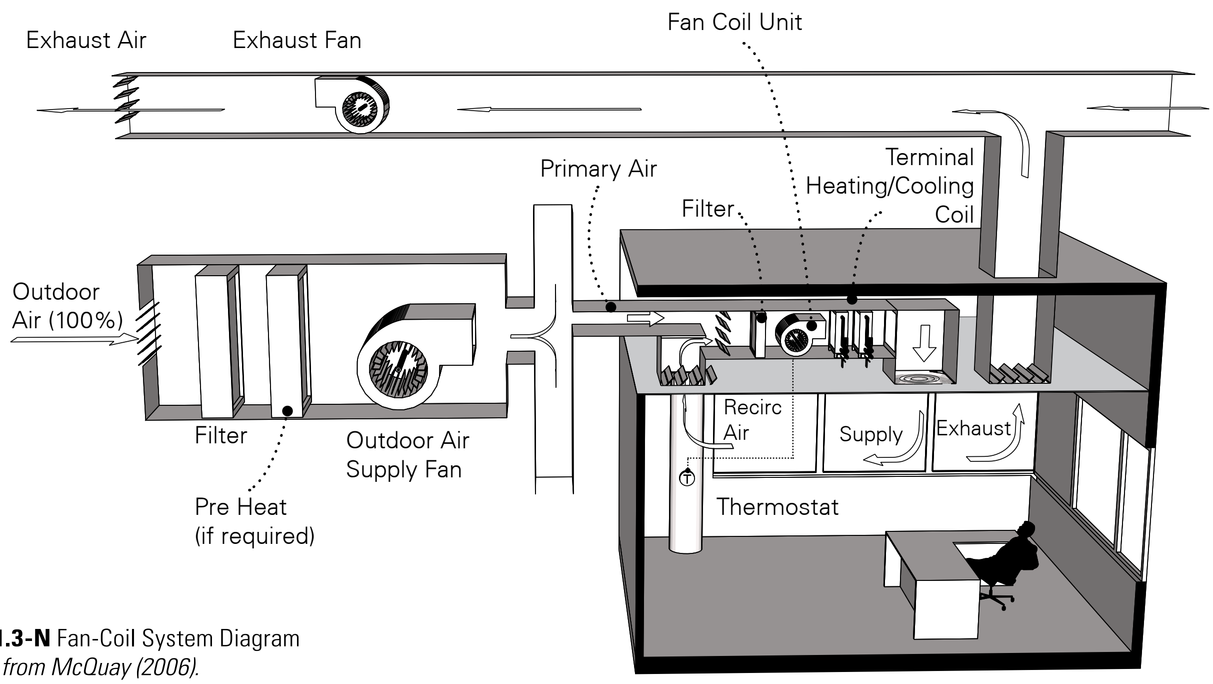


Figure 1.3-N Fan-Coil System Diagram
Adapted from McQuay (2006).

Advantages of Fan-Coils

- Constant-air-volume to the space ensures proper diffuser operation over all operating conditions.
- FC system has effectively two paths: the central air handler and the local return plenum. This increases the system ventilation efficiency, reducing required outdoor air intake at design.
- During unoccupied hours, only a local FC system needs to be started to heat a zone as opposed to starting up the main AHU with standard VAV.

Disadvantages of Fan-Coils

- Heating and sometimes cooling piping, valves, and controls are located in ceiling spaces to serve the fan-coils. Also, air filters in the FCUs require regular service.
- There is possible condensation on coils when they are used for cooling (condensate pan and drain required).
- Plenum air carries particulate and gaseous matter, which can be introduced into the occupied space.
- With fixed outdoor airflow to each zone, total system outdoor air must equal the sum of the design minimum outdoor airflow values for each zone, since no credit can be taken for occupant diversity.
- Operational and energy cost of the fans in the boxes is high compared to a central air-handling system such as a VAV system.
- Free cooling using outdoor air is normally not available.
- Noise can be a problem with the fans in the occupied spaces.
- Maintenance of fan-coil equipment in ceiling spaces is difficult due to access being very often in ceiling spaces over occupied areas of the building and its having to service multiple fans, coils, and filters.

Fan-Powered Box (FPB) Systems

A variation of the FC and the VAV systems is the fan-powered box (FPB) system. The FPBs can be configured with the primary air-handling system in either series or parallel configuration. Figure 1.3-O shows a typical series FPB system configuration. The fans in series boxes operate all the time and provide constant-air-volume to the space. The temperature supplied to the space is varied by mixing primary air with return air as required to meet the cooling load and reheat coils, or perimeter radiation is used to provide space heating (McQuay 2006). (See Figure 1.3-O.)

Parallel configuration is another FPB arrangement. In this configuration, in the cooling mode, the box behaves like a typical VAV box (the parallel fan is off and the plenum damper closed). In the heating mode, the fan operates to provide constant volume to the space. The supply air temperature is varied by mixing plenum air with primary air to meet the space conditions or by a heating coil mounted in the box (McQuay 2006). (See Figure 1.3-P.)

IAQ Considerations. As the primary supply air volume decreases, the amount of outdoor air will decrease unless strategies are implemented to maintain the required minimum outdoor airflow under all operating conditions. Direct measurement of the outdoor airflow and economizer damper reset strategies can help maintain minimum outdoor air quantities throughout the operating range of the system (McQuay 2006).

Different zones need different amounts of outdoor air, but centralized AHUs provide only one outdoor air ratio. However, design procedures give credit for any unused outdoor air that recirculates. See also Strategy 7.4 – Effectively Distribute Ventilation Air to Multiple Spaces.

Strategy 1.3

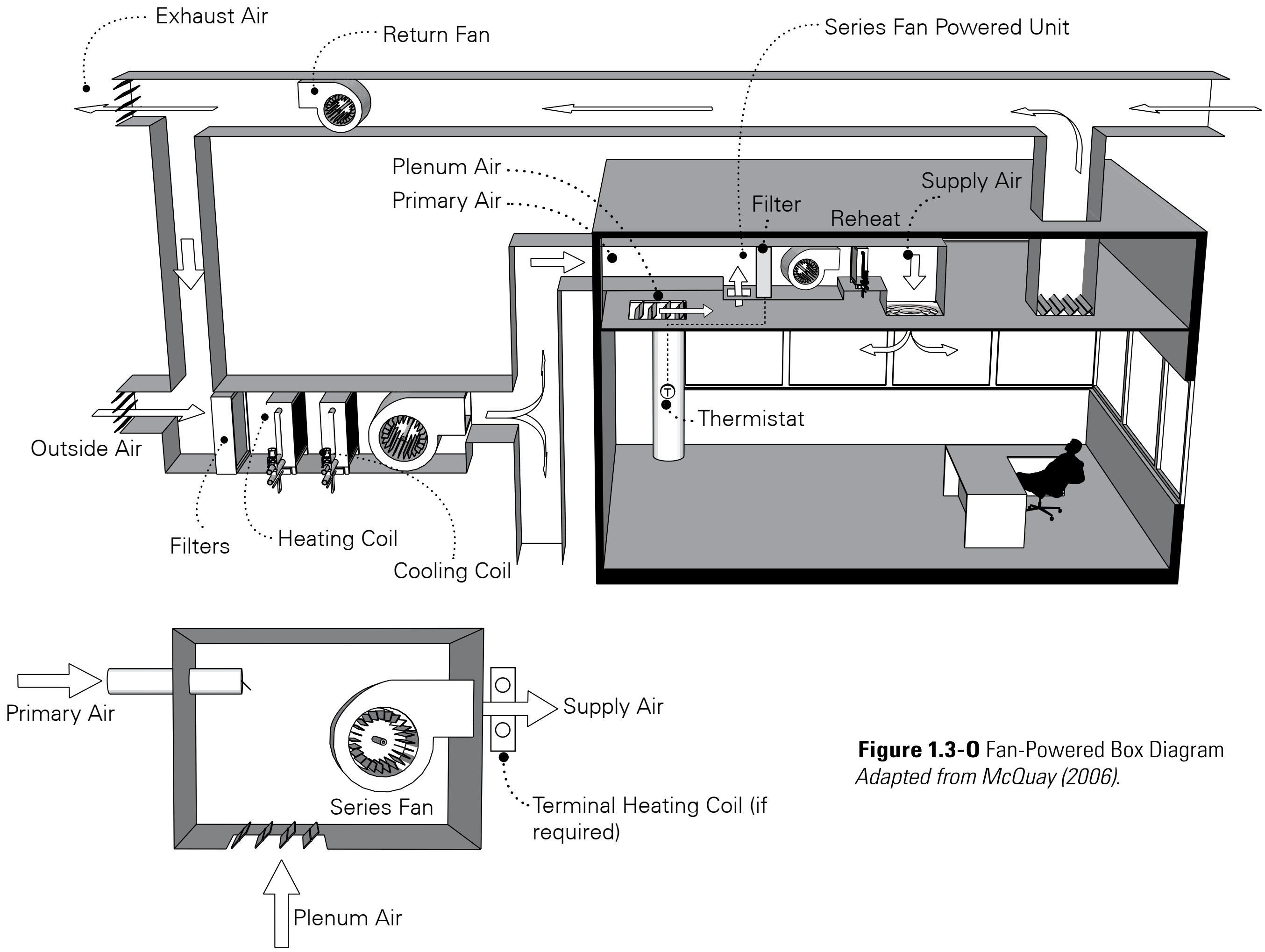


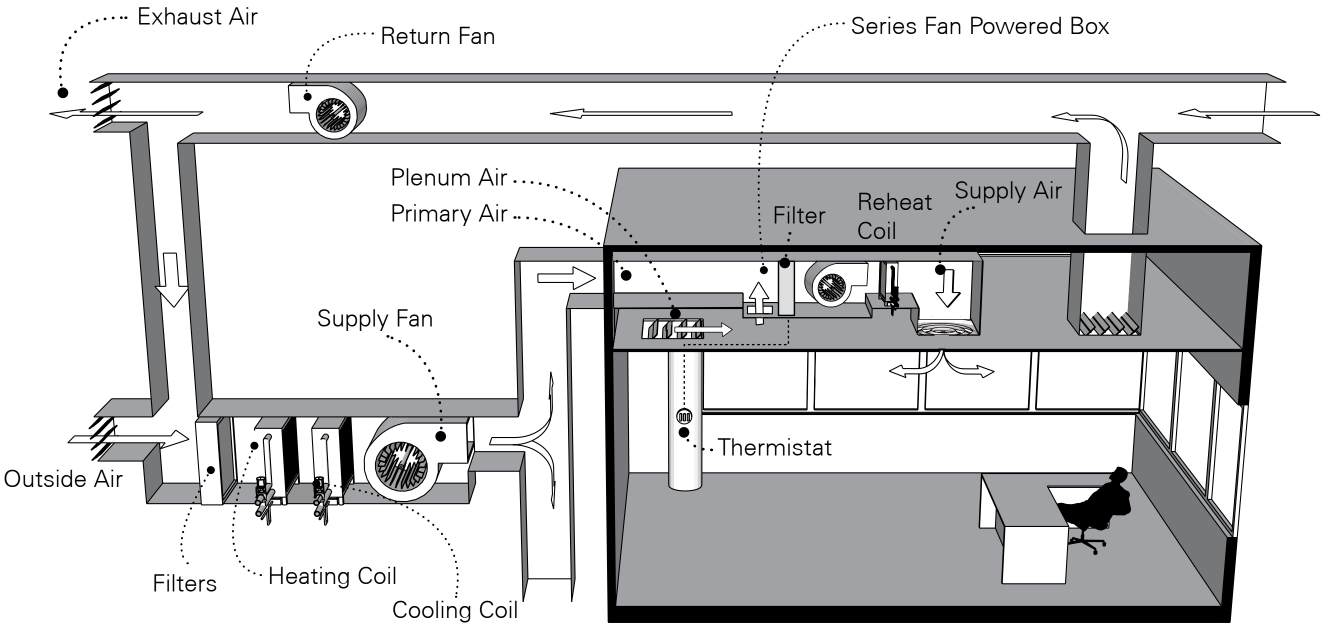
Figure 1.3-0 Fan-Powered Box Diagram
Adapted from McQuay (2006).

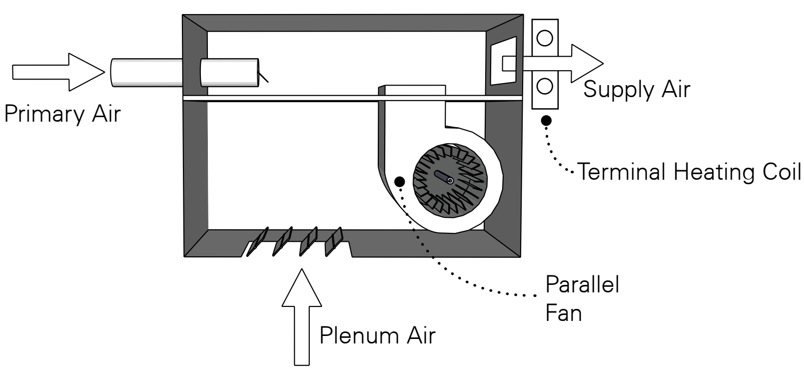
At low cooling loads, and therefore low primary supply airflow, the AHU may be bringing in 100% outdoor air to satisfy the ventilation requirement, which during cold outdoor air conditions may present a pre-heat challenge. FPB systems also sometimes use ceiling or floor plenum air, which can contain particulate and gaseous matter, which in turn can be introduced into the occupied space.

Advantages of Fan-Powered Box Systems

- It is possible, even at design load conditions, to introduce plenum air into the series box so that 55°F (13°C) supply air enters the space even though 49°F (9°C) primary air was distributed through the building. This reducing of the primary supply air temperature can significantly reduce the size of the air-handling plant and distribution ductwork. This approach requires special attention to ensure that minimum ventilation rates are maintained at all times and to prevent condensation in the air distribution system.
- With the series configuration there is a constant supply air volume to the space, which ensures proper diffuser operation over all operating conditions. In the parallel configuration this advantage only applies in the heating mode when the fan is operating; during the cooling mode when the fan is off, the supply airflow varies to meet the space cooling load.
- Plenum air is used as reheat, which is a form of heat recovery.

Strategy 1.3





Parallel Fan Powered Unit

Figure 1.3-P Parallel Fan-Powered Box Diagram
Adapted from McQuay (2006).

- FPBs have effectively two paths: the central air handler and the return plenum. This increases the system ventilation efficiency, reducing required outdoor air intake at design.
- During unoccupied hours, only a local FPB needs to be started to heat a zone as opposed to starting up the main AHU with standard VAV.

Disadvantages of Fan-Powered Box Systems

- Heating piping is located in ceiling spaces to serve the FPBs with reheat coils.
- There is added capital cost due to the multitude of FPBs distributed throughout the building.
- Ceiling or floor plenum air carries particulate and gaseous matter, which can be introduced into the occupied space.
- There are additional operational and energy costs of the fans in the boxes. This inefficiency is reduced in the parallel configuration by cycling off the fan during cooling periods.

- Noise can be a problem, especially from the starting and stopping of the parallel configured fans in the ceiling plenum.
- Maintenance of equipment in ceiling spaces is required (air filters, dampers, etc. in the FPB units require regular service).

Self-Contained Air-Conditioning Systems
Self-contained air-conditioning systems are based on specially designed AHUs distributed throughout the building with integral air conditioning (air filtration, mechanical cooling and heating capability). Each unit usually has water-cooled DX refrigeration circuits (McQuay 2006). Air distribution can be CV or VAV. VAV is the most common for office applications.

Figure 1.3-Q shows a typical self-contained air-conditioning system with water-cooled DX cooling, hot water heating, and an economizer section for free cooling.

IAQ Considerations. If the self-contained units have air-side economizers (as shown in Figure 1.3-Q), ventilation air can be introduced at the AHU. Outdoor ventilation air is introduced at the AHU.

An alternative to the air-side economizer configuration is the use of a water-side economizer. With this arrangement, typically a DOAS is utilized to supply ventilation air to the self-contained air-conditioning units. The DOAS can be placed on the roof and delivers the correct amount of outdoor air through a shaft to each self-contained air-conditioning unit. The IAQ considerations for this arrangement are the same as stated for the FC system.

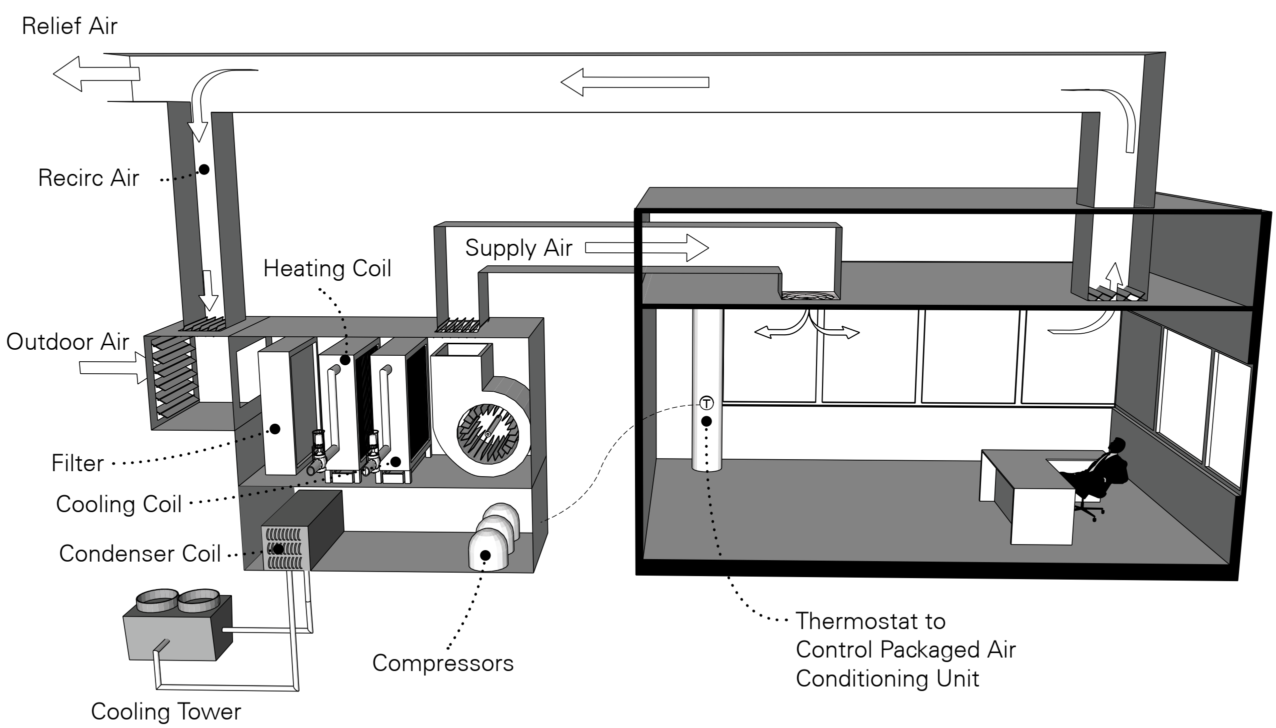


Figure 1.3-Q Vertical Self Contained Diagram
Adapted from McQuay (2006).

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Advantages of Self-Contained Air-Conditioning Systems

- Self-contained units only operate when necessary.
- During unoccupied hours, only a local self-contained unit needs to be started to heat a zone as opposed to starting up the main AHU with standard VAV.

Disadvantages of Self-Contained Air-Conditioning Systems

- There are added operational and energy costs.
- Noise can be a problem, especially from the mechanical cooling compressors.
- More maintenance is required due to distributed system components. Also, maintenance may have to be performed on equipment in occupied spaces.

HVAC System Selection Procedure

Integrated Design Choice Mechanism

HVAC system choice needs to be informed, because there may not be one clear preferred HVAC system for any given application. That is why HVAC system selection cannot be done in a vacuum but rather as part of the integrated design process. Some HVAC selection criteria are yes/no while others will be gauged; e.g., one system may be slightly better than another, but both system options will meet the basic project criteria. Systems need to be systematically compared to determine the optimum HVAC system to meet the overall building needs.

HVAC System Comparison Analysis

A system comparison analysis (see Table 1.3-D) needs to be undertaken for every project. Each analysis is unique and should be done early in the design process while considering the project opportunities/constraints/expectations. Some examples include the following:

- Site/local environmental opportunities (e.g., are the site and building program suitable for a mixed-mode ventilation system?)
- Budget constraints both in terms of first costs and operating costs
- Client/end user expectations
- Sustainability targets and rating systems
- Applicable codes and design standards
- Required flexibility (ability to add zones and plant capacity, etc.)
- Building constraints, such as floor space for equipment, maintenance space, plenum space, and roof space
- Heating, cooling, and humidity loads and space setpoints
- Smoke control
- Maintenance capabilities and cost
- Other constraints

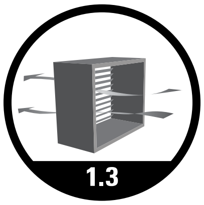
Table 1.3-D is a sample analysis done for a specific office building for a particular set of project circumstances. In this example, the owner required a raised floor for his electrical and communications distribution system, which considerably reduced the first cost of the underfloor air distribution (UFAD) system. The building had height restrictions, which made it difficult to install a conventional ceiling distribution system, and the owner required that the design be as energy efficient as possible. In addition, the building was located in a mild climate zone, requiring little or no humidification control. The resulting scores displayed in the comparison table (Table 1.3-D) would be very different for a building with different base criteria (Stantec 2009).

Strategy 1.3

Table 1.3-D HVAC System Comparison
Source: Stantec (2009).

Performance Attribute	Weight	VAV Reheat Systems	Rank	CV Reheat Systems	Rank	DDDF System	Rank	Raised Floor System	Rank
System Description		**Central VAV AHU system with ceiling mount ductwork supplying air to VAV reheat boxes in perimeter zones and CV reheat boxes in the interior zones and ceiling air distribution**		**Central CV AHU system with ceiling mount ductwork supplying air to CV reheat boxes in perimeter and interior zones and ceiling air distribution**		**Central VAV DDDF AHU system with ceiling mount ductwork to dual-duct VAV boxes and ceiling air distribution**		**Central VAV AHU supplying air into a raised-floor plenum, CV air supply to interior zones, and VAV FC to the perimeter zones with terminal heating; floor air distribution system**	
First Cost	**10**	VAV reheat systems can be cost-effective	9	CV reheat systems can be cost-effective	10	Expensive to install; requires more mechanical equipment and associated space	6	Raised floor can be expensive but the floor system may be justified on the basis of electrical savings/office churn rate/lower floor to ceiling, etc.	8
Energy Efficiency Normal Operation	**10**	VAV takes advantage of reduced fan energy during non-peak load conditions and air- or water-side economizer; inefficiency mainly due to the potential of simultaneous heating and cooling (less significant as compared to a CV system)	8	CV reheat system causes significant inefficient heating of previously cooled air	4	Reduced reheat as compared to CV and VAV reheat system; higher fan power due to multiple AHUs	9	Better economizer and chiller plant performance due to high supply air temperature; coupling of mass with supply air can reduce cooling peaks; reduced reheat in exterior spaces due to lower supply air volumes required due to floor supply/stratification effect	10
Energy Efficiency Off-Hour Operation	**10**	VAV boxes may be used to isolate unoccupied areas to reduce off-hour usage; main AHU required to run	8	CV boxes may be used to isolate unoccupied areas to reduce off-hour usage; main AHU required to run	8	DDDF boxes may be used to isolate unoccupied areas to reduce off-hour usage; main AHU required to run	8	CV boxes and VAV FC units may be used to isolate unoccupied areas to reduce off-hour usage; main AHU required to run; unlikely to need chillers at night due to high supply air temperature	9
Acoustical Impact	**10**	Reduced VAV box noise and water distribution noise	8	Reduced CV box noise and water distribution noise	8	Same as VAV and CV reheat systems, except no water distribution noise	9	Reduced VAV/CV/FC unit noise and water distribution noise; low velocity supply	8
Indoor Air Quality	**10**	Outdoor air economizer allows 100% free cooling for most of the year; difficult to control the minimum outdoor air, especially in the winter when the VAV boxes are in their minimum potion	6	Outdoor air economizer allows 100% free air most of the year	8	Reduced outdoor air supply in winter due to 100% return air on heating fan, but minimum overall circulation rates can be higher	8	Outdoor air economizer used for longer periods of time due to warmer supply air temperatures; good ventilation efficiency with floor supply; perception of improved air quality in interior zones due to control and floor supply	9

Strategy 1.3



Performance Attribute	Weight	VAV Reheat Systems	Rank	CV Reheat Systems	Rank	DDDF System	Rank	Raised Floor System	Rank
Comfort	**10**	Reasonable cooling performance with a potential of dumping of cool air; poor heating performance due to reduced supply air volume and warmer air stratifying at a high level; individual control is difficult to achieve	6	Reasonable cooling performance with a potential of dumping of cool air; poor heating performance due to warmer air stratifying at a high level; individual control is difficult to achieve	8	Reasonable cooling performance with a potential of dumping of cool air; poor heating performance due to warmer air stratifying at a high level; individual control is difficult to achieve	8	Individual cubicles in open office plans can be individually controlled, improving comfort both physically and perceptually; perimeter zones are similar to VAV systems for cooling but have improved performance for heating since heat is supplied underfloor along the window-wall	9
Flexibility	**10**	Any number of zones may be used, but at high cost per zone	7	Any number of zones may be used, but at high cost per zone	7	Any number of zones may be used and zone costs are less than those for reheat	8	Outlets may be moved easily to accommodate changing interior layouts; air tends to be naturally drawn to high heat load areas	9
Total			**52**		**53**		**56**		**62**

STRATEGY OBJECTIVE 1.3

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Strategy 1.4

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Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ

Introduction

Establishing a comprehensive and realistic project construction schedule will help ensure the achievement of good IAQ for the building project. A building owner can have the best intentions, the design team can provide a great building design, and the contractors can achieve their best execution, but if the schedule is too compressed or has sequencing issues and IAQ is not taken into account, the IAQ of the finished project will be compromised.

All phases of the construction project need to be identified and evaluated for scheduling purposes. Aspects of this schedule that are important for IAQ include the following:

- Commissioning activities for IAQ
- Installing construction materials that can absorb moisture after the building is dried in
- Storing certain construction materials and protecting them from the elements prior to installation
- Starting and operating HVAC equipment for temporary heating or cooling during construction

These are just a few project-schedule-related items that will jeopardize the IAQ of the final building project if they are ignored. A sound IAQ plan coupled with proper scheduling and sequencing of the construction project will help ensure achievement of good IAQ.

The schedule needs to allow for adequate time to complete the construction activities and properly sequence them. It is best to involve the design and construction team early in the scheduling process. This could include gathering input from the construction team during the design phase to help with sequencing and planning the duration of construction activities. The schedule needs to be reviewed on a regular basis throughout the project and be maintained and updated as necessary. In addition, proper construction material selection could be evaluated to match the sequencing and scheduling of the construction activities. A thought to keep in mind is that typically an accelerated project schedule leads to poor achievement of good project IAQ.

Building Conception

Early Planning and Organization

The day the owner determines the need for a building is the day the building project scheduling needs to start. The Owner's Project Requirements need to be defined, the budget needs to be set, the required time of building occupancy needs to be determined, and the project team (design professionals, contractors, testing and balancing engineers, commissioning authorities, and others) needs to be selected and assembled. The earlier the project team is assembled the earlier schedule input from all team members is available. This could help alleviate the guessing game and rules of thumb used in the scheduling process. Starting the planning phase earlier is a critical element in coupling proper IAQ management with the scheduling and sequencing of the building project. Every project is different and has its own challenges. Having the experience and knowledge of the *complete* project team early will aid in the scheduling process and attainment of good project IAQ.

Involving the whole project team early in the scheduling process could also lead to proper construction material selection to match the sequencing and scheduling of the construction activities, eliminating long lead time for products for a short construction schedule or allowing the selection of the proper materials that will accommodate the required sequence of construction activities. As shown in Figure 1.4-E, the earlier the decisions are made in the project phase the more influence the decisions will have and the more the costs of actions or solutions will be reduced.

Project Incentives/Goals

It is important to align project incentives/goals toward scheduling that helps achieve good IAQ. The typical project incentive of offering a monetary bonus for early completion of a project could negatively impact the IAQ of the project because it shifts the project focus to completing a project early to obtain the monetary bonus and potentially rewards improper sequencing of construction activities to expedite construction completion.

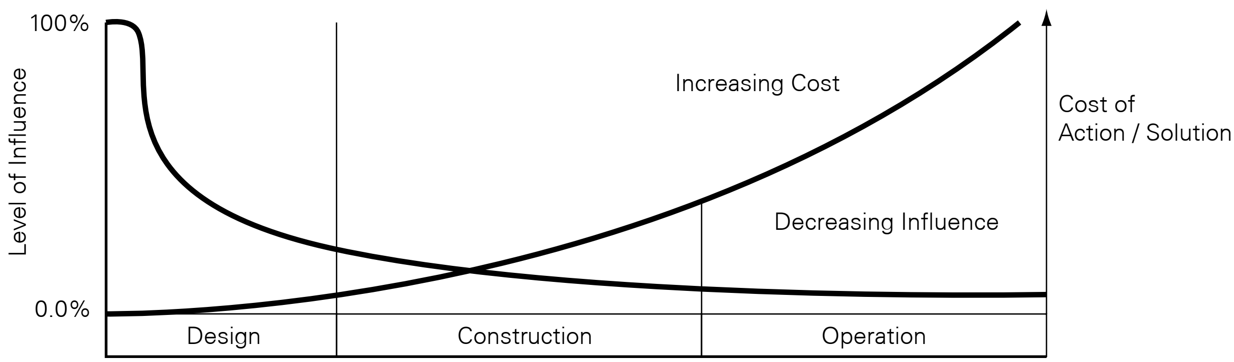

Figure 1.4-E Project Phases of Influence
Adapted from a figure copyright CH2M HILL.

An on-time project is not always a quality project. Any project incentive/goal needs to be carefully evaluated to make sure all aspects of attaining the project goals do not adversely affect the project IAQ. The project team members need to understand the importance of project IAQ and the effects the construction process has on attaining good IAQ.

Design Development

Construction Products/Materials Selection

The design needs to utilize construction products/materials that will aid in proper construction scheduling. If certain areas or portions of the building are required to be constructed before the building can be closed in, the construction methods and materials selected need to be capable of withstanding exposure to the temperatures and moisture. Having to install drywall shafts or installing duct sound attenuators or any hydroscopic material that can retain moisture before the building is closed in can create mold issues.

It makes sense to think about sequencing and constructability while designing as this ensures that the products or materials that are selected have lead/delivery times that will accommodate the construction schedule. If products or materials are selected and wetting of the products/materials occurs, then adequate drying time needs to be provided for in the schedule. In addition, any alternative product/material selections need to be equivalent in this regard in order to prevent quality or functional issues from occurring.

Equipment Access and Installation Logistics

Proper design and layout of the building is needed to allow for equipment access and installation logistics. It is important to schedule the installation of building equipment (HVAC, food service, transportation, etc.) when the equipment is protected from exposure to the elements. Having to install equipment early on during a project due to physical limitations and the unavailability of access or paths once walls, ceilings, or roofs are installed will expose the equipment to the elements, which can damage the equipment and/or promote bacterial growth. This can create issues for maintenance and replacement at a later date. If there are no alternatives to installing equipment early, it is important to protect the equipment from the elements once they have been installed.

Phasing of Projects

Phasing of new construction projects and remodels can be very challenging when trying to maintain project IAQ goals. If proper isolation of the areas to be occupied from the areas under construction are not addressed, exposure of the occupied areas to construction activities (noise, dust, moisture, chemical contaminants, odors, building not dried in completely, etc.) will likely lead to long-term IAQ issues, thus undermining attempts to ensure good IAQ. Proper construction and sealing of the areas or possibly proper space pressurization need to be utilized to help isolate the phased areas. See Strategy 6.4 – Maintain Proper Pressure Relationships Between Spaces.

Completion of the HVAC systems needs to match the rest of the schedule in the phased areas. The complete HVAC duct system and piping system need to be installed and operated for the occupied areas without damage or contamination from construction activities. Operation of partly loaded systems, excessive system pressures, and exposure to construction activities, among other things, are a recipe for potential HVAC system problems impacting IAQ. For example, a single HVAC system (one air-handling unit, for example) serving a multiple-phased project would typically have one common return air system for the entire building/system. If one area is to be occupied and the unit is to be put into operation during the construction of other areas, the unit will be exposed, through the return air path, to the areas under construction. The HVAC systems might have to be segregated per phased area or the return air paths might need to be blocked or filtered. The HVAC system might need to have the capabilities to operate partially loaded to eliminate the possibility of overpressurizing the system.

Piping systems need to be addressed in the same way. The chilled water and hot water systems need to be either completed or isolated and operated partially loaded. The phasing of the project and the location and service of the piping system could affect system selection. Plumbing systems (sewer, domestic water, venting, etc.) need to be piped and connected per the phased areas allowing for a functional system that is partially installed.

HVAC system selection, building material selection, and construction procedures to be utilized all need to be reviewed when phasing a project is considered. It may not be possible to complete some project activities due to the phasing of the project. The HVAC testing, adjusting, and balancing (TAB) work requires that the HVAC system be complete and functional when this work is being done. The bid specifications and drawings, therefore, need to clearly identify the areas to be phased and the sequence of phasing and occupation of the building so that the HVAC is completed in time for the TAB work.

Construction Documents

IAQ Schedule Requirements

IAQ needs to be a consideration in the sequencing and scheduling part of the specification and on the required project submittal of the schedule. This could be in the form of an IAQ project plan addressing items that could affect project IAQ during the construction process. All IAQ items and issues can be addressed and applied to the construction sequencing and scheduling process. Once the IAQ items are applied to the project schedule, they can be reviewed and updated at project construction meetings. Project IAQ needs to become a construction meeting agenda item.

Construction

Sequencing of Construction Activities

The schedule needs to allow time for all phases/trades of construction to be completed. Proper construction sequencing to prevent moisture, mold, and contamination problems is critical for IAQ. A good example of improper sequencing includes installation of construction materials (e.g., drywall and insulation) that absorb and retain moisture before the building is dried in, thus leading to mold growth at a later date. Another example is operating the permanent HVAC equipment during construction, thus contaminating the HVAC system with dirt and debris.

Figures 1.4-F, 1.4-G, and 1.4-H highlight the key issue of protecting ductwork from construction dirt and debris. Figure 1.4-F shows improper storage of ductwork in the construction zone. Figure 1.4-G shows one project where the installed ductwork is sealed during construction and another where it is open and exposed. Figure 1.4-H shows what can happen if ductwork is left unprotected during construction. If the ductwork is not protected during construction, the dirt and debris is probably unlikely to be removed before the system is closed off.

Figure 1.4-F Unprotected Storage of HVAC System Ducts at a Construction Site
Photograph courtesy of Wayne Thomann.

Environmental conditions that will reduce the effects of moisture damage and contamination during construction need to be established by the design team and stated in the contract documents. Such conditions include a) outlining minimum thresholds of acceptance for vapor retarder, gypsum wallboard, and interior finish installation; b) protection of installed products during construction; and c) mechanical systems functionality. In addition, once construction is complete, the design team needs to review the information for certification of compliance with the contract design documents and overall satisfactory performance of the architectural and mechanical building systems (Odom et al. 2005).

To help avoid contamination of installed construction products and materials staging, the entry of construction materials and activities is important. For example, it is important to delay the installation of fleecy absorptive materials (e.g., furniture, workstations, ceiling tiles, carpet) until relatively high emission activities (e.g., painting/staining and use of caulks, sealants, adhesives) have been completed and enough time for airing and flush-out has been allowed. If there is a possibility of construction activity after such products have been installed, these products need to be protected and isolated from these activities during construction.

Figure 1.4-G Two Teams of Installers Working at the Same Construction Site: One Team Covered and Protected the Ductwork and the Other Did Not
Photographs courtesy of Wayne Thomann.

Schedule Compression

Schedule compression can adversely affect good project IAQ. If the project schedule has been delayed, it is important to protect those areas important to IAQ when trying to compress the schedule to meet the contract completion date. Because of this, it is important to get project IAQ on the project construction

Figure 1.4-H Installed Ductwork that Had Been Unprotected During On-Site Storage and After Installation
Photographs courtesy of Wayne Thomann.

meeting agenda to keep all project team members involved with project IAQ. Whenever schedule compression is discussed or implemented, questions and concerns need to be raised in regard to its IAQ impacts.

In addition, certain trades and activities are difficult to compress. For example, automatic temperature controls, TAB work, and commissioning work is systems oriented, and trying to compress these work activities is extremely difficult. The type of work that is performed does not always allow for the use of additional staff to expedite the work process.

Operation of Permanent HVAC Equipment During Construction
Operating the permanent HVAC equipment during construction needs to be avoided. Introduction of moisture, dirt, and debris into the HVAC system occurs when the permanent HVAC system is utilized during construction. *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007), actually prohibits systems designed with particle filters to be operated during construction without those filters in place. However, even with those filters in place, construction dirt and debris can still enter the system; therefore, it is better to avoid operating the systems entirely during construction. Temporary HVAC equipment needs to be utilized during the construction phase for all heating, ventilation, cooling and dehumidification purposes. The project construction site needs to be kept at correctly tempered conditions to allow for proper construction procedures. If the construction environment is kept at the proper conditions of cleanliness, temperature, and humidity, workers will be more productive, construction materials (adhesives, paints, drywall, etc.) will perform as specified, the quality of the construction will be improved, and the IAQ for the project will be improved. Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ and the SMACNA White Paper "Early Start-Up of Permanently Installed HVAC Systems" (SMACNA 2006) have more information regarding the operation of permanent HVAC equipment during construction.

Inspection Access
Enough time and adequate access needs to be planned for inspection of construction assemblies. It is important to avoid covering up joint details, piping, etc. prior to testing and/or inspections. Examples of things not to cover up include pipe leaks, wall leaks, duct that is not insulated, or duct that is not sealed or connected. For additional information, see Strategy 4.3 – Facilitate Access to HVAC Systems for Inspection, Cleaning, and Maintenance.

Post Construction

Building Flush-Out
If building flush-out is implemented, its scheduling can be difficult. It is important to schedule a flush-out to coincide with the time that activities with an impact on IAQ are performed. For instance, when adhesives are utilized or paint has been applied or furniture has been moved in, a flush-out needs to occur to remove the harmful chemicals emitted by these items. The flush-out can also be based on the emissions profile of materials if this data is part of the design/submittals.

The required time for flush-out needs to be determined. If the flush-out is based on 100% outdoor air, the HVAC equipment needs to be sized to treat the outdoor air (dehumidification, heating, cooling, etc.) and prevent any environmental condition concerns inside the building. If the HVAC equipment cannot accommodate 100% outdoor air due to the loads, then the flush-out time needs to be extended utilizing a smaller percentage of outdoor air. For example, as reported in "Part 2—Construction Indoor Air Quality" by Michael Kawecki (2005), an HVAC system design was based on 30% outdoor air, but the two-week USGBC LEED flush-out time was based on 100% outdoor air. Because of this, the flush-out would have had to be extended to ten weeks due to the HVAC equipment sizing. Also, if a water-side economizer is utilized, there is no means for 100% outdoor air and the flush-out cycle will need to be extended.

Retrofits and Remodels

Coordination and communication with the building owner is imperative in retrofits and remodels. The scheduling of construction activities that will create sound issues, odor issues, or particulate matter issues needs to occur when it will not disturb the building occupants. Occupants need to be notified well in advance of the start of construction activities and provided with a process to report any IAQ issues that emerge during construction. Also, a plan needs to be in place to respond to any reported IAQ issues.

ASHRAE Standard 62.1 (ASHRAE 2007) provides limited requirements for construction in occupied buildings when that construction requires a building permit and entails sanding, cutting, grinding, or other activities that generate significant amounts of airborne particles or procedures that generate significant amounts of gaseous contaminants. These requirements include measures to reduce the migration of construction-generated contaminants to occupied areas. Examples of acceptable measures include, but are not limited to, sealing the construction area using temporary walls or plastic sheathing, exhausting the construction area, and/or pressurizing contiguous occupied areas. SMACNA's *IAQ Guidelines for Occupied Buildings Under Construction* (SMACNA 2007) contains a detailed set of recommendations for how to deal with these challenging but critical situations. Figure 1.4-I shows an example of temporary walls used to isolate a construction zone for the occupied portions of a building. In this case, hard walls were used due to the high levels of occupant traffic adjacent to the space. In other cases, plastic sheeting can be adequate, as shown in Figure 1.4-J.

Figure 1.4-I Temporary Walls Isolating Construction Zone from Occupied Areas
Photographs courtesy of Wayne Thomann.

Figure 1.4-J Plastic Sheeting Isolating Construction Zone from Occupied Areas
Photograph courtesy of Wayne Thomann.

Strategy 1.4

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Strategy 1.5

Facilitate Effective Operation and Maintenance for IAQ

Introduction

Operation and maintenance (O&M) can have as great an effect on IAQ as design and construction. O&M itself is outside the scope of this Guide, but the project team can greatly enhance the potential for effective O&M after the building is turned over to the owner by taking certain actions during design and construction. Among the most important of these are to:

- consider the owner's expected level of O&M capability when selecting systems;
- involve O&M staff during project planning, design, construction, and commissioning (Cx) if at all possible;
- provide O&M documentation that explains the design intent of key systems and how they need to be operated and maintained to fulfill that intent;
- provide training of O&M staff, emphasizing how systems need to be operated and maintained to achieve their design intent; and
- prioritize IAQ-related O&M documentation and training to emphasize the issues most important to IAQ for a given project.

Each of these actions is discussed in the following sections.

Considering O&M Capabilities in System Selection

It is highly desirable for the design team to consult with the owner early in project planning to ascertain the anticipated number of O&M staff, their skill levels, the amount and type of O&M work that will be outsourced to contract maintenance services, and the size of the O&M budget. The design team can then select systems that are within the anticipated O&M capabilities in order to reduce the risk of IAQ-related failures down the road. In addition, the design team needs to communicate to the owner the level of O&M needed to effectively manage the risk of IAQ-related failures.

When O&M resources or skill levels are limited, selecting systems that are simpler, more forgiving, less numerous, and less difficult or time-consuming to access is an important aspect of design for IAQ.

Table 1.5-A provides examples of systems with increasing levels of complexity. Simple systems are those that are based on simpler engineering principles, have fewer components, and have relatively simple operating and maintenance procedures. Intermediate and more complex systems are based on more sophisticated principles, have more subsystems and components, and/or require greater training and skill to operate or maintain.

For example, in the context of IAQ:

- A steep slope roof has simpler inspection and maintenance requirements to prevent water intrusion than a low slope roof. A green roof is a specialized roofing system that requires more specialized knowledge to inspect and maintain.
- Operation of a single-zone, constant-volume (CV) system to provide the required minimum outdoor airflow rate is relatively easy to understand. Operation of a single-zone, variable-volume system to provide a constant outdoor airflow rate (using an airflow measuring station) as the total supply airflow rate varies is only slightly more difficult to understand. However, operation of a multiple-zone, variable-volume system to provide the proper minimum outdoor air is more complex, especially if dynamic reset is employed. The concepts (e.g., system ventilation efficiency, occupant diversity, zone ventilation efficiency, and primary and secondary recirculation) can be difficult to understand, and it can be very difficult for an operator

observing system behavior to determine whether the control is operating properly and whether the proper outdoor airflow rate is being delivered.

- Energy recovery ventilation systems are still unfamiliar to many operators (Figures 1.5-D, 1.5-E, and 1.5-F) and may have moving parts, seals, filters, condensate drains, and heat transfer surfaces that require maintenance. In addition, their overall impact on thermal and electrical energy use depends on proper operation of the economizer mode bypass and relief dampers, defrost controls, purge systems, and other devices and controls.
- Cooling towers require regular, properly executed O&M (e.g., for seasonal start-up and shutdown procedures and regular biocide treatment) to control *Legionella*.

Designers need to consider expected O&M staffing, skill levels, and budgets in choosing among these design options (Figures 1.5-D through 1.5-F). Owners who have low O&M staff levels, minimal staff expertise, run-to-failure maintenance, or deferral of preventive and condition-based maintenance—or who are in industries where financial considerations tend to force such O&M practices—are not generally good candidates for IAQ systems with complex O&M requirements. The design team can mitigate the risk of inadequate maintenance to some degree by providing thorough training and documentation but has no control over staffing numbers, staff skill levels, or budgets down the road.

Table 1.5-A Examples of Simpler, Intermediate, and More Complex IAQ-Related Systems

Simpler	Intermediate	More Complex
Steep slope roof	Low slope roof	Green roof
Single-zone CV system	Single-zone variable-volume system Single-zone demand-controlled ventilation system Dedicated outdoor air system	Multiple-zone variable-volume system
	Single-zone CV system with hot gas reheat Single-zone variable-volume system with refrigerant flow modulation	Desiccant dehumidification system
Air-cooled system		Water-cooled system with cooling tower
No energy recovery	Fixed-plate energy recovery ventilation system	Runaround loop energy recovery ventilation system Enthalpy wheel energy recovery ventilation system
Thermostat control	Packaged controller	Automation system

More forgiving systems are those that are less likely to result in significant IAQ problems if not properly operated or maintained. For example, from an IAQ perspective, an air-cooled system may be more forgiving of poor O&M than a water-cooled system with a cooling tower. Although the air-cooled system may experience increased energy use or early failure if it is not well maintained, it will not be associated with an outbreak of Legionnaires' Disease or Pontiac fever. As another example, in humid climates, permeable wall coverings are more forgiving than low-permeability wall coverings. When HVAC systems are not operated and maintained to provide positive building pressurization, permeable wall coverings are less likely to experience condensation and mold growth.

Strategy 1.5

Mismatch between System Complexity and Operator Skill: Basic Runaround Loop in a School

A mismatch between system complexity and operator skill level can contribute to IAQ problems. The operator of a school was not familiar with runaround energy recovery ventilation systems and therefore did not realize that there were coils and filters (Figures 1.5-D, 1.5-E, and 1.5-F) in the outdoor airflow path (which was not in the mechanical room but in an adjacent area). While the other filters in the school were changed regularly, those in the outdoor airflow path for this system were not. The three gymnasium air handlers had a total design supply airflow of 45,000 cfm (21,240 L/s) and a design minimum outdoor airflow of 17,100 cfm (8021 L/s). With the outdoor air dampers 100% open, they were able to deliver only 11,000 cfm (5192 L/s) of total supply air (part of which was actually return air due to incorrect coordination of one of the return air dampers, which was also at 100% when the outdoor air dampers were at 100%). The gym was stuffy and often too warm even in cool weather. The gym doors were frequently opened for cooling and outdoor air, bypassing the MERV 14 filters that had been specified for the air handlers and also undermining building security. System-oriented O&M documentation and training can help to avoid problems like this. Such documentation can explicitly describe the purpose and mode of operation of the energy recovery ventilation system, provide a clear schematic of airflow through the system, and identify components requiring maintenance. These features may be readily apparent to an experienced professional viewing the plans but not to a building operator with limited background and training.

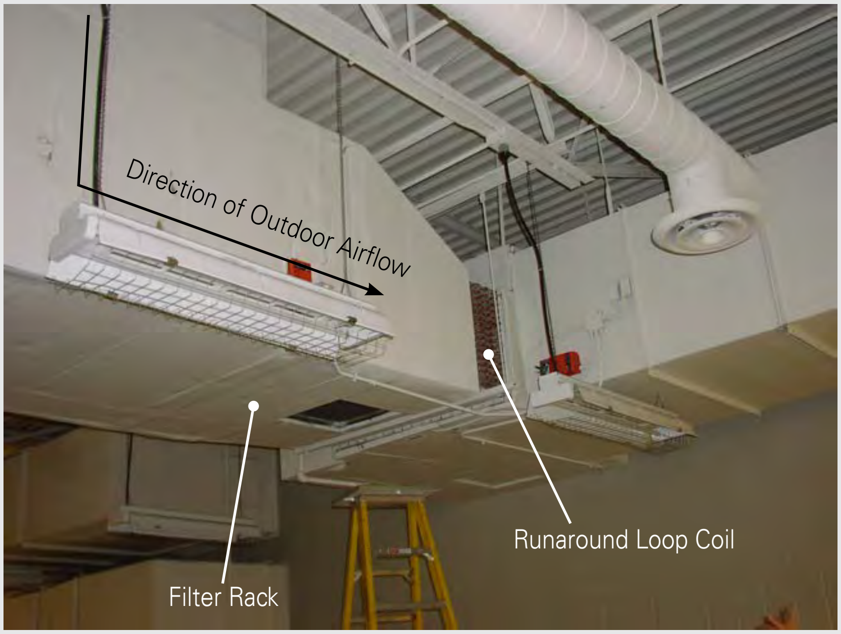

Figure 1.5-D Outdoor Air Portion of Runaround Energy Recovery Ventilation System

Figure 1.5-E Face of Runaround Loop Coil Downstream of the Filter Rack

Figure 1.5-F Long-Unchanged Outdoor Air Filter that Became Clogged and was Sucked Out of the Filter Rack

Photographs courtesy of Martha Hewett.

Mismatch between System Complexity and Operator Skill: DOAS, Desiccant-based Cooling and Gas Engine Driven Chillers with Waste Heat Recovery in a School

A large middle school was extensively renovated to update the building and bring ventilation rates up to current standards. 100% outdoor-air systems were installed in which the outdoor air went first through an energy recovery unit then through a desiccant-based cooling unit before being delivered to the parallel fan-powered VAV boxes installed to serve the classrooms (Figure 1.5-G). The desiccant-based cooling units provided all required moisture removal and included sensible heating and cooling coils to control the discharge air temperature. The VAV boxes had combination heating/cooling coils (sensible only) to control room temperature. A gas-engine-driven chiller was chosen for the sensible cooling loops in order to provide a source of waste heat that could be used to regenerate the desiccant wheels.

The complexity of the HVAC systems, insufficient system-oriented documentation, and insufficient training of O&M staff made it difficult for staff to understand how these systems needed to be operated. For example, the operators did not realize that they needed to perform annual maintenance on the gas-engine-driven chiller exhaust economizers/silencers to remove soot accumulation. Failure to maintain this heat recovery system reduced the heat available to regenerate the desiccant wheels

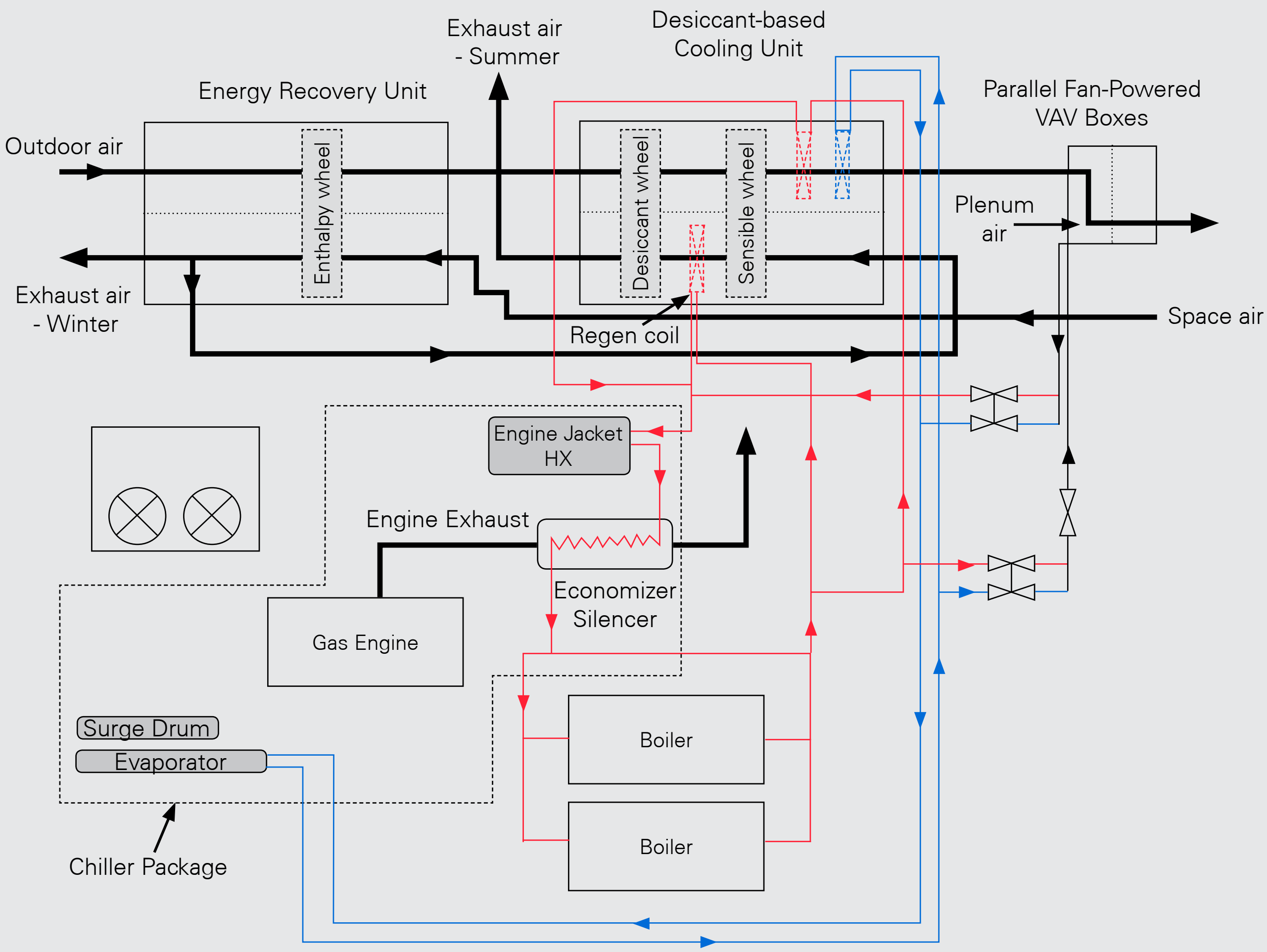

Figure 1.5-G Complex System (with Dedicated Outdoor Air, Desiccant-Based Cooling, Gas-Engine Driven Chiller, and Chiller Heat Recovery for Regeneration) Exceeded O&M Capabilities of School Staff

and dehumidify the building. The operators could have used the boilers to provide additional regeneration capacity, but it was counterintuitive to them to run the boilers in the summer. In addition, a contractor who worked on the boilers but did not understand how they were used as part of the overall HVAC system had lowered their summer setpoint to well below the 215°F (102°C) required for regeneration.

The gas-engine-driven chiller was designed to provide sensible cooling only, so the chilled water setpoint was controlled to be 2°F (1°C) higher than the return air dew-point temperature to prevent condensation on the VAV box coils. Failure to provide adequate heat to regenerate the desiccant wheels led to elevated indoor humidity levels. Moreover, the controls contractor incorrectly programmed the VAV boxes to provide variable primary airflow (in response to space temperature) in occupied mode instead of the intended constant primary airflow. These and other problems resulting from insufficient documentation of the design intent and insufficient O&M training compromised the system's ability to provide the intended IAQ improvements and thus undermined a key goal of the extensive renovation.

Central systems generally have fewer total components to be maintained than small unitary systems. Maintaining filters; cooling coils; drain pans; outdoor air dampers, actuators, and controls; and outdoor air louvers and bird screens for a single central system is less time-consuming than maintaining these same items for many small units serving individual rooms. For example, separate outdoor air intakes at each classroom of a school are more time-consuming to maintain than central outdoor air intakes—even more so if the louvers are screwed in place, as was the case for the intake shown in Figure 1.5-H. This intake was clogged with years of dirt and debris. While this system type was undoubtedly selected to meet other important design criteria, the impact on ventilation rates and therefore IAQ is evident.

Figure 1.5-H Mismatch between the Amount of Equipment to be Maintained and O&M Staffing Levels—Clogged Outdoor Air Intake on One of Many Classroom Unit Ventilators in a School
Photograph courtesy of Mark Hancock.

Central systems located in mechanical rooms are easier to access than smaller systems distributed throughout a facility (especially those in occupied spaces) or systems located on the roof. For example, Figure 1.5-I shows condensation on the bottom of an unmaintained fan-coil unit above a suspended ceiling in an art classroom. This large high school was generally well maintained, but the O&M staff had forgotten that this unit existed. Failure to change the filter over a long period of time caused low airflow, resulting in a very low evaporator temperature and a housing temperature below the ceiling plenum dew point. Condensation formed on the housing and dripped onto the suspended ceiling, providing an opportunity for microbial growth. Figure 1.5-J shows a packaged roof ventilator with a belt that had been broken long enough to for a bird to lay eggs in the unit.

Regardless of the systems selected, the design team needs to ensure that the O&M documentation explains key system concepts, intended system performance, recommended operation, and recommended inspection and maintenance procedures and intervals. The documentation needs to be complete and clear enough to be intelligible to the O&M staff who are its primary audience, not only to architects and engineers whose years of education and experience provide abundant context for the information.

Strategy 1.5

Involving O&M Staff in Planning, Design, Construction, and Commissioning

Where possible, O&M staff should be involved in planning, design, construction, and Cx. O&M staff are sometimes excluded from the design and construction process because they are perceived as wanting features that are "too expensive." Yet O&M can account for 60% to 85% of the life-cycle cost of a facility (Christian and Pandeya 1997), so prioritizing first costs over long-term O&M considerations is often a false economy.

O&M staff can provide valuable input on issues that will affect operability and maintainability (ASHRAE 2005; Schrag et al. 2007; Sapp 2008), including

- access requirements;
- sensors and connections required to enable O&M staff to monitor performance;
- standardization of equipment and components that can reduce inventory, training costs, and the need for multiple maintenance procedures, thereby improving O&M staff efficiency and reducing O&M costs;
- owner directives driven by experience with product quality, repair response times, local parts availability, or other considerations;
- O&M cost impacts of proposed value-engineering changes;
- realistic O&M capabilities and limitations;
- O&M documentation requirements and preferences;
- O&M training needs;
- consecutive numbering of systems and equipment;
- consistent labeling of systems and equipment; and
- required adaptability for future changes and expansion.

ASHRAE Guideline 0-2005, The Commissioning Process (ASHRAE 2005), describes several methods that can be used to obtain O&M staff input, including Nominal Group Technique workshops, interviews, and surveys.

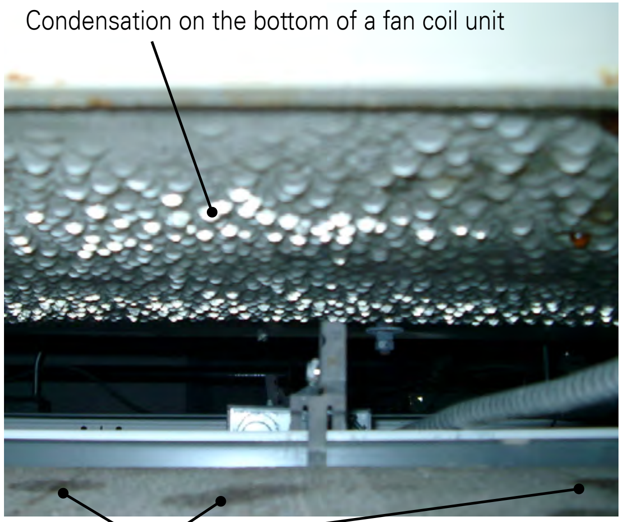

Figure 1.5-I Distributed Equipment in Occupied Space—Unmaintained Fan-Coil Unit above Ceiling in an Art Classroom
Photograph courtesy of Martha Hewett.

Figure 1.5-J Distributed Equipment on Roof—Packaged Roof Ventilator with Long-Broken Belt
Photograph courtesy of Mark Hancock.

Involving O&M staff during design and construction also enables them to gain knowledge that will be useful in operating and maintaining the building. For example, during construction, periodic walk-throughs guided by members of the design team and contractors enable O&M staff to see the details of building exterior enclosure assemblies and the layout of HVAC and plumbing systems to a degree that is often impossible after construction. Participating in the testing of systems and assemblies can give O&M staff a greater understanding of the design intent, greater confidence in the conformance of the work to that intent, and greater confidence in their own ability to operate and maintain the facility in a manner consistent with the intent.

Strategy 1.5

1.5

STRATEGY OBJECTIVE 1.5

Providing O&M Documentation that Facilities Delivery of the Design Intent
O&M documentation is the mechanism by which the project team provides enduring guidance to the facilities staff as to how the building and mechanical systems must be operated and maintained. To be effective, the O&M documentation needs to convey the design intent of key systems and how they need to be operated and maintained to fulfill that intent. Yet the documentation very often falls short of this goal.

The construction documents normally included in the O&M documentation contain the results of the design process but very often do not contain the Owner's Project Requirements (OPR), applicable codes and standards, or the rationale for design choices made to meet these requirements. For example, schedules for air-handling equipment usually show design conditions for mixed air entering the heating and cooling coils, from which minimum percentages of outdoor air may be inferred by parties that are familiar with outdoor design temperatures and are able to do the necessary algebra. However, schedules rarely show the assumed number of occupants, ventilation rate per occupant, ventilation rate per unit area, or other design parameters that would help O&M staff understand the required outdoor airflow rates or the rationale for those rates. Relevant documentation from the planning and schematic design phases often is not kept as up to date as that of the design progresses and rarely is retained long term by the owner or made available to O&M staff. Lacking this type of information about the Basis of Design (BoD), users are obliged to reverse-engineer the plans and specifications to infer what the design team was trying to achieve and why. This can be difficult for other design professionals, let alone for O&M staff with no formal training in engineering or architecture. If O&M staff do not understand the design intent of key systems, they will be less able to operate and maintain those systems to fulfill that intent and less likely to be motivated to do so.

Similarly, O&M manuals contain extensive information on equipment and components but often contain little information on the rationale for their selection or how they must be operated and maintained to deliver the intended performance. For example, the O&M manuals typically contain submittals for filters but usually do not include the rationale for the efficiency level selected. O&M staff are not likely to know that their building is in an area with high levels of outdoor PM2.5 or that PM2.5 can have significant health effects. Without this information, they may switch to less efficient filters to reduce maintenance costs without fully understanding the impact on IAQ.

The sequences of operation in the control submittals are typically the only information provided about the intended operation of the mechanical systems. The rationale for the control strategies is seldom provided. For example, the designer may have provided building pressurization control to keep the building positive, reducing infiltration of humid air and the potential for condensation in the building exterior enclosure. If the rationale for building pressurization is not explained and the recommended calibration interval for the pressure sensor is not provided, the O&M staff may not recognize the importance of operating and maintaining the systems in a manner that ensures positive pressure is provided. It is not realistic to assume that O&M staff will know this rationale or will figure it out for themselves.

ASHRAE Guideline 4-2008, Preparation of Operating and Maintenance Documentation for Building Systems (ASHRAE 2008a), provides general guidance on O&M documentation for building systems. Table 1.5-B outlines a complete documentation library, or systems manual, that includes a number of elements that address system function and performance and are relevant to IAQ, including the following:

- Owner's Project Requirements
- Basis of Design
- Record Documents
- Commissioning Report
- Operations Manual

- Training Manual
- Maintenance Manual

These elements are discussed in the following sections.

Table 1.5-B Components of a Complete Systems Manual*
*Documentation may include more or fewer components depending on the size and complexity of the building.
Source: ASHRAE (2008a).

	Part 1: Planning, Design, and Construction	Part 2: Operation	Part 3: Maintenance
Owner's Project Requirements	X	X	
Basis of Design	X	X	
Energy budget	X	X	
Submittals	X	X	
Record documents	X		
Commissioning documents	X	X	
Operations manual		X	
Emergency procedures		X	
Training manuals		X	
Maintenance manual			X
Maintenance procedures			X
Maintenance budget			X
Maintenance tasks			X
Maintenance reports			X
Emergency procedures			X
Quality control			X

Owner's Project Requirements and Basis of Design

The OPR and the BoD are two of the most important elements of system-oriented O&M documentation. One of the benefits of a full Cx process that starts in the planning phase is that these documents are developed. Projects that are not commissioned not only lose the benefit of the Cx quality assurance process itself but also are a disadvantage in developing system-oriented O&M documentation.

The OPR includes the "project goals, measurable performance criteria, cost considerations, benchmarks, success criteria" and related information. It is prepared by the owner or the planning team to define the owner's functional requirements for the facility. The BoD (also called the *design intent*) 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).

This Guide is based on eight IAQ Objectives (see the Table of Contents), with several Strategies recommended to achieve each Objective. The OPR and BoD need to address each of these objectives:

- Integrated design and project process issues
- Moisture control
- Outdoor contaminants
- Mechanical system moisture and contaminants
- Contaminants from indoor sources

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- Contaminant exhaust
- Ventilation, filtration, and air cleaning
- Advanced ventilation approaches

ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality, requires that specific ventilation system documentation be "provided to the building owner…, retained within the building, and made available to the building operating personnel" (ASHRAE 2007a, 18). The required documentation includes (among other items discussed later) design criteria and assumptions that would fall within the scope of a BoD document prepared for commissioned projects:

- 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 IAQ Procedure (Section 6.3.2).

The standard states that these design criteria and assumptions "shall be documented and should be made available for operation of the system within a reasonable time after installation" (17). Informative Appendix H of ASHRAE Standard 62.1 contains templates that can be used to document these design criteria and assumptions (see Tables 1.5-C through 1.5-F in this Strategy).

Table 1.5-C Suggested Template for Documenting Outdoor Air Quality
Source: ASHRAE (2007a).

Regional Outdoor Air Quality Pollutants	Attainment or Nonattainment According to the U.S. Environmental Protection Agency
Particulates (PM2.5)	(Yes/No)
Particulates (PM10)	(Yes/No)
Carbon monoxide—1 hour/8 hours	(Yes/No)
Ozone	(Yes/No)
Nitrogen dioxide	(Yes/No)
Lead	(Yes/No)
Sulfur dioxide	(Yes/No)

Local Outdoor Air Quality Survey	Date:	Time:
a) Area surveyed	(Brief description of site)	
b) Nearby facilities	(Brief description type of facilities—industrial, commercial, hospitality, etc.)	
c) Odors or irritants	(List and describe)	
d) Visible plumes	(List and describe)	
e) Nearby sources of vehicle exhaust	(List and describe)	
f) Prevailing winds	(Direction)	
g) Other observations		
Conclusions	(Remarks concerning the acceptability of outdoor air quality)	

Table 1.5-D Suggested Template for Documenting Ventilation Design Criteria*
*Sections referenced refer to ASHRAE Standard 62.1 (ASHRAE 2007a).
Source: ASHRAE (2007a).

Building Ventilation Design Criteria						
Total Building Outdoor Air Intake	Total Building Exhaust Air (See Section 5.10.2)	Outdoor Air Cleaning Required (See Section 6.2.1)		Occupied Space Relative Humidity (Choose One Criterion per Section 5.10.1)		Air Balancing (See Section 5.2.3)
		Particulate Matter	Ozone	Peak Outdoor Dew Point at Peak Indoor Latent Load	Lowest Space Sensible Heat Ratio at Concurrent Outdoor Condition	
(cfm or L/s)	(cfm or L/s)	(Yes/No)	(Yes/No)	(% RH based on equipment selection)	% RH based on equipment selection)	(NEBB, AABC, etc.)

Table 1.5-E Suggested Template for Documenting Ventilation Rate Procedure Assumptions*
*Tables and appendices referenced refer to ASHRAE Standard 62.1 (ASHRAE 2007a).
Source: ASHRAE (2007a).

Space Identification	Space Type	Occupant Density	Rate/ Person	Rate/ Area	Zone Air Distribution Effectiveness	System Ventilation Efficiency	Class of Air
(List number or name of each ventilation zone such as office number or name, retail space name, classroom number	(List occupancy category of the space from Table 6-1 such as office space, retail sales, classroom age 5-8, etc.)	(People/ft2 or people/m2)	(cfm or L/s)	(cfm or L/s)	(Table 6-2)	Table 6-3 or Appendix A)	(Tables 5-2 or 6-1; include justification for classification if not in these tables

Table 1.5-F Suggested Template for Documenting IAQ Procedure Assumptions*
*Sections referenced refer to ASHRAE Standard 62.1 (ASHRAE 2007a).
Source: ASHRAE (2007a).

IAQ Procedure Assumptions							
Contaminant of Concern	Contaminant Source	Contaminant Strength	Contaminant Target Concentration			Perceived IAQ	Design Approach
			Limit	Exposure Period	Cognizant Authority Reference		
(Indentify and list)	(Indentify and list)	(Determine and list)	(List)	(List)	(List)	(Percentage of satisfied building occupants)	(Select from Section 6.3.1.4 and include justification)

Other elements of the design intent for ventilation not required by ASHRAE Standard 62.1 also need to be documented to facilitate O&M for IAQ. These could include, for example:

- specific ventilation codes followed,
- methods used to monitor and control minimum outdoor airflow rates and rationales,
- outdoor airflow rates to be provided before and after normal hours of occupancy for morning flush-out of contaminants and after-hours cleaning crews and rationales for these rates, and
- methods used to control indoor humidity and rationale.

For example, it is helpful to the O&M staff if there is documentation of the methods chosen to control minimum outdoor airflow for each air handler, of the rationales for the methods chosen, and of the operating implications.

- For systems using a fixed outdoor air damper position to control minimum outdoor air, the design intent documentation for O&M should explain the rationale for this choice and how the fixed position is to be determined. Many operators do not realize that the control system percent damper signal does not correspond directly to the percent outdoor air or that the minimum outdoor air damper position needs to be based on information from the balancing report. Without this knowledge, operators often overventilate or underventilate spaces because they set the minimum damper signal to the desired minimum outdoor air percentage. They sometimes override settings that were determined by the balancer because they don't understand why the settings are what they are or why the settings for several seemingly identical units are different.
- For systems with airflow measuring stations, the design intent documentation should explain the rationale for using airflow measuring stations, the methods for field calibration, and the recommended calibration interval.
- For systems with carbon dioxide (CO_2) control, the design intent needs to explain how often the CO_2 sensor needs to be calibrated, the expected minimum and maximum CO_2 readings, and generally how the CO_2 levels and damper positions can be expected to change as occupancy changes. Many operators do not know that outdoor and zero-occupancy CO_2 levels are around 350 to 400 ppm (630 to 700 mg/m^3) and so may not realize that a reading of zero or a few ppm indicates a sensor or control system problem. Many operators do not know what a reasonable CO_2 control point is or what the basis of such a control point is. This makes it difficult for them to evaluate observed system operation for potential problems or to explain the control strategy to occupants who may have concerns or complaints.

The design intent also needs to be conveyed in the systems manual for elements of the mechanical system design other than ventilation that may affect IAQ. These may include, for example:

- the rationale and methods used to achieve building pressurization and relative space pressurization,
- other relevant control strategies and rationales,
- the rationale for the level of filtration and air cleaning selected (which may be related to outdoor air quality [Table 1.5-C] or to other factors) and the location(s) of filtration and air-cleaning devices in the HVAC system, and
- the rationale for exhaust systems provided and for exhaust flow rates.

For example, the design engineer may have provided building pressurization control for a building in a humid climate to reduce infiltration of humid air and the potential for condensation within the building envelope. Many operators do not know that building pressurization is important to limit moisture migration and mold growth. The control submittals may provide a building pressure setpoint but will not explain the rationale for pressurization. Documenting this rationale in the design intent included in the systems manual and covering it during operator training makes operators aware of the rationale for and importance of pressurization. This increases the likelihood that they will monitor pressurization and take corrective action if it is not maintained. It also increases the likelihood that they will calibrate or arrange for calibration of pressure sensors at the recommended intervals.

For examples of the OPR and BoD for HVAC issues not covered by ASHRAE Standard 62.1, see *ASHRAE Guideline 1.1-2007, HVAC&R Technical Requirements for The Commissioning Process* (ASHRAE 2007b).

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

- site drainage systems intended to control liquid water,
- building enclosure systems intended to control liquid water,
- building enclosure systems intended to control bulk air and moisture movement,
- building enclosure systems intended to control vapor flow along the vapor pressure gradient,
- natural ventilation systems,
- radon mitigation systems,
- vapor intrusion mitigation systems,
- track-off systems, and
- building materials, finishes, and furnishings.

For example, the architect may have provided an air barrier to reduce movement of warm, moist indoor air into the building enclosure. Maintenance staff may not understand the importance of the air barrier in limiting condensation and the potential for mold growth and may breach the barrier while performing maintenance work. Documenting the purpose of the air barrier in the design intent and O&M training materials makes maintenance staff aware of the rationale for the air barrier and the importance of preserving its integrity.

NIBS Guideline 3-2006, Exterior Enclosure Technical Requirements for the Commissioning Process, provides guidance on development of the OPR and BoD for the exterior enclosure.

Experience suggests that the portion of the systems manual that is most reliably retained on site over time is the drawings. For this reason, it can be beneficial to incorporate key elements of the design intent on sheets in the drawings (see this Strategy's case study titled "Including the Ventilation Design Intent in Project Drawings Facilitates Proper Building Operation" in Part I of this Guide).

Record Documents

Record documents are as-built drawings and specifications showing all changes approved during construction. Obviously, O&M staff can perform their functions more effectively if they have access to record documents that show all of the accepted change proposals, the actual locations of equipment, etc. Section 7.2.6 of ASHRAE Standard 62.1-2007 (ASHRAE 2007a) requires that record drawings and final design drawings of the ventilation system be provided to the owner, kept in the building, and made available to operators.

Commissioning Report

All Cx documents should be included in the O&M documentation. Beyond the OPR and the BoD described previously, the Cx documents most useful for O&M include (ASHRAE 2005):

- Inspection Reports
- Test Data Reports

- Issues Report
- Inspection Checklists
- Test Procedures

The inspection reports and test data reports document the conformance of systems and equipment to the OPR. The issues report summarizes design, installation, and performance issues that did not conform to the OPR and remained unresolved at the conclusion of Cx. Together, the inspection, test data, and issues reports provide a benchmark against which O&M staff can compare the subsequent conditions and performance of components, equipment, assemblies, and systems. The inspection checklists may provide a relevant starting point for development of O&M inspection checklists. The test procedures can be used to guide the execution of subsequent operational and functional tests, either by O&M staff or by a recommissioning consultant.

Operations Manual

Manuals that provide guidance for O&M staff on how to operate building systems are critical for IAQ. Unfortunately, however, O&M manuals are often heavily oriented toward maintenance and provide relatively little information about operation. The control submittals are the most commonly provided operational information, typically including schematic control drawings, narrative sequences of operation, and other information. It is not uncommon for the sequences in the submittals to be copied directly from the specifications. They may be brief and fairly general, and they may not correspond directly to the actual sequences programmed into the automation system. The designer (and commissioning authority, if the project has one) can greatly enhance the utility of the control submittals for the operator by requiring the controls contractor to provide detailed written sequences that accurately reflect the actual control logic.

The emphasis on maintenance over operation in the O&M manuals mirrors the common focus of O&M staff. While many facilities have some form of preventive/condition-based *maintenance* program, it is common for operation to be driven primarily by occupant complaints, which in many ways is the operational equivalent of run-to-failure maintenance. A preventive or condition-based *operations* program periodically checks or tracks system operation and compares it to the owner's operating standards and/or to baseline data to verify proper performance (PECI 1999). As described in the following, better operations manuals can facilitate this approach.

ASHRAE Guideline 4 (ASHRAE 2008a) suggests that the operations manual contain the following components:

- General Information
  - Building function
  - Building description
  - Operating standards and logs
- Technical Information
  - Systems descriptions
  - Operating routines and procedures
  - Seasonal start-up and shutdown procedures
  - Special procedures
  - Basic troubleshooting

The following are suggested to be included in the operating standards and logs:

- Standards of performance for the building, such as space temperature, space humidity, ventilation rate, concentrations of specific contaminants, and other performance criteria
- Log forms used to monitor performance
- General procedures for operating each system

- Relevant inspection procedures
- Reporting requirements for system licensing and inspections for various systems

Such operating standards and logs have obvious potential benefits. In the context of IAQ, explicitly listing performance standards for space temperature and humidity, ventilation rates, and other parameters and providing logs on which to record these values makes the owner's expectations clear to operating staff and facilitates both ongoing monitoring and comparison to meaningful benchmarks. This fosters accountability for building IAQ performance and helps to discourage such practices as closing outdoor air dampers or turning off reheat loops to reduce energy costs. Standards and logs for building pressurization, relative space pressurization, cooling tower biocide levels, service hot water temperatures, and other parameters are also relevant for IAQ management. Standards for contaminant concentrations may be useful in more limited circumstances, such as when the ASHRAE Standard 62.1 IAQ Procedure (ASHRAE 2007a) is used (see Strategy 8.5 – Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate and Appendix A – Environmental Monitoring for further information).

The operating standards and logs ought to indicate the intervals at which performance should be measured (PECI 1999). ASHRAE Standard 62.1 specifies minimum intervals at which minimum outdoor airflow rates must be measured and at which various visual inspections must be performed (see Table 1.5-G).

One very efficient way to log IAQ-related performance parameters is to use the trending capabilities of the building automation system. Most building automation systems can log many data points at frequent intervals (e.g., every 15 minutes) without significantly affecting performance. These trend logs can be saved, plotted, and reviewed by the operator, facilities manager, or retro-commissioning contractor to identify potential performance problems for investigation. For example, if an air handler is supposed to provide a fixed minimum outdoor airflow of 20%, the mixed air temperature should be about 60°F (15°C) on a 20°F (–7°C) day when the return air temperature is 70°F (21°C). If the mixed air temperature is the same as the return air temperature, it may indicate that the outdoor air damper is not opening. This would warrant visual inspection. Of course trend data are only accurate if the building automation system sensors trended are properly located and calibrated.

O&M manuals typically focus on equipment and components rather than systems. Yet system descriptions help O&M staff understand how equipment and components are intended to work together to deliver performance that meets the owner's requirements. ASHRAE Guideline 4 (ASHRAE 2008a) suggests that system descriptions include areas of the building served; locations of meters, gauges, and other checkpoints; expected performance readings at design and part-load conditions; operation during days, nights, and weekends; seasonal start-ups and shutdowns; safety devices and their functions; control devices and their functions; etc.

In the context of IAQ, expected performance readings at part-load conditions might usefully include items such as the expected range of minimum outdoor airflow rates for VAV systems under various conditions of zone and total supply airflow or the expected range of CO_2 values and minimum outdoor airflow rates for demand-controlled ventilation systems as a function of the number of occupants and time since they entered or departed. The importance of start-up and shutdown procedures for cooling towers should also be discussed so that adherence to safe practices does not depend solely on the operator looking up and carefully following information in the cooling tower documentation.

Operating routines and procedures ought to identify and provide checklists and logs for procedures associated with normal operation of the systems and equipment. The section on seasonal start-up and shutdown should list seasonal procedures. Identifying cooling tower start-up and shutdown procedures here gives them prominence, underscores their importance, and can refer the operator to the cooling tower manufacturer's manual for details.

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Training Manual

Unfortunately, most current O&M training focuses on a few large pieces of equipment, is conducted very briefly in a noisy environment, and includes little take-away documentation. Under these circumstances, the initial O&M staff is likely to have difficulty retaining all the key information, and replacement staff must rely on only the conventional O&M materials and information handed down by departing staff.

Section 5.2.8 of ASHRAE Guideline 4 (ASHRAE 2008a) recommends that training material be included in the operations manual and be presented in a way that allows a new operator to use it for self-directed study to understand the design and operation of all systems sufficiently to operate them properly.

Maintenance Manual

Section 5.3.1 of ASHRAE Guideline 4 (ASHRAE 2008a) recommends that the maintenance manual include

- descriptions of each piece of equipment and system;
- descriptions of system and equipment functions, including inputs and outputs at design and part load, procedures required before start-up, and performance verification procedures;
- recommended maintenance procedures and frequencies for the particular application;
- recommended lists of spare parts, part numbers, and sources;
- original purchase order numbers, vendors, and warranty information; and
- installation and repair information

As with operation, maintenance needs to be system-oriented if it is to preserve the functionality of IAQ-related systems and assemblies. Maintenance staff need to understand the functions of the systems and how they must perform to meet those functions.

A solid preventive maintenance program may overlook the key issue of proper functioning if it focuses solely on reducing failures and extending equipment life. For example, outdoor air dampers may be well maintained but may not be opening on the right schedule or may not be admitting the correct minimum outdoor airflow. The chiller may be well maintained but operating at too high a chilled water temperature to control indoor humidity. A preferred approach is a *preventive or condition-based O&M program* that differs from a typical preventive maintenance program in that it includes periodic checks of operational and control issues (PECI 1999).

Maintenance procedures are normally developed by the O&M team during the first year of operation. Many resources are available to help the design team and O&M staff develop inspection and maintenance procedures for IAQ-related systems, such as the following:

- ASHRAE Standard 62.1 (ASHRAE 2007a) requires that the O&M manual include minimum maintenance activities and frequencies for ventilation systems (see the discussion following this bulleted list).
- *ANSI/ASHRAE/ACCA Standard 180-2008, Standard Practice for Inspection and Maintenance of Commercial Building HVAC Systems* (ASHRAE 2008b), defines standard practice for inspection and maintenance of commercial building HVAC systems.
- The EPA *IAQ Building Education and Assessment Model* (I-BEAM) provides “comprehensive state-of-the-art guidance for managing IAQ in commercial buildings” (EPA 2008, par. 1). Among other things, I-BEAM provides guidance and forms that can be used to
  - conduct an IAQ audit and establish an IAQ baseline and
  - establish IAQ management and maintenance programs to reduce the risk of IAQ problems.

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- EPA's IAQ Tools for Schools Program references I-BEAM but provides other guidance as well, including the *Healthy School Environments Assessment Tool*, Version 2 (HealthySEAT2), a self-contained software tool "designed to help school districts evaluate and manage ALL of their environmental, safety and health issues" (EPA 2007, par. 1).

Minimum requirements for O&M of ventilation systems were incorporated into ASHRAE Standard 62.1 (ASHRAE 2007a) for the first time in late 2001 as an addendum to the 1999 edition of the standard and are similar in the 2007 edition. The requirements apply to buildings and ventilation systems built or renovated after adoption of the standard. The standard requires that an O&M manual be developed, maintained, and updated as necessary for the working life of the ventilation system equipment or components. The O&M manual must include

- O&M procedures,
- final design drawings,
- O&M schedules and changes made to them, and
- maintenance requirements and frequencies.

Ventilation system operation must be consistent with the O&M manual, and maintenance must be in accordance with the O&M manual or as required by the standard. Required maintenance activities and frequencies are shown in Table 1.5-G.

Table 1.5-G Minimum Ventilation System Maintenance Activities and Frequencies
*Minimum frequency may be increased or decreased if indicated in the O&M manual.
Source: ASHRAE (2007).

Item	Activity	Minimum Frequency*
Filters and air-cleaning devices	Maintain according to O&M manual	As specified in O&M manual
Outdoor air dampers and actuators	Visually inspect or remotely monitor for proper function	Every 3 months or as specified in O&M manual
Humidifiers	Clean and maintain to limit fouling and microbial growth	Every 3 months of use or as specified in O&M manual
Dehumidification coils	Visually inspect for cleanliness and microbial growth and clean when fouling is observed	Regularly when it is likely that dehumidification occurs but no less than once per year or as specified in O&M manual
Drain pans and other adjacent surfaces subject to wetting	Visually inspect for cleanliness and microbial growth and clean when fouling is observed	Once per year during cooling season or as specified in O&M manual
Outdoor air intake louvers, bird screens, mist eliminators, and adjacent areas	Visually inspect for cleanliness and integrity and clean when necessary	Every 6 months or as specified in O&M manual
Sensors used for dynamic minimum outdoor air control	Verify accuracy and recalibrate or replace as necessary	Every 6 months or as specified in O&M manual
Air-handling systems except for units under 2000 cfm (1000 L/s)	Measure minimum outdoor airflow rate; if less than 90% of minimum rate in O&M manual, adjust or modify to bring above 90% or evaluate to determine if measured rates are in conformance with ASHRAE Standard 62.1-2007 (ASHRAE 2007a)	Every 5 years
Cooling towers	Treat to limit growth of microbiological contaminants	As specified in O&M manual or by the treatment system provider
Floor drains located in plenums or rooms that serve as air plenums	Maintain to prevent transport of contaminants from floor drain to plenum	As specified in O&M manual
Equipment/component accessibility	Keep space provided for routine maintenance and inspection around ventilation equipment clear	—
Visible microbial contamination	Investigate and rectify	—
Water intrusion or accumulation	Investigate and rectify	—

ASHRAE Standard 62.1 (ASHRAE 2007a) further requires that ventilation system design, operation, and maintenance be reevaluated whenever certain changes occur, such as the following:

- Change in building use or occupancy category
- Significant building alternations
- Significant changes in occupant density
- Other changes inconsistent with system design assumptions

The standard also requires that specific ventilation system documentation be "provided to the building owner…, retained within the building, and made available to the building operating personnel" (ASHRAE 2007a, 18). The required documentation includes

- an O&M manual containing basic data relating to O&M of ventilation systems and equipment as installed;
- HVAC controls information, including diagrams, schematics, control sequence narratives, and maintenance and/or calibration information;
- an air balance report;
- record drawings, control drawings, and final design drawings; and
- design criteria and assumptions (described in this Strategy in the "Owner's Project Requirements and Basis of Design" section).

ASHRAE Standard 62.1 states that this documentation "should be made available for operation of the system within a reasonable time after installation" (ASHRAE 2007a, 17).

The stated purpose of ASHRAE/ACCA Standard 180 is "to establish minimum HVAC inspection and maintenance requirements that preserve a system's ability to achieve acceptable thermal comfort, energy efficiency, and indoor air quality in commercial buildings" (ASHRAE 2008b, 2). Thus, its scope is broader than the O&M requirements in ASHRAE Standard 62.1. Meeting the requirements of the standard is the responsibility of the building owner. ASHRAE/ACCA Standard 180 requires that an inventory of HVAC system components that impact building performance be created. The maintenance plan for the inventoried equipment must include

- performance objectives,
- condition indicators,
- inspection and maintenance tasks, and
- inspection and maintenance frequencies.

The standard requires performance objectives to incorporate thermal comfort, energy efficiency, and IAQ metrics. They are to be based on the BoD and operational criteria specific to the system. Thus the focus is not simply on preventing breakdowns or increasing equipment life but on *delivery of the intended function at the intended level of performance*. Condition indicators are defined as "indicators of unacceptable system and equipment conditions…. These indicators are measurements or observations of conditions that could lead to failure or performance degradation" (ASHRAE 2008b, p. 3). ASHRAE/ACCA Standard 180 identifies required inspection and maintenance tasks and frequencies for 24 types of HVAC equipment and systems (Table 1.5-H).

Format of O&M Documentation

ASHRAE Guideline 4 (ASHRAE 2008a) recommends that owners require O&M documentation be provided in electronic as well as in printed form (see Section 4.3 of the standard). The advantages identified include

Table 1.5-H Systems and Equipment for which Inspection and Maintenance Tasks and Frequencies are Established in ASHRAE/ACCA Standard 180 (ASHRAE 2008b)

ASHRAE/ACCA Standard 180 Table No.	Equipment or System
5-1	Air distribution systems
5-2	Air handlers
5-3	Absorption chillers
5-4	Air-cooled chillers
5-5	Water-cooled chillers
5-6	Boilers
5-7	Condensing units
5-8	Control systems
5-9	Cooling towers and evaporatively cooled devices
5-10	Dehumidification and humidification devices
5-11	Engines, micro-turbines
5-12	Free-standing heating or cooling coils
5-13	Free-standing fans (exhaust, transfer, return, etc.)
5-14	Fan coils, hot water and steam unit heaters
5-15	Furnaces, unit heaters
5-16	Indoor section of duct-free split-system air conditioners
5-17	Packaged terminal air conditioners
5-18	Packaged terminal heat pumps
5-19	Pumps
5-20	Rooftop units
5-21	Steam distribution systems
5-22	Terminal and control boxes (VAV, fan powered, bypass, etc.)
5-23	HVAC water distribution systems
5-24	Water-source heat pumps

- better potential for long-term document retention,
- accessibility by multiple users for documentation residing on servers,
- ease of updating and ability to maintain version and revision control and ensure that all users have the most current documentation,
- searchability,
- reduced costs, and
- greater versatility of viewing.

O&M documentation with hyperlinks to O&M manual components can further facilitate rapid access to information. The files provided electronically should include all components of the systems manual (Table 1.5-B), including drawings, specifications, and submittals.

Building information modeling (BIM) is a developing discipline that has the potential to reduce the costs of gathering and maintaining up-to-date, easily accessible building data. A building information model is “a digital representation of physical and functional characteristics of a building” (Smith and Edgar 2008). BIM should eventually allow design teams, vendors, contractors, facilities staff, and others to create and update a building model and to move data between applications based on open standards for data exchange. These applications could include computer-aided design software, manufacturers’ electronic product data files, computer-aided manufacturing software (e.g., at sheet metal fabrication shops), balancers’ spreadsheet software, automation system software, and computerized maintenance management software. O&M documentation residing in a building information model has the potential to greatly reduce costs of re-gathering or reformatting building data throughout a facility’s life cycle (Smith and Edgar 2008).

Providing O&M Training to Support Delivery of the Design Intent

ASHRAE Guideline 0 (ASHRAE 2005) provides general recommendations regarding O&M training that are applicable to O&M training for IAQ. It recommends that O&M training requirements be defined during design-phase Cx, after the systems and assemblies have been determined but prior to issuance of the construction documents, since these need to specify the contractors’ responsibilities for training. The guideline describes several approaches that can be used to define the training requirements. It recommends that the training requirements include

- the specific systems, subsystems, equipment and assemblies to be covered;
- the capabilities and knowledge of the occupants and O&M staff;

- the number and type of training sessions; and
- measurable learning outcomes and teaching outlines.

It suggests that training be organized into a series of instructional modules, the first of which covers the OPR and BoD; other modules should cover portions of the building's systems, equipment, and assemblies. Annex P of ASHRAE Guideline 0 (ASHRAE 2005) provides a sample syllabus, training agenda, and evaluation form. Annex P of ASHRAE Guideline 1.1 (ASHRAE 2007b) provides further suggestions on training related to HVAC systems.

The systems manual needs to be complete before training occurs so that it can be used in the training sessions, both to ensure that complete information is available and to provide an opportunity for O&M staff to become familiar with the organization and contents of the manual.

If possible, O&M training should be digitally recorded, edited, and indexed so that it is available over the long term for use by new staff (ASHRAE 2007b, Annex J). Printed training materials (see previous discussion) need to be included in the O&M manual.

Prioritizing O&M for IAQ

Given the level of deferred maintenance in U.S. buildings and the constraints on O&M budgets, design teams and owners need to prioritize recommended O&M for IAQ. This section offers several sources of information to guide prioritization.

The HVAC system O&M inspections and maintenance requirements of ASHRAE Standard 62.1 (ASHRE 2007a) are an obvious priority since ASHRAE Standard 62.1 is the voluntary consensus American National Standard focused on indoor air quality.

Not enough scientific research is available to define standards for building-related practices (design, operation, and maintenance) to prevent adverse health effects on occupants (Mendell et al. 2006). In the absence of sufficient research, Mendell et al. (2006) undertook a project to develop a prioritized list of strategies to prevent complaints of building-related symptoms in office buildings through a structured workshop process. The workshop participants were a small group of very experienced indoor environmental quality (IEQ) investigators. The problems that these investigators reported as the most important causes of building-related symptom complaints in office buildings and their recommendations for prevention strategies are shown in Table 1.5-I. The prevention strategies this group identified as the highest priorities across all problem categories in Table 1.5-I were water management of the building exterior, operation of the ventilation system according to the design intent (which requires effective controls), providing ASHRAE Standard 62.1 minimum ventilation rates at the air handler, and maintaining indoor temperatures at 72°F ± 2°F (22°C ± 1°C).

This research is not definitive but provides useful information for building owners and managers. In particular, it highlights the importance of regular inspection and maintenance of the building exterior enclosure to prevent significant water intrusion.

Note that the IEQ investigators defined "important" causes of building problems primarily as those that frequently require investigation (Mendell et al. 2006). Thus, they implicitly exclude IAQ problems that are significant from a health perspective but may not lead to occupant complaints connected to the building per se, such as radon, asbestos, lead, tobacco smoke, and *Legionella* problems.

Table 1.5-I Key Problems Causing Building-Related Symptom Complaints, Listed in Descending Order of Estimated Importance, and Recommended Prevention Strategies for Each, Based on the Experience of IEQ Investigators
Table reproduced from Mendell et al. (2006), with additions in brackets.

Problem Category	Top Recommended Prevention Strategies
Excessive building moisture	• Water management of building exterior • Humidity control by HVAC • Maintain water vapor management through envelope
Inadequate amount or quality of outdoor air	• Operate per design intent (effective controls) • At least minimum rates of outdoor air (per ASHRAE) at air-handling unit • Scheduled maintenance of outdoor air system
Surface dust	• Management of renovations (containment and management of air pressure relationships) • Housekeeping • Surface and material selection
Gases and odors	• Locate outdoor air intakes away from sources • Management of renovations (containment and management of air pressure relationships) • Local exhaust venting for special uses/sources

Inadequate thermal control	• Meet ASHRAE 55 [ASHRAE 2004] for temperature and relative humidity
	  • Maintain 72°F ± 2°F [22°C ± 1°C]
	  • Pay attention to radiant heat exchange, proximity to window, and window type
	  • Limit air velocity to 25 ft/min [0.127 m/s] maximum
	• Control of high relative humidity
	• Local control of temperature

Inadequate attention by management to preventing adverse effects of the indoor environment on occupants versus minimizing immediate costs	• Communicate about activities that cause employee complaints and about addressing complaints • Set up IEQ management plan (e.g., EPA/NIOSH building action plan) • Promote employee/management IEQ committees/safety and health committees for ongoing communication

An analysis by Angell and Daisey (1997) of 49 school health hazard evaluation reports conducted by the National Institute of Occupational Safety and Health (NIOSH) between 1981 and 1994 identified a list of building factors associated with occupant complaints (Figure 1.5-K) similar to the list developed by Mendell et al. (2006) for office buildings.

A very effective way to prioritize O&M activities for IAQ is to apply concepts from the field of reliability-centered maintenance (RCM). RCM is a specific, well-defined process used to identify the O&M (and capital improvement) actions that will most effectively reduce the risk of "functional failure," a state in which a piece of equipment or system is unable to perform a specific function at the desired level of performance (SAE 1999).

RCM was originally developed by the commercial aviation industry (Nowlan and Heap 1978) and was subsequently adopted by the U.S. military and U.S. nuclear industry. It began to be used across a broad range of industries starting in the early 1990s. Nowlan and Heap's work demonstrated that there was not a strong, consistent relationship between age and failure rate and that therefore the fundamental premise of time-based maintenance was false for the majority of equipment. This finding was confirmed by subsequent research conducted by the U.S. Department of Defense and U.S. nuclear utilities, as described in *Reliability Centered Maintenance Guide for Facilities and Collateral Equipment* by the National Aeronautics and Space Administration (NASA; 2000). According to NASA (2000), the work by Nowlan and Heap and subsequent

Building Factor Cited	%
Insufficient Outdoor Air	84
Water Leaks in Building Shell	57
Inadequate Source Exhaust	51
Poor Distribution or Balance	45
Poor HVAC Maintenance	39
Controls Dirty or Malfunctioning	27
Maintenance+ w/o Controls	27
Need IEQ Management Plan	24
Re-Entrainment or Exhaust	22
Low Filter Efficiency	22
Poor Outdoor Air Intake Location	20
HVAC Modification-Energy	18
Dirty Supply Ducts, Air Handlers	18
Poor HVAC Condensate Drain	12
Poor Access to Filters, etc.	8
Filter Bypasses	8
Filters Very Loaded	8
No Relief Vents	6
Fan Running Backwards or Off	6
Undersized Fan or Duct	4
Storage in HVAC Return	4
HVAC Modification-Fire Code	2

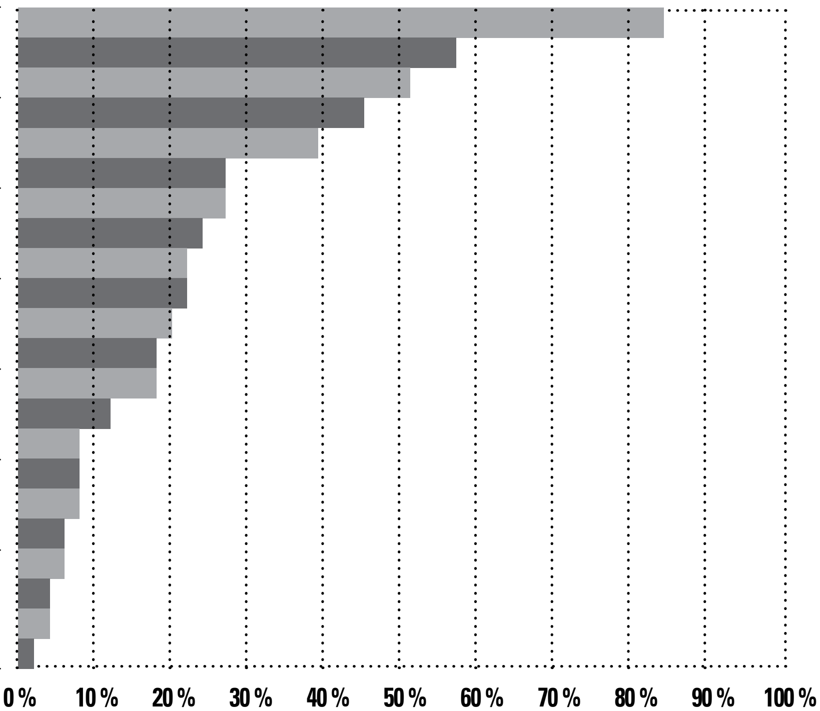

Figure 1.5-K Building Factors Associated with IAQ Problems from 49 NIOSH School Health Hazard Evaluation Reports Conducted between 1981 and 1994
Adapted from Angell and Daisey (1997).

follow-up research found that random failures accounted for 77% to 92% of total failures, and age-related failures accounted for 8% to 23%. The realization that failure rate is not highly correlated with age led to efforts to develop predictive testing and inspection procedures that could be used to direct condition-based maintenance as well as to develop various proactive maintenance tools. It also led to the development of an analytical process, RCM, that enables users to identify the optimal mix of maintenance strategies, including conditioned-based maintenance, time-based maintenance, proactive maintenance, and run-to-failure or reactive maintenance, to maximize reliability while minimizing life-cycle costs (SAE 1999; Pride 2008).

Classic RCM is a rigorous and costly process that is well suited to industries where functional failures can have severe consequences but may not be practical or necessary for facilities maintenance. A more streamlined, intuitive approach has been recommended for use in facilities belonging to several federal agencies (Pride 2008).

The National Aeronautics and Space Administration (NASA) developed a RCM guide for its facilities that uses the maintenance analysis process shown in Figure 1.5-L to determine the appropriate maintenance approach for a particular piece of equipment or system (NASA 2000).

Two condition-based maintenance technologies that can be an effective part of O&M for IAQ are performance trending of mechanical systems (using the building automation system or hand-held or permanently installed instruments) and infrared thermography for condition monitoring of building exterior enclosures. Performance trending was covered in this Strategy's discussion of operating standards and logs. Infrared thermography is a very useful technology for detection of moisture intrusion into the building envelope. Sullivan et al. (2004) provide an example of a state facility with a 360,000 ft^2 (10,000 m^2) low slope roof. The roof was more than 22 years old and was experiencing leaks. Estimates of replacement costs ranged from \$2.5 to \$3 million. Infrared inspections identified a total of less than 3,000 ft^2 (85 m^2) of roof requiring replacement. The cost of repairs for this area was less than \$60,000. Condition-based maintenance preserved the essential function of the roof and protected the facility and its IAQ at a much lower cost than interval-based replacement would have. Further information on predictive maintenance technologies is provided in NASA (2000) and Sullivan et al. (2004).

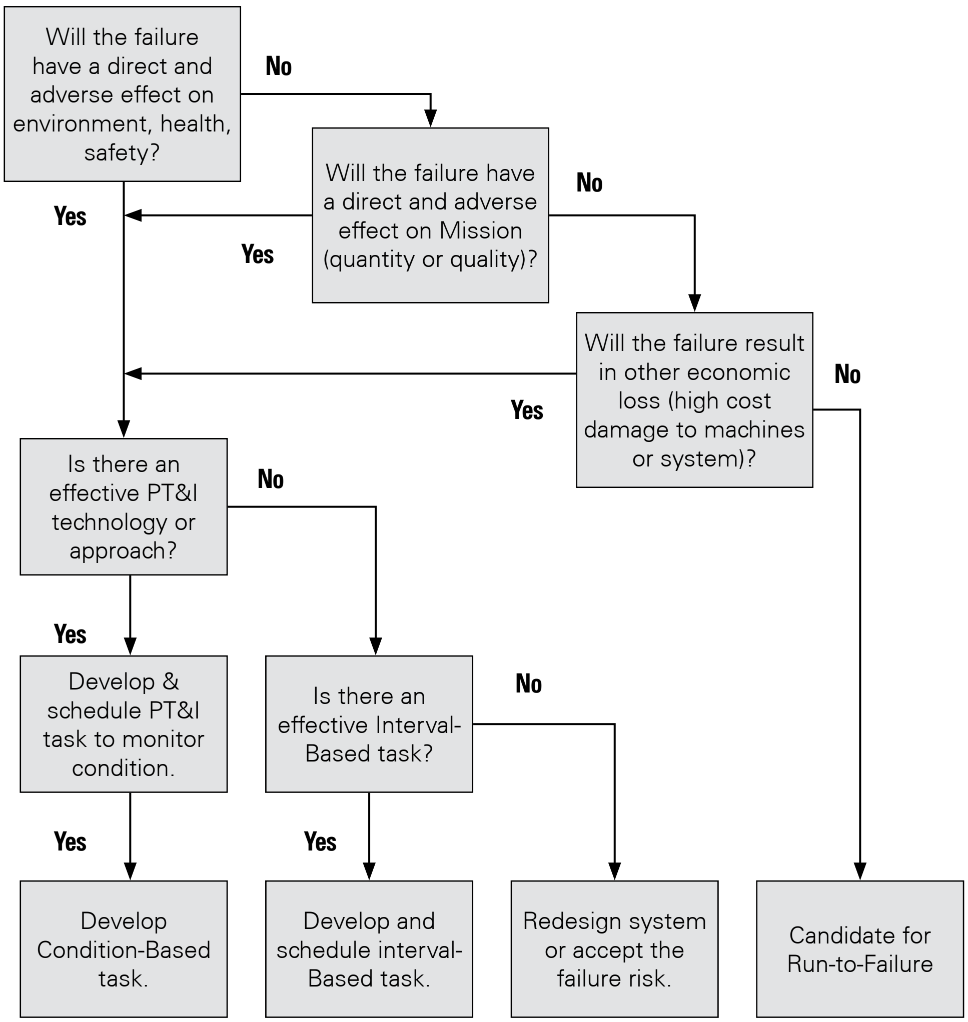

Figure 1.5-L NASA (2000) RCM maintenance Analysis Process

Strategy 1.5

1.5

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Strategy 2.1

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.

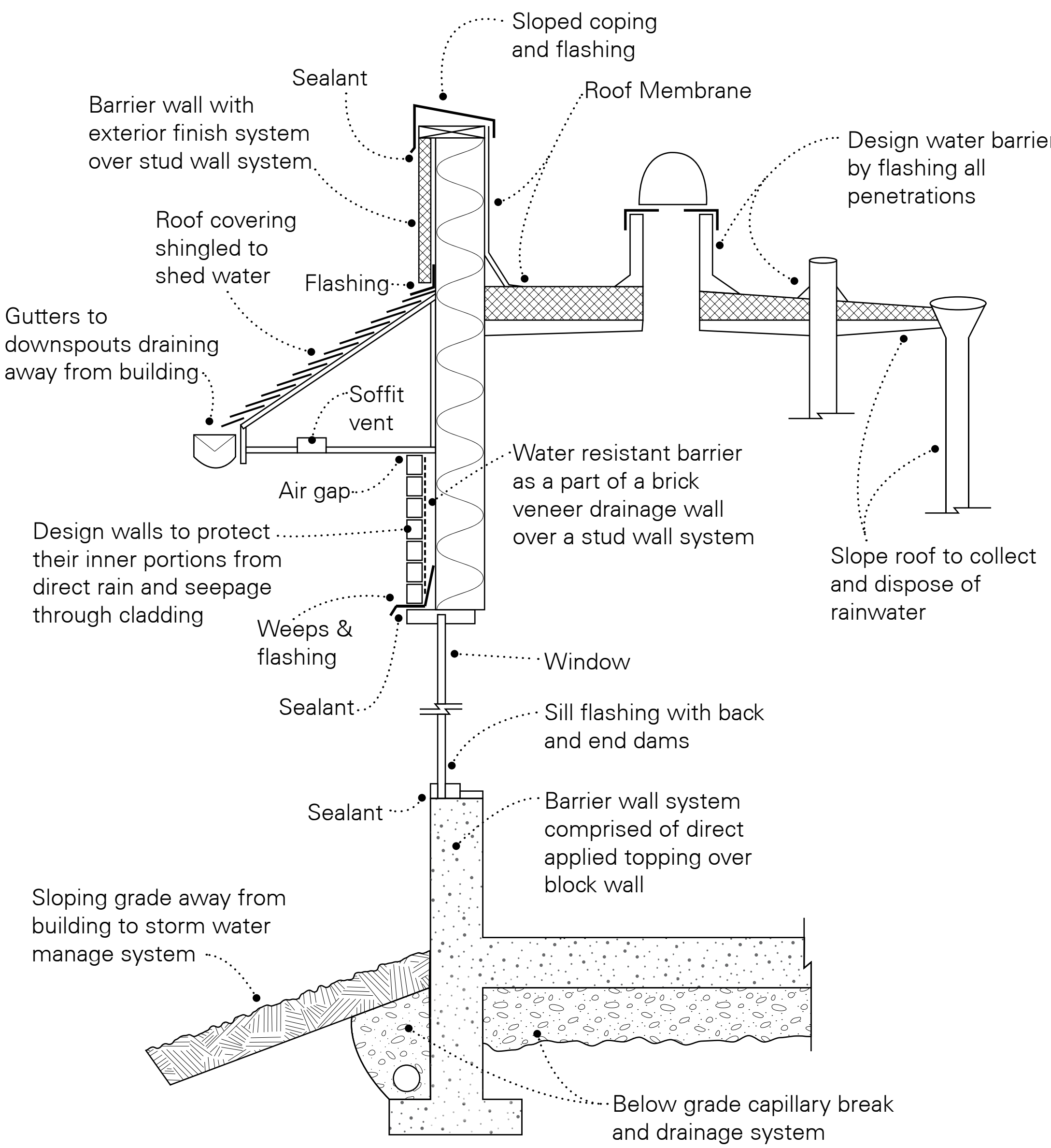

Figure 2.1-F Areas of Waterproofing for a Typical Foundation, Wall, and Roofing System

Strategy 2.1

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.

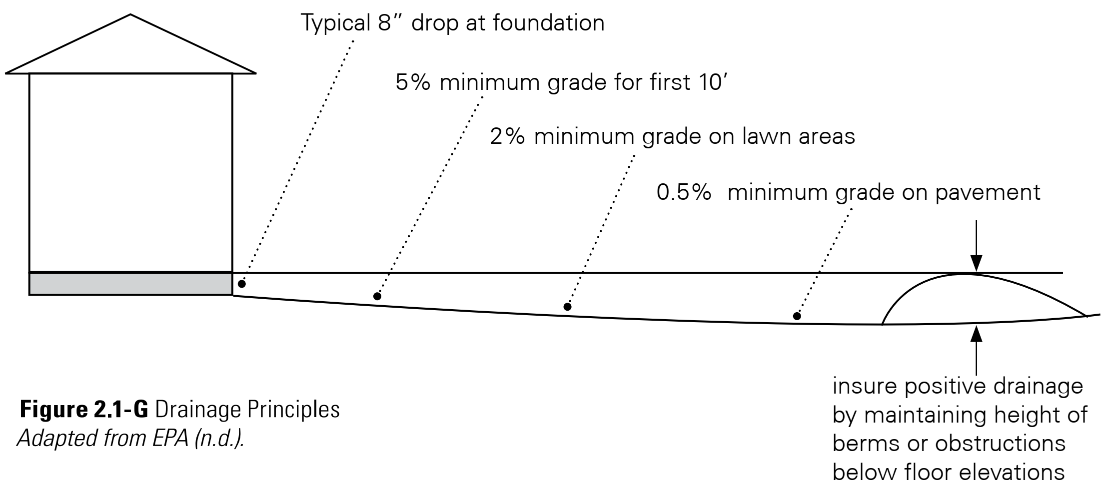

Figure 2.1-G Drainage Principles
Adapted from EPA (n.d.).

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).

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®.

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.

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®.

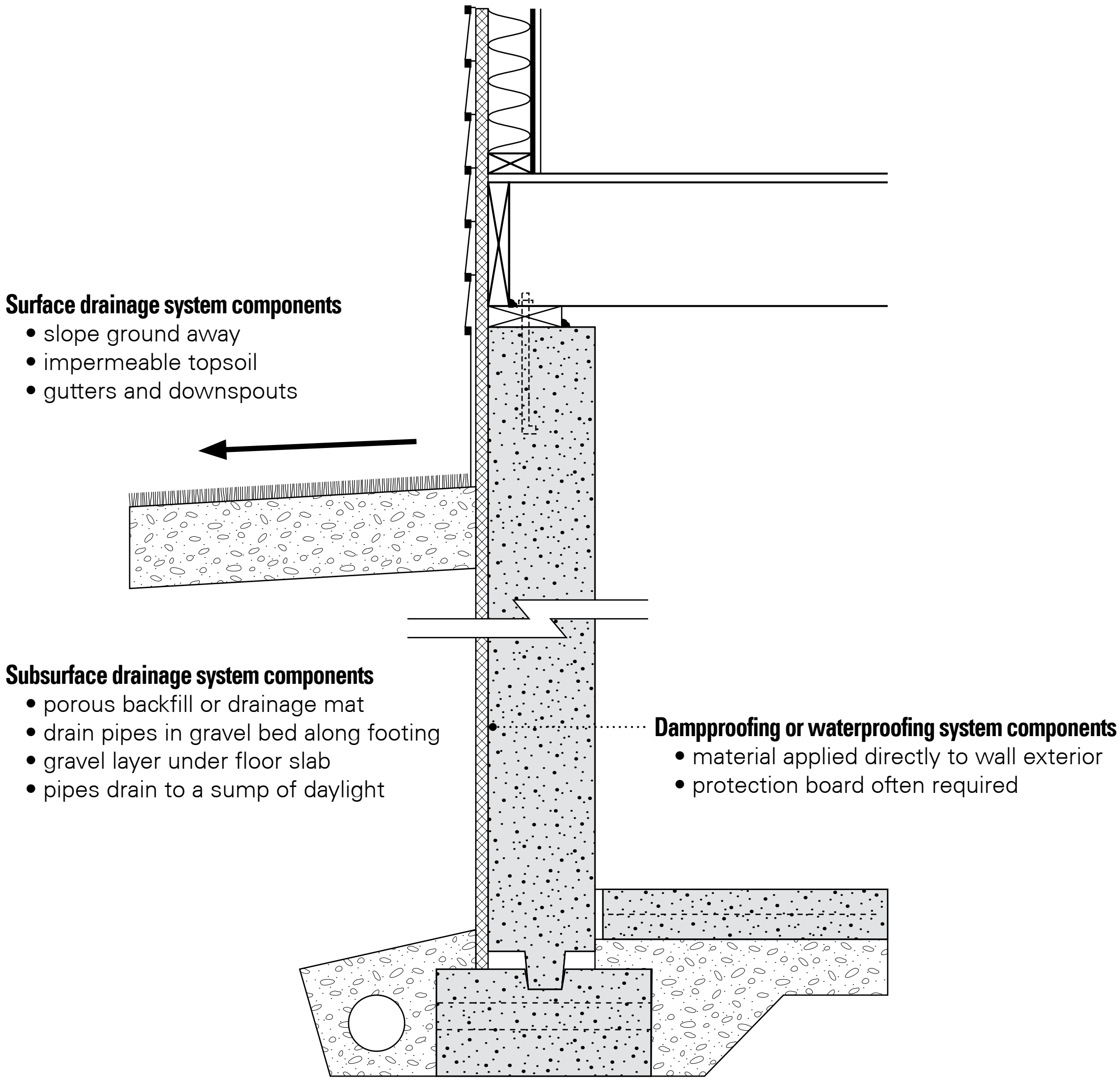

Figure 2.1-L Components of Basement Drainage and Waterproofing Systems
Adapted with permission from ORNL (1991), John Carmody, Jeffery Christian, Kenneth Labs.

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.

- 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.

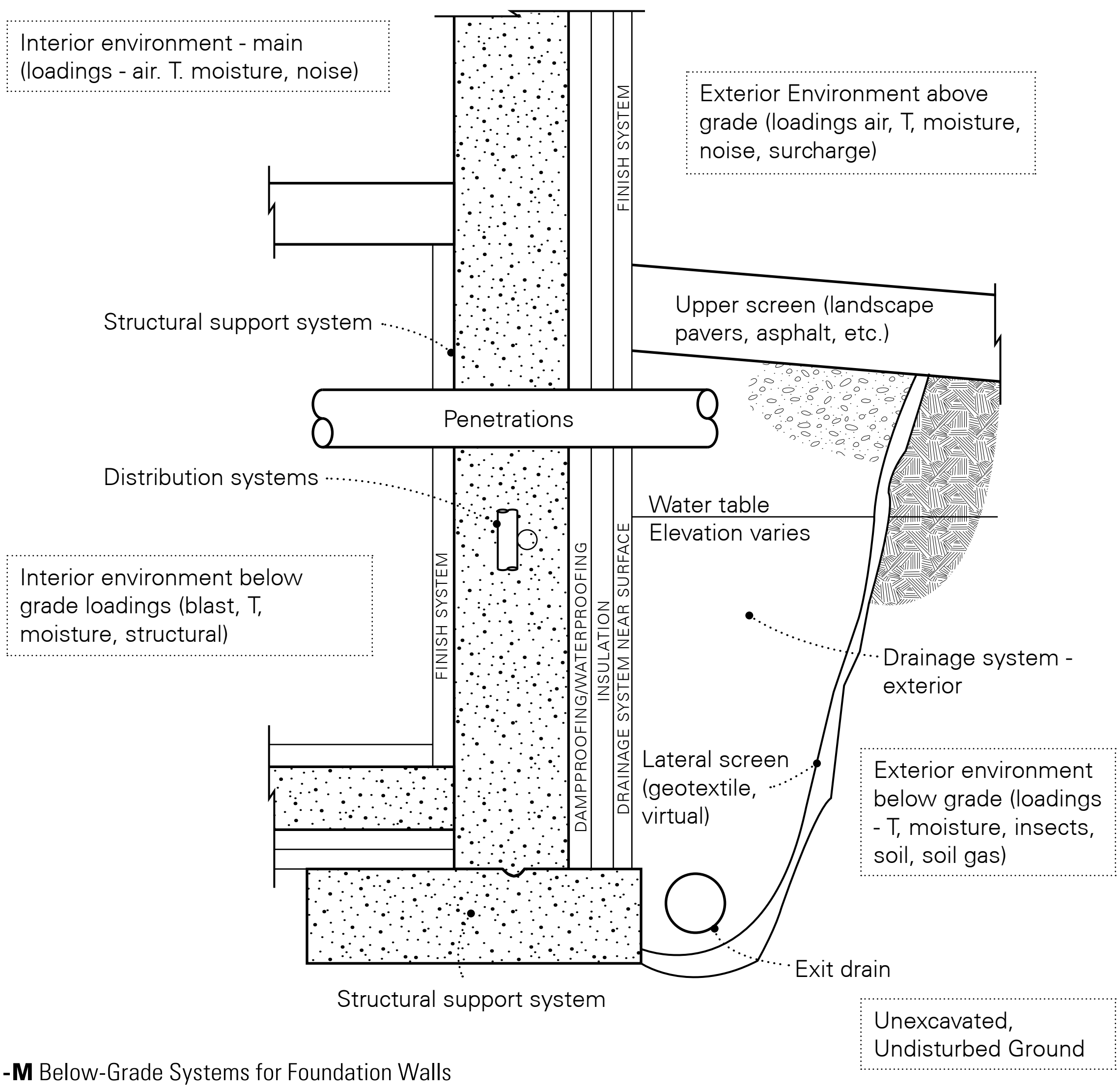

Figure 2.1-M Below-Grade Systems for Foundation Walls
Adapted from Postma (2009); used with permission from the National Institute of Building Sciences.

Strategy 2.1

Wall Design

Solving problems resulting from poorly designed walls can necessitate the replacement of multiple building components, leading to high repair costs. See Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces.

Design of exterior walls needs to prevent rain seepage through the cladding with a continuous drainage plane, the integrity of which can be checked by using a pen test to verify the continuity of the drainage plane from the intersection with the roof, through flashings, and around penetrations to the foundation. Sectional views can be provided to illustrate continuity of the drainage plane from the roof assembly through the walls to the footings. Two-dimensional sections can be provided for intersections with two components (for example, the intersection of a wall with the roof of a lower section of the building or with a plaza), and three-dimensional sections can be provided for intersections with three or more components. It is important to provide details for all penetrations such as windows, doors, piping, and other penetrations. All exterior walls need to be designed to manage rainwater. This can be accomplished in the following manner:

- Design exterior walls to protect their inner portions from direct rain and seepage through cladding.
  - Design walls that have rainwater protection behind the cladding in the form of air gaps and barrier materials (this is often called the *drainage plane*).
  - Specify flashing at penetrations including windows, doors, and roof-to-wall intersections.
- Provide sections and detailing of flashing for all wall penetrations. Flashing for larger penetrations needs to be detailed at the head of the window, at the jambs, and along the sill of the window to divert water away from the interior of the wall. The most common areas that require flashing are the following:
  - Windows (Figure 2.1-N)
  - Doors and trim
  - HVAC system penetrations such as outdoor air intakes and exhaust air vents
  - Penetrations such as ductwork, piping, electrical conduits, and scuppers (Figure 2.1-O)
  - Transitions and changes in the plane of the wall, such as areas where a lower roof meets a vertical wall
  - Terminations in the plane of the exterior wall at areas such as where the exterior wall meets the roof
  - Transitions between dissimilar siding materials

Figure 2.1-N Improper Window Flashing
Photograph copyright Liberty Building Forensics Group®.

Figure 2.1-O Scupper without Sealant or Flashing
Photograph copyright Liberty Building Forensics Group®.

Figure 2.1-P depicts a framed brick veneer wall. This figure depicts a proper design for managing rainwater.

Figures 2.1-Q and 2.1-R present a detailed example of how to properly flash at differing wall conditions. Figure 2.1-Q depicts a typical window condition at the sill to the jamb (the corner of the window), and Figure 2.1-R depicts a typical flashing condition at a lower roof-to-wall intersection.

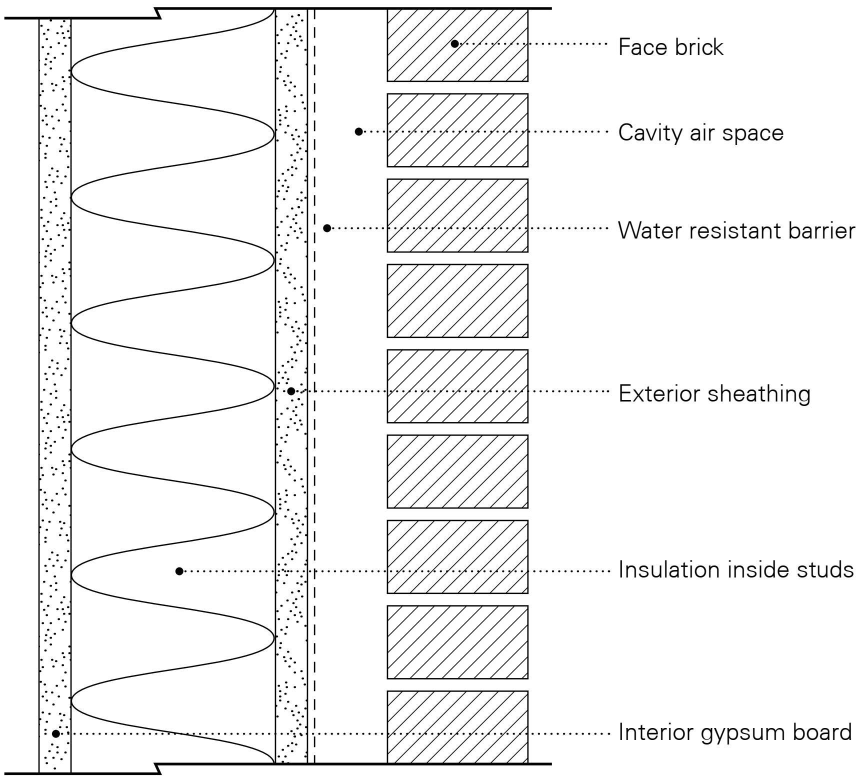

Figure 2.1-P Framed Brick Veneer-Steel Stud System with Proper Design for Managing Rainwater
Adapted from Odom and DuBose (2000).

Roof and Ceiling Assembly Design
The roof slope needs to be designed for the type of roofing system and to fully drain rainwater toward collection and disposal sites that are usually either external gutter and downspout systems or internal roof drainage systems. The capacity of the system needs to match the heaviest anticipated hourly rainfall intensity. Improper roofing flashing (Figure 2.1-S) will result in water intrusion and deterioration of wood framing (Figure 2.1-T). Figure 2.1-U shows an example of a roof layout that highlights the roof sloping needed to manage rainwater.

Design penetrations, parapets, and roof and wall intersections are most susceptible to moisture problems. These joints and penetrations call for special attention to ensure that the integrity of the drainage layers is maintained.

Details on drawings and specifications will help insure the integrity of the drainage layer—i.e., details for joints between pieces of roofing (e.g., how shingles overlap, methods for sealing seams in membrane roofs); details for joints in the inner layer of moisture protection (e.g., how roofing paper overlaps); and details

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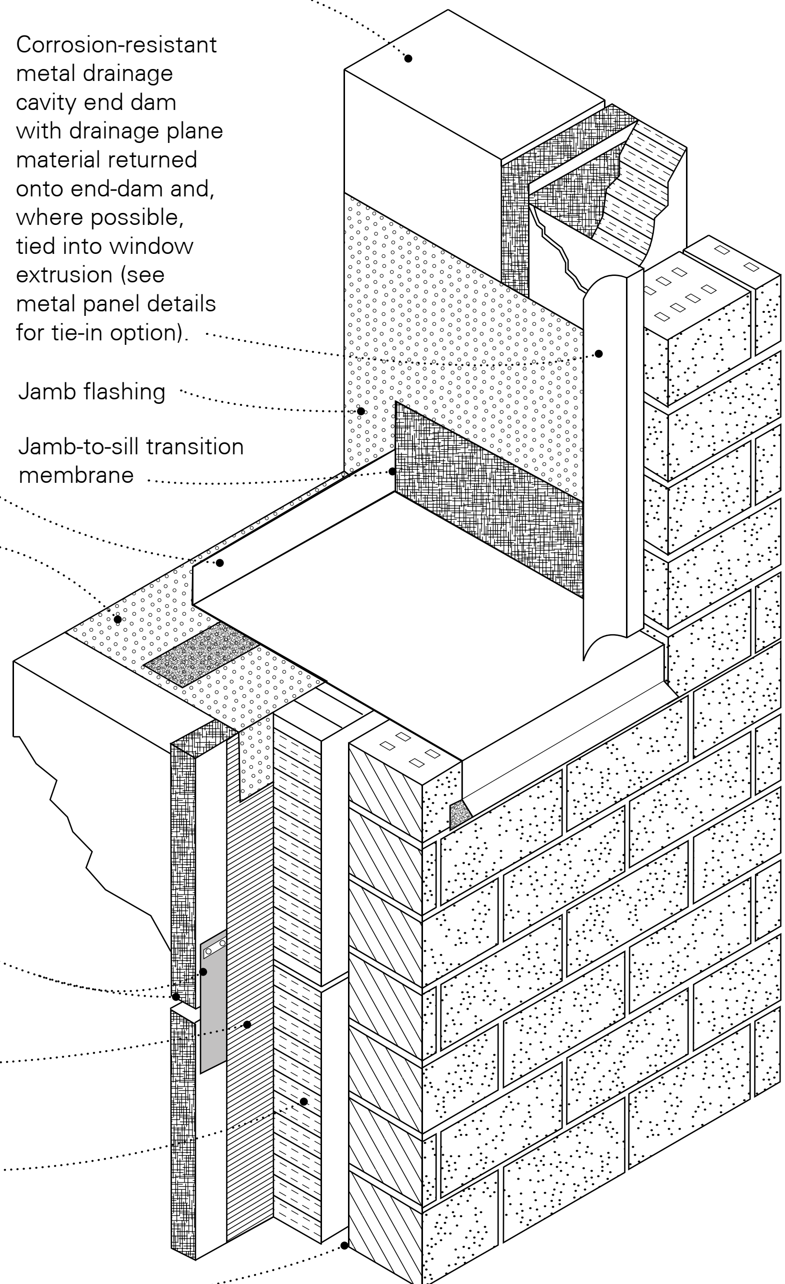

Figure 2.1-Q Window Construction—Sill to Jamb Corner
Adapted from Weber (2009); used with permission from the National Institute of Building Sciences.

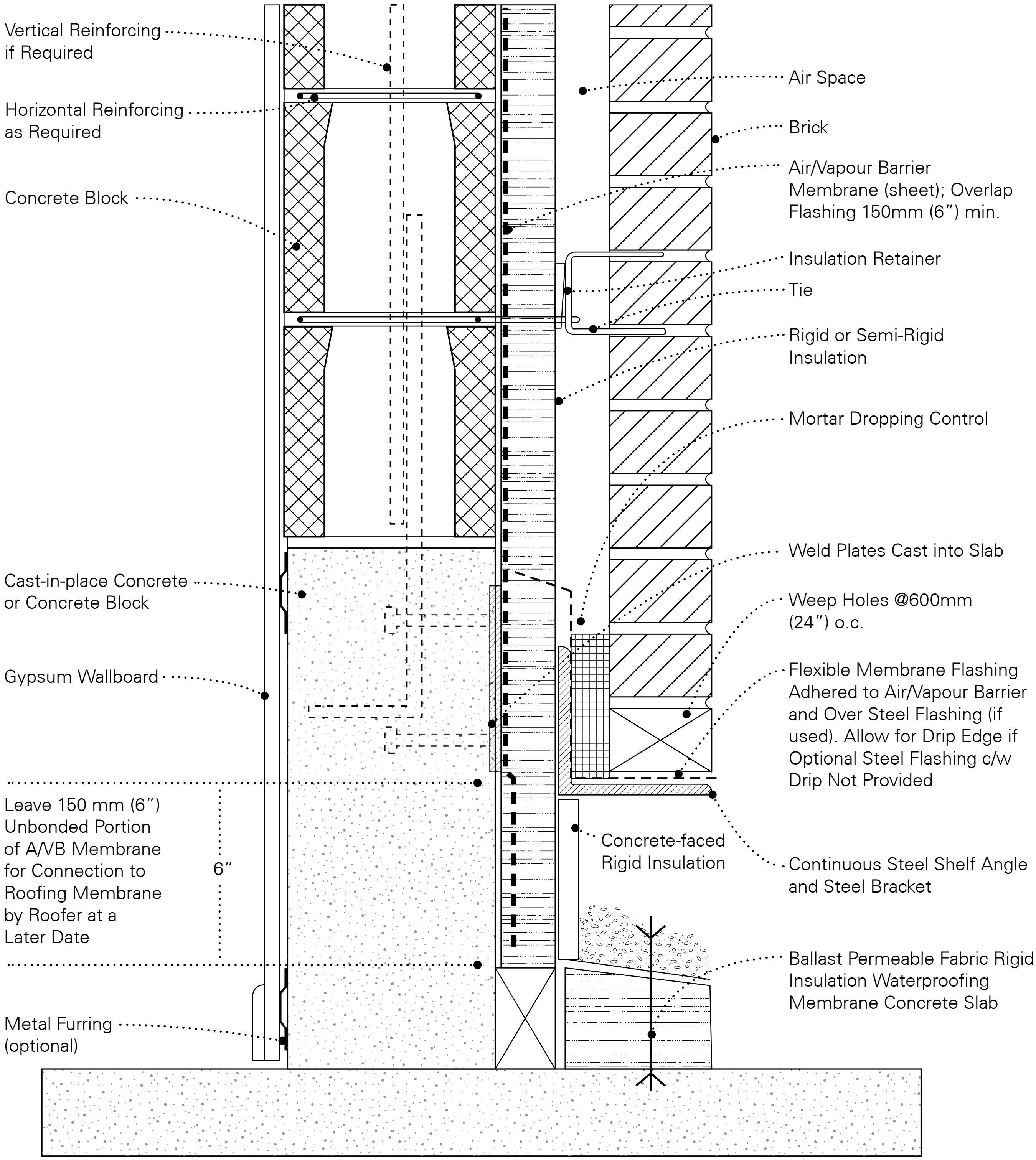

Figure 2.1-R Roof-to-Wall Intersection
Adapted from CMHC (1997).

Figure 2.1-S Improper Roof Flashing Detail
Photograph copyright Liberty Building Forensics Group®.

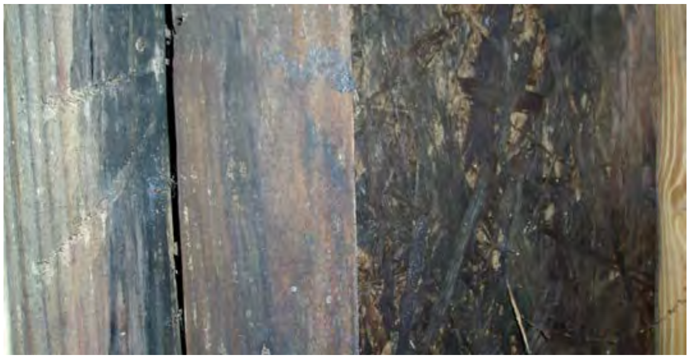

Figure 2.1-T Deteriorated Wood Framing
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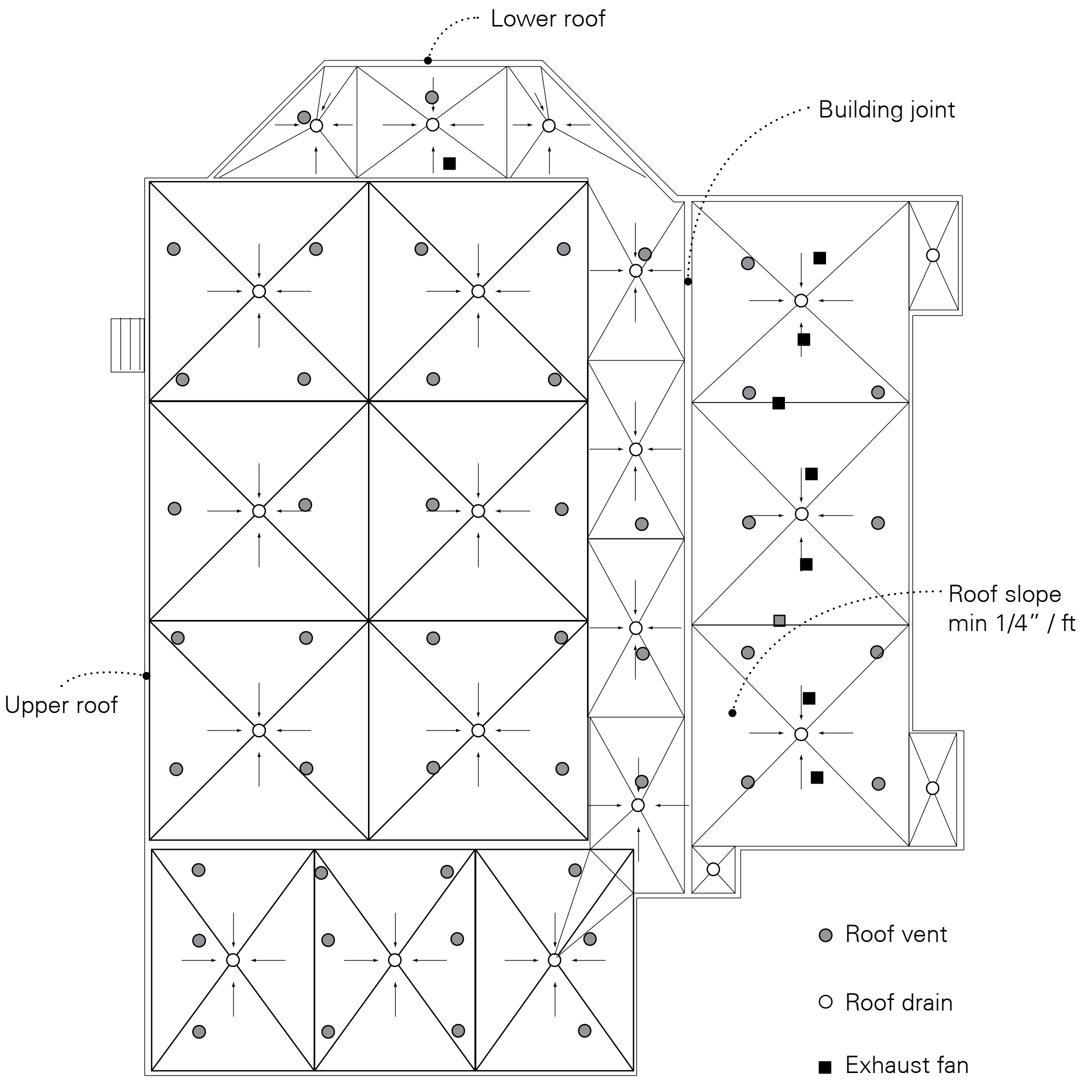

Figure 2.1-U Typical Flat Roof Layout

showing the continuity of roofing and, if present, the inner layer of moisture protection with flashing for curbs, skylights, pipes, ducts, hatches, and other roof penetrations.

Ice Dams

Figure 2.1-V shows the United States climate zones. In climate zones 5, 6, and 7, ice dams can form when melted snow runs down a sloped roof to an overhang that is over unconditioned space. Figures 2.1-W through 2.1-Y show a typical example of an improper ice dam condition that allowed water (melted ice) to backflow into the building.

Roof edges at unconditioned overhangs will often be colder than the parts of the roof over conditioned spaces. When outdoor air temperature is low enough, snow meltwater freezes on the cold roof edge and forms an ice dam. The trough behind the ice dam allows subsequent snowmelt to pool behind it. Water then backs under the shingles and runs down through the wall or ceiling. The snowmelt that leads to ice dams is

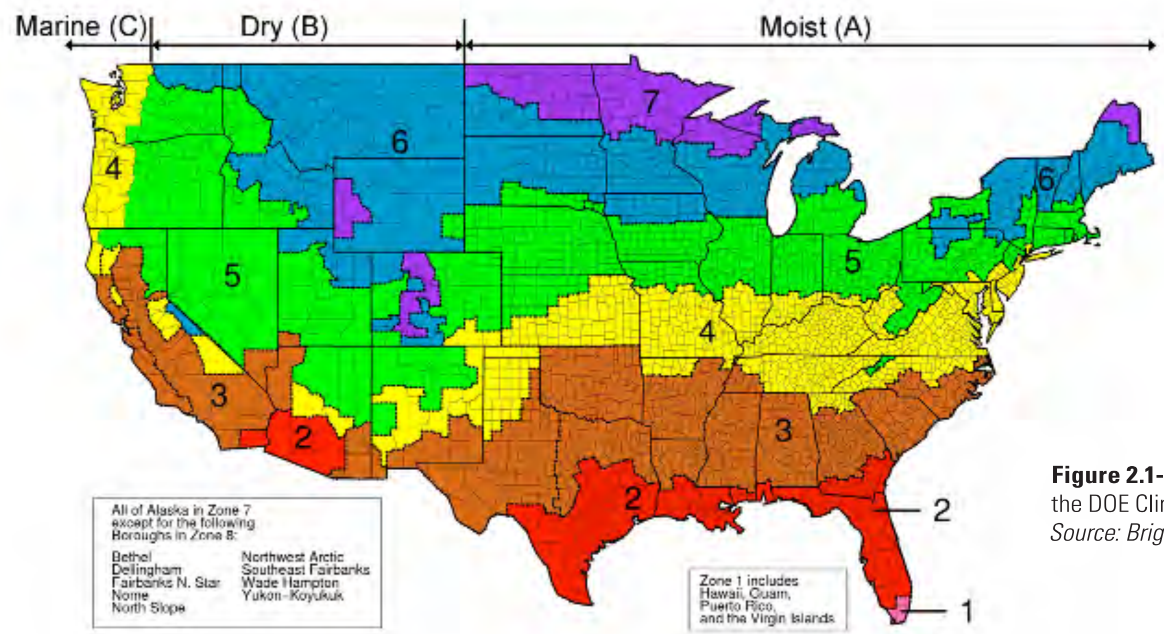

Figure 2.1-V U.S. Map Showing the DOE Climate Zones
Source: Briggs et al. (2003).

Figure 2.1-W Accumulation on Building Eave
Photograph copyright Liberty
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Figure 2.1-X Ice Dam Failure Close-Up
Photograph copyright Liberty Building Forensics Group®.

Figure 2.1-Y Ice Dam Failure
Photograph copyright Liberty Building Forensics Group®.

usually caused by warm air that bypasses the roof insulation and warms the part of the roof deck above the freezing temperature.

To minimize the formation of ice dams, the designer can

- provide a carefully detailed and tested air, vapor, and thermal barrier in the roof system and drain unvented, low-slope roofs to interior drains. Designers can also insulate unvented roofs that slope to eave drainage with spray or board foam (Note: pay special attention to air sealing foam board in this situation) and use vented roofs that slope to eave drainage.

Construction

Implementing a quality control plan is important to ensure that the design is executed correctly during construction. Clear presentations in design documents of the requirements and responsibilities for providing, reviewing, and accepting submittals, shop drawings, proposed solutions, and scheduled inspections and testing are important aspects of the quality control plan.

Implementing construction-phase storm water management controls are important to keep the site dry during construction and to ensure that the site drainage design features are constructed correctly and operating properly. (Also see Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ.)

Verification

Pen Test

The best design tool for verifying that all aspects of the exterior wall have been included in the design is the use of a pen test. The pen test checks the completeness of the rainwater protection tracing on the construction drawings (such as details and wall sections) and the continuity of all the materials for each control function. To verify continuity, create sections in which each element is traced in a different color to show that the design specifically accounts for these moisture-control elements. Contractors can then easily check the sections against their experience with materials, trades, and sequencing. The sections will also provide maintenance workers in buildings and on grounds with information useful in ordinary maintenance work or in the event of a problem during building use.

Pen Test Example: Rainwater Protection Continuity

To demonstrate complete rainwater protection using a section drawing, place the pen on a material that forms a capillary break between the rain-control materials that get wet and the inner portion of the enclosure that must stay dry. Without lifting the pen off the paper, trace from the center of the roof around the walls, windows, and doors and along the foundation to the center of the foundation floor. Figure 2.1-Z serves as documentation for rainwater protection continuity. The following describes the traceable capillary break in a sample section, starting at the center of the roof:

- The roofing membrane separates wet materials from the inner dry materials.
- Tracing to the edge of the roof, the roofing membrane flashes beneath a metal coping, which in turn flashes to a metal fascia.
- The fascia forms a drip edge, channeling water away from the cladding.
- An air gap between the drip edge and the brick veneer forms a capillary break protecting the materials beneath the metal coping from rainwater wicking from below.
- An air gap and water-resistant barrier behind the brick veneer form a capillary break between the damp brick and the inner walls.

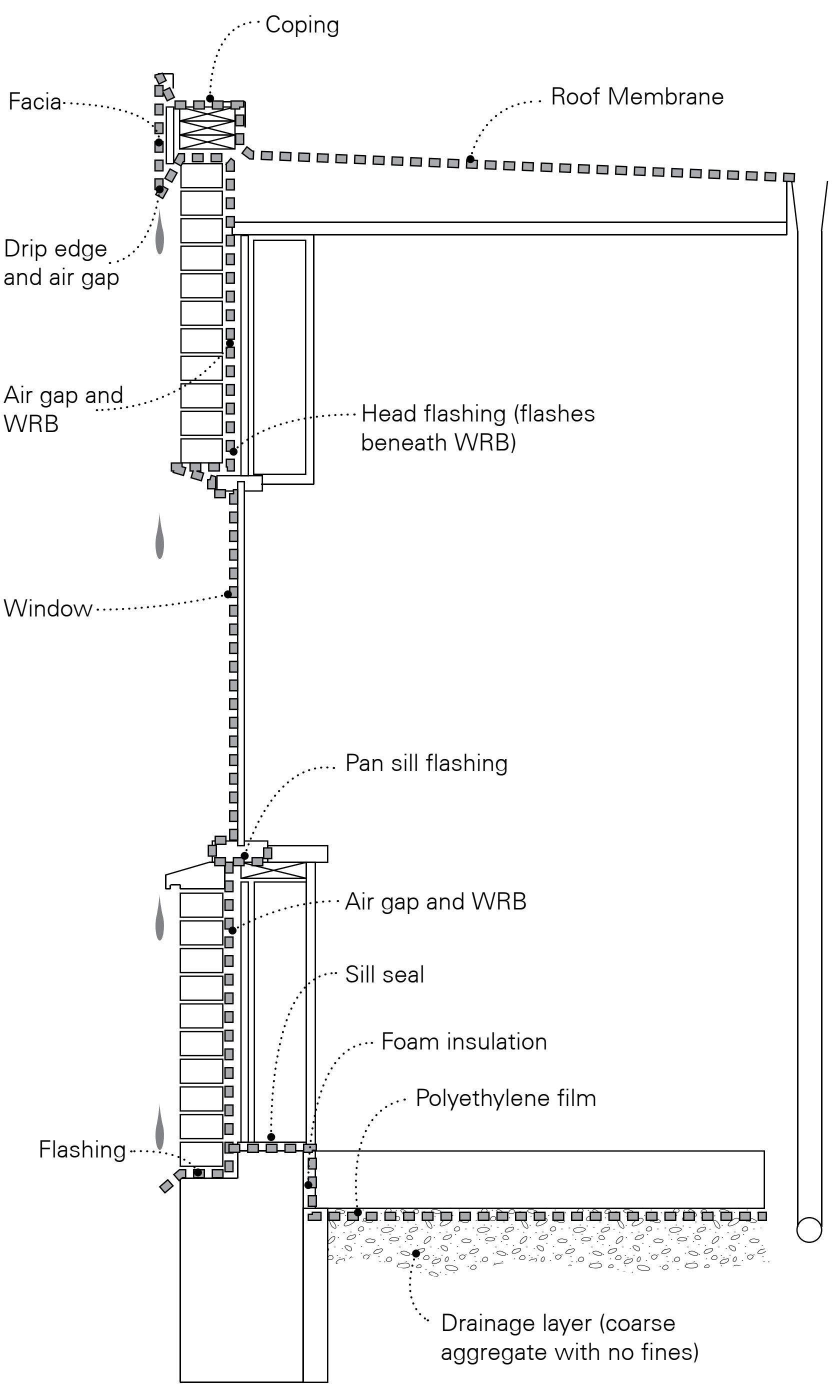

Figure 2.1-Z Typical Pen Test for Proving that Rainwater Barrier is Continuous
Adapted from EPA (n.d.).

- The water-resistant barrier shingles over a head flashing, protecting the window from rainwater with a drip edge and air gap.
- The window frame, sash, and glazing form a capillary break system that sits in a pan sill flashing at the bottom of the rough opening.
- The pan sill flashing forms a capillary break protecting the wall beneath from seepage through the window system.
- The pan sill flashing shingles over the water-resistant barrier in the wall beneath.
- The water-resistant barrier shingles over a flashing that protects the bottom of the wall system where:
  - the closed cell foam or polyethylene sill seal makes a capillary break between the foundation and the bottom of the framed wall, connecting with:
  - an inch of extruded styrene foam insulation, making a capillary break between the top of the foundation wall and the edge of the floor slab.
  - polyethylene film immediately beneath the slab forms a capillary break between the bottom of the slab and the fill below. Note: If the bed of fill beneath the slab consists of pebbles greater than 1/4 in. (6.35 mm) in diameter and contains no fines, then it forms a capillary break between the soil and the slab.

The following are additional suggested steps for verification:

- Verify that all requirements have been included in the building design by reviewing the plans for the appropriate sectional and detail drawings.
- Conduct water penetration testing to ensure the installed assembly meets the required design water penetration requirements.
- Verify that the requirements are properly executed by implementing a quality control program.

- Verify that methods for maintaining water management systems are included in the maintenance documentation and training provided to the operation and maintenance staff (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ.)

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Strategy 2.2

2.2

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

Introduction

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. 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. The information in this Strategy on airtightness, air pressures, and air barriers is primarily adapted from the Whole Building Design Guide paper "Air Barrier Systems in Buildings" by Wagdy Anis (2007).

Designing for Airtightness

The design of building enclosures to avoid/reduce infiltration and exfiltration requires that air retarder (air barrier) technology be utilized; this relies on the respect of and implementation of four design requirements:

- maximum acceptable air permeance of materials, assemblies, and the whole building;
- continuity;
- structural support; and
- durability.

Air Barrier Design Requirements

Introduction. The problems created by infiltration and exfiltration in buildings are reviewed in this Strategy, and the design considerations of an air barrier system to control the problems are reviewed. The discussion includes the air pressures on buildings and the fundamentals of controlling those pressures, air barrier material requirements, combination air and vapor barriers, and the required properties of air barrier systems. Specific designs are reviewed, and warm-side air and vapor barriers vs. cold-side air barrier systems are compared. The complexities of the airtight drywall approach (ADA) (Lstiburek and Lischkoff 1986) are discussed. Finally, roof air barrier concepts are discussed.

Description. Infiltration and exfiltration of air in buildings have serious consequences because they are uncontrolled. Infiltrating air is untreated and can therefore entrain pollutants, allergens, and bacteria into buildings. The accompanying change in air pressures can disrupt the delicate pressure relationships between spaces that HVAC systems create by design. This can be a serious problem, particularly in buildings such as hospitals, where patients' very lives may depend upon maintaining those relationships, and labs, where pollutant control is essential. Exfiltrating air in cold climates can cause condensation and mold growth in the building enclosure and be a source of poor IAQ.

Disrupted air pressure relationships can move pollutants from spaces where they should be contained into other spaces where they are not desired. For example, pollutants can move from such areas as storage rooms or garages under buildings into living or working spaces and cause IAQ problems. Another serious consequence of infiltration and exfiltration through the building envelope is the condensation of moisture from the exfiltrating air in northern climates and from infiltrating hot, humid air in southern climates, causing mold growth, decay, corrosion, and premature building deterioration. Unlike the moisture transport mechanism of diffusion, air pressure differentials can transport hundreds of times more water vapor through air leaks in the envelope over the same period of time (Quirouette 1985). This water vapor can condense within the envelope in a concentrated manner, wherever those air leaks may be. Air leaks through the building enclosure can take one of several forms:

- Orifice flow
- Diffuse flow
- Channel flow

Orifice flow occurs when the air entry and exit are in a linear pathway, such as in the crack between a window rough opening and its frame (Figure 2.2-E).

Diffuse flow happens when materials used in the envelope are ineffective at controlling air infiltration and exfiltration due to many cracks or their high permeance to air, such as fibrous insulation or uncoated concrete block (Figure 2.2-E).

Channel flow is probably the most common and serious of all types of air leaks and is shown in Figure 2.2-F. The air entry point and exit point are distant from each other, giving the air enough time to cool below its dew point and deposit moisture in the building enclosure.

Lastly, air infiltration and exfiltration are the cause of unnecessary energy consumption in buildings due to the added heating and cooling loads and the additional humidification or dehumidification needed.

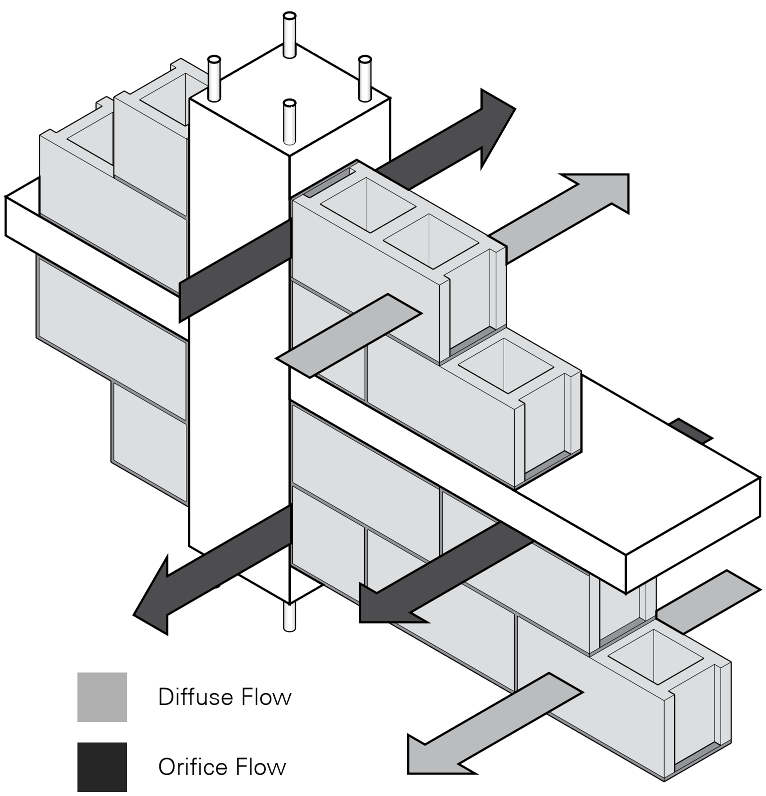

Figure 2.2-E Orifice Flow and Diffuse Flow
Adapted from Anis (2007); used with permission from the National Institute of Building Sciences.

Air Pressures that Cause Infiltration and Exfiltration
There are three major air pressures on buildings that cause infiltration and exfiltration:

- Wind pressure
- Stack pressure (sometimes called *chimney effect* or *buoyancy*)
- HVAC fan pressure

Wind Pressure
The average annual wind pressure on buildings is of significance in calculating energy or moisture-related air leakage. When averaged out over the course of the year, the average annual wind pressure is about 10–15 mph (0.2–0.3 psf) (10–14 Pa) in most locations in North America (Handegord 1996). Wind pressure tends to pressurize a building positively on the facade it is hitting, and as the wind goes around the corner of the building it cavitates and speeds up considerably, creating especially strong negative pressure at the corners and less strong negative pressure on the rest of the building walls and roof (see Figures 2.2-G and 2.2-H) (Hutcheon and Handegord 1983).

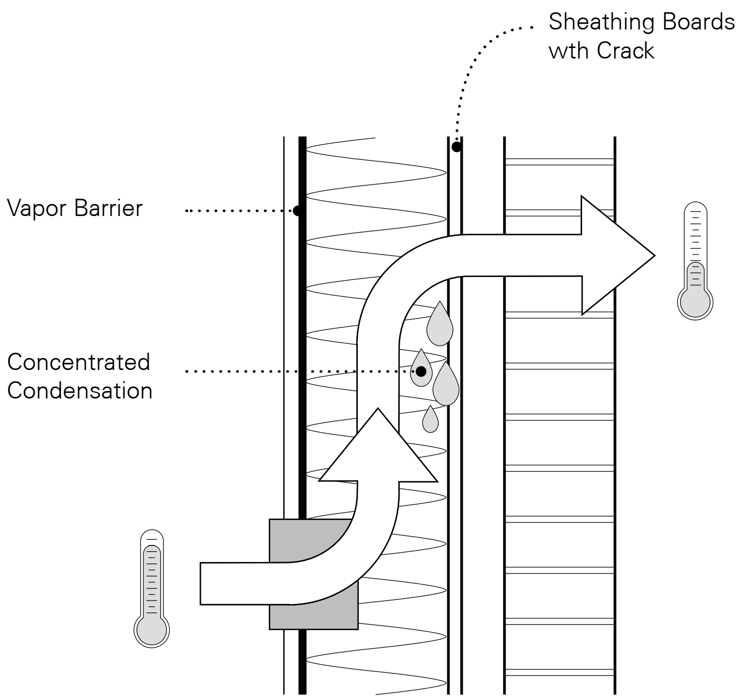

Figure 2.2-F Channel Flow
Adapted from Anis (2007); used with permission from the National Institute of Building Sciences.

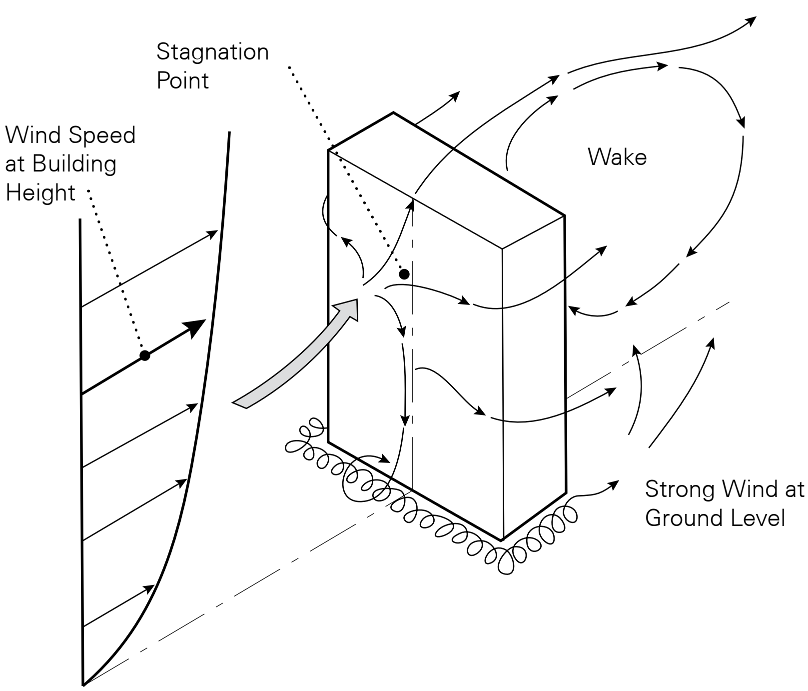

Figure 2.2-G Boundary Layer Flow
Adapted from Hutcheon and Handegord (1983).

Stack Pressure

Stack pressure is caused by a difference in atmospheric pressure at the top and bottom of a building due to the difference in temperature and, therefore, a difference in the weight of the columns of air indoors vs. outdoors in the winter. Stack effect in cold climates can cause infiltration of air at the bottom of the building and exfiltration at the top, as seen in Figure 2.2-I. The reverse occurs in warm climates with air conditioning.

HVAC Fan Pressure

Fan pressure is caused by HVAC system pressurization, usually positive, which is fine in warm climates but can cause incremental envelope problems to wind and stack pressures in heating climates. HVAC engineers tend to do this to reduce infiltration (and with it, pollution) and disruption of the HVAC system design pressure relationships. Figure 2.2-J shows wind, stack, and HVAC fan pressures separately in a combined diagram.

It is reported in *NISTIR 7238, Investigation of the Impact of Commercial Building Envelope Airtightness on HVAC Energy Use* (Emmerich et al. 2005), that additional heating and cooling energy due to infiltration can be between a low of 9% for cooling in warm climates and 43% for heating in cold climates. Using a coupled thermal/airflow analysis technique based on the CONTAM (NIST 2008) and TRNSYS (UW 2004) simulation tools, infiltration can be shown to be responsible for about 25% of the heating load and 4% of the cooling load in commercial buildings (Emmerich and Persily 1998).

To control air infiltration and exfiltration in buildings, a conceptual approach to airtightening is needed, called an *air barrier system*. The Canadian *National Building Code* (NRC-IRC 2005) and, more recently, the Commonwealth of Massachusetts' building code (EOPSS 2008) take this comprehensive and conceptual approach, requiring an air

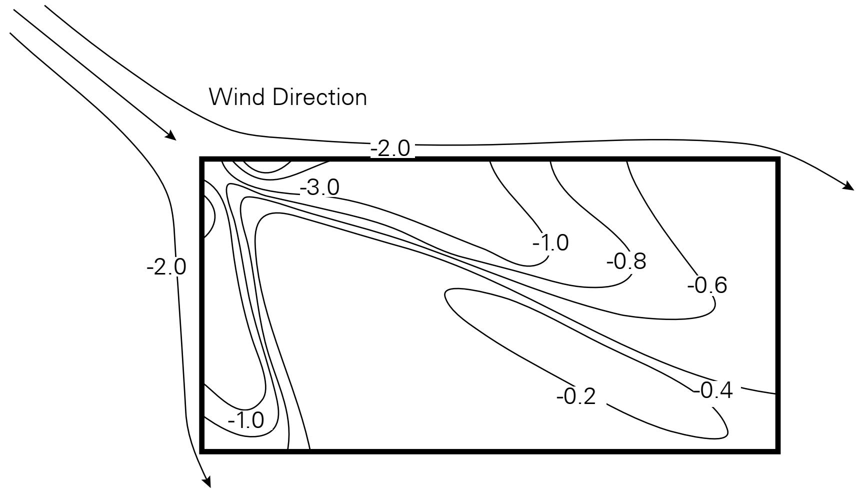

Figure 2.2-H Negative Pressure Distribution
Adapted from Leutheusser (1964).

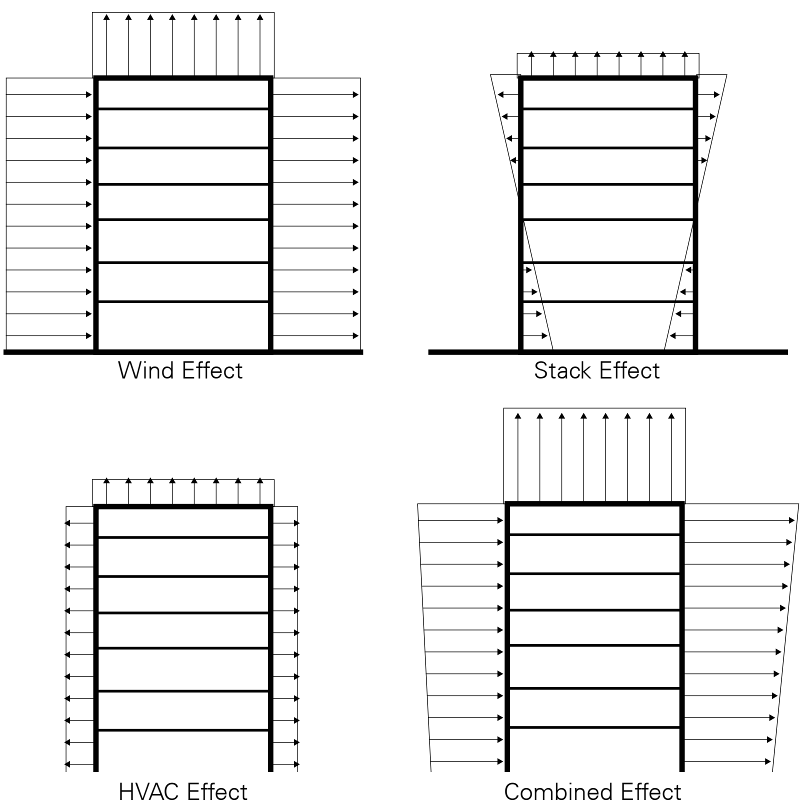

Figure 2.2-I Stack Pressure
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barrier system in the building envelope as a code requirement. A continuous air barrier system is the combination of interconnected materials, flexible sealed joints, and components of the building envelope that provide the airtightness of the building enclosure and separations between conditioned and unconditioned spaces (Lux and Brown 1986) (Figure 2.2-K).

Air Barrier Systems

The concept of air barrier systems is to select and target a component of the wall or roof that is air impermeable and to deliberately make it an airtight "assembly" by sealing the joints and penetrations. This assembly of materials is connected to adjacent assemblies and components such as windows, doors, and the foundation and roof air barrier components. The air barrier system above grade is also connected to the foundation walls and basement slabs to complete the air barrier system of the building. Airtightening below-grade walls and slabs prevents entry of organic gases and radon, as well as pollutants from agricultural activities and brownfields, due to depressurization of spaces with their enclosures in contact with the soil (see Figure 2.2-K)

The important features of an air barrier system in a building are continuity, structural support, air impermeability, and durability.

Continuity

To ensure continuity, each component serving its role in resisting infiltration such as a wall or a window or a foundation or a roof must all be interconnected to prevent air leakage at the joints

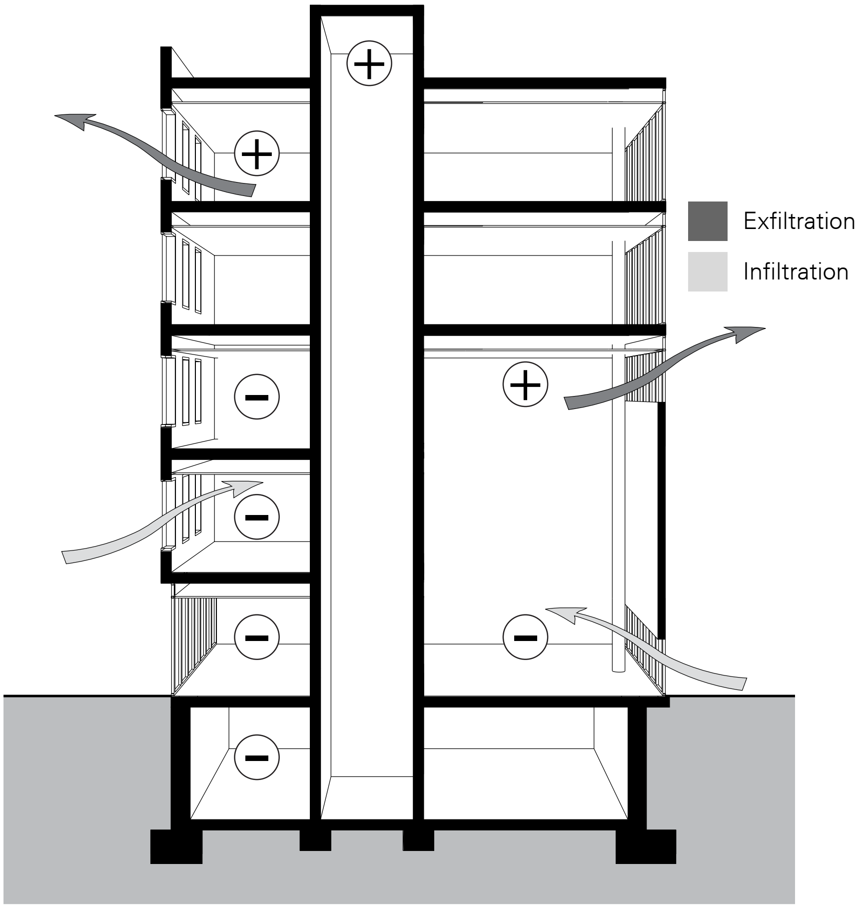

Figure 2.2-J Fan Pressures

between materials, components, assemblies, and systems.

Structural Support

Effective structural support requires that any component of the air barrier system must resist the structural loads that are imposed on that component by wind, stack, and chimney effect without rupture, displacement, or undue deflection. This load must then be safely transferred to the structure. Design consideration must determine adequate resistance to these pressures by fasteners, adhesives, etc.

Air Impermeability

Materials chosen to be part of the air barrier system need to be chosen with care to avoid selecting materials that are too air permeable, such as fiberboard, perlite board, and uncoated concrete block. The air permeance of a material is measured using *ASTM E 2178, Standard Test Method*

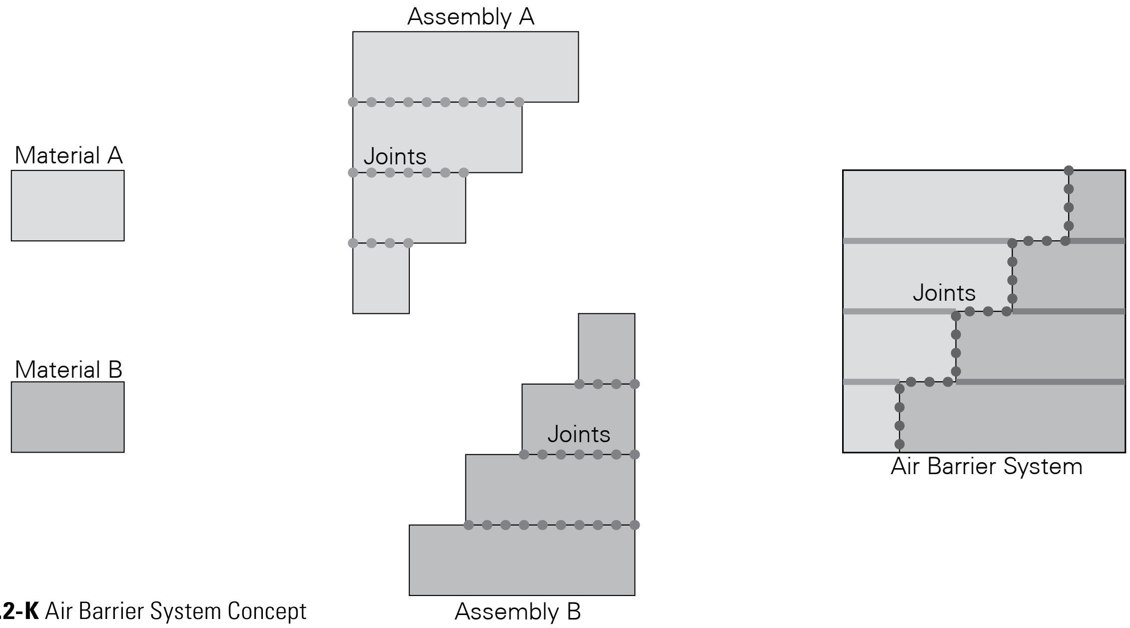

Figure 2 Figure 2.2-K Air Barrier System Concept

for Air Permeance of Building Materials (ASTM 2003a), test protocol and reported in cubic feet per minute per square foot at 0.3 in. w.g. or 1.57 psf (liters per second per square meter at 75 Pa). The Canadian and Massachusetts codes consider 0.004 cfm/ft^2 at 1.57 psf (0.02 L/s·m^2 at 75 Pa), which happens to be the air permeance of a sheet of 0.5 in. (12.5 mm) unpainted gypsum wall board, as the maximum allowable air leakage for a material that can be used as part of the air barrier system for the opaque enclosure. This is more airtight than the requirements for windows and curtain walls, but windows and curtain walls are assemblies of materials and these materials are more resistant to damage due to condensation than ordinary building materials. When fairly airtight materials are assembled together by sealing, taping screws, etc., the assembly will likely leak more air than the basic materials themselves. Also, when these assemblies are joined together into a whole building, the building enclosure will leak more air than the individual assemblies joined together in the first place. So in order to achieve a reasonable end result, the basic materials selected for the air barrier need to be quite air impermeable.

Durability

Materials selected for the air barrier system need to perform their function for the expected life of the structure; otherwise, they must be accessible for periodic maintenance, such as applying elastomeric paint coatings on concrete block.

Air Barrier System Requirements

As shown in the form of an architectural specification, air barrier system requirements may include the following:

- A continuous plane of airtightness must be traced throughout the building envelope with all moving joints made flexible and sealed.
- Air permeance compliance alternatives such as the following:
  - The air barrier material in an assembly of the opaque envelope must have an air permeance not to exceed 0.004 cfm/ft^2 at 0.3 in. w.g. at 1.57 psf (0.02 L/s·m^2 at 75 Pa) when tested in accordance with ASTM E 2178 (ASTM 2003a).
  - An air barrier assembly must have an air permeance not to exceed 0.04 cfm/ft^2 at 1.57 psf (0.2 L/s·m^2 at 75 Pa) when tested according to *ASTM E 2357, Standard Test Method for Determining Air Leakage of Air Barrier Assemblies* (ASTM 2005a), or *ASTM E 1677, Standard Specification for an Air Retarder (AR) Material or System for Low-Rise Framed Building Walls* (ASTM 2005b). The registered design professional shall determine the test air pressures adequate to simulate design conditions for the location of the project.
  - The whole building's air leakage rate must not exceed 0.4 cfm/ft^2 at 1.57 psf (2 L/s·m^2 at 75 Pa) when tested according to *ASTM E779, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization (ASTM 2003b).*
- 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.
- The air barrier must not displace under load or displace adjacent materials.
- The air barrier material used must be durable or be able to be maintained.
- Connections between roof air barrier, wall air barrier, window frames, door frames, foundations, and 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 joints must support the same air pressures as the air barrier material without displacement.
- Penetrations through the air barrier must be sealed.

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- An air barrier must be provided between spaces that have significantly different temperature or humidity requirements.
- Lighting fixtures are required to be airtight when installed through the air barrier.
- Stairwells, shafts, chutes, and elevator lobbies must be decoupled from the floors they serve in order to control stack pressure transfer to the envelope by providing doors that meet air leakage criteria for exterior doors or the doors must be gasketed (Figure 2.2-L).
- Functional penetrations through the envelope that are normally inoperative, such as elevator shaft louvers and atrium smoke exhaust systems, must be dampered with airtight motorized dampers connected to the fire alarm system to open on call and to fail in the open position (MA 2001).

In addition, other pressure differentials within buildings need to be controlled by the following methods:

- Compartmentalizing and sealing garages under buildings with airtight walls to vestibules with weather-stripped doors at building access points.
- Compartmentalizing spaces under negative pressure, such as boiler rooms, and providing makeup air for combustion.
- Decoupling supply or return floor and ceiling plenums from the exterior enclosure. If these are connected, serious consequences will arise that should be considered; the exterior walls become ducts with air forced through them, potentially causing severe condensation, microbial growth, and deterioration (Figures 2.2-M and 2.2-N).

Generic materials that meet the air leakage requirements are provided in Table 2.2-A.

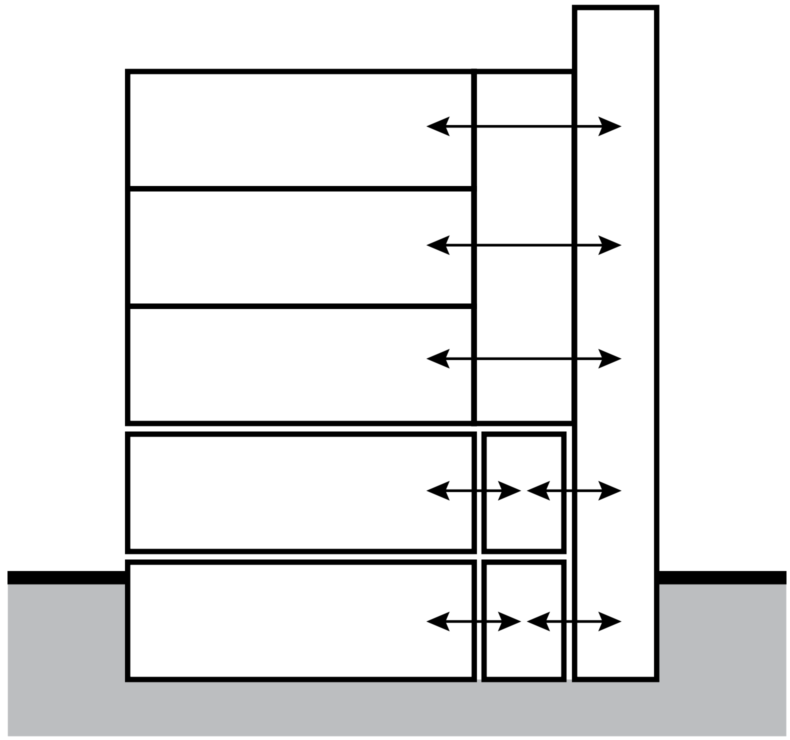

Figure 2.2-L Stack Pressure Control
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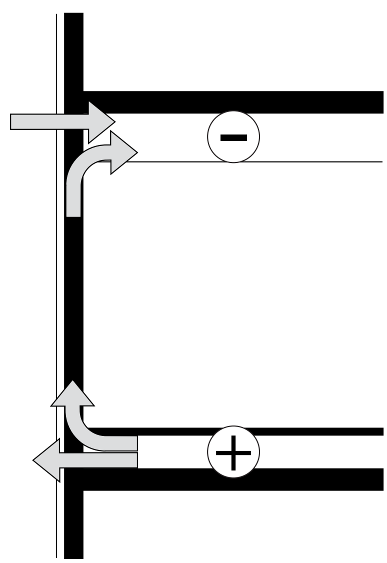

Figure 2.2-M Plenum with Underfloor Air Distribution
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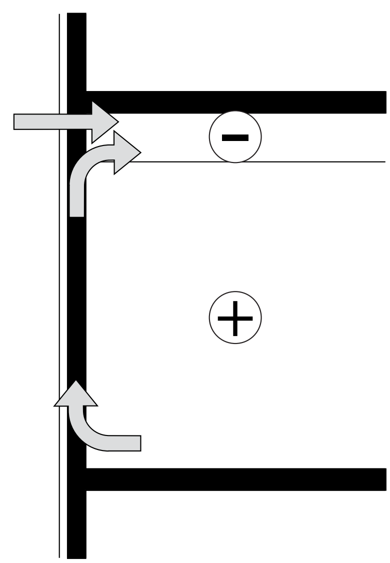

Figure 2.2-N Ceiling Plenum Connection
Adapted from Anis (2007); used with permission from the National Institute of Building Sciences.

Table 2.2-A Material Air Leakage
Source: Bombaru et al. 1998.

Nonmeasurable Airflow Thickness	Measurable Airflow Thickness	cfm at 0.3 in. w.g.	L/s·m² at 75 Pa
0.006 in. polyethylene*	0.315 in. plywood	0.0067	0.001
0.060 in. roofing membrane	0.63 in. waferboard	0.0069	0.001
0.106 in. modified asphalt torched on	0.5 in. exterior gypsum	0.0091	0.002
0.001 in. aluminum foil*	0.433 in. waferboard	0.0108	0.002
0.060 in. sheet asphalt peel and stick	0.5 in. particle board	1.0155	0.003
0.374 in. plywood	nonperforated spun-bonded polyolefin*	0.0195	0.004
1 in. extruded polystyrene	0.5 in. interior gypsum board	0.0196	0.004
1 in. foil-backed urethane			
0.5 in. cement board			
0.5 in. foil-backed gypsum board			

*Membranes need to withstand air pressures in both directions without displacement or damage. If not fully adhered, they must be sandwiched between two board materials.

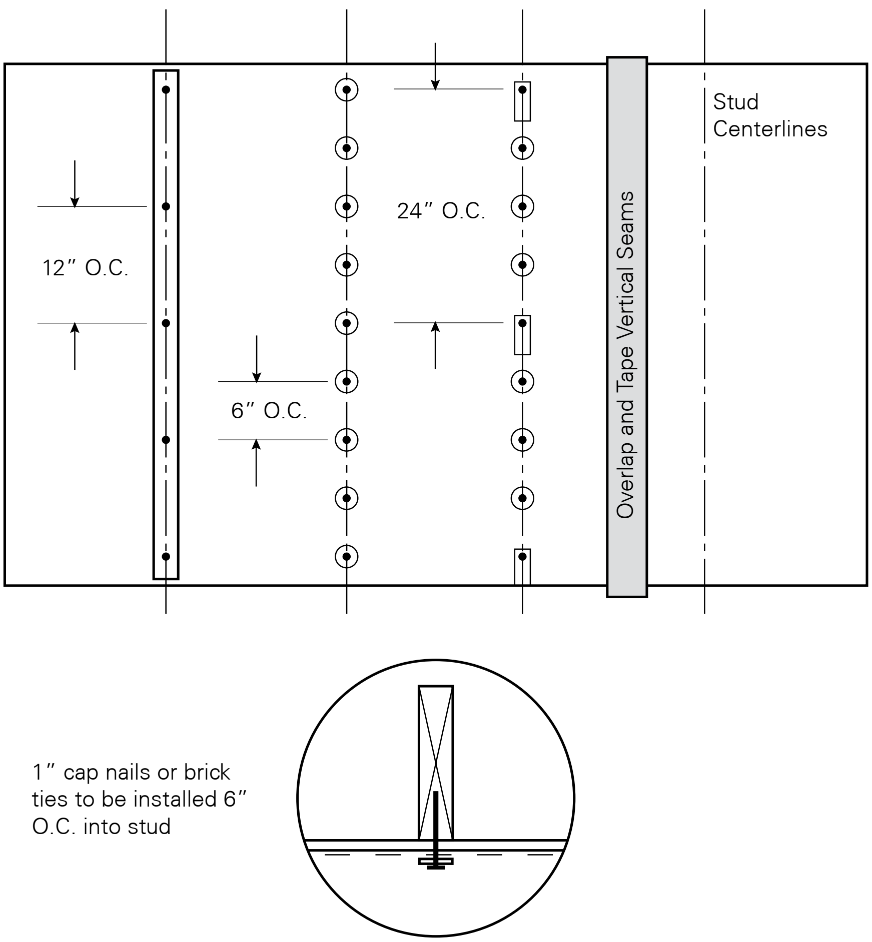

Figure 2.2-O Film Membrane with Brick Tie

If housewraps and other film membranes are not fully supported on both sides, they cannot support negative wind loads without tearing at the staples and brick anchors or rupturing under load (Bosack and Burnett 1998). This is what happens in brick cavity walls where housewraps displace under negative wind pressure and "pump" building air into the assembly, potentially causing condensation in cold climates. While testing in Canada to pre-qualify a membrane for use as an air barrier material, a manufacturer of spun-bonded polyolefin discovered that to withstand negative wind pressures, the membrane needed to be stronger and installed with fasteners having 1 in. (25.4 mm) diameter plastic washers or a brick tie had to be installed every 6 in. (150 mm) into the stud and 16 in. (400 mm) apart (Figure 2.2-O). Alternatively, continuous strapping with a fastener every 12 in. (300 mm) may be used. Note that products sold in Canada and the U.S. with the same name may not have the same air leakage or strength properties.

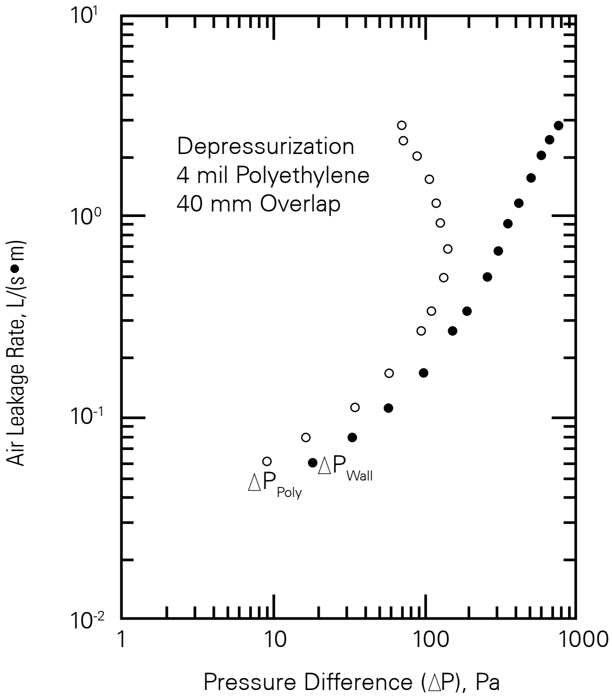

Figure 2.2-P Polyethylene Air Barrier Ruptures in a Wall with Glass-Fiber Batt Insulation
Adapted from Shaw (1985).

It is even more difficult to make a polyethylene vapor retarder into an air barrier. It lacks structural support when it is against glass-fiber batts and has the inherent quality of displacing and stretching, even rupturing, under high wind loads. It is also difficult to seam to itself or other materials (Figure 2.2-P). Fastener holes through polyethylene can stretch and compromise its airtightness (Shaw 1985).

Materials that do not qualify as air barrier materials without additional coatings are the following (Bombaru et al. 1998):

- Uncoated concrete block
- Plain and asphalt impregnated fiberboard
- Expanded polystyrene
- Batt and semi-rigid fibrous insulation
- Perforated housewraps
- Asphalt impregnated felt, No. 15 or No. 30
- Tongue-and-groove planks
- Vermiculite insulation
- Cellulose spray-on insulation

Of course there are many products formulated to qualify as air barrier materials. Some of these are supported by the Air Barrier Association of America (ABAA), which also provides specifications, technical help, contactor and workmen training, and certification (ABAA 2009).

Air Barrier Materials

The simplest approach to airtightening a wall is to select one of the layers such as the sheathing and to airtighten it using durable tapes, adhesive sheet products, liquid-applied materials, or the like. Walls constructed out of materials that are very permeable to air, such as concrete block, need to be airtightened using an applied elastomeric (flexible) coating, either as a specially formulated paint or specially formulated air barrier sheet product or as a liquid-applied spray-on or trowel-on material. Transition peel-and-stick membranes are most commonly used at window and door perimeters or when changing materials or wall systems (Figures 2.2-Q and 2.2-R), but sheet membranes can also be used on the whole wall. Metal backpans are often used as part of the air barrier system in the spandrel areas of curtain walls.

Finally, the complexities of airtightening a building using interior finish gypsum board are worth highlighting (Figure 2.2-T). The airtight drywall approach, or ADA, as it is known in Canada, using the interior drywall as the airtight plane (Lstiburek and Lischkoff 1986) is useful in residential work where renovation is not expected for many years. In commercial work, however, the intent of the designer will most likely be lost during renovation. Also, continual rewiring for data lines compromises the drywall's airtightness as the contractor punches holes above the ceiling. It is a very complex, three-dimensional problem.

With the ADA, ensuring a tight seal around electrical boxes in exterior walls and ceilings is important. Figures 2.2-U and 2.2-V show two available approaches. One is a "back box" made of either rigid or flexible heavy-duty polyethylene that fits around a standard electrical box—caulk is applied where the box and the

Figure 2.2-Q Peel-and-Stick Membrane Trimwork and Transitions Being Applied at Georgetown Law School (Shepley Bulfinch Richardson and Abbott, Architect)
Photograph courtesy of Wagdy Anis.

Figure 2.2-R Liquid-Applied Air Barrier Being Applied to Balance of Wall (Shepley Bulfinch Richardson and Abbott, Architect)
Photograph courtesy of Wagdy Anis.

drywall meet as well as around wiring. The other approach is to use a specially made electrical box that has closed-cell foam gaskets around the drywall flange and cable entry tabs.

Air Barriers Subject to Temperature Changes

Air barriers on the exterior side of the insulation are subject to thermal changes and lots of movement due to expansion and contraction; therefore, these joints are more difficult to keep airtight for the life of the building due to the stresses applied to the jointing tape or sealant by the thermal cycling over time. The best joint materials for these applications should be used, such as the following:

- Extruded silicone bedded in wet silicone
- Wet silicone applied in a "band-aid joint" across board joints
- Other liquid-applied elastomeric air barrier products
- Modified asphalt peel-and-stick tape with surface properly primed

Roof Air Barriers

The roof membrane can be considered an air barrier since it is designed to withstand wind loads if it is fully adhered or hot- or cold-mopped. Mechanically fastened and ballasted roof systems, because they displace and momentarily billow or pump building air into the system, do not perform the required functions of containing air without displacement. In those cases, another air barrier must be selected for the system. Either a peel-and-stick air and vapor barrier on the inboard side of the roof system (dependent on interior conditions and weather) or taped gypsum underlayment board beneath the insulation can be used in a system with adhered underlayers of thermal protection board and insulation. Those layers must be designed to withstand maximum wind loads without displacement. Because of the critical importance of continuity with the wall air barrier, a pre-construction conference on the air barrier system needs to include the trades involved in the air barrier system, such as the wall air barrier subcontractor, the window subcontractor, the sealant subcontractor, and the roofing subcontractor, to discuss the connection between the roof air barrier and the wall air barrier as well as the sequence of making that airtight and flexible connection. It is also important to ensure that the materials being joined together are compatible.

Strategy 2.2

Penetrations into roof systems, such as ducts, vents, and roof drains, must be dealt with, perhaps by using spray polyurethane foam (or other sealant) or membranes to airtighten those penetrations at the targeted air barrier layer.

In conclusion, an air barrier system is an essential component of the building enclosure so that air pressure relationships within the building can be controlled, building HVAC systems can perform as intended, and occupants can enjoy good IAQ and a comfortable environment. Reducing the need for a "fudge factor" to cover infiltration and unknown factors leads to a reduction in the capacity of the HVAC system, energy use,

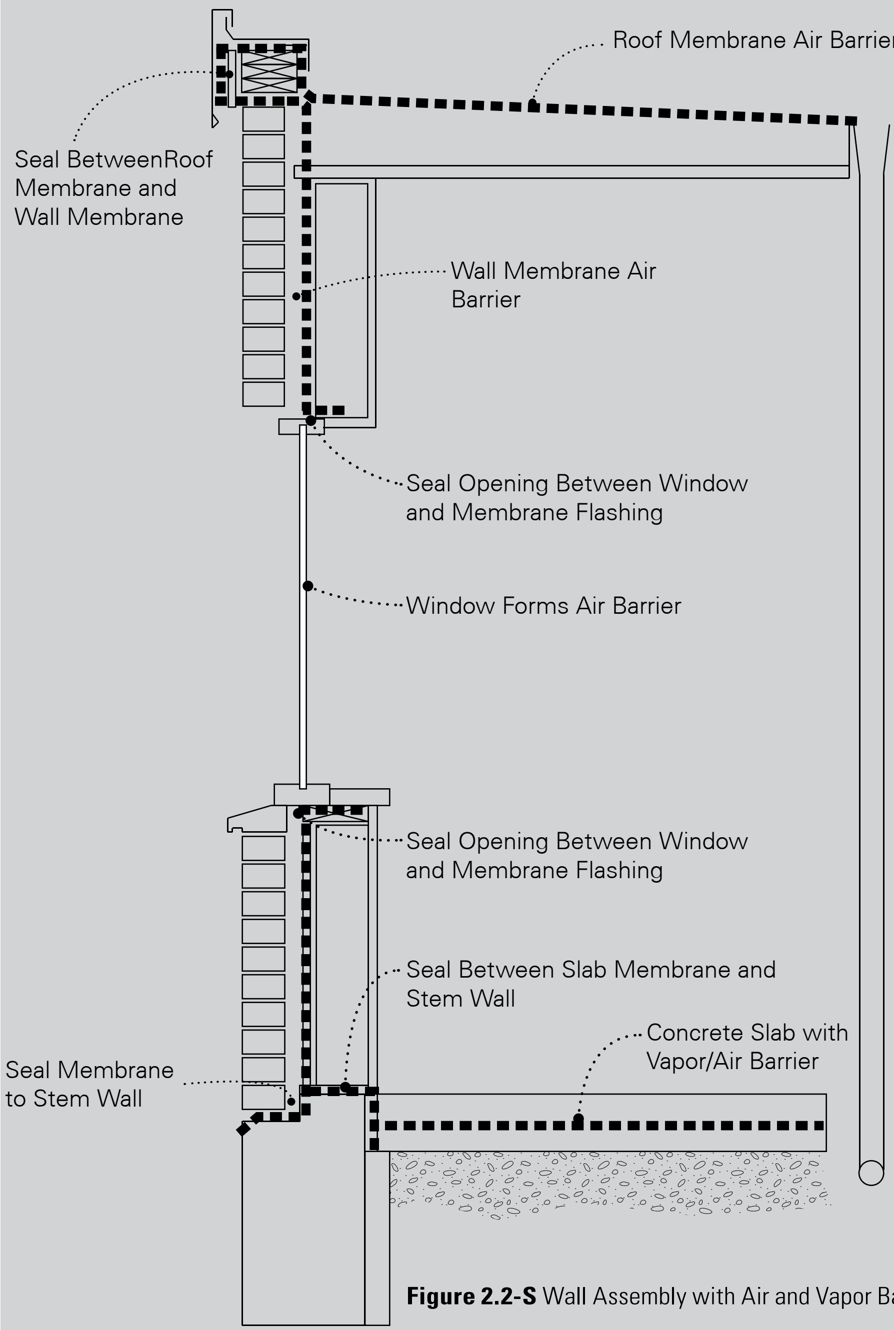

Figure 2.2-S Wall Assembly with Air and Vapor Barrier

Location of the Air Barrier

The air barrier, unlike the vapor retarder, (since its function is to stop air movement, not control diffusion), can be located anywhere in the envelope assembly (see Figure 2.2-S). If it is placed on the predominantly warm humid side (high vapor pressure side) of the enclosure, it can control diffusion as well and would be a low-perm vapor barrier material. In that case, it is called an *air and vapor barrier*. If placed on the predominantly cool drier side (low vapor pressure side) of the wall, it should be vapor permeable (5–10 perms or greater).

Commissioned by the Board of Building Regulations and Standards of the Commonwealth of Massachusetts and developed by a task force from the Boston Society of Architects, an entire series of sample construction details is available for free download on the official Web site of the Executive Office of Public Safety and Security (EOPSS) (follow the links Consumer Protection and Business Licensing > License Type by Business Area > Construction Supervisor License > Sample Details): www.mass.gov/?pageID=eopsterminal&L=4&L0=Home&L1=Consumer+Protection+%26+Business+Licensing&L2=License+Type+by+Business+Area&L3=Construction+Supervisor+License&sid=Eeops&b=terminalcontent&f=dps_inf_bbrs_sample_detail&csid=Eeops.

Strategy 2.2

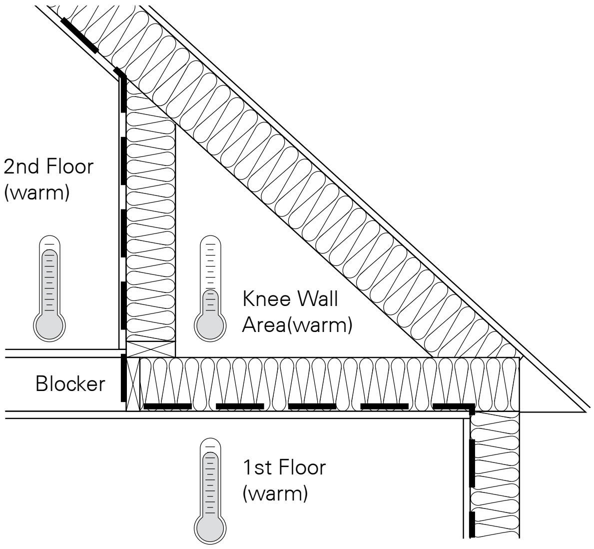

Figure 2.2-T Airtightening with Interior Finish Gypsum Board
Adapted from Anis (2007); used with permission from the National Institute of Building Sciences.

Figure 2.2-U Back Box that Fits around a Standard Electrical Box
Photograph copyright Stephen K. Lentz.

Figure 2.2-V Specialty Electrical Box with Foam Gasket Seal
Photograph copyright NuTek.

Air Barriers Subject to Temperature Changes

Figure 2.2-W Foam Sealant Applied between Insulation Boards

Figure 2.2-X Modified Asphalt Tape
Photographs courtesy of Wagdy Anis.

Figures 2.2-W and 2.2-X show foam sealant applied to all insulation board edges of the Boston College Administration Building (Shepley Bulfinch Richardson and Abbott, Architect) followed by peel-and-stick modified asphalt tape on the primed insulation sheathing boards used as the air barrier.

and demand. Air barrier systems in the building envelope also control concentrated condensation and the associated mold, corrosion, rot, and premature failure; they therefore improve and promote durability and sustainability. Building codes should require air barrier systems, and designers and builders need to be aware of the negative consequences of ignoring building airtightness.

Controlling Convection in Enclosure Assemblies
Figure 2.2-Y demonstrates the need for controlling convection currents within envelope assemblies by sealing the interior. In the figure, the air on the cold side is connected to air on the warm side of the

insulation (or the interior air). When air that is adjacent to a cool concrete basement wall cools down, it gets heavier and drops and pulls in warm humid air at the top of the insulated wall. This is the typical mechanism of mold formation in insulated basements.

Gaps in insulation due to obstructions create air pockets conducive to promoting convection (Figures 2.2-Z and 2.2-AA). Convection of moist air in enclosure assemblies can cause condensation and mold growth. Poorly installed rigid insulation can promote convection that will cool down the sheathing and promote condensation (Figure 2.2-AB). See Figure 2.2-AC for an example of good installation practice for avoiding convection.

Construction Observation of an Air Barrier System

The following is an example of construction observation of an air barrier system.

CO 1 Mock-Up

CO 1.1 Build a mock-up of the air barrier system before proceeding with the work of each airtight joint type, juncture, and transition between products, materials, and assemblies.

CO 1.1.1 Test the mock-up according to *ASTM E 1186*, *Standard Practices for Air Leakage Site Detection in Building Envelopes and Air Retarder Systems* (ASTM 2009) using smoke tracers to discover air leakage pathways.

CO 2 Qualitative

CO 2.1 Provide daily reports of observations, with copies to the owner, contractor, and architect, covering the following:

- Site conditions are appropriate for application, including temperature and dryness of substrates.
- Structural support of the air barrier system is constructed to withstand design air pressures prior to application of air barrier.
- Sheathing surfaces are smooth, clean, and free of holes or gaps as required by the manufacturer of the air barrier material.
- Masonry and concrete surfaces are smooth, clean, and free of cavities, protrusions, and mortar droppings, with mortar joints struck flush or as required by the manufacturer of the air barrier material.
- Surfaces are properly primed.

Qualitative Inspection of Air Barrier Application

There is continuity of the air barrier system throughout the building enclosure, with no gaps or holes.
Laps in material are 2 in. (50 mm) minimum, shingled in the correct direction (or mastic applied on exposed edges), with no fishmouths.

Mastic is applied on cut edges.

A roller has been used to enhance adhesion.

Measured application thickness of liquid-applied materials is to manufacturer’s specifications for the specific substrate.

Materials used have been confirmed for compatibility.

Transitions at changes in direction are installed, and structural support at gaps is provided.

Inspect the connections between assemblies (membrane and sealants) for cleaning, preparation, and priming of surfaces, structural support, integrity, and continuity of seal.

Strategy 2.2

All penetrations are sealed.
The maximum length of exposure time of materials to ultraviolet deterioration is not exceeded.

Qualitative Testing of Air Barrier Application
Follow ASTM E 1186 (ASTM 2009)

- Chamber pressurization/depressurization in conjunction with smoke tracers
- Chamber depressurization using detection liquids to identify any leaks or breaches in surface of air barrier
- Infrared scanning with pressurization/depressurization
- Smoke pencil with pressurization/depressurization
- Pressurization/depressurization with use of an anemometer
- Generated sound with sound detection
- Tracer gas measurement of decay rate

Construction Verification
CO 3 Testing and Verification

CO 3.1 Ensure material compliance for maximum air permeance following ASTM E 2178 (ASTM 2003a).

Minimum dry or wet film thickness for liquid-applied materials conforms to the manufacturer's requirements.

Bond to substrate following *ASTM D4541, Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers* (ASTM 1995).

Quantitative Testing of Assemblies

Test assemblies following ASTM E 2357 (ASTM 2005a); the maximum test pressure and allowable air leakage rate must be determined by design professional for exterior design conditions and location of project.

Test following *Canadian National Master Specification 07272.1, Durability Assessment of Bead-Applied Urethane-Based Sealant Foam for Air Barriers* (PWGSC Ongoing).

Test windows and connections to adjacent opaque assemblies following method B of ASTM E783, Standard Test Method for Field Measurement of Air Leakage Through Installed Exterior Windows and Doors (ASTM 2002).

Quantitative Testing of Whole Building

Test following *CAN/CGSB Standard 149.10, Determination of the Airtightness of Building Envelopes by the Fan Depressurization Method* (CGSB 1986).

Test following *CAN/CGSB Standard 149.15, Determination of the Overall Envelope Airtightness of Office Buildings by the Fan Depressurization Method Using the Building's Air Handling System* (CGSB 1996).

Test whole building, floors, or suites following *ASTM E779, Standard Test Method for Determining Air Leakage Rate by Fan Pressurization* (ASTM 2003b).

Conduct tracer gas testing following *ASTM E741, Standard Test Method for Determining Air Change in a Single Zone by Means of a Tracer Gas Dilution* (ASTM 2006).

Strategy 2.2

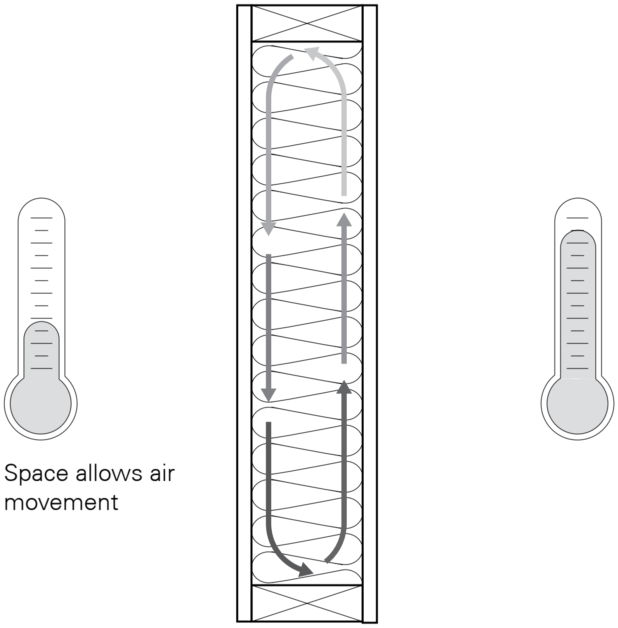

Figure 2.2-Y Convection Currents
Adapted from Anis (2007); used with permission from the National Institute of Building Sciences.

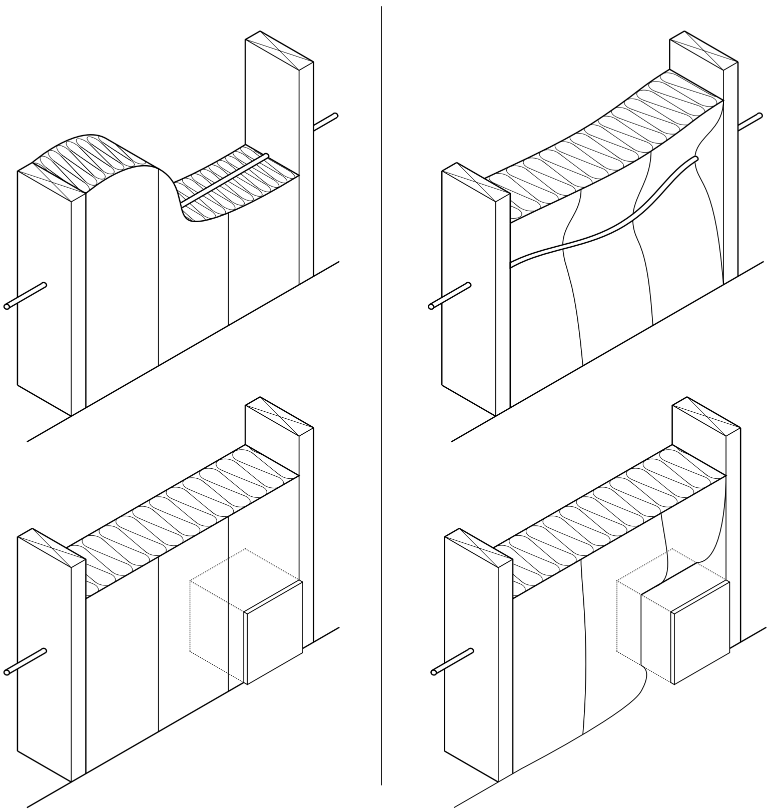

Figure 2.2-Z Gaps in Insulation due to Obstructions Promote Convection

Controlling Condensation due to Diffusion

Vapor barriers are intended to retard the migration of water vapor. Air barriers retard the migration of air. Air barriers can also be considered vapor barriers when they control the transport of moisture-laden air. Vapor retarders can be divided into several classes based upon their permeance rating, or *perm*.

Recommendations for Building Enclosures

Building assembly recommendations are climatically based and sensitive to cladding type and structure and do not apply to special-use enclosures. It is important to

- avoid use of vapor barriers where vapor retarders will be satisfactory,
- avoid use of vapor retarders where vapor-permeable materials will be satisfactory,
- avoid installation of vapor barriers on both sides of assemblies, and
- avoid use of vapor barriers and vinyl wall coverings on the interior of air-conditioned assemblies.

Vapor barriers were originally intended to prevent assemblies from getting wet, but incorrect use of vapor barriers is leading to an increase in moisture-related problems. The moisture can appear in several forms or phases: liquid, solid, vapor, and adsorbed. The fundamental principle of water control in any form is to keep it out and, if it gets in, let it out. However, some of the best strategies to keep water vapor out also trap water vapor in. The difficulty is climatological; therefore, vapor control measures need to be defined on a regional climatic basis. Additional information on vapor barriers can be found in Appendix B – Understanding Vapor Barriers.

Strategy 2.2

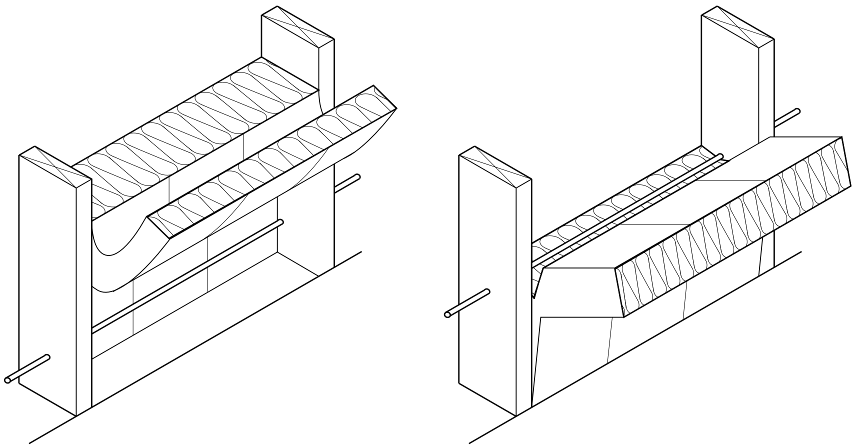

Figure 2.2-AA Wires Concealed within Insulation by Slitting or Splitting Insulation
Adapted from NAIMA (2006); copyright NAIMA—may not be reused without permission from NAIMA.

Figure 2.2-AB Poorly Installed Rigid Insulation in Brick Cavity with Air Gaps between and behind Boards
Photograph courtesy of Wagdy Anis.

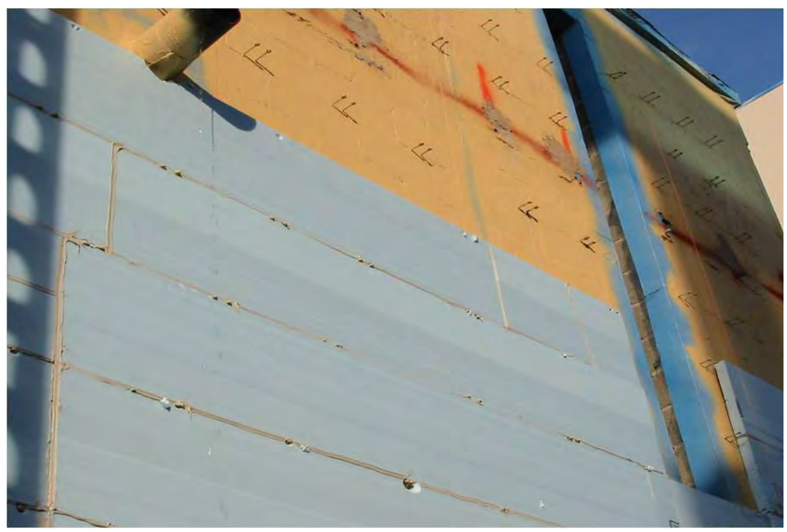

Figure 2.2-AC Well-Installed Rigid Insulation Embedded in Mastic with Sealed Joints
Photograph courtesy of Wagdy Anis.

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Strategy 2.3

2.3

Maintain Proper Building Pressurization

Introduction

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. (5.0 to 17.5 Pa) differential (across the building envelope) in the lobby, this is not always advisable. The nature and extent of 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.

Design Considerations

Climatological Requirements

The desired pressure differential across the building envelope depends on the climate and may be positive or negative. Commercial and institutional buildings are advised to be slightly positive, on average, except for those in colder climates, where a slightly negative average pressure differential is appropriate when the outdoor air temperature falls below 32°F (0°C). In humid climates buildings are advised to be slightly positive. In all climates, a negative pressure differential is appropriate for buildings that are humidified when the outdoor air temperature falls below the dew-point temperature maintained indoors. Examples include medical facilities, museums, or spaces with significant internal moisture sources such as natatoriums, spas, or indoor gardens.

For mixed climates with extreme conditions in both summer and winter, buildings can be equipped with dew-point control. When the outdoor dew point rises above the indoor dew point, the HVAC system can switch from neutral pressure to positive pressure. This helps limit infiltration and the associated dehumidification load. For buildings with temperature-controlled outdoor economizers instead of dew-point control, the HVAC system can switch when the outdoor dry-bulb temperature reaches the maximum dew-point indoor temperature. Using a dry-bulb comparison in this way is more conservative, because the outdoor dew-point temperature may not yet have been reached; this results in more hours of positive pressure (more fan cost) than if the actual dew points were compared (Harriman et al. 2001).

Regional and Local Outdoor Air Quality Requirements

The outdoor air quality at the building location is another important condition in considering building pressurization. If the building is depressurized, the outdoor air contaminants will likely be drawn into the building. The outdoor air quality could be affected by neighboring businesses such as dry cleaners or restaurants, nearby activities such as manufacturing processes, etc., or the existence of any site- or location-specific pollutants or contaminants. In situations where the building is required to be negatively pressurized, a tight building envelope is required with treatment of the outdoor air intake to remove the outdoor pollutants. Additional information can be found in Strategy 1.3 – Select HVAC Systems to Improve IAQ and Reduce the Energy Impacts of Ventilation.

Strategy 2.3

2.3

Approach to Building Usage and Layout

The layout of building space and its usage can affect the building pressurization requirements. The uniformity of the layout from floor to floor, space usage, and construction style (atrium lobby areas or continuous slabs between all floors) affect air distribution and the required degree of pressurization. Atria and a lack of between-floor air barriers provide airflow paths connecting multiple levels, making pressure relationships more difficult to control. The building layout needs to be analyzed both vertically and horizontally for its effects on pressurization. For example, laboratories or hospital areas with infectious disease control will likely be depressurized; if these areas are located on the perimeter of a building, infiltration will likely draw in outdoor moisture and contaminants through the building envelope and thereby degrade IAQ and possibly create building structural problems. Interior spaces under localized negative pressure are best placed in the center of the building floor plan so that the air travels into them from adjacent conditioned spaces. This helps ensure that the air traveling to the depressurized space is conditioned, and the HVAC system has a better chance of maintaining the overall positive building pressure (Odom et al. 2005).

Various architectural features can be used to maintain proper building pressure relationships. These include, for example, the use of two-door vestibules or revolving doors and compartmentalization of spaces with separate HVAC systems. An atrium could be separated architecturally from the building and have a separate HVAC system that makes it possible to maintain proper building pressure relationships.

Improper pressurization can create problems during remodeling and new construction. Positive pressurization strategies may be needed to protect building interiors from construction contaminants or outdoor climatic conditions. Sequencing of HVAC equipment operation or lock-out during construction may be required to avoid building pressurization problems. Starting exhaust systems before starting supply systems can draw in moisture in hot, humid climates or drawn in dust and dirt particles into occupied spaces during the construction process.

Phasing of the construction and remodeling process can also create pressurization issues. Typically, the phased areas of construction are not served by an HVAC system dedicated to serving the phased areas only. If an HVAC system is put into operation and it creates a negatively pressurized area during the occupied phase, it can draw moisture and contaminants from the construction areas or incomplete building openings into the completed area. In such cases, it is best to segregate the HVAC systems for phasing, if possible, or to remodel or design them to match phasing requirements for the project. Also see Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ.

Building Orientation and Wind Load

Building orientation and wind load impact the amount of infiltration into a building and therefore affect the outdoor airflow and fan capacity required to provide proper building pressurization. The impact of the wind on the static pressure distribution on the outside of a building will vary with the wind's angle of attack. In general, the static pressure caused by the wind will be positive on the upwind surface until the angle of attack exceeds 45°. The static pressure will be negative on the upwind surface when the angle of attack exceeds 75°, while both positive and negative pressures exist when the angle of attack is between 45° and 75°. On the leeward side, the static pressure will always be negative. The pressure on the roof caused by wind, on average, will be negative, but roof angles steeper than 20° will have parts of or the whole upwind side at a positive pressure (McIntosh et al. 2001). The turbulence or gustiness of the approaching wind and the unsteady character of separated flows cause surface pressures to fluctuate. Pressures that are utilized for design purposes are time-averaged values, with an averaging period of perhaps 600 s. This is approximately the shortest time period considered to be a steady-state condition when considering atmospheric winds; the longest is typically 3600 s. Instantaneous pressures may vary significantly above and below these averages, and peak pressures two or three times the mean values are possible. Although peak pressures are important with respect to structural loads, mean values are more appropriate for computing infiltration and ventilation rates (ASHRAE 2009).

A pressure difference of 0.2 in. w.c. (50 Pa) is created whenever the wind blows against the outside wall at a velocity of 25 mph (11.2 m/s). As noted previously, the outdoor wind pressure is never uniform around the whole building (Harriman et al. 2001).

Data from a field investigation of 70 buildings in the southern U.S. (Cummings et al. 1996) illustrate the magnitude and variation of wind forces on air leakage rates in typical low-rise commercial buildings. In this field investigation, each building was pressurized internally with a blower to simulate wind forces across the exterior walls of buildings so that the average pressure difference across the exterior wall was 0.2 in. w.c. (50 Pa). Once that pressure difference was achieved, the airflow through the blower into the building was measured with a calibrated venturi nozzle. Some buildings leaked more than 50 complete air changes per hour; others leaked less than 5 air changes per hour. The average leakage for all of the buildings was about 20 air changes.

For a more detailed discussion and calculation of the wind pressure on a building, see *ASHRAE Handbook—Fundamentals*, Chapters 16 and 27 (ASHRAE 2009).

Stack Effect

Stack effect is a condition that exists in tall buildings when the outdoor temperature is significantly different from the temperature inside the building. In cold weather, the warm air in the building rises, creating negative pressure on the lower floors and positive pressure on the higher floors. The building, surrounded by cold air, thus acts like a chimney with natural convection of air entering at the lower floors, flowing upward through the building, and exiting through the upper floors. The cause of stack effect is the difference in density between the denser cold air outside the building and the less dense warm air inside the building.
The pressure differential that is created by the stack effect is directly proportional to the building height and the difference in temperature between the indoor and outdoor air. A simple diagram of stack effect under heating and cooling (reverse stack effect) is shown in Figure 2.3-C.
Figure 2.3-D shows the estimated inside-to-outside pressure differences as a function of inside-to-outside temperature difference and building height. For example, the total pressure difference from stack effect for a building 600 ft (183 m) high with an inside-to-outside temperature difference of 100°F (38°C) is about 2 in. w.c. (500 Pa).

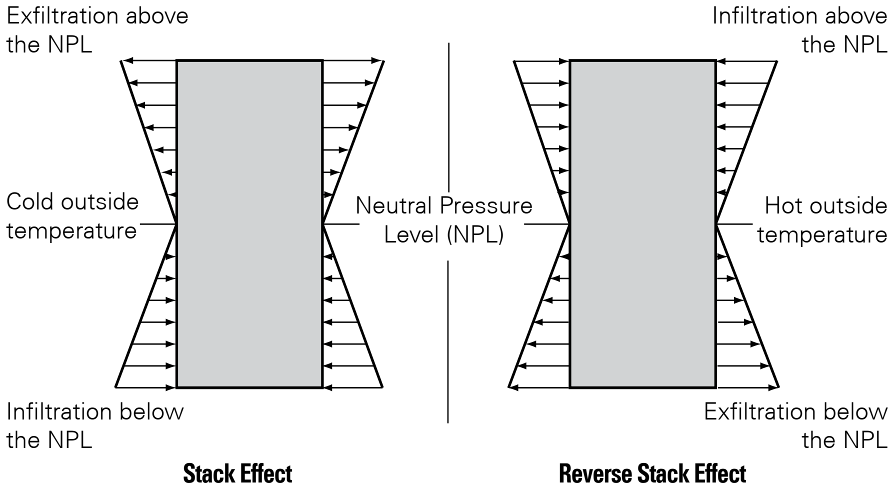


Figure 2.3-C Stack Effect
Adapted from Ross (2004), p. 22.

Strategy 2.3

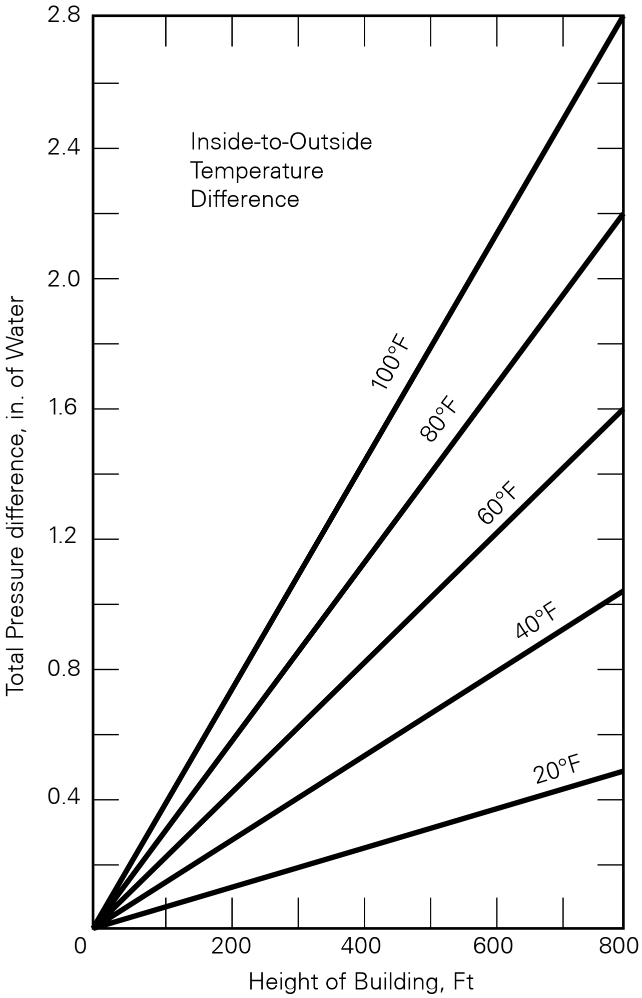


Figure 2.3-D Total Pressure Difference Caused by Stack Effect
Adapted from Wilson and Tamura (1968).

Measurements made on several multi-story buildings have shown that up to 80% of the total pressure difference is taken across the outside walls and that the remainder is distributed across various interior separations. This indicates that with current construction methods there is a relatively low resistance to airflow from floor to floor compared with airflow through exterior walls. The level of the neutral pressure plane, which depends on the vertical distribution of openings through which air flows, is generally near mid-height.

Figure 2.3-E shows the pattern of pressures and airflow caused by stack effect for an idealized building with uniform distribution of openings in the exterior wall, through each floor, and into the shaft at each story. For a uniform distribution of openings, as in Figure 2.3-F, pressure differences from stack effect can be estimated. For example, with 80% of the total pressure difference taken across the outside walls and a neutral pressure plane at mid-height, the pressure drop at the entrance is equal to 40% of the total. Similarly, the pressure difference across the walls of vertical shafts at the first floor level is equal to 10% of the total. In this example, the pressure difference across the entrance is about 0.8 in. w.c. (200 Pa) and across the vertical shaft at the ground floor level is 0.2 in. w.c. (50 Pa) (Wilson and Tamura 1968).

A reverse stack effect can occur in hot climates, where the hot, less dense outdoor air enters the upper floors of a tall building and the colder, denser air in the building exits through the lower floors.

A thorough discussion of tall-building HVAC system design and stack effect can be found in *HVAC Design Guide for Tall Commercial Buildings* (Ross 2004), from which the following strategies and recommendations for addressing stack effect in tall buildings are taken.

- Reduce air leakage into and out of the building. Address entrances, exits, truck docks, air intakes or exhausts, and overhangs in construction with light fixtures. Internally address fire stairs, elevator shafts, and mechanical/electrical shafts for wiring, duct, and piping.
- Vestibules or air locks can be provided for loading docks. Utilize two-door vestibules with adequate heat and make sure that doors can operate independently of each other.
- Utilize revolving doors where there is the most traffic into and out of the building, such as at entrances from attached parking garages or the main employee entrance. It is inappropriate to use two-door vestibules for employee entry, as a large number of people means both doors will be opened simultaneously, which needs to be avoided.
- Utilize good door and sill gaskets on fire-stair doors.
- Utilize compartmentalization where possible. Place doors at the entries to the elevator banks to create an elevator vestibule on each floor. Where possible on vertical shafts, seal vertical faces to reduce

airflow into the shaft that would travel vertically. This vertical compartmentalization, vertically dividing the building into separate systems, may be required to reduce the height of the indoor air column. Floor penetrations in tall buildings are required by code to be sealed with a fire seal. Some fire seals are designed to expand with heat and are not airtight before the fire. Ensuring that the floor penetrations are airtight is required for vertical compartmentalization. Figure 2.3-F displays the effects of compartmentalization.

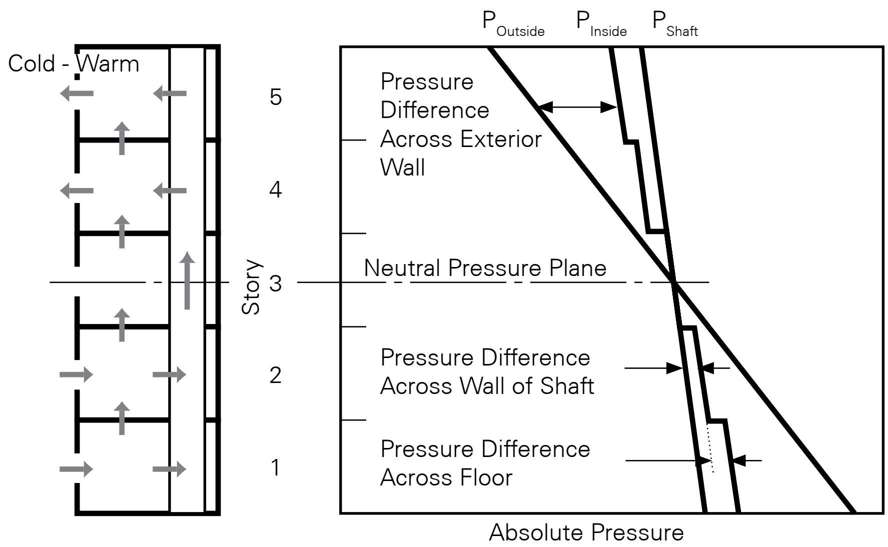


Figure 2.3-E Stack Effect for Idealized Building
Adapted from Wilson and Tamura (1968).

- If a single air-handling unit (AHU) serves multiple floors, each floor needs to have mechanically operated dampers on the supply and return ductwork to isolate the shaft from the floor when the AHU is off.
- Provide independent HVAC systems for lobbies in high-rise and complex buildings that are tailored to meet the HVAC requirements of the lobbies, including pressurization. This allows for proper building pressure control and reduces the adverse effects of stack effect. A higher percentage of outdoor air for pressurization can be introduced through this independent HVAC system. This will also allow for night set-back control strategies for the main HVAC system (the independent lobby system can maintain lobby pressurization and comfort while the main system is turned back or off) (Sellers et al. 2004).
- The outdoor, exhaust, and return airflows need to be evaluated in the design process then be field measured and verified.

Building Envelope

The effectiveness of building pressurization is dependent upon the leakiness of the building envelope. The design and construction of the building envelope needs 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 building envelope.

Planned Openings

Identify planned openings in the building envelope that may impact the ability of the HVAC system to provide overall positive pressurization by inadvertently increasing envelope leakiness. Such openings can include mechanical planned openings such as roof vents, louvers, and floor drains (traps), as well as other penetrations. Architectural planned openings such as vents, penetrations, door and window openings, and even building envelope drainage openings need to be considered when addressing envelope leakiness. Once these planned openings are identified, employ strategies to reduce the amount of openings, if possible. Options include providing airtight motorized dampers on elevator shaft louvers, utilizing revolving doors, etc. Any planned openings that cannot be sealed must be considered when evaluating the amount of outdoor air required to pressurize the building, or possibly interior compartmentalization could be utilized.

Unplanned Openings

Estimate the envelope leakiness so that the amount of outdoor air can be determined to provide proper building pressurization. Typical air leakage values per wall unit area at 0.30 in. w.c. (75 Pa) (positive building test pressure) are 0.10, 0.30, and 0.60 cfm/ft^2 (0.5, 1.5, and 3.0 L/s·m^2) for tight, average, and leaky walls, respectively (Tamura and Shaw 1976). At a pressure of 0.016 in. w.c. (4 Pa), which is a more typical building pressure, the air leakage values per wall unit area are 0.015, 0.045, and 0.089 cfm/ft^2 (0.08, 0.23, and 0.45 L/s·m^2). Keep in mind that the building pressure is not evenly distributed across the building envelope and that a differential pressure across the building envelope can exceed the 0.016 in. w.c. (4 Pa) at various locations. This will most likely occur for any tall building due to stack effect and wind loading. The only way to determine the leakiness of a building is to measure it. A more thorough discussion on envelope leakiness can be found in *ASHRAE Handbook—Fundamentals*, Chapter 27 (ASHRAE 2009) and Persily (1999).

HVAC System

Airflow Considerations

Air volume considerations include analyzing the issues noted previously in this Strategy; building orientation and wind load, stack effect, building envelope leakiness (planned and unplanned), and HVAC system air volume requirements (required outdoor air for ventilation and exhaust air systems). The airflow rates due to these separate forces need to be determined by adding the pressure differences together, not the airflow rates, because the airflow rate through each opening is not linearly related to the pressure difference. A thorough discussion of this calculation can be found in *ASHRAE Handbook—Fundamentals*, Chapter 27 (ASHRAE 2009).

Due to the complexity of the pressure difference calculations and the summation of total airflows of the different sources noted in the previous paragraph, a rule of thumb is often used for determination of required airflow for building pressurization. In most cases, but not all cases, buildings can be positively pressurized if the combined total of relief airflow and

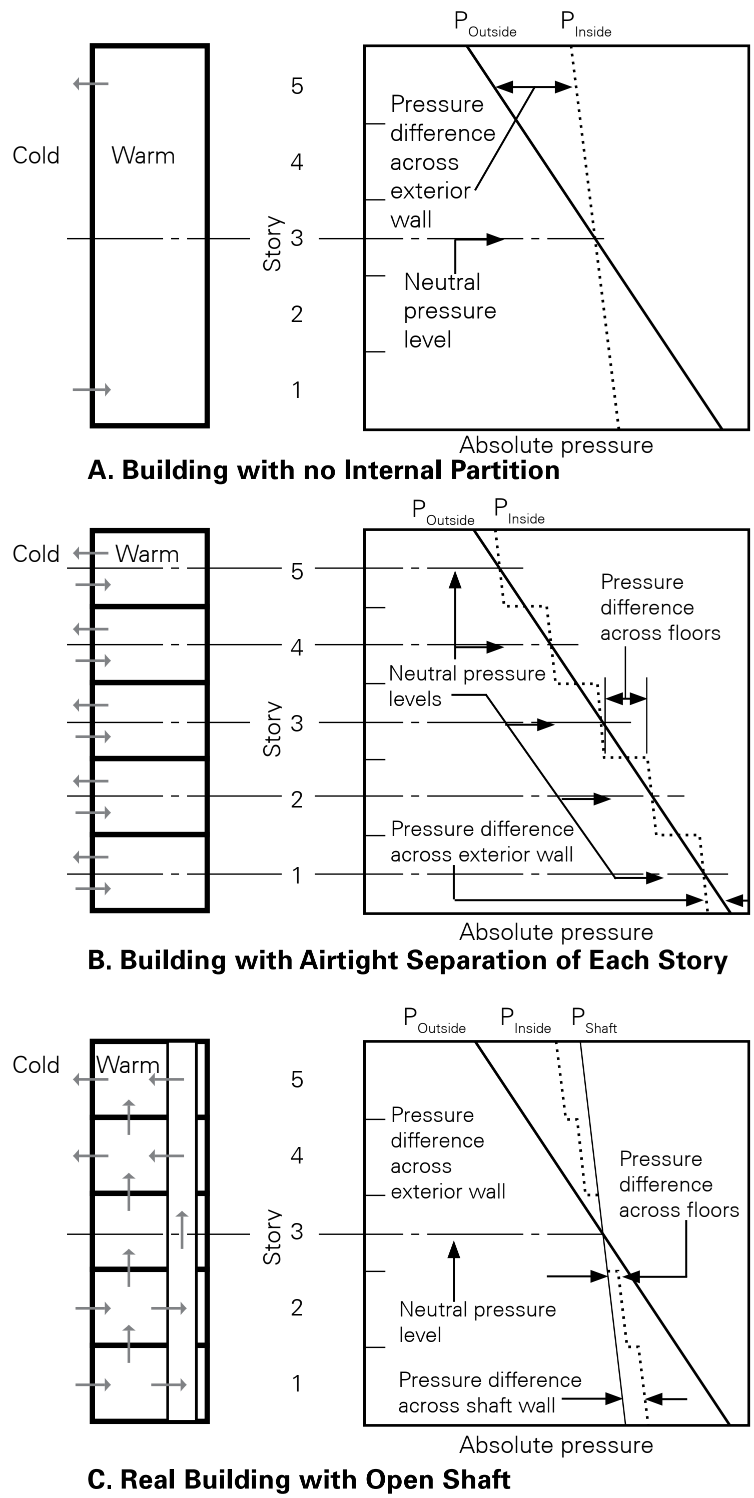


Figure 2.3-F Stack Effect and Compartmentalization
Adapted from ASHRAE (2009).

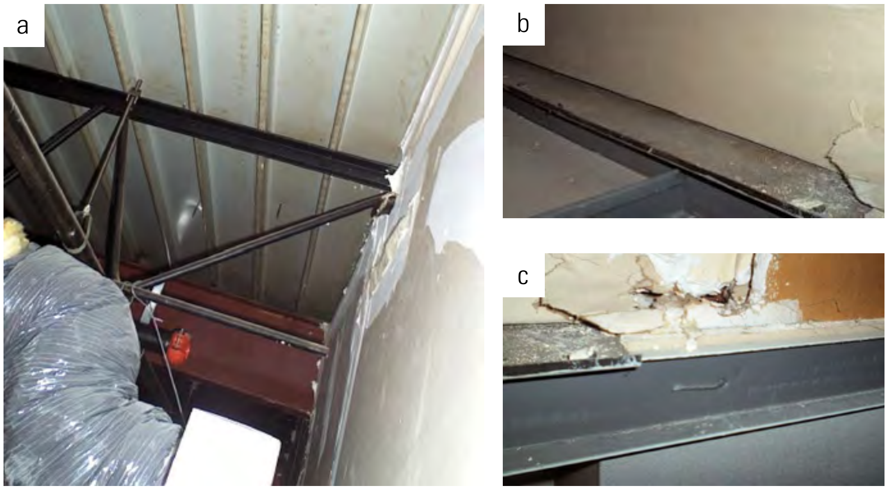


Figure 2.3-G Excerpt from Brennan et al. (2007) Showing Building Sealing a) Gypsum Board Separating the second floor plenum from the soffit has been installed with a good fit around structural steel and sealed with joint compound. b) Joint at bottom of gypsum board has not been sealed. c) Sealing detail at a jog in the wall section is incomplete *Adapted from Brennan et al. (2007).*

exhaust airflow from the building is between 80% and 90% of the total outdoor air intake flow into the building. However, using a rule of thumb such as this is to be done in conjunction with, not as a substitute for, addressing the specific pressurization issues previously noted. For example, if a tall building is being considered, then stack effect issues, building orientation and location as they relate to wind load issues, and the type of envelope construction as it affects envelope leakiness all need to be addressed. Further, critical applications require that pressure differences across the building envelope and airflow rates required to achieve these pressure differences be calculated. The CONTAM software, developed by the National Institute of Standards and Technology (NIST), can assist in these calculations (NIST 2008).

Air Distribution Considerations. It is also important to address the distribution of the air within the building spaces. The location at which the makeup air is provided is critical to avoiding depressurization due to stack effect and/or wind effect and building compartmentalization. Direct delivery, by ducting the makeup air to the space, is more effective for pressurization control than indirect delivery such as through door undercuts. Indirect delivery does not ensure that the makeup air makes it to the space of concern, and the space may not be pressurized properly.

Toilet exhaust systems and other exhaust systems are best viewed as systems for controlling odors and localized moisture only, not as methods of drawing outdoor ventilation air into a building or meeting a building's outdoor air requirements. The ventilation air required for building pressurization needs to be conditioned and cleaned prior to being introduced into the building.

HVAC System Dehumidification Capacity

The moisture removal (dehumidification) capacity of an HVAC system can be an issue when the HVAC system is positively pressurizing the building by supplying conditioned outdoor air. HVAC systems are often designed to maintain sensible temperature rather than relative humidity or dew point. For these systems, unconditioned outdoor air is cooled to the desired temperature before it is dehumidified. This can create elevated moisture levels and microbial growth inside the building. Furthermore, because the HVAC system is controlled by temperature (thermostat) instead of humidity (humidistat), the equipment will not sense the elevated space moisture levels and will not fully remove it. It is therefore important to size HVAC systems that provide outdoor air for pressurization to handle both the sensible and latent load requirements and employ control strategies to allow for proper dehumidification of the outdoor air (Odom et al. 2005). See Strategy 2.4 – Control Indoor Humidity for additional information on humidity control.

Strategy 2.3

2.3

Building Static Pressure Monitoring and Control Strategies

This section discusses some control strategies that can be used to maintain proper building pressurization. For additional information on HVAC system types and descriptions and IAQ implications, reference Strategy 1.3 – Select HVAC Systems to Improve IAQ and Reduce the Energy Impacts of Ventilation. In addition, the following papers and articles can provide some guidance on various control strategies:

- Kettler, J.P. 1988. Field problems associated with return fans on VAV systems. *ASHRAE Transactions* 94(1):1477–83.
- Kalasinsky, C.C. 1988. The economics of relief fans vs. return fans in variable volume systems with economizer cycles. *ASHRAE Transactions* 94(1):1467–76.
- Kettler, J. 2004. Return fans or relief fans: How to choose. *ASHRAE Journal* 46(4):28–34.
- Alcorn, L.H., and P.J. Huber. 1988. Decoupling supply and return fans for increased stability of VAV systems. *ASHRAE Transactions* 94(1):1484–92.
- Kettler, J.P. 1995. Minimum ventilation control for VAV systems: fan tracking vs. workable solutions. *ASHRAE Transactions* 101(2):625–30.
- Elovitz, D.M. 1995. Minimum outdoor air control methods for VAV systems. *ASHRAE Transactions* 101(2):613–18.
- Taylor, S.T. 2000. Comparing economizer relief systems. *ASHRAE Journal* 42(9):33–42.

Decoupling Temperature and Pressure Control. One fundamental strategy is to decouple the temperature control and building pressure control functions. This is especially true when the HVAC systems utilize air-side economizers (Sellers et al. 2004).

Natural Relief. Every building has some form of natural relief. This can include cracks around doors and windows and other planned or unplanned openings. Natural relief pressurization is more typically employed in smaller buildings. This is technically not a control option for building pressurization as there is no actual control. Since building envelopes have become tightened because of energy efficiency concerns, natural relief is no longer considered a pressurization control option.

Barometric Relief. Barometric relief controls positive space pressure by utilizing a nonpowered gravity damper that opens with increases in the indoor-outdoor pressure differential. This is typically used in small buildings with constant-volume (CV) HVAC systems. Locating the barometric damper in the conditioned space is critical so that it senses space pressure almost directly. Proper setup of the barometric relief damper is required; the damper needs to be adjusted to start relieving air for a slightly positively pressurized building. Barometric relief cannot be used to control a negatively pressurized building and limits the application for 100% outdoor air economizers.

Airflow Monitoring. Airflow monitoring of the outdoor airflow and exhaust airflow offsets can be utilized for proper building pressure. Proper selection and location of the airflow measuring stations is important. For additional information see Strategy 7.2 – Continuously Monitor and Control Outdoor Air Delivery. Airflow monitoring works well with smaller buildings and HVAC systems that will allow for measurement of all airflows. However, in other cases, many exhaust flows (e.g., toilet exhaust, electrical room exhaust) are not monitored and the total differential of airflow cannot be determined. In addition, the measurement of outdoor airflows and exhaust airflows in larger buildings could have significant errors, even to the point that the error in the difference of the two flows could equal or exceed the airflow rate needed to maintain proper building pressure (Kettler 1995).

Return Fan Plenum Pressure. One of the more reliable control designs is controlling the return fan to maintain a positive static pressure in the return plenum and modulating the relief dampers to maintain building static pressure. A pressure sensor in the return air plenum adjusts the capacity of the return fan, usually by a variable-frequency drive (VFD). In addition, pressure sensors monitor the indoor and outdoor pressure difference. This pressure difference signal modulates the position of the relief damper, directly controlling building pressure. The relief damper will have to be controlled separately from other dampers to accommodate varying building pressure setpoints. In most cases, it is best if the relief damper, whose purpose is to relieve positive pressure when economizing, is closed when at minimum outdoor air. The return fan configuration is typically used when there is a ducted return air system or when there is a large pressure drop that the supply fan needs to overcome. The return fan plenum pressure control typically requires setup and coordination of the return fan speed, the exhaust/relief damper position, and the outdoor air damper position at all operating conditions. Coordination of these control strategies is required to eliminate any possible conflicts between the individual component control strategies that could create problems with return fan plenum pressure control. Reference Table 2.2-A for advantages and disadvantages of return fan plenum control (ASHRAE 2003; Stanke and Bradley 2002).

Relief Fan with Direct Control. Pressure sensors monitor the indoor and outdoor pressures to calculate a differential pressure. This differential pressure directly controls the building pressure by adjusting the relief fan's capacity. The fan capacity control typically uses a VFD. The relief fan only operates when necessary to

Table 2.3-A Return Fans vs. Relief Fans in VAV Systems
Source: Stanke and Bradley (2002), Table 1.

Return Fan—Advantages	Relief Fan—Advantages
Lower differential pressure across the supply fan if the pressure drop of the return air path is greater than the pressure drop of the outdoor air path.	**Lower operating cost.** Typically the relief fan can remain off during "non-economizer" hours and operate at low airflow during many "economizer" hours. Also, the recirculating damper can be sized for a lower pressure drop.
Potentially lower initial cost for systems with ducted returns. Less supply fan pressure can mean lower fan horse-power and/or a smaller fan and smaller variable-speed drive.	**Great layout flexibility.** The relief fan can be positioned anywhere in the return path (lower initial cost) because the supply fan draws the return path negative (relative to the occupied spaces) during modulated economizer operation. A ground-floor air handler with top-floor relief can take advantage of winter stack effect to lower operating costs.
	Simpler control scheme. Having one less sensor and one less actuator simplifies installation and balancing. Applications with a low return path pressure drop can accommodate lower-cost fans as well as fewer (less costly) controls.
Return Fan—Disadvantages	**Relief Fan—Disadvantages**
Higher operating costs, especially in climates with extended hours of economizer cooling. (The return fan must run whenever the supply fan operates.)	**Negative building pressure at low loads.** This condition can occur when a variable-speed drive controls relief fan capacity, the supply airflow rate is low, *and* required relief airflow is less than the minimum airflow at the lowest fan speed. (Using a constant-speed relief fan with a modulated relief damper avoids this disadvantage.)
More complex (expensive) fan speed control. Return air plenum pressure control requires an additional pressure sensor and modulating device (either a damper actuator or variable-speed drive).	**Greater likelihood of outdoor air leakage at the relief damper.** The return air plenum operates at negative pressure whenever the relief fan is off. (Using low-leak relief dampers can minimize air leakage from outdoors.)
Difficult to situate the return air plenum pressure sensor (in systems with return air plenum pressure control) because the return air plenum is usually small and turbulent.	**Higher differential pressure across the supply fan** than in return fan systems. When the relief fan is off, the supply fan must overcome the pressure drops of the supply path. (For this reason, relief fans may or may not be appropriate for systems with ducted returns.)
Requires more fan horsepower at part load. Return air plenum pressure must always be positive enough to establish relief airflow; the recirculating damper must therefore drop significant pressure between the negative mixed air plenum and positive return air plenum. (Optimized damper control can reduce part-load fan horsepower.)	
Limited layout flexibility. The return fan must be situated between the air handler and the closest leg of the return path (usually near the air handler) because it must draw the entire return path negative relative to the occupied spaces. It must also discharge into the return air plenum during modulated economizer operation.	

relieve the building pressure. Relief fans with direct control are typically easier to control, less expensive to install, and less costly to operate than return-fan configurations. Generally, the relief-fan configuration works best in variable-air-volume (VAV) systems designed with a ceiling-plenum return and when the supply fan can handle the pressure drop from the air handler's discharge opening to its return opening. For advantages and disadvantages of relief fan direct control, see Table 2.3-A (Stanke and Bradley 2002).

Pressure Sensor Location. Careful selection of the indoor and outdoor sensor locations is important if building static pressure control is utilized with measurement of indoor and outdoor static pressures. The indoor sensor needs to be located away from openings to the outdoors or elevator lobbies and in a large representative area shielded from wind pressure effects or drafts. The outside location is typically 10 to 15 ft (3.0 to 4.6 m) above the building and oriented to reduce wind effects from all directions.

- For tall buildings in cold climates and for a single fan system serving all floors, the inside and outside taps need to be at ground level. However, if the outdoor sensor is roof mounted, a positive pressure at the roof level is created along with an extremely negative pressure at ground level. The discrepancy between ground and roof pressures varies with the indoor-outdoor temperature difference (stack effect). This temperature variation needs to be considered when selecting the control point, as a fixed offset will not compensate for the temperature variance.
- If the building has fans for the upper floors and separate fans for the lower floors, the indoor and outdoor taps need to be on or near the lowest floors served.
- For tall buildings in hot climates, it would be better to have the outdoor pressure sensor at the top of the building to help ensure that all parts of the building are positive.
- If the building is compartmentalized for pressure control, it is wise to position an outdoor pressure sensor at the elevation of each compartment with associate indoor pressure sensors. Depending on building orientation and vertical design, multiple static pressure sensors, on the exterior and interior of the building, could be utilized to help provide dynamic readings that could be constantly read and evaluated.

Economizer Considerations

When an economizer is enabled, excess outdoor air is supplied to the building and the building will become pressurized unless an adequate relief system is available.

There are three common types of relief systems: relief dampers, relief fans, and return fans. Illustrations of these systems are provided in Figure 2.3-H, and descriptions of the systems are provided in the following (Taylor 2000).

- *Relief Dampers.* Some of the advantages of relief dampers are lowest first cost, least amount of space required, lowest energy cost, and simple and quiet operation. Limitations are that they usually are limited to small systems, have increased damper leakage, and are susceptible to wind effects.
- *Relief Fan Systems.* Relief fan systems offer advantages over return fan systems such as greater layout flexibility, lower energy costs, less complicated controls for VAV applications, and lower first cost. Limitations include control instability with high pressure drop return air systems, negative building pressures at low outdoor air rates, and fluctuating building pressure controls.
- *Return Fan Systems.* Because the supply fans and motors of return fan systems are smaller than those of relief fan systems, they are preferred for CV systems. However, they are prone to control issues due to flawed control schemes. Signal tracking can lead to varying building pressures since the same capacity control signal is sent to the supply and return fans, and fan volume tracking is not an effective means for controlling minimum outdoor air rates in VAV systems. The most reliable control design is probably to control the return fan to maintain a positive static pressure in the exhaust plenum and modulate the relief dampers to maintain building static pressure.

Strategy 2.3

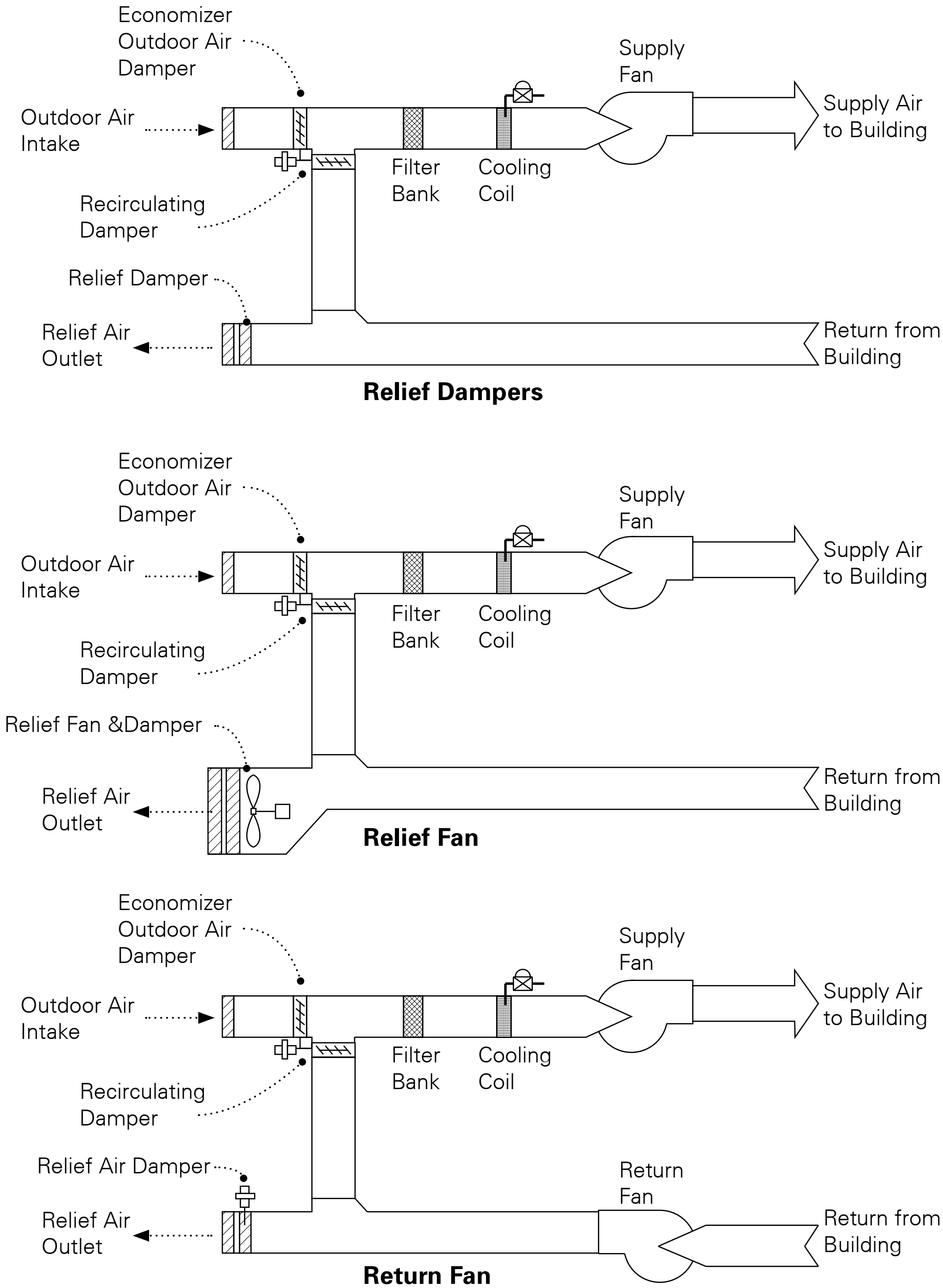


Figure 2.3-H Three Common Types of Relief Systems
Adapted from Taylor (2000).

Strategy 2.3

The "Building Static Pressure Monitoring and Control Strategies" section in this Strategy and *ASHRAE Guideline 16, Selecting Outdoor, Return, and Relief Dampers for Air-Side Economizer Systems* (ASHRAE 2003), have more information on building pressure control strategies.

Constant-Volume Exhaust

Figure 2.3-I Humid Outside Conditions and Design Errors Combine to Cause Severe Mold Problems at a Luxury Hotel
Photograph copyright CH2M HILL.

This case study, excerpted from the National Council of Architectural Registration Boards (NCARB) publication *Mold and Moisture Prevention*, reports:

In the summer of 1988, construction of a large luxury resort was coming to a close. Because the vinyl wall covering on the interior side of the exterior walls had an impermeable vanish, it functioned as a vapor retarder (also referred to as a vapor barrier). The HVAC system consisted of a continuous toilet exhaust and packaged terminal air-conditioner (PTAC) units. The outside air exchange rate in each guest room averaged six times an hour, all from infiltration. In this case, problems developed inside the building and inside the wall [Figure 2.3-I].

The combined effect of excessive outside air infiltration and an improperly located vapor retarder caused $5.5 million in moisture and mold damage, even before the facility was opened... If the same design combinations had occurred in a more temperate climate, the problems would have been limited to increased energy consumption and possibly to complaints about guest comfort. (Odom et al. 2005, pp. 10–11)

This case study illustrates that to help alleviate CV fan issues, an intermittent toilet exhaust system would have reduced the airflow exhausting from the building and makeup air introduced directly to each individual room could have allowed for the makeup air to be distributed at the area of concern. This makeup air would have to be conditioned, dehumidified, cleaned, etc. by an HVAC system. Providing the makeup air to the corridors and through the door undercuts does not guarantee that the makeup air will travel to the areas of concern.

Constant-Volume Exhaust Fan Considerations

Centralized CV exhaust systems are best avoided where possible. Localized exhaust systems that only operate when the space is occupied are a superior alternative. This helps reduce the depressurization of spaces and the required directly ducted makeup air to the spaces. It is important not to oversize exhaust systems but to size them for adequately removing odors or contaminants of concern.

The case study "Constant-Volume Exhaust" demonstrates the climate and vapor barrier issues along with the pressurization impacts of CV exhaust.

Variable-Air-Volume (VAV) System Considerations

For VAV systems, the outdoor airflow to the building needs to be reviewed for proper airflow rates during operation of the VAV boxes from maximum airflow to minimum airflow. The individual VAV airflow rates need to be coordinated with the total system supply airflow (AHU, RTU, etc.) to verify that minimum system outdoor airflow and minimum VAV airflow rates are sufficient to maintain proper building pressurization at various levels or wings of the building and are also sufficient to satisfy the outdoor airflow requirements for dilution ventilation.

For example, consider a VAV AHU that is sized for 10,000 cfm (4720 L/s) total airflow with a required minimum outdoor airflow of 3000 cfm (1416 L/s). There is a connected load of 12,000 cfm (5664 L/s) of VAV boxes at maximum airflow and 4000 cfm (1888 L/s) with the VAV boxes at minimum airflow. When the total supply airflow is reduced, typically with a VFD, to accommodate the VAV boxes controlled at minimum airflow, the system needs to make adjustments, typically with return air and outdoor air damper control, to allow for the 3000 cfm (1416 L/s) of minimum outdoor airflow to be introduced into the air-handling unit/ system. At full minimum flow, the AHU needs to be providing 4000 cfm (1888 L/s) of total supply airflow, which consists of 3000 cfm (1416 L/s) of outdoor airflow and 1000 cfm (472 L/s) of return airflow. In addition, each VAV zone needs to be analyzed at maximum airflow and minimum airflow. If the system utilizes an uncontrolled return airflow in the zone, then a routinely low cooling load zone could often be negatively pressurized and thus present problems in a hot, humid climate. See Strategy 7.1 – Provide Appropriate Outdoor Air Quantities for Each Room or Zone for more details.

Return Air Plenums

For HVAC systems using an open plenum above the dropped ceiling for return air instead of a hard connected duct, the plenum pressure will be negative relative to the occupied space. Depending on building pressurization control and return grille pressure drop, the return plenum may also be negative relative to outdoors. In those cases, this negative pressure difference can create infiltration of untreated air and can create condensation in building cavities in both summer and winter (Figure 2.3-J). In the summer, humid air is drawn into an air-conditioned building, while in the winter the infiltration cools the envelope interior. If the building can't be pressurized properly or if return grilles result in significant negative pressure in the return plenum, return ducts can help reduce the potential for infiltration. If ducted returns are not possible, the case for providing the proper building envelope with a good air barrier would become even more important. For detailed information on building envelopes and air barriers, see Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces.

Figure 2.3-J Negatively Pressurized Return Air Plenum with Respect to the Outdoors
Photograph courtesy of Wagdy Anis.

Duct Leakage

Excessive air leakage in either the supply or the return duct will cause the supply air or return air within the space to become unbalanced. If the supply ducts are leaking air into the ceiling space, the AHU may deliver less air than it returns. This imbalance would depressurize the space, resulting in infiltration of unconditioned outdoor air into the space or wall cavity (Figure 2.3-K). Conversely, if the unit has a return-side air leak, it will deliver more air to than it returns air from the space (Figure 2.3-L). In this case, the mechanical space housing the unit and the attached wall systems would become depressurized. Depressurization could cause unconditioned outdoor air to infiltrate the wall cavity, even if the conditioned space were at a positive pressure. Preventing ductwork leakage is critical for controlling building pressurization.

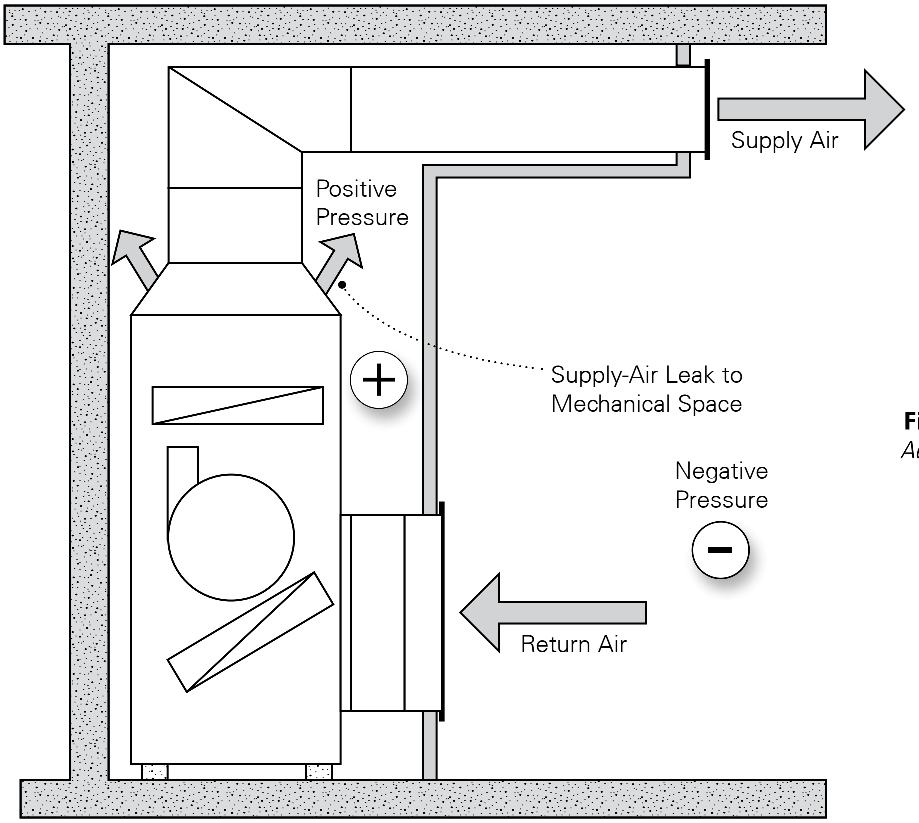


Figure 2.3-K Typical AHU Installation
Adapted from a figure copyright CH2M HILL.

An example of unsealed exhaust duct (Cummings et al. 1996) is shown in Figure 2.3-M. In a small hotel, unsealed exhaust ducts pulled outdoor air through the outside wall continuously. The air carried moisture that condensed behind the vinyl wall covering in the cool hotel rooms, resulting in mold infestation. The building's interior walls had to be pulled out and replaced to address the mold problem and the associated health risk. In this study, the field investigators measured the airflows entering and leaving the one unsealed central toilet exhaust system in the hotel. A single fan on the roof drew air from exhaust grilles in 40 guest rooms. The total of all airflows entering all 40 exhaust grilles was 1324 cfm (625 L/s). The airflow leaving the fan on the roof was 2799 cfm (1321 L/s). In other words, the leaking exhaust duct pulled more air from the building cavities than from the bathrooms (Harriman et al. 2001).

Following SMACNA guidelines for proper construction and sealing of ducts can help reduce excessive duct leakage. For additional measures, the ducts can be pressure-tested for air leakage. SMACNA's *HVAC Duct Air Leakage Test Manual* (SMACNA 1985) provides procedures and guidelines for leak testing of ducts.

Airflow Measurement

To evaluate building pressurization performance, one needs to determine the actual building pressure and the actual airflow rates into and out of the building. Therefore, it is important to allow for accurate and repeatable field measurements of airflows: outdoor airflow, supply airflow, return airflow, and exhaust airflow.

Duct Traverse. Duct traverse is one of the most accurate methods for determining airflow rates. For all ducted fan systems, both the Air Movement and Control Association (AMCA) publication *Field Performance Measurement of Fan Systems* (AMCA 1990) and *ANSI/ASHRAE Standard 111, Measurement, Testing,*

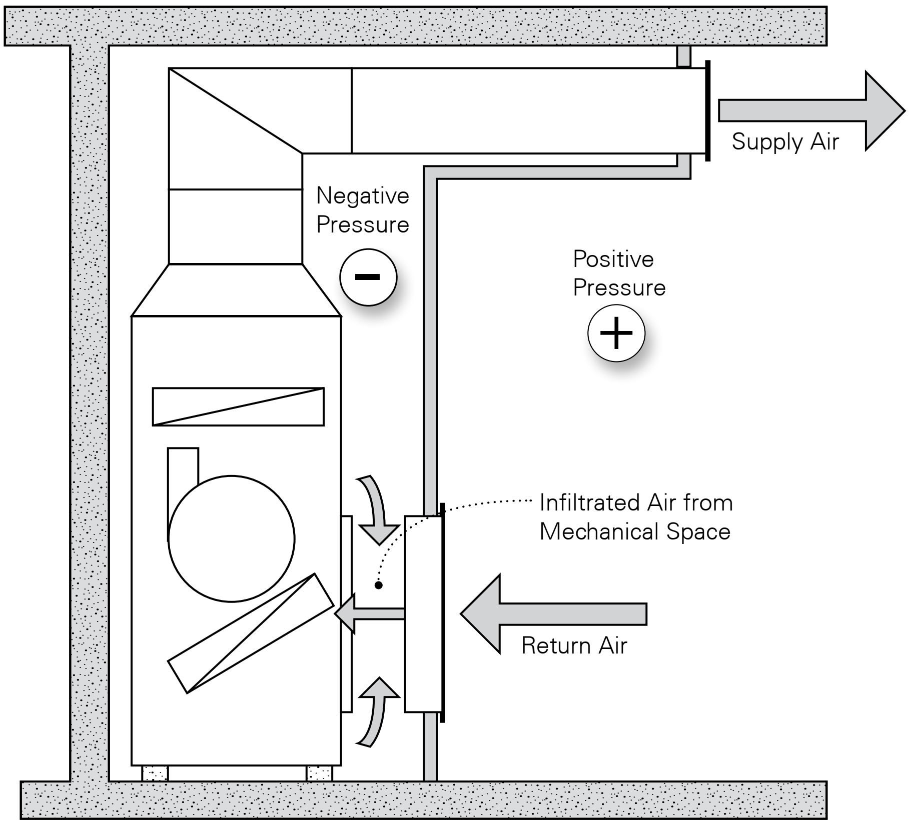


Figure 2.3-L AHU with Return-Side Leak
Adapted from a figure copyright CH2M HILL.

Adjusting, and Balancing of Building HVAC Systems (ASHRAE 2008), specify that an ideal duct traverse plane is 2.5 equivalent duct diameters from condition (discharge, elbow, etc.) for up to 2500 fpm (12.7 m/s)—this is both upstream and downstream of the duct traverse. For air velocities exceeding 2500 fpm (12.7 m/s), 1 equivalent diameter is added for each additional 100 fpm (0.5 m/s). For rectangular ducts, an equivalent length is calculated as $E_L = (4a{\cdot}b/\Pi)^{0.5}$, where a and b are the duct dimensions.

Duct Layout and Control Strategies. The duct layout and the control strategies need to be evaluated so that the HVAC fan/systems can be manipulated to the critical operational modes for airflow measurement. For example, for a CV AHU, airflow measurements need to be taken in minimum outdoor air mode and full air-side economizer mode. The control sequencing can become more complex when a VAV air-handling system is employed with an air-side economizer. It is important to determine what airflow measurements are required and how these measurements can best be obtained—both actual field measurements and those taken through control manipulation. To do this, one would have to account for the system outdoor air minimum, the full air-side economizer airflow, the maximum and minimum VAV airflow conditions, and the building pressure control strategies (relief fan control or return fan plenum pressure control).

Rooftop Units. The use of rooftop units (RTUs) presents a problem for outdoor airflow measurement. Unless the intake hood for the outdoor air is extended with the proper duct length to allow for a duct traverse, as noted in the previous two subsections, the outdoor airflow rate on a RTU cannot be accurately determined. In addition, if the RTU supply and return ductwork is installed without the proper equivalent duct length required for a duct traverse, the supply and return airflow rates cannot be accurately determined.

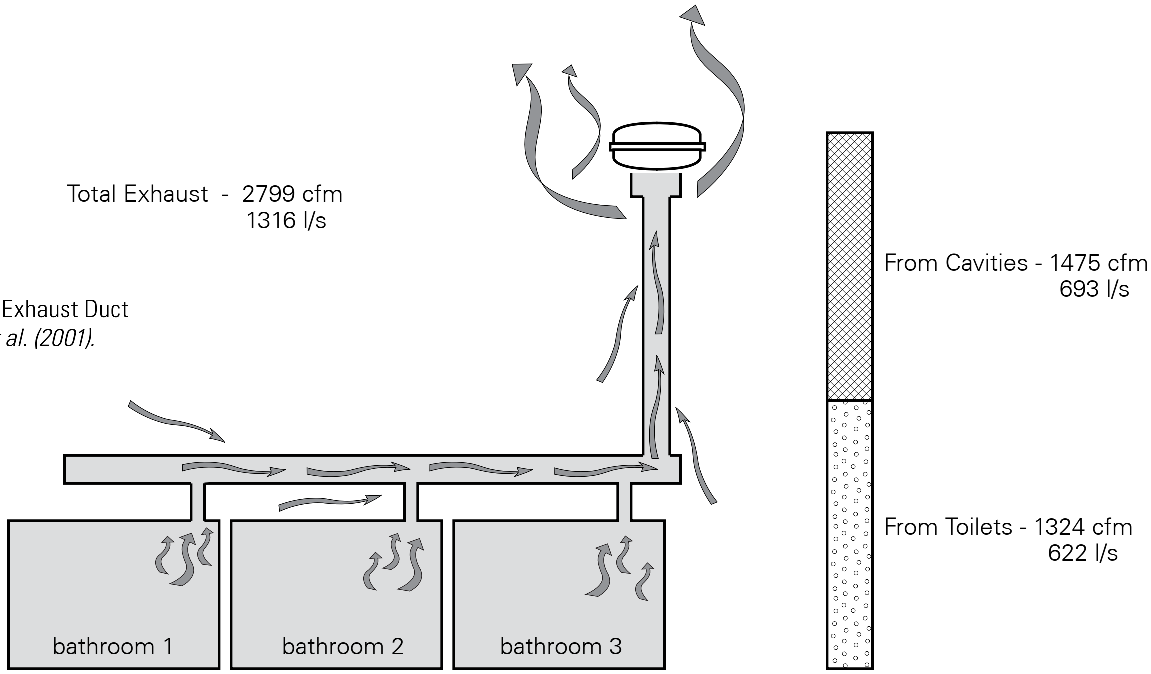


Figure 2.3-M Unsealed Exhaust Duct
Adapted from Harriman et al. (2001).

Exhaust Fans without Duct. Many buildings utilize exhaust fans that are installed without duct. These are typically wall-mounted or roof-mounted fans exhausting mechanical rooms, janitorial rooms, electrical rooms, or kitchen areas. In the majority of theses installations, there are no means available to accurately measure the airflow. It is wise to avoid such situations by installing ducts or grilles to allow for airflow measurement.

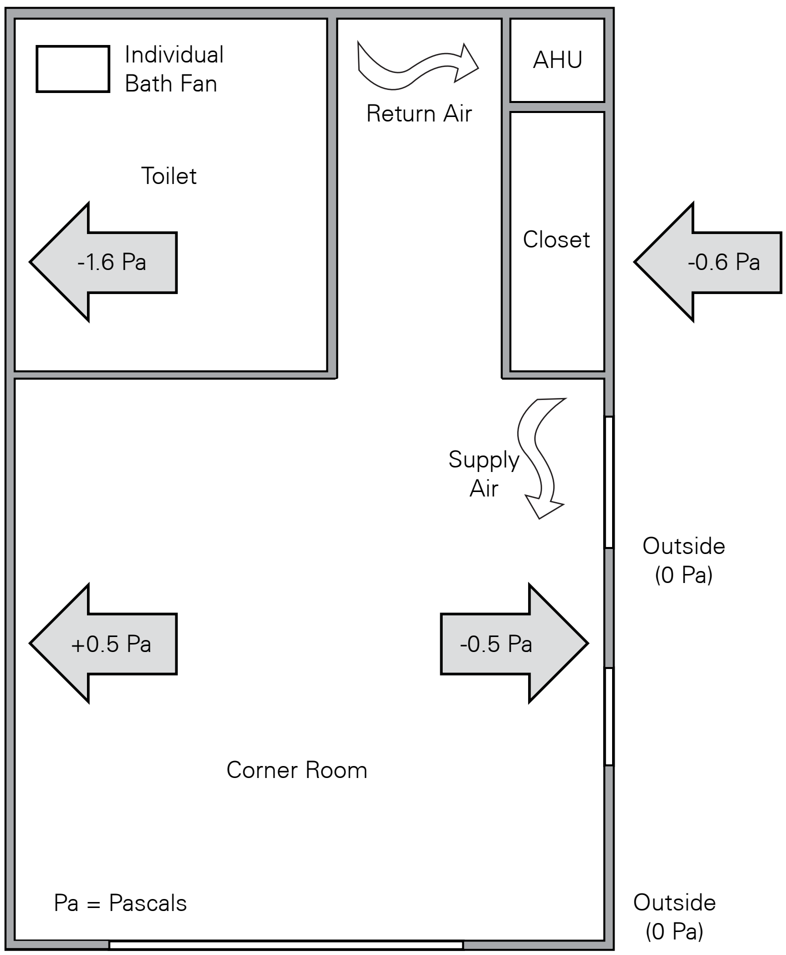
For a description of proper design and installation considerations to allow for accurate and repeatable measurement of airflows, see Strategy 7.2 – Continuously Monitor and Control Outdoor Air Delivery.

Verification of Pressurization Control
The following are suggested methods for verifying proper building pressurization.

1. Provide design information for the building pressurization requirements on the contract drawings. This should include total airflows into and out of the building, required directional airflow, and/or the required pressure differential for the building. A summary of the building pressurization requirements and airflow and pressure values in tabular format is extremely helpful.
2. Verify proper construction of the building envelope, including but not limited to proper use of air barriers and sealing of all pipe, conduit, ductwork, and any other envelope penetrations. For more detail see Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces.
3. Test, adjust, and balance the HVAC system and verify the outdoor air, exhaust air, supply air, and return airflows to ensure that the building is maintaining the proper pressurization relationship. This includes testing the systems in minimum and maximum airflow modes, as described in the previous section. In addition, 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. Limiting the measurements to the indoor-outdoor pressure differential can lead to misunderstanding of building pressurization. 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 pressure identical to that of the space. If infiltration positively pressurizes a wall cavity to the space, the infiltrated air could migrate into the space through an electrical outlet or similar pathway. Include measurements of the ceiling plenum pressures to verify that they are positive relative to the outdoors. Take measurements after all HVAC systems have been tested and balanced. If possible, take measurements at varying system operating conditions (i.e., maximum and minimum airflows for VAV systems, on and off for room fan-coil units). Depending on building orientation and HVAC system configuration, pressure readings might be required at close-to-peak seasonal conditions. For tall buildings this could include winter pressure readings to determine pressurization effects due to stack effect and summer readings to determine any reverse stack effect conditions. Figure 2.3-N shows an actual pressure map from a building room in central Florida.

5. If proper pressure relationships cannot be obtained utilizing the HVAC systems, then additional building envelope or interior partition airtightening may be required. See Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces.



Experience with commissioning indicates it is possible to have pressurized rooms and depressurized wall systems, both with respect to outside conditions. (These measurements were obtained from a building in central Florida that was significantly damaged by moisture and mold.) Even small negative pressures with respect to outside conditions can have devastating results, particularly in hot, humid climates. This building also had a misplaced vapor retarder on its demising walls, which trapped moisture that entered via air infiltration.

Measurement Location	FCU	Room Pressure	Wall Pressure
Outlet at Exterior Wall	On Off	+3.5 +0.5	-0.5 -0.5
Outlet at Demising Wall	On Off	+2.5 +1.7	- 0.5 +1.7
Penetration in Closet Wall	On Off	+4.0 +2.5	- 0.6 +2.5
Vanity Outlet	On Off	+3.2 +1.8	- 1.6 +1.6

Figure 2.3-N Pressure Mapping
Adapted from a figure copyright CH2M HILL.

Strategy 2.3

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Control Indoor Humidity

Introduction

Controlling indoor humidity is important for the delivery of thermal comfort for occupants, to help prevent condensation on surfaces whose temperatures are below the dew point of the surrounding air, and to avoid damp conditions in areas that are not designed to be damp. Dampness or wet conditions can foster bacterial and mold growth, causing both building damage and adverse health effects for occupants. High humidity also supports dust mite populations. Since dampness and condensation can occur in specific areas of the building subject to cold surfaces or infiltration/exfiltration through a building envelope chilled by cold outdoor temperatures or mechanical cooling indoors, the subject of indoor humidity is closely related to the following other strategies:

Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces
Strategy 2.3 – Maintain Proper Building Pressurization
Strategy 8.1 – Use Dedicated Outdoor Air Systems Where Appropriate

Principles of Indoor Condensation

As air is cooled, its capacity to hold moisture diminishes. Relative humidity (RH) is a measure in percent of the amount of water that air contains relative to the amount it is capable of holding. That is, "65% RH" means that the air contains 65% of its moisture-holding capacity. Thus, as air cools and its capacity to hold moisture diminishes, the relative humidity of that air increases. If the air continues to cool until the relative humidity is 100%, it is at full capacity and any further cooling will cause the moisture in the air to pass from a vapor to a liquid state (condense). The temperature at which air containing a given amount of water is cooled to 100% RH is called the *dew point*. Outdoors, air heats up during the day and absorbs water that changes from a liquid to a vapor state (evaporates). Then, when the air cools at night, it reaches its dew-point temperature and the vapor turns back into a liquid (condenses).

Whatever the thermal (temperature and humidity) characteristics of the air,[1] it always has a corresponding dew-point temperature, and when the air is cooled to this temperature condensation will result. Indoors, condensation occurs on cold surfaces. While the relative humidity of the air may be 50%–66%, a cold surface will cool the surrounding air sufficiently to cause a 100% RH at the surface, and the moisture in the air will condense.

Figure 2.4-B is a psychrometric chart (called a *psych chart* for short). This is a two-dimensional graph that relates the temperature and humidity characteristics of air to each other. The horizontal axis is the dry-bulb temperature. The vertical axis is the absolute humidity ratio measured in mass of water vapor per mass of dry air. Each point on the graph represents a unique condition of moist air. To fully characterize the "moist air conditions," we must know two properties and at least one of them must be related to humidity. For instance, we may know the dry-bulb and wet-bulb temperatures or the dry-bulb temperature and the relative humidity. For example, as shown on the psych chart (Figure 2.4-B), for a dry-bulb temperature of 78°F (26°C) and a humidity ratio of 0.0102 lb_w/lb_{da} (pounds of water per pound of dry air), the wet-bulb temperature is 65°F (18°C), the relative humidity is 50%, the dew point is 58°F (14°C), and the enthalpy (total heat content, both latent and sensible) is 30 Btu/lb_{da}. Table 2.4-B allows users of this Guide to test themselves on reading the psych chart shown in Figure 2.4-B.

[1] It takes two measurements to determine the properties of moist air at a given atmospheric pressure. At least one of these measurements must be humidity related (relative humidity, wet-bulb temperature, absolute humidity, dew point, etc.)

Strategy 2.4

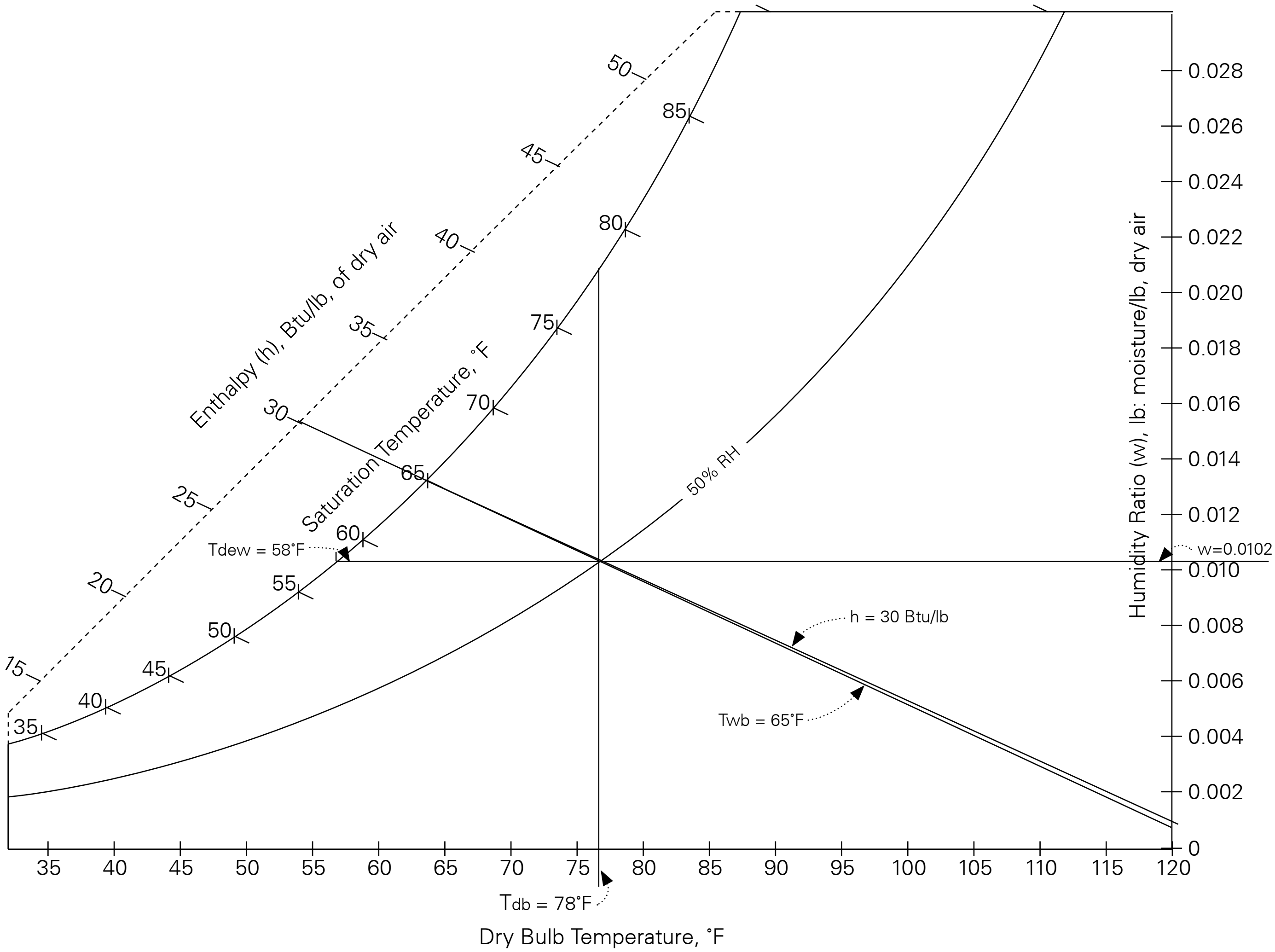


Figure 2.4-B Simplified Psychrometric Chart

Table 2.4-B Reading the Psychrometric Chart

Temperature	Humidity	Dew Point
78°F (26°C)	68°F (20°C) wet bulb	63°F (17°C)
85°F (29°C)	40% RH	58°F (14°C)
70°F (21°C)	70 % RH	60°F (16°C)

Whether or not condensation occurs at an air temperature of 75°F (24°C) depends on the humidity conditions (see the psych chart in Figure 2.4-C) of the air and the temperatures of the surfaces (see, for example, the discussion of the insulated pipe in Figure 2.4-D) that the room air is exposed to.

What Can Go Wrong?

It is common for air-conditioning system designers to choose indoor conditions such as 50% RH or 60% RH, so how can condensation occur? Wouldn't it take some very cold surfaces to result in condensation? The answer is yes, if the spaces are conditioned all the time at the peak design condition. More frequently, however, systems operate at part-load conditions at which they may not provide enough dehumidification

2.4

Psychrometric (Psych) Chart Example

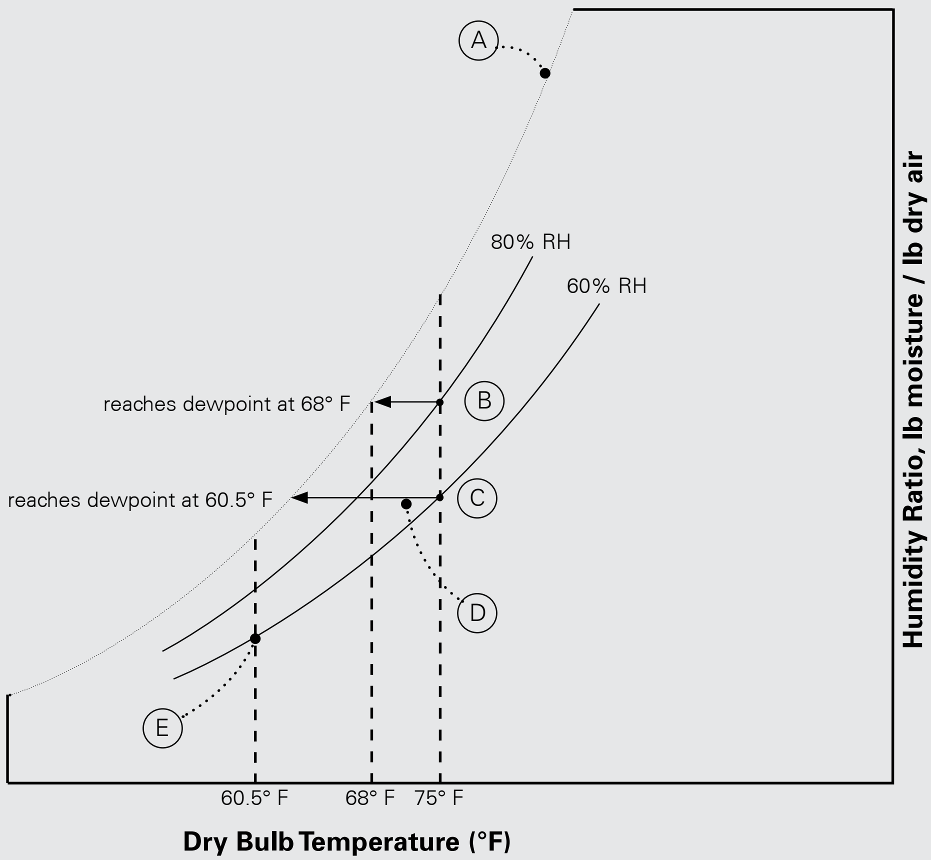


Figure 2.4-C Sample Psych Chart

Figure 2.4-C shows an example of a psych chart. The details that follow explain the labeled portions of the chart as indicated.

A. This is the saturation curve, at which air is saturated with as much water vapor as it can hold at any given temperature. Air can only exist at conditions to the right of this curve; its physical molecular properties prevent it from holding more moisture (going vertically above its saturation curve) or being colder at a given moisture content (going horizontally to the left of its saturation curve).

B. Moist air at the starting condition of 75°F (24°C) and 80% RH will reach saturation at 68°F (20°C), resulting in condensation.

B. 75°F (24°C) at 80% RH is an example of a condition that can occur when indoor relative humidity is not properly controlled (see the *ANSI/ ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality*, requirements on controlling aindoor humidity [ASHRAE 2007a]).

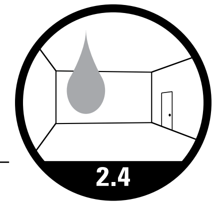
C. 75°F (24°C) at 60% RH is a common indoor room condition when indoor humidity is well controlled (see ASHRAE Standard 62.1 and the *Handbook—Fundamentals* [ASHRAE 2009] regarding indoor design conditions).

D. This horizontal line and the direction arrow to the left represent what happens to air when it cools, such as would happen when it approaches a cold surface. This process is called *sensible cooling* until the air reaches the saturation curve. If the air is cooled any more, it will roughly follow the saturation curve down and to the left, resulting in the appearance of liquid moisture, known as *condensation*.

E. The air at 60.5°F (15.8°C) and 60% RH will not result in condensation at the conditions given. It is dry enough that it will stop cooling before it reaches the saturation line.

(see the section in this Strategy titled "System Design Tips"). Furthermore, just like outdoor daily cycles of temperature and humidity, changes in temperature and humidity indoors, such as when systems are turned off, can lead to condensation.[2] (See Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces for more information.)

2 All building envelopes leak to some extent, and when systems are off the indoor conditions migrate toward outdoor humidity conditions. If outdoor humidity is high, this can result in condensation on cold surfaces. Cold surfaces (for example, on ducts and pipes) may result when the systems are turned back on. The more leaky the envelope and the more extreme the outdoor/indoor differential, the more potential that this condition exists. A different effect can occur if it is cold outdoors when the system is off and the walls cool down lower than the indoor dew point.



Example of Condensation on an Insulated Pipe

Figure 2.4-D shows the effects of humidity on an insulated pipe. The details that follow explain the labeled portions of the chart as indicated.

a. Insulation systems always result in surface temperatures somewhat different from the temperature of the surrounding air (colder than the surrounding air in the case of chilled-water piping). The surface temperature that would result from the conditions shown in Figure 2.4-D is approximately 68°F (20°C).

b. The condensation could drip on the ceiling, where, in combination with organic matter (dust, drywall paper, paint, etc.) it can result in biological growth—a bad result for good IAQ. Furthermore, it can wet the pipe insulation, allowing the growth of mold, degrading its insulation properties, and resulting in lower surface temperatures and even more condensation. Unchecked, this process can soak the insulation and even cause it to slough off the pipe.

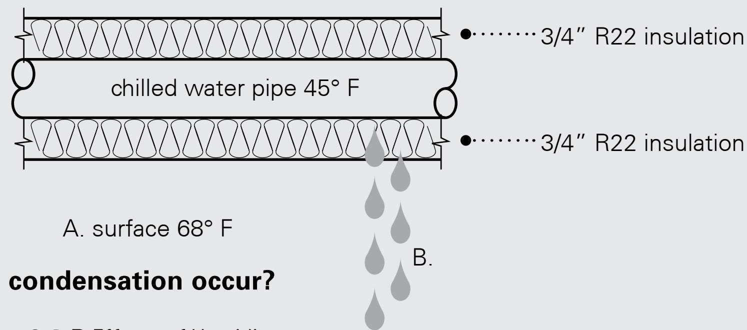


Figure 2.4-D Effects of Humidity

A leaky envelope, an unpressurized building (see Strategy 2.3 – Maintain Proper Building Pressurization), and building materials that absorb and then emit moisture can foil the system's ability to control indoor humidity. ASHRAE Research Project (RP) 1254 found such difficulties with many packaged systems and climates (Witte and Henninger 2006) at the maximum leakage rate allowed by *ANSI/ASHRAE/IESNA Standard 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings* (ASHRAE 2007b). ASHRAE Standard 62.1 (ASHRAE 2007a) requires a vapor retarder and caulking of exterior joints, although it does not prescribe an envelope leakage rate. Humidity considerations may require a tighter envelope than the minimum, but this may not occur. If perimeter spaces are depressurized, such as when systems are off or when makeup airflow does not keep up with exhaust airflow, infiltration of outdoor air will occur. If the outdoor air is humid and the exterior wall material is cold, moisture problems can occur inside the walls and be hidden from view.

Strategies to achieve building pressurization by controlling exhaust and makeup need not be complex. For instance, in hotel rooms, toilet exhaust can be limited by making the exhausts operate intermittently, for example, based on occupancy (e.g., interlocking the fan with the light switch).

Since HVAC designers do not have control over the tightness of the envelope, they may seek HVAC strategies to compensate for infiltration. Some buildings may require system operation when unoccupied to limit indoor humidity.

Strategy 2.4

Integrated Design Process

Indoor Conditions, Loads, and Special System Capabilities

An integrated design process to meet multiple needs, including avoiding condensation, starts with the selection of indoor design conditions. These conditions will normally be based on comfort (see Strategy 7.6 – Provide Comfort Conditions that Enhance Occupant Satisfaction) and building codes and standards. For example, ASHRAE Standard 62.1 requires 65% RH for systems that dehumidify. If there are conditions that can lead to condensation, such as high indoor humidity sources, unusually cold surfaces, or continuous

Building Interactions

Figure 2.4-E illustrates building interactions. The details that follow the figure explain the effects demonstrated in the diagram.

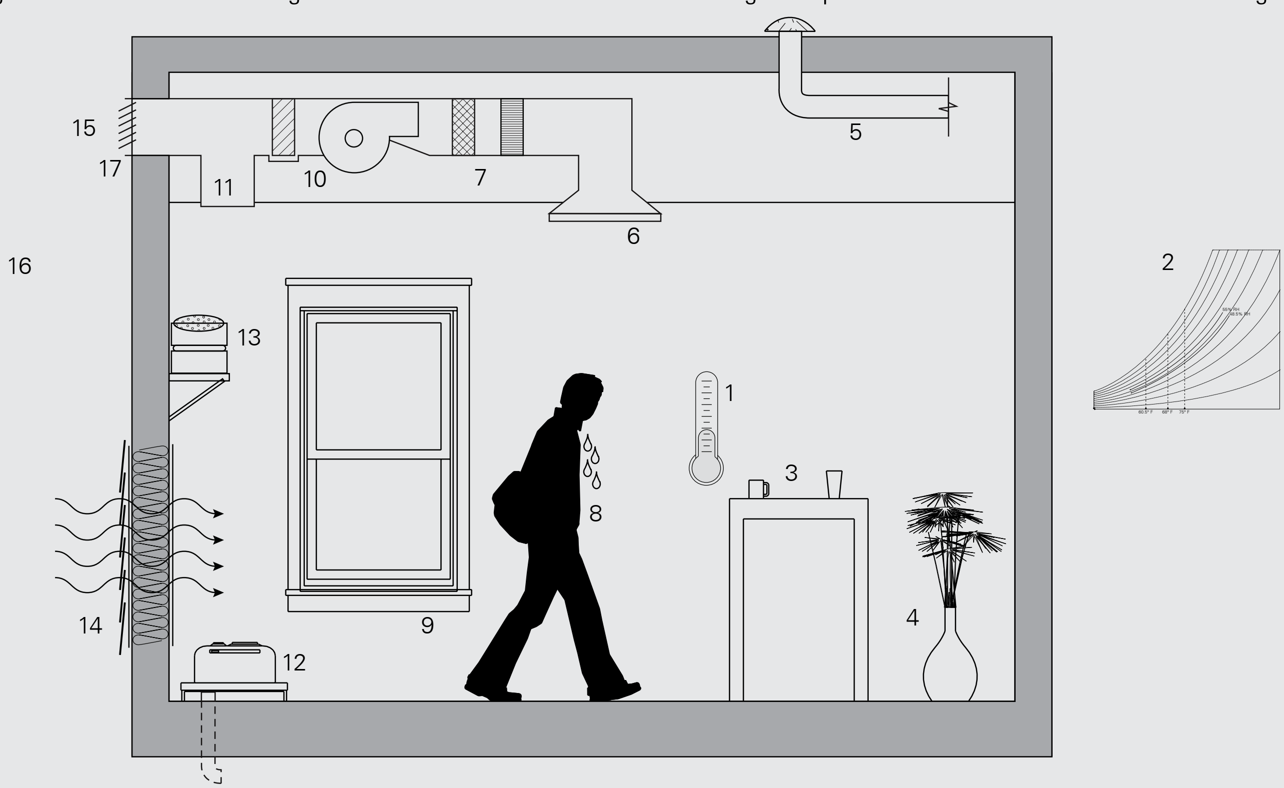


Figure 2.4-E Building Interactions

1. Room air (as shown on the simplified psych chart [see Figure 2.4-B]) contains moisture that has the potential to condense into liquid when it meets a cold surface.

2. This chart represents the psychrometric condition of the air in the room. As the air approaches the cool surface of the glass, it cools sensibly and moves horizontally to the left on the psych chart. When it cools sufficiently that it reaches its dew point (the saturation condition), liquid moisture condenses from the air.

2. The psych chart is not required in every indoor space, but it is a required accessory for every engineer's office.

3. Moisture may condense from the air at a cold surface, such as this drinking glass. Although condensation on the glass may not create a problem, a similar occurrence elsewhere is to be avoided. The psychrometric condition of the air at the cold surface where condensation occurs is shown on the simplified psych chart (1). Hot drinks and hot food also add moisture to the space. This can be a significant factor in food serving and preparation areas.

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4. Moisture sources that occupants may introduce into a space, such as this plant, should be considered. Other unusual sources include decorative water features.

4. Moisture transmission from other indoor spaces must be considered in the space humidity load calculation. This may come from sources such as kitchens, steam rooms, natatoriums, etc.

5. Rainwater and snowmelt from a roof drain enters the roof drainpipe. This pipe may be insulated, but this is not always the case. Condensation may occur at any surface that is colder than the dew point of the surrounding air.

6. Supply air that has lower absolute humidity (the vertical axis on the psych chart) than room air has the effect of lowering the room air humidity.

7. Dehumidification that is part of the HVAC system is another way to maintain indoor humidity conditions in certain unusual cases, such as when a latent load exists and the sensible load is zero. Dehumidification can use a mechanical refrigerant cycle or a desiccant. The desiccant can be recharged (the process of removing the moisture so it can dry a new batch of air) using the exhaust airstream, waste heat, or another heating fuel. There may be energy considerations and restrictions on the use of such heat.

7. In certain unusual cases, a reheat coil may be required to maintain indoor humidity conditions, such as when a latent load exists and the sensible load is zero. Energy considerations may require that recovered heat be used for this purpose. See note 17 for another way to achieve the conditions.

8. This person is sweating profusely, but all people give off water vapor, even when at rest. The quantity is affected not only by emotional state but also by the level of physical activity and even indoor thermal conditions themselves. Moisture given off by people is taken into account in the heat gain values for persons at various activities (see *ASHRAE Handbook—Fundamentals*, p. 9.6, Table 4 [ASHRAE 2009]).

9. The window mullion or the windowpane may be the coldest surface in the room and therefore can be the location where condensation first occurs. If the surface is clean and not organic, biological contamination may not result. However, organic building materials or organic dust or dirt on surfaces in the presence of moisture can permit growth.

9. If condensation first occurs on the windowpane, liquid moisture can then drip down onto other window and wall surfaces or even inside the wall cavity.

10. Varying the volume of the airflow at part-load conditions and keeping the cooling/dehumidification coil temperature low (rather than keeping a constant volume and raising the coil temperature or cycling it on and off) can be an effective strategy to control indoor humidity. While variable-air-volume (VAV) is more often thought of as an efficient zone control method (and it can indeed accomplish that), it is also useful for such humidity control, even in a single-zone system. This is especially important in spaces with high humidity loads that result from hot, humid air and/or large sources of indoor humidity.

10. The condensate pan should collect and remove the moisture that condenses on the cooling coil and drain it safely out of the occupied space.

10. In order to remove moisture, a cooling coil must be sufficiently colder than the dew-point temperature of the airstream. If the coil has a control valve that throttles flow and raises the coil temperature at part-load conditions, then the coil may not do its job. A similar result can occur if the coil cycles from on to off due to re-evaporation that occurs during the off cycle. Keeping the cooling/dehumidification coil temperature low rather than raising the coil temperature or cycling it on and off can be an effective strategy to control indoor humidity.

11. Room air that enters the system as return air can then be cooled and dehumidified. This diagram depicts a system where the return air mixes with outdoor air before going to the cooling/dehumidification coil.

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12. A stand-alone room dehumidifier can be used to remove moisture. See the dehumidifier installed in the HVAC system (10, 11) for another option.

12. For a dehumidifier to be effective, condensate from it must be removed from the room.

13. Humidifiers can be freestanding in the room or part of the HVAC system. Occupants sometimes use the former type to improve comfort (Schoen 2006), but this type can have negative consequences if the building is not designed to handle the humidity load. Freestanding humidifiers can also be sources of biological contaminants, especially if not properly maintained.

14. Outdoor air comes through walls and doors by natural driving forces such as wind and thermal buoyancy (stack effect) and adds humidity to the room. As shown by ASHRAE RP-1254 (see discussion in text), this can have a significant effect both immediately and as moisture is stored by building furnishings during system-off periods (Witte and Henninger 2006).

14. The building membrane must control the entry of unconditioned air and not just liquid moisture.

14. If air does get into the building's outer membrane, then condensation can occur inside the wall, especially if there is an impermeable layer, such as vinyl wallpaper.

15. The intake louver is where outdoor air is intended to enter. The quantity must be properly controlled; louvers must prevent the entry of liquid moisture (there are industry ratings for controlling entry of wind-driven rain), and the cooling coil must be properly designed to handle the humidity load. There also must be a way to relieve excess pressure—for instance, when the system is in economizer or excess outdoor air mode. A relief air louver (not shown) with a motor or gravity-operated back draft damper is one way to do this. The damper prevents the louver from operating in reverse and becoming a source of unconditioned outdoor air. The HVAC system should generally not introduce unconditioned air that is hot and humid, as this creates an uncontrolled humidity load on the room and can cause localized conditions that lead to condensation.

16. Outdoor air can be a source of water vapor (typical for hot, humid climates) or it can absorb moisture (typical of the drying effect that occurs in the winter in cold climates). Determining which is the case depends on the absolute humidity of the outdoor air (weight of water vapor/weight of air—the vertical axis on the psych chart) compared to indoor air and not on its relative humidity. Cold air that is 100% relative humidity can have a drying effect indoors when it heats up, while hot air at moderate humidity (even 40% at high temperatures) can be a source of moisture indoors.

17. The building envelope can allow unconditioned outdoor air to enter—for instance, at mating joints of building elements. This can add moisture to the indoor environment. A good building envelope controls the entry of liquid moisture (rain, snow, meltwater) as well as air and vapor.

ventilation combined with conditioning cycling on and off in humid climates, then additional analysis of potential condensation is advisable. See Figure 2.4-E for an overview of the interactions among the conditioned space, humidity sources, and the HVAC system.

Figure 2.4-E illustrates the interactions among the building envelope, cold surfaces, space use, humidity sources, and the HVAC system that only an integrated design process can fully address. Once all the heat and humidity sources and the loads they add to the space are known, the common peak load calculation will provide the equipment capacity needed to meet the sensible and latent design loads. Equipment capacity ratings alone are not sufficient because they are rated at standard conditions that usually do not correspond to the needs of spaces with humidity-control challenges. System-specific parameters based on the load calculation (see *ASHRAE Handbook—Fundamentals*, Chapter 18 [ASHRAE 2009]) need to be used to rate the performance of equipment. Otherwise, the equipment may not achieve design conditions.

A high humidity load (low sensible heat ratio) requires a flow rate lower than the standard 400 cfm/ton (54 L/s per kW); selections of 200 cfm/ton (27 L/s per kW) or even lower are not uncommon. The low flow rate is matched with a sufficiently low discharge air temperature leaving the coil to fully dehumidify the air. For instance, the assembly room example in the summary guidance portion of this Strategy (Part I of this Guide) is designed for parties and has a large latent room load compared to sensible room load due to people actively dancing and from hot food vapors. This system at peak load requires a discharge air temperature of 48.5°F [7.5°C]) and only 180 cfm/ton (24 L/s per kW), which was achieved using a chilled-water coil with cooler-than-typical chilled water (39°F [4°C]) and sufficient surface area to meet this low air temperature requirement. The very cold air coming off the coil is much drier than air at 55°F (13°C). These few degrees make a bigger difference to latent load than to sensible load. Air this low is typically below the published catalog rating tables for packaged equipment and may require discussion with the manufacturer's equipment applications personnel, an upgrade of the equipment selection, selection of special equipment options, or a change in the system type. *That is, off-the-shelf packaged equipment at average selection points may not suffice.*

A second load calculation at a "humidity challenge" condition is required by ASHRAE Standard 62.1 (ASHRAE 2007a). This condition requires that the designer consider the dehumidification performance of the system at a high latent/low sensible load condition. However, even this new requirement does not mean that special humidity control systems need to be added. Simpler solutions are often available, as described in the following section titled "System Design Tips." Example 5-F from *62.1 Users Manual* (ASHRAE 2007c) illustrates the "humidity challenge" condition and required calculations and is shown in Appendix C – Dehumidification in Virginia.

One definition of hot, humid climates, provided in *Mold and Moisture Prevention* (Odom et al. 2005), is simple and helpful in identifying the latent/sensible issues for different climates (see the italicized portion of the following quotation). According to Odom et al. (2005), the ASHRAE definition of a humid climate may omit some areas with high dew-point conditions where moisture problems tend to occur (ASHRAE 2009, Chapter 14). They note, for example, that Atlanta, Georgia, does not meet the ASHRAE definition of a humid climate, but problem buildings often occur there. They conclude that

> [i]ndustry experience with building failures suggests the need for a new definition of humid climates that more clearly identifies the geography where problem buildings are more likely to be found and better explains why these problems occur at all. This new definition is based on observations about latent and sensible load: *A humid climate is defined as one where the average monthly latent load of outdoor air meets or exceeds the average monthly sensible load for any month during the cooling season.* ....Infiltration of air with a high latent load will cause moisture to accumulate in building materials such as gypsum board, with subsequent material degradation and mold growth. This infiltration may also exceed the ability of the HVAC system to remove moisture from the supply air. On any given day in many temperate areas, the latent load may be greater than the sensible load without causing problems; however, when these conditions persist for a longer period (a month, for example), the resulting moisture accumulation is sufficient to cause building failure. The occurrence of a high latent load during the cooling season is a critical factor in building failure. Thus, defining hot, humid climates in terms of the relationship of sensible to latent load in ambient air expands the ASHRAE humid climate zone to include other parts of the United States that are highly susceptible to moisture-related building failures. (Odom et al. 2005, pp. 11–12)

The authors present examples from Peart and Cook (1994) that illustrate the use of this definition (see Figure 2.4-F).

As shown in Figure 2.4-F, in Orlando, Florida, the latent load of the outdoor air exceeds the sensible load in many months. In Atlanta, the latent load approximately equals the sensible load in July and is close to it in other summer months. Odom et al. (2005) conclude that although standard air-conditioning systems have a better chance of handling the latent load in Atlanta than in Orlando, Atlanta still should be considered to be within the boundary of the humid zone. Columbus, Ohio, on the other hand, consistently has average monthly latent loads lower than the sensible load.

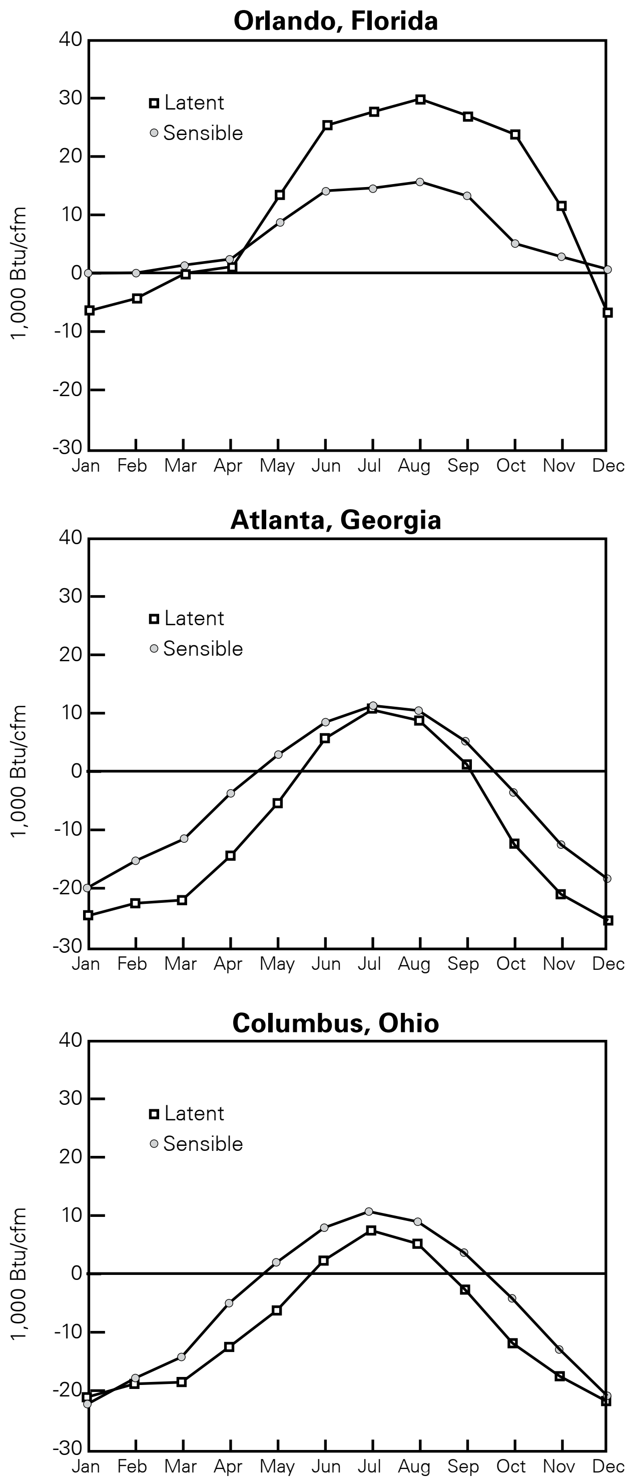

Figure2.4-F Comparison of Average Monthly Latent and Sensible Loads for Three Locations *Adapted from Peart and Cook (1994).*

System Design Tips

Indoor humidity can be controlled in many designs without the use of additional energy inputs for reheat or a dedicated dehumidifier. This can be done by using strategies such as dedicated outdoor air systems (DOASs), hot gas reheat, or variable volume control, (as opposed to cycling control or supply air temperature reset). In addition, special analysis and modification of small packaged units may be required in some situations.

Dedicated Outdoor Air Systems (DOASs)

Decoupling the conditioning and delivery of outdoor air ventilation from the airstream that thermally conditions the space is one way to assist in controlling indoor humidity, especially when outdoor air humidity is high and variable. In order to do this, a dedicated outdoor air ventilation conditioning system handles 100% outdoor air and is designed to deal with humidity and sensible loads at all outdoor air conditions. In many climates this means it must have heating and cooling/dehumidification capabilities. Systems that achieve this are sometimes called *dedicated outdoor air systems* (*DOASs*) (Morris 2003), and one version of this technique has been referred to as *single coil twin fan* (Sekhar et al. 2004, 2007).

A hotel with through-the-wall packaged terminal air conditioners that control temperature to each guest room is a candidate for a separate central DOAS. Whether the thermostat calls for conditioning or not, the outdoor air ventilation can still be provided, and it can be dry enough to control the room humidity that comes from infiltration, people, or other room sources.

If the discharge air temperature of the DOAS is kept constant, then the outdoor air it introduces will not add humidity load to the space. (If the supply air dew point is kept low enough, then the system can also address humidity load from people and other indoor sources as well as from outdoor air that infiltrates through wall cracks, open windows, or doors. Pressurizing the space will reduce but may not avoid such infiltration loads.

Hot Gas Reheat

Hot gas reheat uses recovered energy (hot refrigerant gas that the compressor in a refrigeration cycle discharges on its way to the condenser) to reheat air that has been cooled and dehumidified. This is essentially the same cycle that a dedicated refrigerant cycle dehumidifier uses, but it can be incorporated into the main conditioning system. With this capability, the system can remove humidity from a space without sensible overcooling. Thus it is useful at conditions of low sensible heat ratio (SHR), which may, for instance,

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occur at part load. In hot gas reheat, some of hot gas is diverted to a separate coil downstream of the dehumidification coil. While the hot gas is recovered waste heat, the entire process is not without energy cost.

Variable-Air-Volume (VAV)

VAV, usually thought of as a method for zone control, also works for dehumidification because less air at a low coil discharge temperature retains the moisture removal capacity of the system at part load. Reset of supply air temperature does not accomplish this (see the *62.1 User's Manual* [ASHRAE 2007c]). The energy conservation and zone control benefits of VAV also benefit dehumidification at part load. This is because the lower discharge air temperature at part load retains the dehumidification capability.

However, providing sufficient outdoor air in VAV systems at part load can pose challenges. As the pressure inside the air intake plenum changes with varying air volume, special methods of controlling outdoor air are needed. See Strategy 7.2 – Continuously Monitor and Control Outdoor Air Delivery for techniques; such control is necessary to satisfy both the IAQ requirements of ASHRAE Standard 62.1 (ASHRAE 2007a) and also to balance exhaust and avoid depressurization, particularly along the perimeter of the building and especially in hot and humid climates.

Many systems are equipped with air-side economizers, which use cool outdoor air to provide free cooling when its enthalpy (total sensible and latent heat content) is less than that of the return air. If the system is not designed to handle the humidity load of outdoor air that is very moist (even though it has lower enthalpy), then it may be necessary to "lock out" such economizer air based on dew-point temperature. For more information about this strategy, see *Humidity Control Design Guide for Commercial and Institutional Buildings* (Harriman et al. 2006).

Small Packaged Systems

The designer may need to upgrade the type of cooling unit in small packaged systems to control humidity. ASHRAE RP-1254 (Witte and Henninger 2006) evaluated multiple system configurations and options and discussed their ability to meet the dehumidification requirements of ASHRAE Standard 62.1 in various climates and load conditions. It was found that meeting the requirements in offices was not a problem and in retail was only occasionally a problem. However, it was found that in numerous situations packaged equipment could not meet the needs even at full load, especially for those spaces requiring high proportions of outdoor air (restaurants, 45%–60%; theaters, 40%–65%; schools 40%–50%) and those with long unoccupied periods (such as motel rooms, which require 16%–20% outdoor air).

The research project used the 65% RH requirement in ASHRAE Standard 62.1 combined with a detailed model including off-hours infiltration and the moisture storage capacities of building finishes and furnishings. The detailed model goes beyond what many designers do. While the model may accurately describe how real-world walls and furnishings behave, condensation and moisture problems may not necessarily occur at 65% RH, which allows for some safety factor. Nevertheless, the research suggests that designers pay more attention to this issue.
The research found that latent degradation of cooling and dehumidification coils when the unit cycles off was a significant detractor from good humidity control. A VAV system, as discussed at the end of this section, would avoid much of this degradation. It is essential to closely examine the latest packaged equipment options of all kinds and their abilities to meet the sensible and latent loads at full- and part-load conditions. For instance, some packaged rooftop units are now available with additional stages of cooling and hot gas reheat. Furthermore, some are also available with airflow as low as 200 cfm/ton (27 L/s per kW), which is even lower than the research project considered. Even through-the-wall "motel" type units are available now with enhancements such as reheat of subcooled discharge by air heat pipes that recover heat from return air.

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Edited Guidelines Excerpted from ASHRAE RP-1254 (Witte and Henninger 2006)

1. In nearly all cases, simple variations of lower airflow/lower SHR do little to improve humidity control but may be useful to save fan energy.
2. Demand-controlled ventilation (DCV) saves energy but does little to improve humidity control in most cases.
3. Semi-active humidity control systems like subcool reheat and coil bypass can help but often fall short, especially in the most humid climates.
4. Certain applications, such as in restaurants, theaters, and motels in very humid climates, have high humidity issues, primarily at times when there is no sensible load on the coil due to cool moist outdoor air. Only active humidity control systems (desiccants and reheat) can control humidity at such times. Depending on the control settings, enthalpy wheels may not operate at such times and therefore will provide fewer benefits for humidity control.
5. For all of the systems without direct humidity control (all cases except desiccant and reheat), system capacity vs. load profile is crucial. The poor humidity control performance of many of these system options can be attributed primarily to a high percentage of hours operating at low part loads. Two-stage systems with a 60% stage 1 capacity help significantly but do not overcome this issue. Direct expansion (DX) without latent coil degradation (a VAV system would be expected to perform close to this) represents the ideal in capacity staging where the coil never evaporates condensed moisture back into the supply airstream.
6. For offices, humidity control is not an issue.
7. For restaurants, theaters, and schools, systems with direct humidity control (desiccant and reheat) are the only systems that can provide adequate humidity control in the most humid climates. In less humid climates, enthalpy wheel systems can also provide adequate control.
8. For motels, continuous operation and single-stage equipment result in excessive hours of high humidity. Only dual path with desiccant provides adequate (or near-adequate) humidity control in the most humid climates. Reheat and dual-path systems can help significantly and are sufficient in moderate climates.
9. For retail stores, a wider range of options can be beneficial.
10. The enthalpy wheel and DCV options generally provide equal or better humidity control compared to the base system, with significant energy cost and life-cycle cost savings. Significantly better humidity control (but not necessarily adequate control) is found in restaurants with the 2004 standard, in retail locations with both standards, and in schools with both standards. Poorer humidity control is found in restaurants and theaters in certain locations.

The research project points out some real-world issues with humidity that many ordinary engineering office load calculations do not take into account. One very significant issue is the difficulty meeting the 65% RH criterion from ASHRAE Standard 62.1 if one takes into account off-hours infiltration and storage of moisture in the building and its furnishings. Designers are not required by ASHRAE Standard 62.1 to assume a leaky envelope or to model moisture storage, even though these may correspond to reality more accurately. Designers exercise judgment when selecting the infiltration rate (most load calculations do include this; a broad range is within reason), and this has a big impact on whether the design will meet the 65% RH criterion (which has a margin of safety built into it). Real buildings do store moisture and because of this will be more humid than the load calculation predicts, especially if they are leaky. In the guidelines excerpted from ASHRAE RP-1254 in the sidebar, space types and system types that present special challenges are pointed out. When selecting packaged equipment, pick the low-hanging fruit first: look for factory options discussed in this Strategy such as very cold supply air temperatures, VAV, multiple stages of cooling, hot has reheat, and heat pipes for reheat, then consider the other system configurations the research project discusses.

Other options for small packaged systems as well as for large ones, such as DOAS and VAV, involve system type selections that must be made early in the HVAC design process. While VAV systems are often thought of for large multi-zone systems, they can provide humidity control even in single-zone systems. VAV can almost always be applied to packaged rooftop equipment larger than 20 tons (700 kW) (and may be available at even smaller sizes), chilled-water air handlers, and built-up DX air handlers. In order for this strategy to be effective in a DX system, the coil must run continuously cold. Therefore, part-load refrigerant flow control, such as hot gas bypass, variable-refrigerant-volume, and variable-flow compressors may be needed. Sometimes, using VAV to control humidity may be available with an upgrade of the HVAC system type to a built-up system or multi-zone unit.

In most spaces, using one or several of the techniques discussed in this section will be sufficient to achieve indoor conditions of sufficiently low humidity to avoid condensation. For instance, if the SHR of the space at the part-load conditions is above 0.5 (latent load not more than half of the total load), sufficiently low humidity can be achieved with VAV but may require a low coil discharge temperature and higher thermostat setpoints. To determine, with a high degree of reliability, whether indoor humidity will be controlled with open-loop control (no humidity sensor to feedback and control system functions) requires calculations at a range of common and demanding part-load conditions. See the *62.1 User's Manual* (ASHRAE 2007c) for more details about how to do this calculation.

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. Spaces that may exhibit these characteristics include underground spaces, swimming and bathing areas, kitchens, and spaces where large amounts of unconditioned humid outdoor air enter, for instance by door openings or other forms of infiltration.

In the case of showers, natatoriums, and cooking areas, for example, it is accepted that humidity will be high and condensation will occur; therefore, surfaces are constructed using materials that are inorganic and cleanable. Even in a natatorium, not all the surfaces or materials may be so tolerant of very high humidity and condensation can be objectionable for other reasons. For these reasons, dehumidification is often used in natatoriums.

When such spaces with high humidity are in buildings with other spaces not so tolerant of these conditions, it is best to keep them at negative pressure with respect to the rest of the building; otherwise, the building itself may require special consideration for humidity control.

Some designs call for *intentionally cool surfaces*, such as chilled ceiling systems 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. These systems recover the sensible and latent heat from the exhaust airstream for use in the outdoor airstream. This recovery can be done using equipment such as rotating heat wheels and heat pipes, both of which are commercially available. The former uses a rotary recovery matrix turned by a motor, which transfers heat between the exhaust and intake airstreams. A heat pipe uses an internal heat transfer medium to transfer a large amount of energy over its length with a small temperature drop through liquid evaporation in the evaporator section of the heat pipe (heat source), vapor condensation in the condenser (heat sink), and liquid movement in the opposite direction inside a wick by capillary force (see Strategy 8.2 – Use Energy Recovery Ventilation Where Appropriate).

Dedicated Dehumidification Systems

As discussed, certain spaces with high humidity loads in proportion to their sensible loads may require a dedicated dehumidifier. These systems may be based on the refrigerant cycle or on a desiccant.

Refrigerant cycle dehumidifiers use both the cold and hot sides of a refrigeration cycle first to cool and dehumidify an airstream and then to reheat it. The resulting discharge air is both warmer and drier than the air that entered the dehumidifier. One common application for this type of dehumidification is in natatoriums, where a combined pool heating, ventilating, and dehumidification unit is often used.

Dry desiccant dehumidifiers typically use a crystalline substance (desiccant) in a rotating wheel that adsorbs moisture from the airstream to the occupied space. The most typical liquid desiccant is a strong solution of lithium bromide and water. In all cases, collecting moisture via a desiccant releases the latent heat of vaporization, so the air comes out dry but warmer; it likely needs to be cooled before it can be used. The desiccant must be regenerated with air at low relative humidity, usually accomplished by a heated airstream, which may use recovered heat to conserve energy.

Humidification

Humidifiers can have benefits if properly applied and maintained (Schoen 2006). Extremely dry air may affect human health and comfort enough to warrant its use. However, risks of using humidifiers include the possibilities of overhumidification, resulting in moisture problems and the release of contaminants from the humidifier itself.

Following the requirements of ASHRAE Standard 62.1 (ASHRAE 2007a) and addressing the other design and maintenance issues identified in the following paragraph can reduce the risks of humidification.

ASHRAE Standard 62.1 (Section 5.13) has two requirements related to humidifiers: water quality and obstructions (see Figure 2.4-G).

- *Water Quality.* Using water from a potable source will often be the easiest way to meet the water quality requirement. If water from a non-potable source is used, then it must have equal or better quality, which can be achieved by treatment and verified by testing, but the standard does not give specific guidance. Chemicals used for treatment of steam by this requirement must be suitable for drinking, and inhaling them may trigger additional considerations.
- *Obstructions.* Downstream air cleaners and duct obstructions such as turning vanes, volume dampers, and duct offsets greater than 15° away from the humidifier need to be located downstream of the absorption distance recommended by the manufacturer.

Humidification Using Energy Recovery Ventilation

As an alternative or even in addition to a dedicated humidifier, consider preconditioning outdoor air using a total energy recovery wheel. During winter operation, this approach transfers both sensible heat and moisture

Mixed Evidence of Health Effects of Humidification

Mendell (1993) found that insufficient information was available to assess the risks of steam humidification. Furthermore, some potential inconsistencies were found regarding humidification in that newly installed humidification systems reduced worker symptoms in general, yet cross-sectional studies of buildings found the presence of humidification systems to be associated with a higher prevalence of some symptoms.

The explanation Mendell proposes is that short-term humidification may reduce symptoms of low indoor humidity, but long-term humidification may more substantially increase the risk of symptoms from microbiologic contamination (in the humidifier or elsewhere).

More recent studies have found different results and reached different conclusions. Preller et al. (1990), for example, found that office absenteeism was higher when there was no humidification (spray or steam type). Seppänen and Fisk (2002), in their synthesis of previous work, reference Mendell and Smith (1990) and conclude that insufficient information is available for conclusions about the potential increased risk of sick building syndrome symptoms with humidification in office buildings. Air-conditioning systems with steam humidification did not seem to be associated with a higher prevalence of symptoms than systems without humidification. However, air-conditioning systems with liquid-water-based humidification were associated with an increased prevalence of some symptoms compared with systems without humidification.

Nagda and Hodgson (2001) performed a literature search to make conclusions regarding health effects from low humidity in aircraft. They point out that few studies have examined the health effects of low humidity and that most of the past research addressed perceptions of humidity and thermal comfort.

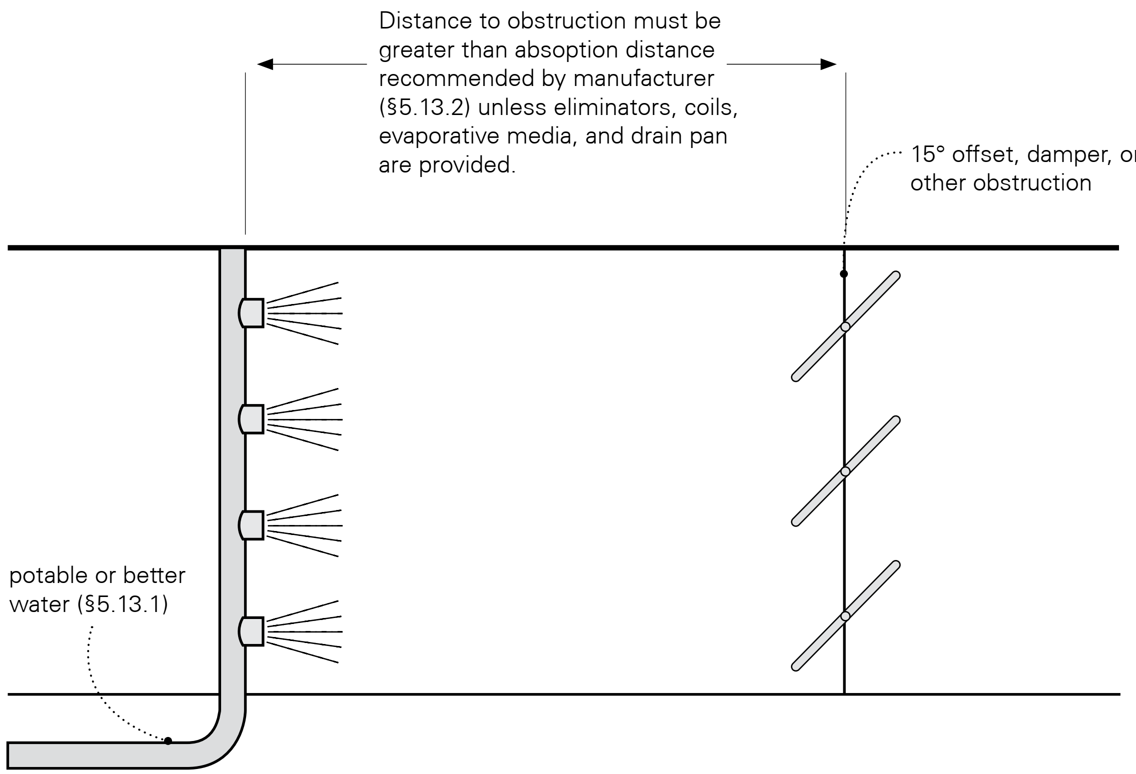

Figure 2.4-G Humidifier/Water Spray System
Adapted from ASHRAE (2007c), Figure 5-V.

from the relief airstream to the intake airstream, effectively recovering and retaining some of the moisture generated by occupants. However, there are limitations to the use of exhaust airstreams.

Because there is some cross-contamination between intake and exhaust, some exhaust air, such as that from commercial kitchen and laboratory hoods is not suitable for energy recovery ventilation, and ASHRAE Standard 62.1 specifically prohibits this. There are restrictions on the amount of cross-contamination from other types of exhaust air described in Section 5.17.2.2 of the standard.

Type of Humidification System
Different types of humidifiers have different advantages and disadvantages. In general, it is a good idea not to have reservoirs of standing water, as they can increase the likelihood of biological growth. If water has low levels of dissolved solids, spray or ultrasonic humidifiers may be appropriate. Hard water (water with high levels of dissolved solids) may require special actions such as water softening or frequent parts replacement. For computer rooms, infrared evaporative pads often are used, but these cause high levels of electric power demand and consumption. In many applications, steam humidification may be favorable, provided the water source has not been treated with harmful chemicals.

Location of Humidifier
The humidifier needs to be located appropriately—for instance, after the heating coil, where relative humidity is lowest, and with water-tolerant nonporous airstream surfaces provided downstream. Consult

manufacturers and their representatives skilled in application of systems in the climate and water conditions at the project location.

Humidity Levels

Higher levels of indoor humidity concurrent with low outdoor temperatures increase the potential for condensation. Therefore, control methods should be selected to avoid overhumidification. Levels of relative humidity should be lower when outdoor temperatures are lower to avoid condensation within the building envelope. A setpoint of 20% RH or lower may be reasonable for many buildings during very cold weather.

Maintenance Specification

Consider writing a maintenance specification so that contractors may provide pricing with the installation bids. A high level of attention to maintenance (beyond that ordinarily found in many commercial buildings) is required with humidification equipment. If the resources for extra maintenance are not available, it might be better to have no humidifier than risk having its maintenance slip through the cracks. Since the potential disadvantages of humidifiers are magnified considerably with low maintenance, it is especially important that building operators get additional assistance. Therefore, it is wise to include maintenance of humidification equipment in the operation and maintenance manuals and training (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ).

Monitoring Humidity and Automatic Control

Monitoring humidity refers to measurement of the humidity-related properties of moist air. Whether adding or removing moisture from the building, directly monitoring humidity has benefits both during testing and balancing and during the commissioning process, as well as during operations. However, monitoring and using humidity information is more challenging than using dry-bulb temperature information. The reasons for this include 1) the instruments being more expensive, 2) the calibration being more difficult, 3) the accuracy being lower, 4) the sensors being more subject to dirt and degradation, and 5) the calculations and control algorithms being more involved. These and many other considerations are covered in Chapter 17 of *Humidity Control Design Guide for Commercial and Institutional Buildings* (Harriman et al. 2006).

All of the moist air properties (including dew point, relative humidity, wet bulb, and absolute humidity) can be calculated from knowing any one of them along with the dry-bulb temperature, provided that both measurements are taken from the same air sample. For instance, you can't use the dry-bulb temperature measured in a room and the dew point measured in the return air duct after air has heated several degrees to accurately compute relative humidity, even though the moisture content has not changed.

Thermal comfort goals and the way information will be used will assist in deciding whether to monitor humidity, what type of sensors to use and where to locate them, and what other information to monitor. For instance, measuring relative humidity directly in the room with a sensor having reasonable accuracy at the middle range of relative humidity can be useful simply to track relative excursions of room conditions from design targets. However, if excursions are found and a troubleshooting process is being used to do something about them, then it will likely be important to know the indoor dry bulb, system status, outdoor dry bulb, humidity, and wind speed.

The location of sensors in the room is important depending upon whether you are more interested in thermal comfort or identifying conditions that may lead to condensation. If the goal is to control an outdoor air economizer, on the other hand, then considerations such as tolerance to dirt and higher accuracy required at close to 100% RH will aid in selecting the outdoor sensor.

Another type of real-time monitoring that can prevent serious problems is the use of liquid moisture sensors in secondary condensate pans, water heater overflow pans, and subgrade floors subject to flooding.

Strategy 2.4

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Strategy 2.5

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

Introduction

Building envelopes need to be carefully designed and constructed with moisture resistance and control as a priority (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 there are many places within buildings that may be subject to frequent wetting or to damp conditions resulting from indoor activities. In these areas, careful selection and installation of appropriate building materials that can withstand frequent wetting are critical. In addition, certain moisture-resistant materials may have significant chemical emissions, so the potential emissions should not be neglected (see Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection). Green roofs are a special application outside the area covered in this Strategy, but material considerations for dealing with the moisture associated with green roofs can be found in Strategy 2.6 – Consider Impacts of Landscaping and Indoor Plants on Moisture and Contaminant Levels.

Indoor Areas Subject to Repeated Wetting

Areas within buildings that may be subjected to high moisture or repeated wetting events include those where water is used frequently (such as is the case in kitchens/cafeterias, washrooms, custodial closets, indoor pools, spas, and locker rooms and with counters and backsplashes around sinks). Entranceway areas may also experience frequent wetting depending on the climate; hence the need for careful design of track-off systems (see Strategy 3.5 – Provide Track-Off Systems at Entrances). Mechanical rooms are also an area where frequent wetting may occur.

Any flooring area subjected to wet cleaning practices as well as the wall materials that are in contact with these floor zones will also require special consideration. Particular attention is called for in carpeted areas to minimize the use of water and make careful provision to ensure adequate post-cleaning drying. Locations at or below grade in geographic areas subject to flooding are primary candidates for the use of appropriate moisture-tolerant materials, as are building assemblies susceptible to condensation.

A practical first step is to avoid wet surface problems by designing buildings such that condensation is unlikely to occur (see Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces); however, it is prudent to use moisture-tolerant materials in locations where this is difficult to achieve. In all cases, the individual Strategies identified in Objective 2 – Control Moisture in Building Assemblies should be considered essential components of good building design.

Problems Associated with Wet Materials

The following problems have been associated with damp conditions (EPA n.d.):

- Colonization of building materials by molds, wood-decaying fungi (see also ASTM [2008a]) , and insect pests (e.g., termites and carpenter ants)
- Warping of wooden materials
- Corrosion
- Dissolving of water-soluble building material components
- Moisture-induced reactions with latex flooring adhesives or elevation of the pH of concrete so that applied adhesives do not cure
- Damage to brick or concrete products (without air entrainment) due to freeze/thaw cycles

- Damage to paints and varnishes

In addition, chemical emissions from materials may increase under conditions of dampness or increased humidity (Wolkoff 1998), contributing to IAQ problems.

Materials Susceptible to Moisture Damage

Materials that are vulnerable to moisture-triggered damage have one or more of the following characteristics (EPA n.d.):

- Nutrient content (carbon based) that can support growth of biocontaminants (e.g., paper, fiberboard, particleboard, oriented strand board, plywood, and solid wooden materials).
- Porous structure that readily absorbs water and subsequently also takes longer to dry once wet (e.g., wood, particleboard, fiberboard, concrete, concrete masonry, and brick and fiber-based insulations such as fiberglass, mineral wool, and cellulose).
- Composition susceptible to crumbling, dissolving, delaminating, or deforming due to the presence of moisture or upon drying (e.g., wood, paper, wood-based composites, and some gypsum board materials).
- Lack of effective anti-microbial properties (e.g., untreated paper, fiberboard, particleboard, oriented strand board, plywood, and some solid wooden materials, as well as some plastics, paints, and varnishes).

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Damage from molds, bacteria, or wood-decaying fungi will not likely occur unless the material contains sufficient moisture for a long enough time (e.g., if drying does not take place within 24–48 hours), has sufficient bio-nutrients, and does not possess natural anti-microbial characteristics. Other materials may tolerate wetting conditions if they possess characteristics (and conditions) that support rapid drying. A material such as concrete, though not particularly susceptible to moisture damage, may contribute to the damage of materials in direct contact with it due to the nature of concrete to absorb and transport moisture.

Porous materials that are not allowed to dry adequately following wetting episodes or that are installed such that they are continuously dampened by capillary action from moisture sources in contact with them can contribute to moisture-related problems. For example, when gypsum wallboard coated with a moisture-impermeable vinyl surface becomes wet or damp from moisture penetration through the back surface, the material cannot properly dry and mold and/or material damage will likely result.

Selection of Moisture-Resistant Materials

As is the case with most design decisions, selection of building materials involves consideration of multiple criteria. Where repeated wetting is unavoidable, moisture resistance may become a dominant factor; however, this does not mean that other considerations can be ignored (see Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection). A material that successfully tolerates frequent wetting but also emits significant gaseous or particulate contaminants is not the best choice for indoor use.

The potential source of moisture that will affect the material is also an important consideration. Flooring materials subject to wet mopping require very different attention when compared with flooring materials overlaying poorly engineered or installed concrete slabs that may absorb and transfer moisture from below. A wall material that occasionally becomes wet may be satisfactory if it has properties enabling rapid drying under its particular installation conditions.

FEMA's guidance on flood-resistant materials (FEMA 1993) cites the U.S. Army Corps of Engineers system of ranking materials into five classes of water resistance, where the first three categorized are unacceptable. This classification system is summarized in Table 2.5-A. Tables of common building materials ranked with this five-point scale of flood resistance qualities are also presented in the FEMA document and are duplicated here as Tables 2.5-B (flooring materials) and 2.5-C (wall and ceiling materials). Although this is somewhat specialized guidance, it nevertheless gives some indication of material properties appropriate for unavoidably wet areas. For detailed guidance related to the durability of specific materials, specific standards such as those prepared by ASTM International should be examined. Several examples are provided in the references section for this Strategy. In all cases, local building codes and regulations must be adhered to.

Table 2.5- A Flood-Resistant Classification of Materials
Source: USACE (1995).

Class		Description
Unacceptable	1	Not resistant to water damage. Materials within this class require conditions of dryness.
	2	Not resistant to water damage. Materials within this class require essentially dry spaces that may be subject to water vapor and slight seepage.
	3	Resistant to clean water damage. Materials within this class may be submerged in clean water during periods of intentional flooding.
Acceptable	4	Resistant to floodwater damage. Materials within this class may be exposed to and/or submerged in floodwaters in interior spaces and do not require special waterproofing protection.
	5	Highly resistant to floodwater damage. Materials within this class are permitted for partially enclosed or outside uses with essentially unmitigated flood exposure.

Flooring materials are deemed “unacceptable” in terms of flood resistance if they

- use water-soluble adhesives,
- contain wood or wood products,
- are not resistant to alkali or acid in water,
- restrict evaporation of moisture from sources below flooring, and/or
- are dimensionally unstable.

The basis for FEMA’s classification of wall and ceiling materials as “unacceptable” is similar to that for flooring materials, with additional unacceptable wall and ceiling materials that

- contain wood, wood products, gypsum products, or other material that dissolves or deteriorates, loses structural integrity, or is adversely affected by water; or
- absorb or retain water excessively after submergence.

Materials such as stainless steel, copper, some stones, china, and porcelain tile are favored for use in bathrooms, kitchens, and entryways, where they are likely to get wet. These products contain no nutrients, do not absorb water, and are stable when wet.

Ceramic tile, glass, plastic resins, metals, and cement-based products may be highly resistant to fungal growth if properly installed using appropriate adhesives, grout materials, and caulking compounds or sealants. These materials are commonly used in areas such as entryway floors, bathroom floors, tub surrounds, showers, locker rooms, pool and spa rooms, and kitchens. Cement (or *backing*) board may be used in areas subject to repeated wetting. This material is not waterproof but has excellent drying characteristics and is resistant to water absorption. These properties give cement board the ability to resist mold and mildew.

Table 2.5-B Flooring Material Classifications for Flood Resistance
Source: FEMA (1993).

Types of Flooring Materials	Acceptable		Unacceptable		
	5	4	3	2	1
Asphalt tile[1]					✓
Asphalt tile with asphaltic adhesives			✓		
Carpeting (glued-down type)					✓
Cement/bituminous, formed-in-place		✓			
Cement/latex, formed-in-place		✓			
Ceramic tile[1]					✓
Ceramic tile with acid- and alkali-resistant grout			✓		
Chipboard					✓
Clay tile	✓				
Concrete, precast or in-situ	✓				
Concrete tile	✓				
Cork					✓
Enamel felt-base floor coverings					✓
Epoxy, formed-in-place	✓				
Linoleum					✓
Magnesite (magnesium oxychloride)					✓
Mastic felt-base floor covering					✓
Mastic flooring, formed-in-place	✓				
Polyurethane, formed-in-place	✓				
Polyvinyl acetate emulsion cement					✓
Rubber sheets[1]					✓
Rubber sheets with chemical-set adhesives[2,3]	✓				
Rubber tile[1]					✓
Rubber tile with chemical-set adhesives		✓			
Silicone floor, formed-in-place	✓				
Terrazo		✓			
Vinyl sheets (homogeneous) [1]					✓
Vinyl sheets (homogeneous) with chemical-set adhesives[2,3]	✓				
Vinyl tile (homogeneous) [1]					✓
Vinyl tile (homogeneous) with chemical-set adhesives		✓			
Vinyl tile or sheets (coated on cork or wood product backings)					✓
Vinyl-asbestos tile (semi-flexible vinyl) [1]					✓
Vinyl-asbestos tile with asphaltic adhesives		✓			
Wood flooring or underlay merits					✓
Wood composition blocks, laid in cement mortar				✓	
Wood composition blocks, dipped and laid in hot pitch or bitumen				✓	
Pressure-treated lumber, .40 chromated copper arsenate (CCA)[4]	✓				
Naturally decay-resistant lumber[4,5]	✓				

Notes:
1. Using normally specified suspended flooring (i.e., above-grade) adhesives, including sulfite liquor (lignin or "linoleum paste"), rubber/asphaltic dispersions, or alcohol-type resinous adhesives (culmar, oleoresin).
2. Not permitted as Class 2 flooring.
3. For example, epoxy-polyamide adhesives or latex-hydraulic cement.
4. Not in the U.S. Army Corps of Engineers list; added by FEMA.
5. Refer to local building code for guidance.

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Table 2.5-C Wall and Ceiling Material Classifications for Flood Resistance
Source: FEMA (1993).

Types of Wall and Ceiling Materials	Acceptable		Unacceptable		
	5	4	3	2	1
Asbestos-cement board (and cement board[1])	✓				
• Brick					
• Face or glazed	✓				
Common				✓	
Cabinets, built-in					
• Wood				✓	
• Metal	✓				
Cast stone (in waterproof mortar)	✓				
Chalkboard					
• Slate, porcelain glass, nucite glass	✓				
• Cement-asbestos				✓	
• Composition, painted				✓	
Chipboard					✓
• Exterior sheathing grade				✓	
Clay tile					
• Structural glazed	✓				
• Ceramic veneer, ceramic wall tile-mortar set		✓			
• Ceramic veneer, organic adhesives				✓	
Concrete	✓				
Concrete block	✓				
Corkboard				✓	
Doors					
• Wood, hollow				✓	
• Wood, lightweight panel construction				✓	
• Wood, solid				✓	
• Metal, hollow	✓				
• Metal, kalamein				✓	
Fiberboard panels, vegetable types					
• Sheathing grade (asphalt coated or impregnated)				✓	
• Otherwise					✓
Gypsum products					
• Gypsum board (including greenboard[1])				✓	
• Plaster including acoustical				✓	
• Sheathing panels, exterior grade				✓	
Glass (sheets, colored tiles, panels)		✓			
Glass blocks	✓				
Hardboard					
• Tempered, enamel or plastic coated				✓	
• All other types				✓	
Insulation					
• Foam or closed-cell types		✓			
• Batt or blanket types					✓

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Types of Wall and Ceiling Materials	Acceptable		Unacceptable		
	5	4	3	2	1
• All other types				✓	
Metals, non-ferrous (aluminum, copper, or zinc tiles)			✓		
Metals, ferrous	✓				
Mineral fiberboard					✓
Plastic wall tile (polystyrene, urea formaldehyde, etc.)					
• Set in waterproof adhesives, pointed with waterproof grout			✓		
• Set in water-soluble adhesives				✓	
Paint					
• Polyester-epoxy and other waterproof types		✓			
• All other types					✓
Paperboard					✓
Partitions, folding					
• Wood, pressure treated, .40 chromated copper arsenate (CCA) minimum 1 (if not treated, then material is Class 2)	✓				
• Metal		✓			
• Fabric-covered					✓
Partitions, stationary					
• Wood, pressure treated, .40 CCA minimum 1 (if not treated, then material is Class 2)	✓				
• Metal	✓				
• Glass, unreinforced		✓			
• Glass, reinforced		✓			
• Gypsum, solid or block					✓
Rubber, moldings, and trim with epoxy polyamide adhesive or latex-hydraulic cement		✓			
• All other applications					✓
Steel (panels, trim, tile) with waterproof applications	✓				
• With non-waterproof adhesive				✓	
Stone, natural solid or veneer, waterproof grout	✓				
Stone, artificial non-absorbent solid or veneer, waterproof grout	✓				
• All other applications				✓	
Strawboard					
• Exterior grade (asphalt-impregnated kraft paper)				✓	
• All other types				✓	
Wall covering					
• Paper, burlap, cloth types					✓
Wood					
• Solid, standard				✓	
• Solid, naturally decay-resistant[1,2]	✓				
• Solid, pressure treated, .40 CCA minimum[1]	✓				
Plywood					
• Marine grade[1]	✓				
• Pressure treated, .40 CCA minimum[1]	✓				
• Exterior grade				✓	
• Otherwise					✓

Notes:
1. Not on the U.S. Army Corps of Engineers list; added by FEMA.
2. Refer to local building code for guidance.

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Polyvinyl chloride (PVC) materials are among the most frequently used wall and floor finishing materials because they provide inexpensive, easy-to-clean surfaces. They typically resist microbial growth but, as discussed in the following, may degrade in the presence of moisture under certain conditions. (See the section on PVC materials in Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection.

Flooring materials considered to be moisture resistant include clay tile, quarry tile, terrazzo, and ceramic tile as well as concrete materials such as concrete tile or pre-cast concrete. Rubber sheets or tiles may be considered (keeping emissions properties in mind) while non-porous stone, slate, or cast stone with waterproof mortar may also be used successfully in potentially wet areas. For restroom flooring, Ashkin (1998) recommends the use of terrazzo, glazed ceramic, or other types of stone tile with minimal porosity. By employing larger tiles, problematic grout lines can be reduced (use of dark grout is recommended). Drains should be installed properly to facilitate cleaning, while floor moldings should be rounded in corners and constructed from materials that are easily cleaned. Problem avoidance can be achieved through proper design of restroom counters/sinks that incorporate drainage to limit spillage of water onto flooring materials.

Moisture-resistant wall materials include ceramic veneer or ceramic wall tile, glass blocks or glass panels, and concrete. Latex paints will permit moisture transfer and so should not be used on the wet side of an interior wall assembly. However, they may be beneficial on the dry side of the wall assembly since they facilitate drying of wall materials. In general, the use of anti-microbial agents to increase the moisture resistance of an otherwise unsuitable material should be discouraged in favor of strategies that utilize material assemblies capable of providing adequate moisture tolerance without additional modification.

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Strategy 2.6

2.6

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

STRATEGY OBJECTIVE 2.6

Introduction

Transpiration is a physiological process fundamental to the life of vascular plants. Water molecules are absorbed from the soil via plant root hairs. Water is then transported as a column of liquid from the roots, through the stem, and into the leaves through xylem or wood cells. Water molecules evaporate from leaves through small pores known as *stomata*. This transpiration process is associated with a rise in the relative humidity of the air and evaporative cooling regardless of the location of the plants.

The amount of water vapor transpired by potted plants varies from about 0.03 to 0.3 oz/h (1 to 10 g/h) and is influenced by variables such as seasonal humidity, the kind and size of the plant, and the water activity (a_w) at the soil-root interface (see TenWolde and Pilon [2007] for review). The a_w 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. The transpiration process is beneficial indoors in dry seasons or climates when the relative humidity rises. Too many transpiring plants indoors in warm, humid climates or seasons may result in an unwanted increase in relative humidity. A benefit of transpiration associated with green roofs and roof gardens is the evaporative cooling effect as water molecules exit the plant stomata—a process resulting in reduction of the heat island effect in urban areas.

It is important to keep trees and vegetation away from the building. Investigations in the 1970s (Kozak et al., 1980, 1985) showed that occupants of homes with conventional roofs that were heavily shaded by trees tended to have more allergies possibly due to elevated mold levels associated with debris on damp roofs and beside buildings.

Overwatering of planter boxes located at grade level contiguous with the building envelope is known to result in capillary entry of water through porous masonry into the building interior. High water tables around buildings as well as overwatering of landscaping around building perimeters can also result in capillary entry of water into the building foundation. Builders need to reduce capillary penetration of water by damp-proofing foundation materials. In addition, dampness problems around planter boxes near building foundations can be reduced by making sure that water drains away from the foundation and that water sprinklers, if used, are directional, with the spray pointed away from the building envelope.

Outdoor Plantings

Green Roofs

Green roofs that involve installation of a shallow layer of porous soil (depth 2 to 8 in. [50 to 200 mm]) above the roof structure are described as “extensive.” Small herbaceous plants like *Sedum* with noninvasive root systems are typically grown in such roof gardens. For those roof gardens described as “intensive,” a thicker layer of soil up to 39 in. (1 m) in depth is used in conjunction with the installation of shrubs and small trees.

Green roofs are thought to be beneficial because of their potential to help reduce certain environmental problems in urban areas (Clark et al. 2008; Carter and Fowler 2008; Kosareo and Ries 2007). Benefits associated with green roofs are thought to include reduction in heat island effects, reduction in storm water runoff, and reduction in levels of outdoor pollutants such as nitrogen oxides (NO_x) and sulfur dioxide (SO_2) (Clark et al. 2008; Yang et al. 2008). Additionally, green roof gardens are thought to provide better thermal insulation of the roof and protection of the roof waterproofing membrane from deterioration caused by direct contact with atmospheric ozone and ultraviolet light, as well as protection from temperature extremes. All roof gardens involve an increase in the weight of the roof structure (see Graham [2006] for code implications).

Strategy 2.6

2.6

Disadvantages associated with roof gardens include the increased difficulty of finding potential sources of roof leaks and, for intensive gardens, the increase in dead weight as trees and shrubs grow and the potential for blow-off botanical debris during a windstorm.

Very little information is available in the literature on long-term testing of green versus conventional roofs for leakage, though some information is provided by Henshell (2005a, 2005b). A well designed and properly installed water proofing membrane below the roof garden is required to prevent leakage.

Figure 2.6-B provides a description of the typical components of the roofing system present under an intensive roof garden characterized by the presence of shrubs and small trees with invasive roots (Henshell 2005a). An important component of the roofing system is a protective or insulation layer above the waterproofing membrane. The protective layer safeguards the waterproofing membrane from puncture by gardening tools and from penetration by invasive plant roots.

Henshell (2005b) provides design recommendations for green roof systems in order to maintain the integrity of the waterproofing membrane as follows:

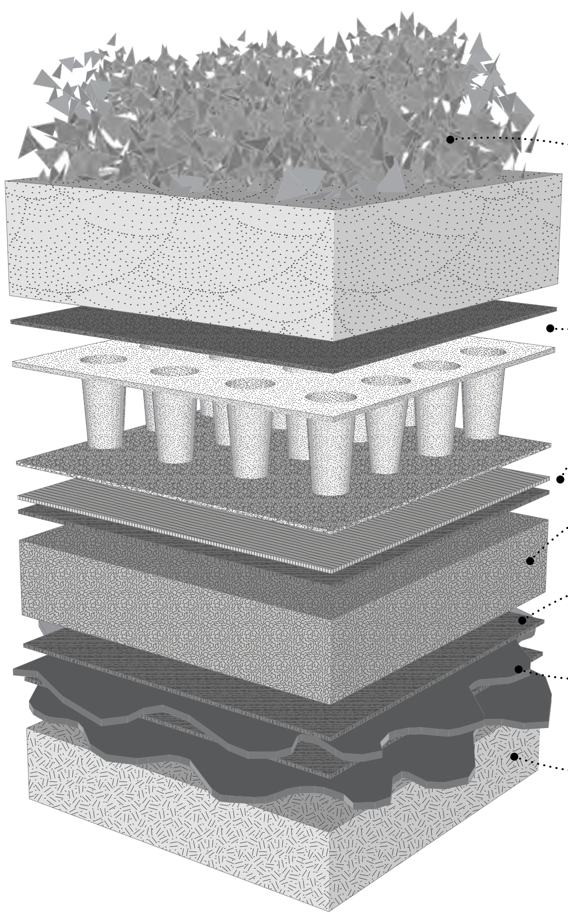

Figure 2.6-B Typical Roofing System Components
Adapted from Henshell (2005a).

- Avoid unplanned penetrations of the roofing system, for example by utility conduits. Flashing systems utilized need to avoid seams.
- Use a seamless or root-resistant waterproofing membrane.
- Use a waterproofing membrane that is resistant to the acid and alkali components of fertilizers.
- Provide barriers that prevent root penetration by physical means (e.g., metal foil) or chemical means (e.g., incorporate an herbicide into barrier fabric).

One of the benefits of green roofs is that the garden/vegetation provides a habitat for insects, birds, and small animals in an environment that would otherwise be hostile to life. If air-handling units (AHUs) are installed in the roof garden, consideration needs to be given to elevating the height of the unit above the vegetation or locating AHUs on a portion of the roof devoid of vegetation in order to reduce the entry of microorganisms (from the soil) and to reduce the possible entry of herbicides and insecticides that may be used in garden maintenance.

Figure 2.6-B shows a suggested composition of a green roofing structure underlying a roof garden with shrub and small tree landscaping. The waterproofing membrane needs to be protected from penetration from invasive roots and from spades and pitchforks used by gardeners. The membrane needs to be seamless or root resistant (e.g., thermoplastic with heat-fused seams), and any roof penetrations need to be carefully flashed or waterproofed. Moisture from a moderate amount of rain will likely be retained by the soils and plantings. Excess moisture from a heavy rainfall will leave the roof through a drainage system.

Because of the greater likelihood of increased bird and insect populations associated with green roof vegetation, use of bird and insect screens in rooftop AHUs is essential. In addition, because of the likelihood of entry of debris from dead vegetation and soil into outdoor intakes, AHUs in roof gardens need to be subject to an enhanced maintenance program (e.g., more frequent replacement of filters, more frequent removal of dust and debris that may accumulate in plenums and ducts). Because molds such as *Aspergillus fumigatus* grow in rotting vegetation, careful maintenance is necessary to ensure removal of dead vegetation from the vicinity of AHUs. Similar enhanced maintenance is also required for AHUs with grade-level or below-grade outdoor air inlets.

Green Facades and Vertical Gardens

Green facades are trellis systems added to the envelope wall that support the growth of climbing plants (vines) rooted along the building foundation (Sharp 2007). Several years are required for the climbing plants to grow along the trellis system and create a green facade along the entire wall. Trellis systems are mounted on an engineered support structure 3 to 18 in. (80 to 450 mm) from the envelope surface (Sharp 2007). In selecting trellis vines, it is important to avoid plants with invasive root systems that can damage envelope integrity.

Living or vertical gardens (Gonchar 2007) differ from vine-covered facades in that panels or baskets containing vegetation are affixed onto a structural framework on the envelope wall. Shrubs, ferns, and other vegetation growing in the panels can be installed along the wall in a few days, creating an "instant" living wall. An irrigation system is installed in the living wall to provide moisture for the plant roots in each affixed

The Failure of a Waterproofing Membrane beneath a Roof Garden

Figure 2.6-C Failure of a Three-Ply Asphalt/Felt Membrane beneath a Roof Garden Resulting in Root Penetration into the Roof Substructure
Photograph copyright Justin Henshell.

Case study data courtesy of Justin Henshell.

The first criterion for a waterproofing membrane under a garden roof is that it be watertight. The second criterion is that it remain serviceable in a continuously moist environment for at least 25 years. It is obvious that low water absorption is critical, but among the more significant physical properties that distinguish it from a membrane designed for waterproofing foundations below grade is resistance to root penetration, fungi, and bacteria. Roots can penetrate seams in multi-ply or single-ply membranes with adhered seams such as ethylene propylene diene monomer (M-class) rubber (known as *EPDM*) and butyl. Fluid-applied membranes and single-ply membranes with heat-fused seams do not share that disadvantage.

Figure 2.6-C illustrates a failure of a three-ply asphalt/felt membrane. Within three years after its installation, the asphalt had hydrolyzed in the presence of water and chemicals. As a result, the asphalt had embrittled, the seams had opened, and the desaturated felts wicked water throughout the membrane, which caused it to delaminate. The presence of roots that penetrated the membrane further aided in its failure.

vegetative panel. The designer needs to consider the added weight to the envelope associated with the presence of wet vegetation and wet rooting mulch.

In cold climates, occurrence of ice on vertical gardens can add a substantial weight load to the envelope. With both green facades and vertical garden walls, it is important that plant roots do not come in contact with the building envelope (Sharp 2007). The panels or baskets containing wet mulch or growing mediums need to also be kept out of contact with the surface of the building envelope.

Care needs to be taken during installation of vertical gardens and green facades to make sure that the structural framework holding the botanical materials does not penetrate or disrupt the waterproofing integrity of the envelope wall. In addition, both green facades and living walls require attention to watering, fertilizer application, and pest control. The designer needs to therefore develop a plan for the irrigation system as well as for landscape housekeeping (e.g., fertilizer and pesticide application) to maintain the vegetation covering the building envelope. Periodic pruning is required to remove dead botanical materials for both aesthetic purposes and in dry climates in order to reduce fire risk.

Indoor Plantings

Potted Plants

Potted plants are commonly found in indoor environments. A moderate number of well-maintained plants in a commercial building is aesthetically pleasing and can offer modest psychological benefits (Bringslimark et al. 2007; Ceylan et al. 2008; Shibata and Suzuki 2002, 2004). However, if watering of the plants results in wetting of carpets, fiberboard, or other biodegradable finishing materials, microbial growth (especially fungi) will occur. In addition, some potting materials such as wicker baskets are susceptible to water damage and mold growth (Kozak et al. 1980, 1985).

Dense indoor vegetation is found in some buildings in atrium gardens. In general, the presence of an atrium garden is beneficial to the indoor environment as long as the garden is carefully maintained (e.g., green vegetation produces oxygen during photosynthesis). However, mold growth can occur on moist mulch (e.g., bark and wood chips) and dead leaves present on the atrium floor. Therefore, maintenance activities in the atrium garden such as removal of moldy vegetation and mulch need to be carried out with care so as to reduce dispersion of bioaerosols.

Some literature suggests that in buildings with attached greenhouses, high levels of mold spores occur in the indoor air relative to that found outdoors (Botzenhart et al. 1984). The sources of elevated indoor mold spores include fungi growing on green leaves (e.g., *Cladosporium* and other leaf-sourced molds) and *Aspergillus* (including *A. fumigatus*) and *Penicillium* that grows on dead vegetation found on the moist greenhouse floor. Substantial literature (Guieysse et al. 2008; Summerbell et al. 1989; Staib et al. 1978) shows that decaying botanical debris in potted plants and the surface of the potting soil itself contains fungi including pathogenic *Aspergillus* species such as *A. fumigatus*. Simple activities such as cultivation of the soil and watering can increase indoor levels of molds. The literature collectively suggests that large numbers of plants indoors can increase mold levels and unusual species (*A. fumigatus*) indoors.

It has been known for many decades that root-zone microorganisms play an important role in the growth of plants. Mycorrhizal fungi can colonize the roots of pines and maples and aid in the uptake of minerals from the soil. *Rhizobium* species (bacteria) colonize the roots of legumes such as the soybean and convert atmospheric nitrogen into ammonia, thus promoting plant growth. Additionally, many kinds of soil microorganisms are capable of degrading petroleum-based hydrocarbons and are used in bioremediation of contaminated soils (Margesin et al. 2003; Chaianeau et al. 2005).

Studies originating from the National Aeronautics and Space Administration (NASA) in the 1970s suggested that indoor potted plants or their potting components could reduce volatile organic compound (VOC) levels (see review by Levin [1992]). These studies suggested that a very large number of indoor plants were needed to achieve a moderate reduction in VOC levels. Some recent work suggested that VOC levels indoors can be reduced by potted plants primarily caused by the activity of root-zone soil microorganisms and not the plant foliage (Guieysse et al. 2008; Kim et al. 2008; Wood et al. 2006). However, the results of these studies should be viewed with caution because the VOC reductions were not statistically significant except at higher concentrations and because ventilation was not measured or controlled. At present, the use of potted plants indoors cannot be considered a validated technique to control VOC concentrations. Because this is an active area of investigation, this situation could change as more research findings become available.

Some consideration has been given to using vertical garden walls (also called *living walls*, *biofilters*, or *active walls*) as part of ventilation systems in green buildings (Darlington et al. 2001). This concept involves passage of ventilation air through living wall vegetation and is based on the concept that the plant itself or the microbes associated with the plant root system remove contaminants like VOCs from the circulating air. The designer, however, needs to be cautious with regard to the installation of large numbers of plants in buildings (biofilters, living walls) because the economics of biofilters has not been worked out (Darlington et al. 2001) and because the technology is complex and additional maintenance associated with the indoor botany will add to the cost. In addition, the risks associated with the aerosolization of soil microorganisms and the fertilizers and pesticides used to maintain the health of the plantings need to be balanced against possible psychological benefits and any potential reductions in VOCs (Guieysse et al. 2008; Wood et al. 2006) associated with this new green technology.

Moisture Content, Water Activity, and Dampness

Engineers and architects are familiar with the term *moisture content*, which refers to the total amount of water present in a construction or finishing material. Biologists are more familiar with the terms *water activity* and *equilibrium relative humidity* (ERH), which relate to the ease with which free water can be extracted by living cells from the substrate in order to support growth. A piece of pinewood with a moisture content of about 17% is equivalent in biological terms to an ERH of 80% or a water activity of 0.8 (on a decimal system). An ERH of 80% or water activity of 0.8 is equivalent to the ratio of the vapor pressure of water in the pores of the pinewood relative to the vapor pressure of pure water at the same temperature and pressure. At this point (water activity of 0.8), some fungi can extract enough moisture from the pinewood to begin the growth process.

Unfortunately, there is no easy way to measure water activity in the field as compared to direct reading methods for moisture content by a moisture meter. This is because of the variation in the amounts of bound water (held tightly by strong chemical bonds) and free water (held less tightly by absorptive and absorptive forces) among various substrates (Flannigan 1992; Flannigan and Miller 2001).

Flannigan (1992) Flannigan and Miller (2001) have published instructive examples of differences between moisture content and water activity in common food items. Table 2.6-A shows how the water activity levels of various foods can be different even though they have the same moisture content.

Table 2.6-A Water Activity Levels of Foods with the Same Moisture Content

Foods with 14% Moisture Content	Water Activity
White raisins	0.57
Wheat grains	0.70
Peanuts	0.90

Although the moisture content of raisins, wheat grains, and peanuts is identical, spoliation fungi are able to easily extract free water from the peanut but not the raisin. The free water in the raisin is tightly held and no fungus can grow at a water activity of 0.57. A few (xerophilic) fungi can grow at a water activity of 0.7, and many fungi can grow at a water activity of 0.9. In practical terms, although the moisture content is identical, the peanut becomes moldy (free water is more easily extracted from the peanut) while at the same time the raisin remains edible (non-moldy).

These authors have also provided similar examples contrasting moisture content and water activity for construction materials (Flannigan 1992; Flannigan and Miller 2001). Table 2.6-B demonstrates how the moisture content of building materials can be different even with the same water activity levels.

Table 2.6-B Moisture Contents of Building Materials with the Same Water Activity Level

Building Materials with 0.8 Water Activity	Moisture Content
Softwood	17%
Wallpaper	11.3%
Cement	1%
Brick	0.5%

At the moisture contents listed in Table 2.6-B for the four building materials, some xerotolerant fungi can extract free water to support growth. While the percentage of water content by weight varies widely, the water activity levels at the surfaces of these four building materials are identical. The available free water for microbial surface growth is the same.

Nutrient (e.g., the presence of organic material) and temperature also play important roles in controlling biological growth (Flannigan 1992; Flannigan and Miller 2001). Temperature is seldom a limiting factor with regard to fungal growth, as various species can grow over a wide range of conditions (e.g., *Cladosporium herbarum* on refrigeration door gaskets and *Aspergillus fumigatus* in warm compost piles). In practical terms, the growth of fungi on construction materials depends on a favorable water activity and the occurrence of organic material in the substrate. Moist organic material like paper and fiberboard are readily colonized by fungi. Moist dirt and dust (which contain some organic components) on materials such as sheet metal and brick will also support a limited amount of growth. In general, the conditions that allow for fungal growth on construction materials are similar to the conditions that will support the growth of plants.

Figure 2.6-D shows ferns growing from carpeted flooring in a room previously damaged by a water disaster (hurricane). The ferns are growing nicely even though the debris on the floor surface feels dry to the human hand. The root systems of green plants require a water activity level of at least 0.95 in order to extract free water from soil. In the example in Figure 2.6-D, the root system (rhizomes) of the ferns is finding adequate water for growth in the building infrastructure, where plant root systems are located below the flooring. Thus, the presence of plants in Figure 2.6-D indicates with high certainty that adequate moisture is also present to support the growth of fungi and bacteria in the flooring substructure.

In summary, the designer needs to be aware that while there are potential benefits to the presence of plantings in or on buildings, there are potential problems as well. Dampness in buildings and HVAC systems has been associated with building-related symptoms and building-related illness (IOM 2004). Also see the discussion on dampness in HVAC systems in Strategy 4.1 — Control Moisture and Dirt in Air-Handling Systems.

Figure 2.6-D Ferns Growing on the Flooring Indicating Conditions Moist Enough to Support the Growth of Fungi and Bacteria that Contribute to Building Biodeterioration
Photograph courtesy of Phil Morey.

Thus, installation of green roofs and vertical gardens on the building envelope needs to be done cautiously to avoid leakage into the building interior. The designer should be aware that the use of plants indoors to control indoor pollution is, at present, largely unproven technology and cannot be relied upon in the same way that ventilation can be used to control indoor pollution. The installation of large numbers of plantings indoors, as with vertical garden walls, needs to be approached cautiously by the designer because these moist materials are also growth sites for microorganisms.

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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.)

Strategy 3.1

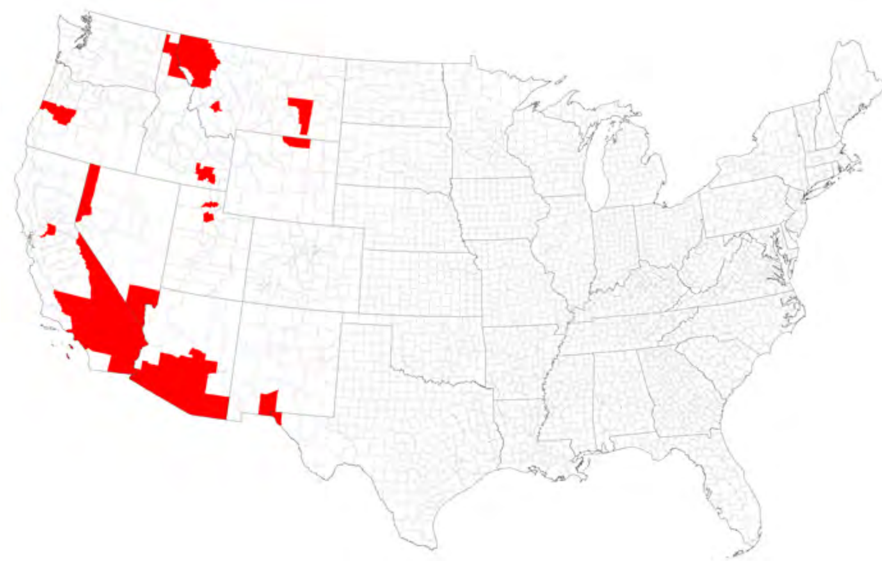

Figure 3.1-B U.S. Counties with PM10 Nonattainment Areas
Graph courtesy of EPA.

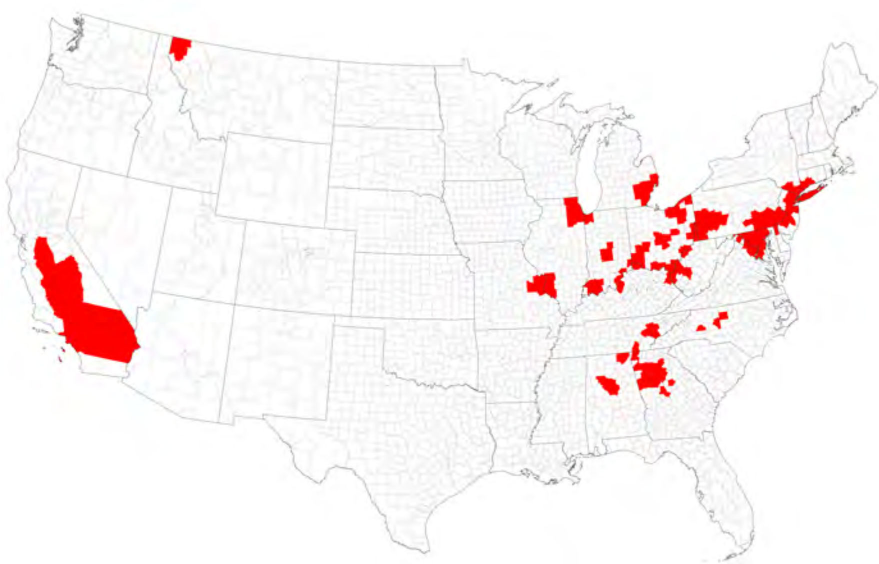

Figure 3.1-C U.S. Counties with PM2.5 Nonattainment Areas
Graph courtesy of EPA.

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).

STRATEGY OBJECTIVE 3.1

Strategy 3.1

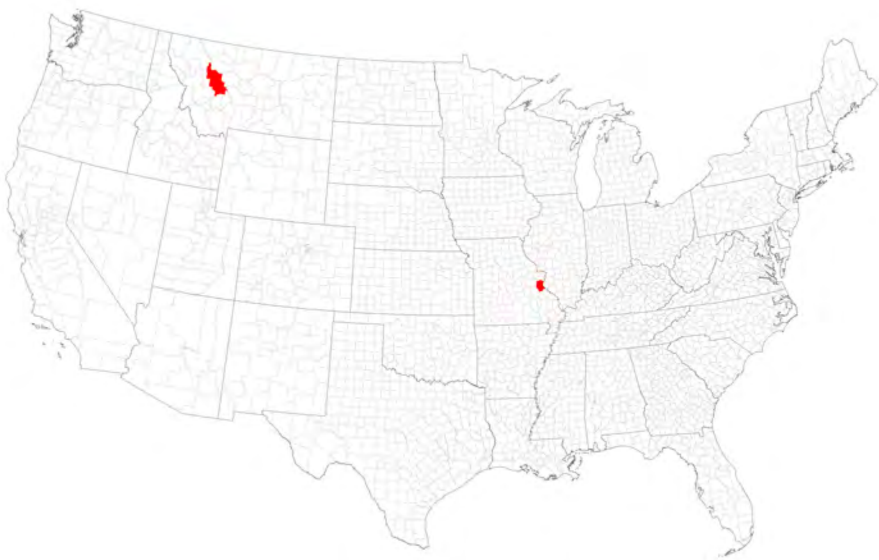

Figure 3.1-D U.S. Counties with Lead Nonattainment Areas
Graph courtesy of EPA.

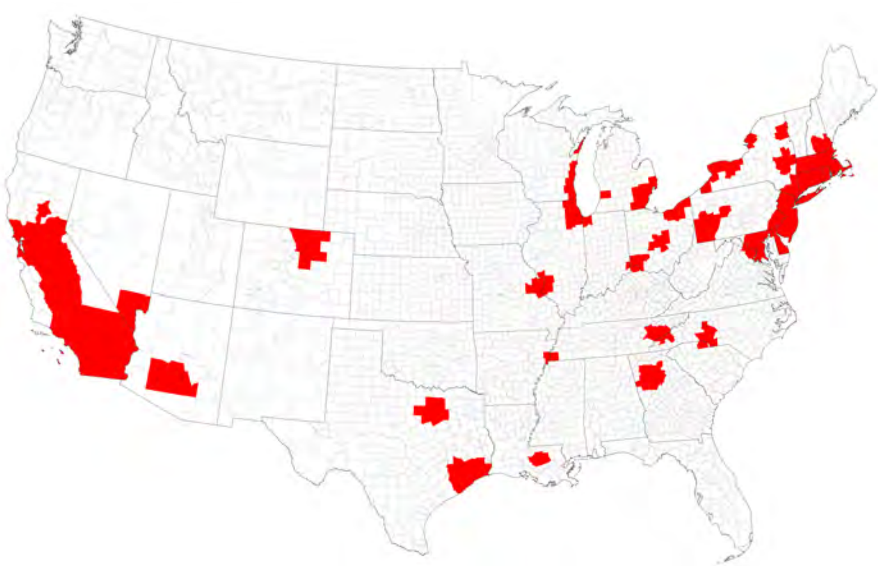

Figure 3.1-E U.S. Counties with 8-Hour Ozone Nonattainment Areas
Graph courtesy of EPA.

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

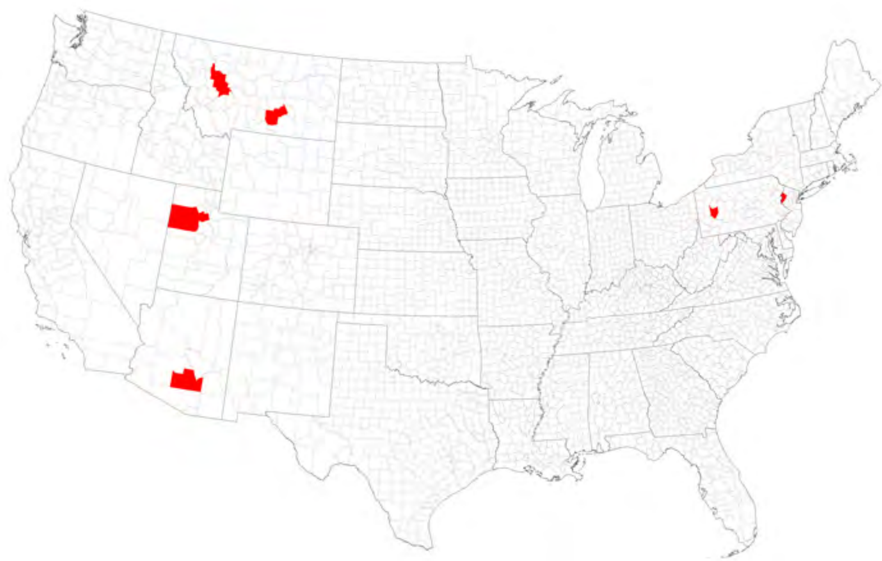

Figure 3.1-F U.S. Counties with SO_2 Nonattainment Areas
Graph courtesy of EPA.

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

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.

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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		

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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							

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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.

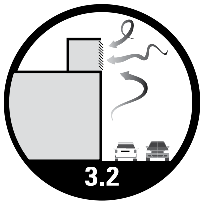
Note 7: Where snow accumulation is expected, distance listed shall be increased by the expected average snow depth.

*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



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).

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'

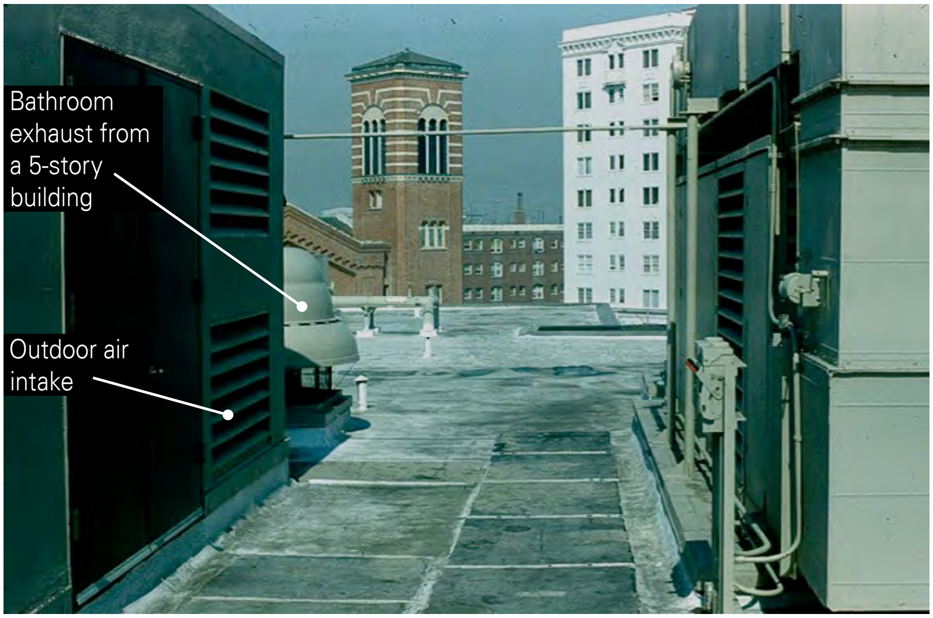


Figure 3.2-B HVAC Outdoor Air Intake Located Downwind of and in Close Proximity to Main Bathroom Exhaust of a Five-Story Office Building
Photograph courtesy of Hal Levin.

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.

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

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

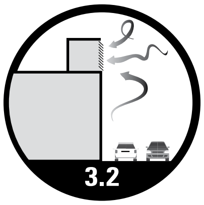


Figure 3.2-D Cooling Tower with Adequate Number of Extension Cylinders Added to the Exhaust Plume
Photograph copyright SPX Cooling Technologies, Inc.

Figure 3.2-E Unit Ventilator Outdoor Air Intake Located Too Close to Ground Level
Photograph courtesy of Mark Hancock.

system is avoided when implementing the following alternatives. Some plumbing vents may have to remain unrestricted at all times to avoid build-up of such gases.

- *Air Admittance Valves*. Air admittance valves are pressure-activated one-way mechanical valves. The normally closed air admittance valve opens when a plumbing fixture is operated, allowing air to enter and equalize the pressure in the plumbing system for proper drainage. When the water flow stops, gravity closes the valve, thus preventing plumbing odors from escaping through the valve while maintaining a trap seal.
- *Gas-Phase Filtration.* A "tub" with a blend of carbon, potassium, and alumina pellets can be used to cap sewer vent outlets. The deep bed of pelletized sorbent provides a pressure deterrent while controlling the contaminants if the vent pressure is sufficiently positive to force the air through the bed. The open bed allows the system to breathe when the vent pressure is negative (Burroughs 2008).

In high-rise buildings, location of plumbing vents in relation to outdoor air intakes may require additional analysis.

Wind Tunnel Modeling, Computer Simulations, and Computational Fluid Dynamics (CFD)

In cases where calculations show that concentrations of chemicals from nearby exhausts are likely to be close to or exceed odor or health guidelines at an intake, a range of options exist to assist the designer in proper placement of the exhausts and intakes. Wind tunnel analyses with scale models, computer simulations, and CFD analyses are some of the tools available to a designer (ASHRAE 2009).

Special Considerations for Packaged HVAC Units

In packaged HVAC units with short exhaust stacks (see Figure 3.2-F), an elevated exhaust stack, 10 in. (250 mm) or more, can reduce re-entrainment of combustion products (see Figure 3.2-G) (Stickford et al. 2002). Some gas-fired packaged HVAC units have or can accommodate such elevated stacks. However, since some HVAC units cannot accommodate such elevated stacks, it is important that the manufacturer of the HVAC unit be consulted before any field modifications are performed.

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Figure 3.2-F Downward-Facing Vent
Photograph copyright Battelle Memorial Institute.

Figure 3.2-G Plume Dispersion from Tall Vertical Vent
Photograph copyright Battelle Memorial Institute.

Figure 3.2-H Economizer Hood Installed on Packaged HVAC Test Unit
Photograph copyright Battelle Memorial Institute.

Figure 3.2-I Side Wall Obstruction for Packaged HVAC Test Unit—Wall Installed 10 ft (3 m) from Unit
Photograph copyright Battelle Memorial Institute.

In units where the intake 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. Researchers reported that in one study the minimum dilution ratio in the economizer mode of a packaged HVAC unit was 9, representing a maximum building air exhaust re-entrainment of 11%; for the same unit the dilution ratio for a tall vertical flue vent (Figure 3.2-G) had a minimum dilution ratio measured as 1284, corresponding to only 0.08% entrainment of flue gases (Stickford et al. 2002). For larger HVAC packaged units, extending the intake or exhaust needs to be considered in order to reduce re-entrainment of the exhaust air into the intake (see the case study titled “Relocating Outdoor Air Intake”).

Packaged HVAC units need to be located so that their air intakes and exhausts are directed away from large obstructions. Re-entrainment rates can be especially high when obstructions are close to the exhaust or flue vent. For example, short-term maximum re-entrainment rates for the previously mentioned packed HVAC unit (see Figure 3.2-H and 3.2-I) ranged from 11% with a wall obstruction 15 ft (4.6 m) from the exhaust hood to 32% for a wall obstruction 5 ft (1.5 m) from the exhaust hood (Osborne et al. 2005).

Cooling Tower Exhaust Locations

Figure 3.2-J Cooling Tower Located Near Outdoor Air Intake

Figure 3.2-K Shroud Added to Outdoor Air Intake

Figure 3.2-L Outdoor Air Intake Shroud Location Relative to Cooling Tower

In this example, the architect decided to relocate the cooling tower inside the parapet wall where the HVAC packaged units were located (Figure 3.2-J). This resulted in the cooling tower exhaust being located less than 20 ft (6 m) from the outdoor air intake. The design mechanical engineer corrected the problem by specifying that the packaged unit manufacturer modify the location of the outdoor air intake from the end of the unit to the side of the unit through the addition of a shroud (Figures 3.2-K and 3.2-L).

Photographs courtesy of Leon Alevantis.

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Relocating Outdoor Air Intake

Figure 3.2-M Packaged HVAC Unit

In this example, a packaged HVAC unit was constructed with the outdoor air intake right below the exhaust outlets. Figure 3.2-M shows the unit during installation before it was operational. The final system configuration was designed with an indirect evaporative cooler. When installed, this was placed some distance away and facing in another direction from the exhaust outlets. The outdoor air intake was connected to the evaporative cooler via additional ductwork (Figures 3.2-N and 3.2-O). This installation configuration provided adequate separation distance between the outdoor air intake and the exhaust outlet.

Figure 3.2-N Relocated Outdoor Air Intake

Figure 3.2-O Indirect Evaporative Cooler

Photographs courtesy of Leon Alevantis.

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Strategy 3.3

Control Entry of Radon

Introduction

Why Radon Control is Important

Radon is a radioactive gas formed from the decay of uranium in rock, soil, and groundwater. Exposure to radon decay products in residences is the second leading cause of lung cancer in the U.S. after cigarette smoking and is responsible for 10% to 14% of lung cancer deaths in the nation (NAS 1999). The additional cancer risk due to exposures in nonresidential buildings has not been quantified. Based on pooled analysis of multiple case-control studies by Darby et al. (2005) and Krewski et al.(2006), the World Health Organization (WHO) estimates that radon causes 6% to 15% of all lung cancers globally (WHO 2005).

Sources of Radon

The most common way radon enters buildings is in soil gas drawn in through ground-contact points. Radon is drawn in through cracks and penetrations whenever the pressure inside the building at that point is negative relative to the ground. Negative building pressures occur due to stack effect, wind effect, or an excess of mechanical exhaust relative to outdoor air supply (ASHRAE 2009).

In some areas, groundwater contains high levels of radon. If well water is supplied directly to a building, radon can be released into the indoor air when the water is used (NAS 1999). This is not believed to be a common source of elevated indoor radon levels in commercial and institutional buildings and is not covered further in this Guide. In rare instances, radon may emanate from building materials such as aggregate in concrete masonry units (CMUs) or fill if such materials contain radium-rich wastes. This is believed to be an extremely rare source of elevated indoor radon levels in commercial and institutional buildings in the U.S. and is not covered further in this Guide.[1]

Action Levels and Available Radon Measurements from U.S. Buildings

Radon concentrations are measured in picocuries per liter of air (pCi/L) or Becquerel per cubic meter (Bq/m^3). A picocurie is an amount of radioactive material that undergoes 0.037 disintegrations per second. The average outdoor level of radon in the U.S. is 0.4 pCi/L (15 Bq/m^3) (Hopper et al. 1991). Any indoor exposure above outdoor background levels carries some increased risk of lung cancer (NAS 1999).[2]

The U.S. Environmental Protection Agency (EPA) recommends that action be taken to reduce radon levels in schools and homes where levels are 4 pCi/L (150 Bq/m^3) or higher (EPA 2009b, 2009c). Additional information on recommended radon limits is provided in Appendix E – Additional Information on Radon Control.

Over 19% of schools in the U.S. have at least one ground-contact classroom with a level of 4 pCi/L (150 Bq/m^3) or higher (Table 3.3-A). About 5% of measurements taken in U.S. federal workplaces were above 4 pCi/L (150 Bq/m^3) (Table 3.3-B).[3]

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1 At the time of publication of this Guide, the media have been drawing attention to the possibility of elevated radon levels due to emanations from granite countertops. At this time this does not appear to be a significant contributor to indoor radon levels (EPA 2009a; Kitto and Green 2005).

2 This is based on review of cellular and molecular evidence, including "good evidence that a single alpha particle can cause major genomic changes in a cell… [and] convincing evidence that most cancers are of monoclonal origin, that is, they originate from damage to a single cell" (NAS 1999, p. 6).

3 Because the studies in schools and federal buildings were mostly or entirely based on measurements integrated over days or months, they may overestimate exposures. Research that has involved continuous measurements has found that radon concentrations tend to be lower during occupied hours when the HVAC system is on than at night (Denman et al. 2004; Durcik et al. 1997; Marley 2000; Marley et al. 1999; Tokonami et al. 2003). On the other hand, if the HVAC system depressurizes part or all of the building relative to the sub-slab, it can draw radon into the building (Leovic et al. 1990). See, for example, this Strategy's case study titled "How Complaints of Headache and Nausea led to Discovery of High Radon Levels" in Part I.

Table 3.3-A Radon Levels in U.S. Public Schools (EPA 1993a)

Radon Level, pCi/L (Bq/m^3)	Ground-Contact Classrooms*	EPA Regional Radon Potential	Estimated Percentage of Classrooms ≥ 4 pCi/L	Ground-Contact Rooms ≥ 4 pCi/L	Percentage of Schools
0–2 (~0–75)	91.0%	High (Zone 1)	6.8%	None	80.7%
2–4 (~75–150)	6.3%	Medium (Zone 2)	2.7%	1 or 2	9.9%
4–10 (~150–375)	2.3%	Low (Zone 3)	0.8%	3, 4, or 5	4.2%
10–20 (~375–750)	0.3%	All	2.7%	6 or more	5.1%
20–200 (~750–7500)	0.1%			Total	100.0%
200+ (~7500+)	0%				
Total	100.0%				
Sample size	31,353				

*EPA (1993a) reported 91% ≤ 2 pCi/L (75 Bq/m^3), 2.7% ≥ 4 pCi/L (150 Bq/m^3), 0.4% ≥ 10 pCi/L (375 Bq/m^3), and 0.1% ≥ 20 pCi/L (750 Bq/m^3). The percentages at specific intervals were calculated from these reported figures.

Table 3.3-B Radon Levels in U.S. Federal Agency Buildings (EPA 1992)*

Radon Level, pCi/L (Bq/m^3)	Measurements, Including Living Quarters	Buildings, Including Living Quarters	Measurements, Excluding Living Quarters
0–2 (~0–75)	86.7%	84.2%	86.8%
2–4 (~75–150)	9.2%	11.0%	8.8%
4–10 (~150–375)	3.4%	3.9%	3.5%
10–20 (~375–750)	0.6%	0.7%	0.7%
20–200 (~750–7500)	0.1%	0.2%	0.1%
200+ (~7500+)	0.0%	0.0%	0.0%
Total	100.0%	100.0%	100.0%
Sample size	89,571	56,758	50,898

*Data from agencies that reported individual measurements.

Other studies have measured radon in institutional or commercial buildings in the U.S., for example in California (Zhou et al. 1998), Indiana (Godish et al. 1990), and Pittsburgh (Cohen et al. 1984). Many studies have been conducted in institutional and commercial buildings in Europe, Asia, and Australia as well.

Assessment

In order to determine whether radon-resistant construction techniques are warranted for a particular building, it is useful to assess the potential for high indoor radon concentrations based on both regional and local data.

Regional Radon Potential

EPA (2009d) has developed a map of radon zones to rank the potential for elevated radon levels in the U.S. (Figure 3.3-B) and recommends that architects and engineers use this map to help determine where radon control techniques might be needed in schools and other large buildings.

Zone 1 counties have a predicted average indoor radon screening level greater than 4 pCi/L (150 Bq/m^3) and have the highest potential for elevated indoor radon levels. Zone 2 counties have a predicted average indoor radon screening level between 2 and 4 pCi/L (~75 and 150 Bq/m^3) and have moderate potential for elevated indoor radon levels. Zone 3 counties have a predicted average indoor radon screening level of less than 2 pCi/L

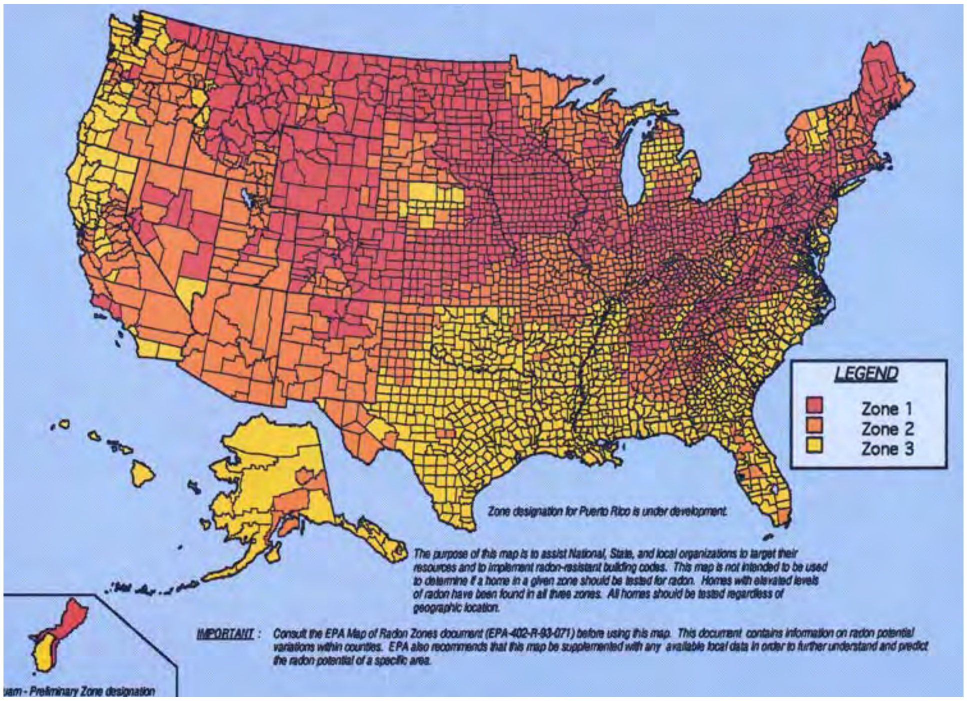

Figure 3.3-B EPA Map of Radon Zones
Source: EPA (2009d).

(~75 Bq/m^3) and have low potential for elevated indoor radon levels. Larger-scale maps of individual states are available from the EPA Map of Radon Zones Web site at www.epa.gov/radon/zonemap.html (EPA 2009d).

To date, no method has been developed that can accurately determine prior to construction whether radon-resistant construction is needed for a given site. While radon potential does exhibit regional variations related to geology, it can also vary locally by several orders of magnitude due to local variations in geology and soils. To illustrate this point, while classrooms in areas with high radon potential are more likely to have radon levels over 4 pCi/L (150 Bq/m^3), almost 60% of all classrooms with levels over 4 pCi/L (150 Bq/m^3) are in areas with medium or low radon potential (EPA 1993a).

Local Radon Potential

Regional, state, or local officials may be able to provide information about radon levels in buildings near the project site that may help the owner and design team decide whether to implement radon control techniques. In the U.S., the EPA maintains a list of state and regional indoor environment contacts (EPA 2009e).

Other Considerations

Other factors that may warrant consideration in deciding whether to apply radon-resistant construction techniques include the incremental cost, synergies and conflicts with other IAQ measures, and the owner's risk tolerance.

The incremental cost of radon-resistant construction is fairly low, especially in areas where sub-slab aggregate and vapor retarders are routinely used for other reasons. In addition, the cost of radon-resistant new construction is substantially less than the cost to retrofit a radon mitigation system after construction.

In areas where elevated radon levels are more common (Zone 1 and other radon-prone areas that have been identified in Zones 2 and 3), the EPA (2009f) recommends that new schools incorporate

- a roughed-in active soil depressurization (ASD) system—see details under "Active Soil Depressurization (ASD)" in the following section;
- sealing of potential radon entry routes; and
- post-construction radon measurements.

With the ASD system roughed in, a suction fan (or fans) and controls can be added later at low cost if measured radon levels exceed recommended action levels or exposure limits.

Many radon control techniques are relevant to other IAQ issues, as shown in Table 3.3-C.

The design team needs to discuss action levels, percentages of buildings with elevated radon levels, incremental costs, and synergies with other IAQ measures with the owner so that the owner can make an informed decision about the use of radon-resistant construction techniques. Decisions made need to be documented in the Owner's Project Requirements and Basis of Design.

Table 3.3-C Synergies and Conflicts between Radon Control Techniques and Other IAQ Strategies

Radon Control Techniques	Limit Penetration of Liquid Water into the Building Envelope	Limit Condensation within the Building Envelope	Maintain Proper Building Pressurization	Control Intrusion of Vapors from Subsurface Contaminants	All Ventilation Recommendations
S = Synergy; C = Conflict					
Active Soil Depressurization (ASD)					
• Design of load-bearing elements to facilitate ASD				S(1)	
• Sub-slab aggregate, geo-textile, vapor retarder	S	S		S(1)	
• Suction pit		S		S(1)	
• Radon vent pipe		S		S(1)	
• Suction fan		S		S(1)	
• Sub-membrane depressurization of crawlspace		S		S(1)	
Sealing of Radon Entry Routes					
• Sealing of joints, cracks, and penetrations	S	S	S	S(1)	
• Construction and sealing of below-grade walls	S	S	S	S(1)	
Building Pressurization and Dilution Ventilation					
• Location of ductwork			S	S	
• Building envelope airtightness		S	S	S	
• Building pressurization		S	S/C(2)	S	
• Ventilation rates				S	S

Notes:

1. Although the general features of an ASD system are the same for radon and vapors from site contaminants, specific requirements may differ.

2. Some situations require neutral or negative building pressurization. In these circumstances the ASD system needs to maintain the sub-slab at a lower pressure than the adjacent neutral or negative building areas.

Controlling Radon Entry
Design for control of radon entry includes the following three elements:

- An ASD system, which uses a suction fan (or fans) to draw radon from the area below the building slab and discharge it where it can be harmlessly diluted to background levels. By keeping the sub-slab area at a lower pressure than the building, the ASD system greatly reduces the amount of radon-bearing soil gas entering the building. A permeable sub-slab layer (e.g., aggregate) allows the negative pressure field created by a given radon fan to extend over a greater sub-slab area.
- Sealing of radon entry routes, including ground-contact joints, cracks, and penetrations and below-grade CMU walls.
- Use of HVAC systems to maintain positive building pressure in ground-contact rooms and to provide dilution ventilation.

Active Soil Depressurization (ASD)
ASD is the most effective, reliable, and widely applied radon reduction technique (ASTM 2007). An ASD system uses a suction fan (or fans) to create a zone of negative pressure below the building slab. Radon-laden soil gas extracted by the fan is vented to a discharge point where it can be harmlessly diluted to background levels. ASD greatly reduces the amount of radon-laden soil gas flowing into the building. Measurements in residences have shown that ASD systems can reduce indoor radon concentrations by up to 99% (EPA 2005). In new construction, designing the load-bearing elements to reduce barriers to sub-slab airflow and providing a gas-permeable layer (e.g., aggregate) below the slab enables each suction fan to depressurize a more extensive area.

Figure 3.3-C illustrates an ASD system and sealing of radon entry routes. The zone of negative pressure below the slab causes air to flow from the building into the sub-slab area, preventing flow of soil gas into the building. The radon-laden soil gas is drawn up the vent pipe and exhausted outdoors, where it is quickly diluted to ambient levels.

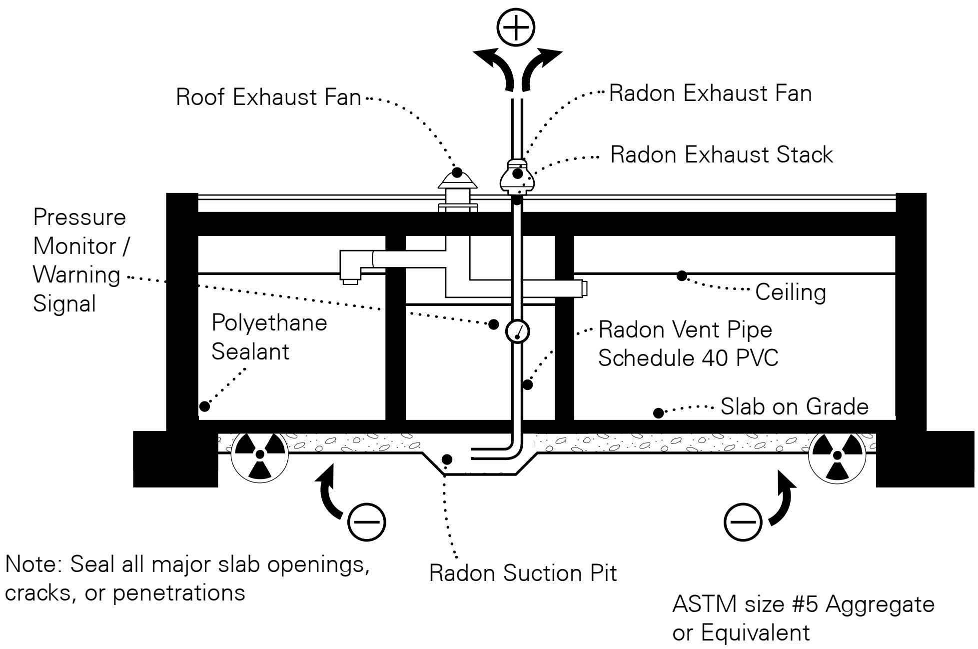

Figure 3.3-C Schematic of ASD System and Sealing of Radon Entry Routes
Source: EPA (1994).

Strategy 3.3

Adherence to design and construction details is critical to successfully reducing radon levels. Where radon is a concern, the owner or design team may want to obtain the services of an individual with expertise in radon testing and mitigation. Two privately run radon proficiency programs in the U.S. issue credentials to qualified professionals. They are the National Environmental Health Association National Radon Proficiency Program (NEHA NRPP) and the National Radon Safety Board (NRSB).

Design of Load-Bearing Elements to Facilitate ASD. Each sub-slab area isolated by sub-slab walls needs its own suction pit, suction vent pipe, and suction fan. Reducing the number of barriers to sub-slab airflow therefore reduces the cost of ASD. EPA (1994) has demonstrated that a single suction pit, vent pipe, and fan can depressurize the entire sub-slab of a large building if barriers to sub-slab airflow are avoided by using one of the following foundation designs (see Appendix E – Additional Information on Radon Control for illustrations):

- Post and beam construction
- Thickened slab footings with aggregate run continuously below the footings
- Conventional spread footings with interruptions such that the entire sub-slab is interconnected

If conventional spread footings are used below all walls, many separate sub-slab zones will be created and many suction pits/vent pipes/suction fans will be needed unless regular penetrations through the interior stem walls are included in the design.

Sub-Slab Aggregate. ASD systems include a gas-permeable layer to permit each radon exhaust fan to draw a negative pressure over as large a sub-slab area as possible. The extent of the negative pressure field created by a given suction pressure depends on the fraction of the building footprint covered by the gas-permeable layer, its thickness, and its permeability (ASTM 2007). The following design criteria are recommended by the EPA (1994):

- Use 4 to 6 in. (100–150 mm) of ASTM C-33-03 (ASTM 2003a) size #5 aggregate.[4]
- If the aggregate is placed over material with high fine content, and if compaction of the aggregate is required for code, provide a geotextile fabric[5] below the aggregate to exclude fines.
- Provide a vapor retarder over the aggregate below the slab to keep wet concrete from filling voids in the aggregate layer.[6]

According to the EPA (1994), these design criteria will allow a single radon suction pit and suction fan to create a zone of negative pressure extending over 100,000 ft^2 (9300 m^2) of ground-contact area if all other recommendations are followed.

The gas-permeable layer needs to be reasonably well sealed at the bottom, sides, and top if the radon control system is to be effective. The undisturbed ground is usually considered to provide a sufficient seal on the bottom of the gas-permeable layer unless the soil is very permeable or has been disturbed, e.g., by blasting. See ASTM (2007) for further information. Sealing of the overlying slab and of below-grade walls, including stem walls, is described in the section "Sealing of Radon Entry Routes" in this Strategy. Post-tensioned slab foundations do not normally have below-grade walls. For these foundations, curtain walls

[4] In the U.S., sub-slab aggregate is frequently required by code. Even where not required, it is usually included in designs to provide a drainage bed for moisture and a stable, level surface on which to pour the slab.

[5] A geotextile is a permeable geosynthetic fabric used with foundations, soils, aggregates, etc. to achieve various engineering objectives. A common use of geotextiles is to separate two materials with different particle size distributions (e.g., aggregate and underlying soil) to prevent undesirable mixing.

[6] A vapor retarder is commonly installed under the slab in many areas of the country to reduce liquid water penetration and vapor diffusion and therefore does not necessarily add costs related to radon control.

are needed to seal the edges of the gas-permeable layer (ASTM 2007). Penetrations needed for the radon system, including suction vent piping, drain traps, etc., need to be installed before the slab is cast.

If crushed aggregate is not readily available or is very expensive, drainage mats[7] may be able to provide a sufficiently permeable sub-slab layer. ASTM (2007) states that drainage mats installed according to the manufacturer's recommendations have an order of magnitude less void space than does a layer of crushed aggregate and that residential radon reduction systems using these mats do not always reduce indoor radon concentrations below the EPA action level. The installation described by ASTM consists of strips of drainage mat around the perimeter of the foundation, with a few additional strips parallel to the short side of the foundation footprint, thus underlying about one-fifth of the sub-slab area. Sheet drainage mats are available for use below commercial building slabs and, if used under the entire foundation, could provide a void space volume much closer to that of aggregate.

Horizontal runs of utility pipes and conduits need to be placed below the aggregate layer or above the slab so that they do not form barriers or restrictions to airflow (ASTM 2007).

Suction Pit. A suction pit is a void space in which the radon vent pipe terminates.[8] The following design criteria are recommended by EPA (1994):

- Provide a suction pit for each area isolated by sub-slab walls.
- For large buildings, provide an interface between the void space and the aggregate of about 7 ft^2 (2 m^2) (about 30 times the cross-sectional area of the vent pipe).
- For smaller buildings, a smaller suction pit is sufficient.
- Follow appropriate structural design criteria for reinforced concrete poured over the radon pit.

One suction pit/vent pipe/fan can be expected to depressurize at least 100,000 ft^2 (9300 m^2) of continuous (non-isolated) ground-contact area if all recommendations regarding aggregate and sealing are followed (EPA 1994).

See Appendix E – Additional Information on Radon Control for illustrations of suction pit designs.

Radon Vent Pipe. A vent pipe is used to connect each suction pit to an outdoor location where soil gases with high radon concentrations can be safely vented. The following design criteria are recommended:

- Use 6 in. (152 mm) diameter vent pipe or equivalent to provide sufficient airflow to depressurize large ground-contact areas without sealing expansion joints (EPA 1994).
- Run vent pipe horizontally below the slab from the centrally located suction pit to a convenient riser location. Pitch vent pipe toward suction pit to ensure that any condensed moisture will drain back to the pit. EPA (1994) recommends a pitch of at least 1/8 in./ft (10 mm/m) for 6 in. (152 mm) pipe. ASTM (2007) states that 3 in. (750 mm) pipe may need a pitch of as much as 1.5 in./ft (290 mm/m) depending on the air velocity and that 4 in. (100 mm) pipe should be pitched about 3/8 in./ft. (31 mm/m).
- Run vent riser vertically to a vent fan located above the roofline.

[7] Drainage mats are often made of geocomposites having a core with a very high void area and a layer of geotextile attached to one or both sides. The core has a high hydraulic transmissivity (and soil gas transmissivity) within the manufactured plane, even under compressive stress. The geotextile is permeable to water (and soil gas), allowing it to flow into the core, but serves as a separator and filter to exclude soil particles from the core. For further information, visit the Web sites of the Geosynthetic Institute (www.geosynthetic-institute.org/), The International Geosynthetics Society (www.geosyntheticssociety.org/indexigs.htm), and InfoGEOS.com (www.infogeos.com/portal.php?setlang=2).

[8] Some designers have used horizontal perforated pipe connected directly to the vent pipe for collection of sub-slab soil gases. The suction pit recommended here is lower cost and equally effective if all design recommendations are followed.

- Locate and terminate the vent in a manner consistent with codes and standards for discharge of laboratory fume hood exhaust or other rooftop exhausts venting toxic fumes. The discharge can contain extremely high radon concentrations.
  - See *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007a) (relevant portions are summarized in Strategy 3.2 – Locate Outdoor Air Intakes to Minimize Introduction of Contaminants for guidance on minimum distances to outdoor air intakes).
  - See *Industrial Ventilation: A Manual of Recommended Practices*, 25th edition, (ACGIH 2004) or Chapter 44 of *ASHRAE Handbook—HVAC Applications* (ASHRAE 2007b) for examples of suitable discharge configurations. Ensure that the radon fan can generate sufficient static pressure to overcome the pressure drop of the vent termination.
  - If it is not possible to terminate the vent high enough above the roof and far enough from air intakes to prevent the discharge from re-entering the building, EPA (1994) recommends that a configuration be chosen to provide at least a 1,000:1 dilution ratio to the nearest air intake or operable window. See Chapter 44 of *ASHRAE Handbook—HVAC Applications* for procedures to calculate dilution ratios.

Suction Fan. A suction fan is needed for each vent pipe. Passive systems (without a fan) are sometimes effective in single-family residential constructions but are not generally recommended for commercial or institutional buildings because negative pressures from various exhaust systems, insufficient building pressurization, stack effect due to greater building heights, and other factors are more likely to overcome a passive system in these buildings. In addition, passive systems would require a greater number of suction pits and vent pipes to be effective and would be more expensive than an ASD system.

The following design criteria are recommended:

- Use a fan (or fans) manufactured specifically for outdoor installation and continuous duty in radon control systems. Tubular in-line centrifugal fans are typically used.
- For a sub-slab depressurization zone on the order of 50,000 to 100,000 ft^2 (4650 to 9300 m^2), EPA (1994) recommends a fan rated for 500 to 600 cfm (4650 to 9300 L/s) at 0 in. w.c. (0 Pa) static pressure. As a point of comparison, ASTM (2007) calls for 75 cfm (35 L/s) at 0.75 in. w.c. (188 Pa) for low-rise residential systems and allows a lower flow rate as long as the fan maintains at least –0.02 in. w.c. (5 Pa) in all parts of the gas-permeable layer. In commercial buildings where stack effect, wind effect, or mechanical system imbalances could cause ground-contact rooms to be at negative pressure relative to outdoors, greater sub-slab depressurization could be needed to maintain the sub-slab at a lower pressure than the ground floor under all weather conditions.
- Locate the fan above the roof. Pipe downstream of the fan is under positive pressure, and leaks could allow radon to enter the building (see Strategy 6.3 – Design Exhaust Systems to Prevent Leakage of Exhaust Air into Occupied Spaces or Air Distribution Systems).
- Connect the fan to the vent pipe with watertight flexible connectors.
- Provide a waterproof electrical service switch at the fan as required by code.
- Provide a warning device to alert the building operator if the radon exhaust system is not operating properly. The warning device (light, audible alarm, etc.) will need to activate whenever the system pressure drops below the nominal operating suction pressure. This value needs to be determined at system start-up by measuring the suction required at the sensor location to maintain the desired negative pressure everywhere under the slab. The warning device needs to be installed in an area frequently visited by the building operator, facilities manager, or other responsible person and needs to be clearly labeled. One option is to connect the pressure sensor to the building automation system (BAS) and generate the alarm via the BAS.

If there is a significant likelihood that the building will not have elevated radon levels, the venting can be capped at roof level and the fan installed after radon testing if determined necessary.

Labeling. Labeling radon system components decreases the likelihood that future owners or operators will remove or defeat the system. EPA (1994) recommends that vent piping be labeled at least every 10 ft (3 m) along its entire pipe run and that the vent termination be labeled, including a statement regarding the minimum distance to be maintained from the termination to any air intake. Although *ASTM E 1465-07a, Standard Practice for Radon Control Options for the Design and Construction of New Low-Rise Residential Buildings* (ASTM 2007), does not apply to commercial buildings, its requirements for the location and content of labels for radon systems in low-rise residential systems may provide useful guidance. The standard addresses pipe labels, radon system labels, sump cover inspection labels, membrane inspection labels for plastic membranes in crawlspaces, and radon system maintenance provider identification labels.

Sub-Membrane Depressurization of Crawlspaces. Radon control for crawlspaces is described in Appendix E – Additional Information on Radon Control.

Sealing of Radon Entry Routes

Radon can enter buildings through innumerable routes (see Figures 3.3-D and 3.3-E). Sealing the major entry routes greatly increases the effectiveness of ASD and is an essential element of radon-resistant construction. Sealing alone (without ASD) is not an effective radon reduction technique because it is practically impossible to seal every opening that could allow soil gas to enter the building.

Sealing of Joints, Cracks, and Penetrations in the Slab. The following design criteria are recommended for sealing of joints, cracks, and penetrations in the slab above the gas-permeable layer:

- Reduce cracking of slabs in contact with the ground. Follow recommended industry practices (ACI 2004a). Reinforce concrete with rebar and wire mesh, reinforce with fiber additives (ACI 2002), use water-reducing admixtures (plasticizers) (ACI 2004b), cure properly, and/or use higher strength concrete.
- Seal all joints in slabs, including joints between the floor slab and exterior and interior load-bearing walls, pour joints, and control saw joints. Seal openings around penetrations through the slab including water lines, sewer lines, floor drains, gas lines, electrical service entries, air-conditioning condensate drains, roof drains, and others.
    - Use a sealant with strong adhesion to concrete under difficult conditions, long service life, and good elasticity.
    - Prepare surfaces and apply sealant according to the manufacturer’s instructions. Proper preparation typically requires that surfaces be clean and dry and that the surface temperature be above freezing.
    - For recommended sealing techniques, see EPA (1994) and ASTM (2007).
- Seal drains and sumps.
    - Provide water traps in all floor drains.
    - If interior footing drains extend beneath the footing to daylight or to a sewer, use water traps to keep the drains airtight while still allowing water to drain.
    - If interior footing drains terminate in a sump, seal the sump hole airtight with a gasket and lid, use a submersible pump, and vent the sump to the outdoors using plastic or other piping.
- Seal elevator shafts.
    - Thoroughly seal ground-contact portions of elevator shafts.
    - Design drains and sumps to prevent flow of soil gas into elevator shaft.

Construction and Sealing of Below-Grade Walls. The following design criteria are recommended for basement walls, stem walls, curtain walls, tunnel walls, and other below-grade walls:

- Follow recommended industry practices to reduce cracking of poured concrete walls (ACI 2005) and concrete masonry walls.

Strategy 3.3

- Seal openings around all penetrations through walls.
- For concrete masonry walls:
  - Use CMUs with low air permeability if possible (it may be difficult for the manufacturer to provide CMUs with a specific permeability); 100% solid CMUs or fully grouted masonry units are another alternative.
  - Use solid concrete soil gas entry barriers near the top of the wall, immediately below ledges (e.g., ledges supporting brick veneer), and at the top and bottom of doors, windows, and other openings that are below the solid top course or that interrupt it. The solid course near the top of the wall needs to be above the surface of the finished grade. This course could consist of a continuous course of solid concrete masonry or a continuous course of fully grouted masonry units. The solid courses for ledges and openings could be either of these or a solid concrete beam (see ASTM [2007]).

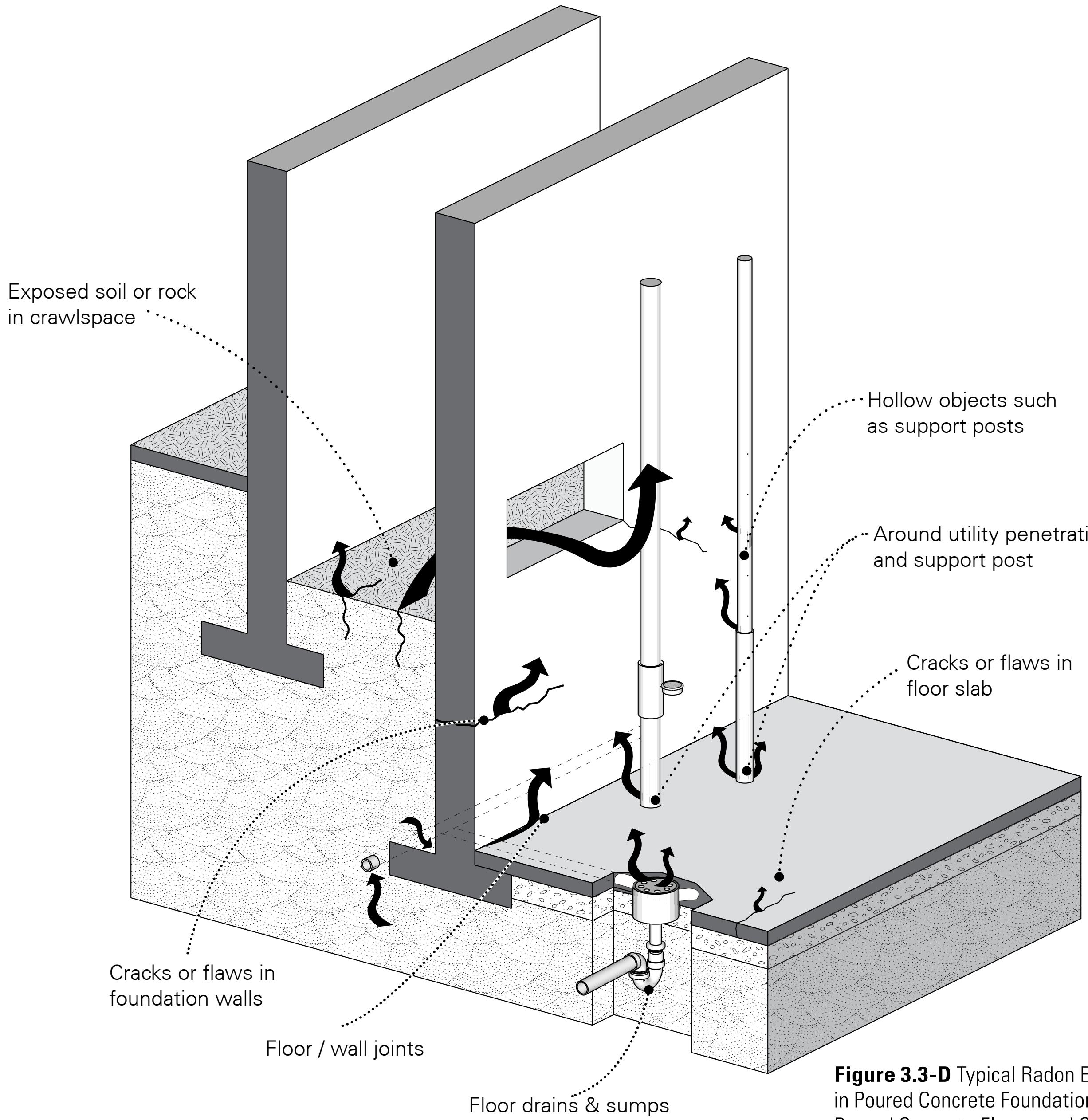

Figure 3.3-D Typical Radon Entry Routes in Poured Concrete Foundation Walls, Poured Concrete Floors, and Crawlspaces
Adapted from CMHC (2007).

Strategy 3.3

- Seal the joint between the bottom course of block and the underlying footing or slab.
- Seal concrete masonry walls with a suitable waterproofing treatment (Table 3.3-D). Neither uncoated concrete blocks nor blocks having only a dampproofing treatment are effective water or soil gas barriers. The waterproofing treatment needs to provide:
  - good adhesion,
  - crack-spanning ability,
  - flexibility and elasticity through a wide temperature range,
  - puncture resistance, and
  - long-term chemical and structural stability in the type of environment where it will be located (e.g., in contact with soil and groundwater, etc).
- Closely follow the manufacturer's recommended application procedures.

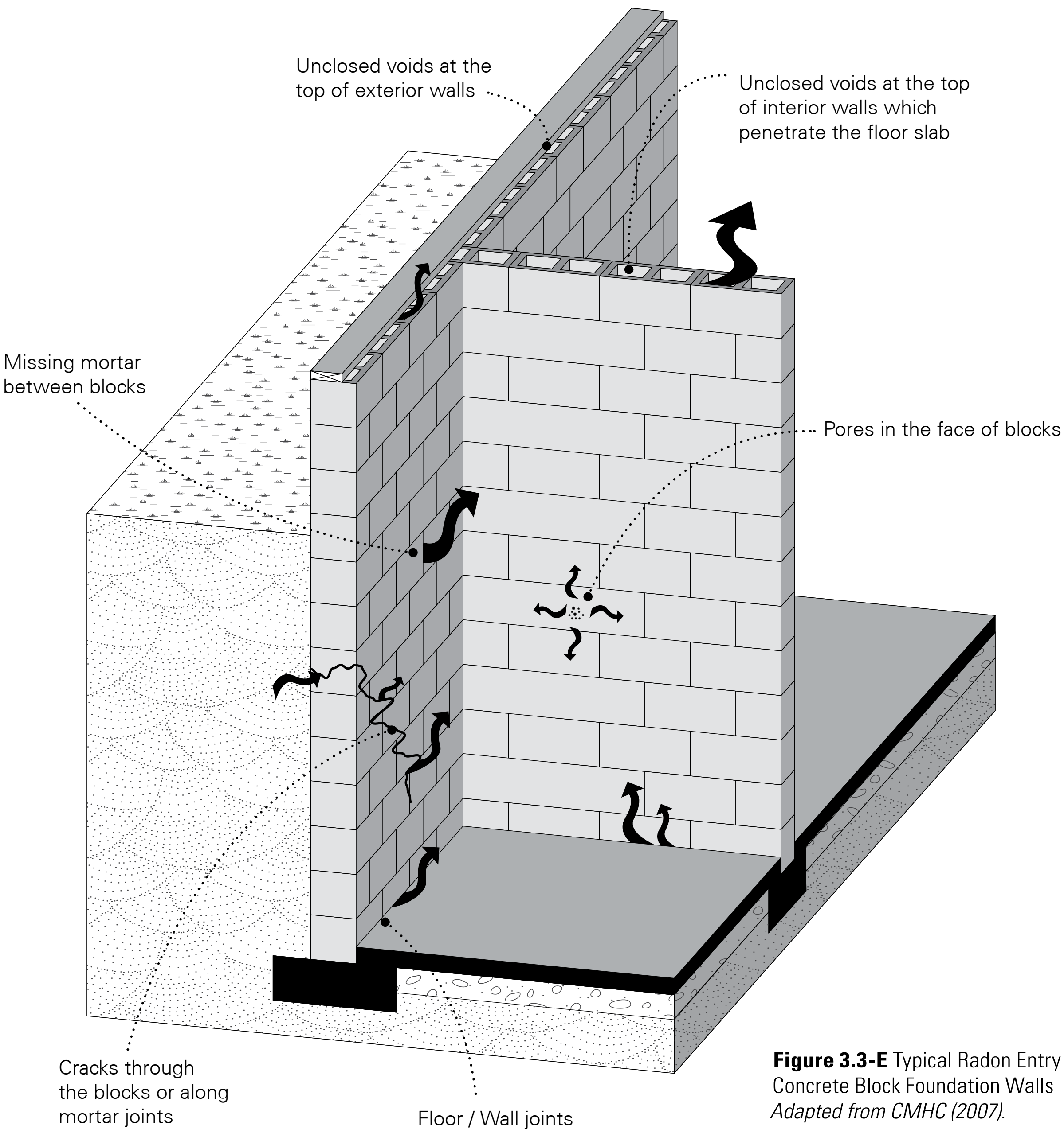

Figure 3.3-E Typical Radon Entry Routes in Concrete Block Foundation Walls
Adapted from CMHC (2007).

- Consider depressurizing the block wall itself if the measures in this section do not sufficiently reduce radon concentrations. Depressurizing block walls can cause basement depressurization (and back drafting of combustion equipment) and in some cases can enhance intrusion of radon, so it should be used only where sub-slab depressurization or drain tile depressurization is inadequate to achieve the required radon reductions (EPA 1993b).

Table 3.3-D Foundation Wall Coatings (EPA 1991, 1994; Ruppersberger 1991)

Wall Coating	Notes
Exterior	
Cold-applied coal tar-modified polyurethane (waterproofing)	Can be attacked by acids in groundwater but can be defended by a protection board. Dries hard but has some elasticity. Performance is limited by capabilities of the applicator. Difficult to achieve even coats on vertical surfaces.
Cold-applied polymer-modified asphalt (waterproofing)	Less resistant to chemicals than coal tar-modified polyurethane but has better elasticity, crack-spanning ability, and re-sealability. Performance is limited by capabilities of the applicator. Difficult to achieve even coats on vertical surfaces.
Membrane waterproofing systems	Uniform thickness. Most are chemically stable and have good crack-spanning ability. Concrete seams need to be smooth so that membrane is not punctured. Thermoplastic membranes are rated high for resistance to chemicals and longevity. Rubberized asphalt polyethylene membranes have superior crack-bridging ability compared to fully adhered thermoplastic membranes. Seams and overlaps need to be carefully and completely sealed for membranes to function as effective radon barriers. Manufacturers' recommendations for sealants, application procedures, and safety precautions need to be followed.
Bituminous asphalt parge or spray coat (dampproofing only)	Undependable as waterproofing treatment or to seal radon entry routes. Can be attacked by soil and groundwater chemicals, specifically acids. May lose elasticity at below-freezing temperatures.
Surface bonding cement or mortar (dampproofing only)	Undependable as waterproofing treatment or to seal radon entry routes. Some may be chemically unstable in the alkaline environment of portland cement.
Interior	
Cementitious coatings	Inelastic, does not have good crack-spanning ability, cannot resist hydrostatic pressure.
Masonry paint	Some can be effective as radon barriers if properly applied.

Building Pressurization

Positive pressurization of grade-level and below-grade spaces is an important adjunct to ASD and sealing of radon entry routes.

Location of Ductwork. Locating ductwork below grade (buried, in tunnels, or in crawlspaces) in radon-prone areas is likely to increase indoor radon concentrations. Below-grade ductwork can draw radon into the air distribution system. Return ductwork leaks can create a strong negative pressure, but even supply ductwork may be negatively pressurized at the duct wall. Where ground-contact mechanical rooms serve as plenums and are at negative pressure during HVAC system operation, it is particularly important to carefully follow recommendations for sealing of slabs and below-grade walls.

Envelope Airtightness. Following the recommendations for airtightness of the building envelope in Strategy 2.2 – Limit Condensation of Water Vapor within the Building Envelope and on Interior Surfaces can reduce the leakiness of the building envelope, thereby reducing the excess of outdoor air over exhaust air required to maintain positive building pressure.

Building Pressurization. Following the recommendations in Strategy 2.3 – Maintain Proper Building Pressurization will make it easier to maintain positive pressure in most ground-contact rooms during occupied hours. This will reduce entry of radon. Ground-contact rooms with high exhaust rates, such as laboratories, commercial kitchens, and locker and shower rooms, pose a particular challenge to radon control systems. The ASD system needs to impose sufficient suction on the sub-slab to keep the sub-slab at lower pressure than these spaces, even though the spaces themselves may be negative with respect to adjacent rooms or the outdoors. If climate considerations, high humidity spaces, or the use of natural ventilation require pressure in ground-contact rooms to be neutral or negative, the ASD system flow rate needs to be adjusted to keep the sub-slab area more negative than the occupied space. ASTM (2007) calls for the sub-slab pressure to be at least –0.02 in. w.c. (5 Pa) relative to the overlying space in all locations.

Morning Start-Up. If ground-contact rooms have a high negative pressure when the HVAC system is off (for example, due to stack effect or wind effect), they may be more negative than the sub-slab area, allowing radon-laden air to flow into the building. If this is the case, it is important to start HVAC operation and ventilation far enough in advance of occupancy to establish positive pressurization and dilute radon that built up while the HVAC system was off.

Quality Assurance of Radon Control Systems

As noted previously, two organizations in the U.S. issue credentials to individuals who are proficient in radon testing and mitigation. Where radon is a concern, the design team may want to obtain the services of a credentialed professional to assist with design, construction observation, and performance verification.

Quality Assurance Steps

Design Verification. A radon professional, commissioning authority, or other person responsible for quality assurance (QA) of a radon system needs to check that radon control measures are properly implemented in the design, including the following:

- Design of load-bearing elements
- Sub-slab aggregate material and thickness, geotextile, and vapor retarder
- Crawlspace membrane and permeable material or perforated piping network
- Location, size, and construction of suction pits
- Location, size, termination, sealing and labeling of radon vent pipe
- Suction fan type, sizing, location, and installation
- Warning device sensors, alarms, and location
- Sealing of below-grade joints, cracks, and penetrations
- Construction and sealing of below-grade walls, especially concrete masonry walls
- Ductwork locations
- Building airtightness and building pressurization and dilution

Submittal Review. The person responsible for QA also needs to review submittals to ensure that they are consistent with the design criteria, including the following:

- Geotextile
- Sub-slab aggregate
- Sub-slab vapor retarder
- Crawlspace membranes

- Permeable material for crawlspace
- Perforated piping network for crawlspace
- Radon vent piping
- Radon suction fan and flexible connectors
- Warning device sensors and alarms
- Sealants for below-grade joints, cracks, and penetrations
- Permeability of CMUs for below-grade walls
- Solid top blocks for below-grade CMU walls
- Waterproofing materials for below-grade CMU walls

Construction Coordination. The person responsible for QA of the radon system needs to meet with construction management, the general contractor, and relevant subcontractors to communicate

- the design intent of the ASD system and foundation sealing,
- prescriptive and performance requirements, and
- construction observation and verification requirements for the ASD system and foundation sealing.

Key construction observation items need to be incorporated into the construction schedule.

Construction Observation. The person responsible for QA of radon control measures will need to observe construction at critical points to ensure that the measures are installed in accordance with the contract documents. Appropriately timed site inspections are needed to verify the following:

- No unintended sub-slab barriers divide any design depressurization zone into more than one zone (prior to installation of aggregate)
- Installation of geotextile fabric below slab (prior to installation of aggregate)
- Installation of aggregate below slab to proper thickness and with no introduction of fines (prior to pouring of concrete)
- Proper location and installation of suction pits, including horizontal vent pipe and support/reinforcement for concrete above suction pit (prior to pouring concrete)
- Installation of vapor retarder over aggregate (prior to pouring concrete)
- Installation of concrete to reduce cracking
- Installation of solid top blocks on CMU walls
- Installation of waterproofing/radon barrier on CMU walls (prior to backfilling [exterior] or covering [interior])
- Installation of permeable material or perforated piping in crawlspaces
- Preparation and sealing of floor/wall joints (prior to installation of floor covering)
- Preparation and sealing of pour joints and control saw joints (prior to installation of floor covering)
- Sealing of all penetrations, drains, and sumps (prior to floor covering or wall surface installation, if any)
- Installation and sealing of polyethylene or other ground cover in crawlspace
- Installation, sealing, and labeling of vent pipe riser (prior to installation of gypsum board or other wall surface)
- Installation and labeling of radon suction fan and vent pipe termination
- Installation and labeling of warning device

Construction Verification. The person responsible for QA of radon control measures will need to verify that radon levels during occupied hours are below action levels.

- EPA recommends that radon levels be measured during occupied hours under normal operation of the ASD and HVAC systems, at least 24 hours after ASD system operation is started. Further information on conducting radon measurements is provided in Appendix E – Additional Information on Radon Control.
- If radon levels are above action levels and fans were not installed, fans can be installed to activate the ASD system.
- If radon levels are above action levels with depressurization fans operating, the person responsible for QA of radon control measures needs to conduct tests to evaluate the pressure field extension and troubleshoot problems. See EPA (1994) for further information on conducting pressure field extension tests.

The person responsible for QA also needs to ensure that warning devices and labeling are installed as recommended and to test the response of the warning device to a reduction or reversal of negative pressure.

O&M Documentation and Training for Radon Control Systems

It is important to provide documentation and training to the facilities staff on the purpose, importance, location, and operation and maintenance (O&M) of radon control systems (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ).

The following information is useful to include in the O&M manual for the radon control system:

- System description, purpose, and components.
- As-built drawings showing locations of suction pits, vent pipes, and suction fans.
- Results of any radon tests obtained without or with operation of the ASD system.
- Instructions as to how to read the radon system monitor and the manufacturer's information on monitor installation and calibration.
- Description of how to interpret the system failure warning device and what to do if it indicates a failure.
- Contact information for the company to be called for radon system service.
- Contact information for the agency in charge of the state's radon program.
- Radon fan warranty and installation documentation.
- Recommended periodic maintenance procedures. EPA (1994) recommends the following:
  - Weekly:
    - Check pressure gauge(s) in radon vent pipe(s) and system alarm to ensure that fan is maintaining adequate negative pressure to depressurize the sub-slab area.
  - Annually:
    - Inspect radon suction fan(s) for bearing failure or signs of other abnormal operation and repair or replace if required.
    - Inspect discharge location of radon vent pipe to ensure that no air intake has been located nearby and that no change in building usage has placed the exhaust near operable windows.
    - Check HVAC system to verify that its operation is not creating negative building pressures that could overcome the ASD system.
    - If building has settled, check for slab, floor, or basement wall cracks and perform radon testing and additional sealing, if needed, to ensure the continued effectiveness of the system.
    - Inspect impermeable membrane in crawlspace and repair or replace if necessary.
  - When work is performed in foundation area:
    - Ensure that any new or disturbed penetrations are sealed following the specifications for the original construction.
  - When work is performed on HVAC systems:
    - Ensure that requirements for building pressurization and ventilation are maintained.

Training and O&M documentation on building pressurization is covered in Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ and Strategy 2.3 – Maintain Proper Building Pressurization.

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Strategy 3.4

Control Intrusion of Vapors from Subsurface Contaminants

Introduction

Vapor intrusion is "the migration of a [chemical of concern] vapor from a subsurface soil or groundwater source into the indoor environment of an existing or planned structure" (ASTM 2008, p. 5). Although vapors can intrude into buildings from naturally occurring subsurface gases,[1] most regulations, standards, and guidance materials are specific to vapors from soil or groundwater contaminants.[2] Volatile substances in buried wastes or in contaminated soil or groundwater can vaporize and move through the vadose zone by diffusion. Once they reach the zone of influence of a building, they are drawn through the soil and through cracks and openings in the foundation whenever the building is at negative pressure relative to the surrounding soil (EPA 2004). Such negative pressures can occur due to thermal stack effect, wind effect, exhaust and combustion vent flows that exceed make-up airflows, or other factors (ASHRAE 2005). The potential for vapor intrusion was not widely recognized by U.S. regulators until the 1990s (IRTC 2007a), and both the science and the regulatory environment are still evolving.

The chemicals of concern for vapor intrusion are those that are sufficiently volatile to migrate through the soil as a vapor and sufficiently toxic that they may adversely affect human health[3] (EPA 2002). These include many volatile organic compounds (VOCs), some semi-volatile organic compounds, and some inorganic substances such as mercury. Vapor intrusion is a concern primarily because of the potential for chronic health effects from long-term exposure to low concentrations, although in extreme cases vapor concentrations can be high enough to cause acute health effects. Some may also create an explosion or suffocation hazard (EPA 2002). For example, intrusion of methane or carbon dioxide from landfills can create risks of explosion or suffocation, respectively (EPA 2005). These acute effects and hazards are outside the scope of this Guide but need to be evaluated when a building project is on or near a contaminated site. ITRC's (2007a) guideline states that step 1 of the screening process should be to evaluate whether the site may present an acute exposure concern or emergency hazard. If so, immediate collection of indoor samples or implementation of interim remedial measures such as evacuation of occupants or sub-slab depressurization must be undertaken.

Contaminants can be present below ground due to accidental spills, improper disposal, leaking landfills, or leaking underground or aboveground storage tanks (Tillman and Weaver 2005). Some of the most common present and past land uses associated with chemicals of concern include gas stations, dry cleaners, former industrial sites that had vapor degreasing or other parts-cleaning operations, and former manufactured gas plants (ASTM 2008). Other land uses potentially associated with chemicals of concern include landfills, circuit board manufacturing plants, electrical power facilities, military bases, and many others. There are hundreds of thousands of contaminated or potentially contaminated sites in the U.S., including Superfund sites, Resource Conservation and Recovery Act (RCRA) sites, underground storage tanks (USTs), brownfields, and oil sites (EPA 2002). For example, it is estimated that there are about 36,000 active dry cleaning facilities in the U.S., of which 75% are contaminated with volatile solvents (EPA, cited in ITRC [2003]). The U.S. Government Accountability Office has estimated that 200,000 active USTs in the U.S. may be leaking (GAO 2002). There are an estimated 3000 to 5000 sites of former manufactured gas plants in the U.S. (EPA 1999).

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[1] Examples of naturally occurring subsurface gases are radon, methane, and hydrogen sulfide. Radon is a decay product of uranium and is widespread. Mitigation of radon is addressed in Strategy 3.3 – Control Entry of Radon. Naturally occurring methane includes natural gas in geologic formations as well as methane formed from the anaerobic decay of more recent organic matter. Hydrogen sulfide gas occurs naturally in crude oil, natural gas, and volcanic gases and can also be formed from the anaerobic decay of more recent organic matter.

[2] The exception is radon. See Strategy 3.3 – Control Entry of Radon.

[3] A chemical is considered sufficiently volatile if its Henry's law constant is 1×10^{-5} atm·m^3/mol or greater. It is considered sufficiently toxic if the vapor concentration of the pure component poses an incremental lifetime cancer risk greater than 10^{-6} or a non-cancer hazard index greater than 1 (EPA 2002).

Strategy 3.4

The geographic extent of vapor intrusion associated with a given source can vary tremendously. For example, in Redfield, Colorado, use of solvents at a former manufacturing facility had contaminated the groundwater with 1,1 dichloroethene in a plume extending about 1.5 mi (2.4 km) under residential properties (Folkes and Kurz 2002). Identification of this problem led to indoor air testing of nearly 800 homes and mitigation of nearly 400 (ITRC 2007a). On the other hand, an investigation conducted for the U.S. Environmental Protection Agency (EPA) at a retail dry cleaner in Michigan found that perchloroethylene contamination of the soil caused vapor intrusion in one nearby residence but no others (EPA 2006).

Vapor intrusion can occur even though a contaminated site has undergone remediation. For example, at an industrial site in Endicott, New York, over 73,000 gal (~280,000 L) of VOCs had been removed and over 2 billion gal (~8×10^9 L) of groundwater pumped over a period of 20 years when the state directed that the potential for vapor intrusion be investigated. Testing was conducted in a sample of homes and businesses located above the 300 acre (1.2 million m^2) groundwater plume. Elevated concentrations of tricholorethene and other VOCs were found in indoor air even in cases where groundwater concentrations were low, and remediation was conducted in over 400 structures (McDonald and Wertz 2003; NYSDEC 2007).

A few states are moving to evaluate closed cases for vapor intrusion. New York has decided that all past, current, and future contaminated sites will be evaluated (NYSDEC 2006). This policy decision affects several hundred sites already remediated and either in the long-term monitoring phase or closed out (NYSDEC 2006; ITRC 2007b). Maine has also reopened selected closed sites (ITRC 2007b). In addition, some other states have investigated a few sites without formally reopening them, have reviewed old sites on a case-by-case basis, are evaluating their policies on this issue, or note that they have the authority to re-open sites if warranted (ITRC 2007b).

Screening and Assessment

Federal Guidance

The EPA developed draft guidance for evaluation of vapor intrusion in 2002 (EPA 2002). This guidance was suggested for use at RCRA Corrective Action sites, sites on the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) National Priorities List (NPL), and Superfund Alternative and Brownfields Sites, but not for UST sites, for which EPA recommended continued use of an earlier directive (EPA [1995a]; see also ASTM [2002]). In 2005, EPA published guidance for evaluating landfill gas emissions with respect to both explosion hazard and vapor intrusion (EPA 2005). The U.S. Department of Defense has its own guidance documents as well (U.S.A.F. 2006; U.S. Army 2006).

Glossary for Vapor Intrusion

Brownfields: Section 101 of CERCLA defines brownfields as "real property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant" and estimates that there are more than 450,000 brownfields in the U.S. More information on brownfields can be found in EPA (2008a), and those interested can find information about the EPA's Brownfields Program at www.epa.gov/swerosps/bf/index.html (EPA 2009a).

CERCLA (42 U.S.C. 9601 et seq.): The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) was enacted in 1980 and amended by the Superfund Amendments and Reauthorization Act of 1986; the Asset Conservation, Lender Liability, and Deposit Insurance Protection Act of 1996; and the Small Business Liability Relief and Brownfields Revitalization Act of 2001 (EPA 2009b, 2009c). This act is commonly known as the **Superfund Act**. CERCLA "gives the Federal government the authority to respond to chemical emergencies and to clean up uncontrolled or abandoned hazardous waste sites. The Superfund program addresses both short and long term risks, from toxic chemical spills and threats to the permanent cleanup and rehabilitation of abandoned hazardous waste sites. Superfund also provides authority for the prosecution of those responsible for the releases of hazardous waste and a trust fund to subsidize cleanup when no responsible party can be identified" (EPA 2009b). As of October 26, 2007, there were 1245 final sites and 66 proposed sites on the National Priorities List (NPL) where long-term remediations can be conducted under CERCLA (EPA 2009d): www.epa.gov/superfund/sites/query/queryhtm/npltotal.htm.

LNAPL: LNAPLs are light, non-aqueous phase liquids. They are not readily soluble in water and are less dense than water. As a result, they may pool on top of the water table. Oil and gasoline are examples.

RCRA (42 U.S.C.6901 et seq.): The Resource Conservation and Recovery Act (RCRA) was enacted in 1976 and amended by the Hazardous and Solid Waste Amendments of 1984. RCRA regulates the management of solid waste, hazardous waste and underground storage tanks for petroleum products and certain chemicals. RCRA solid waste means "any garbage, or refuse, sludge from a wastewater treatment plant, water supply treatment plant, or air pollution control facility and other discarded material, including solid, liquid, semi-solid, or contained gaseous material resulting from industrial, commercial, mining, and agricultural operations, and from community activities" (GPO 2006). RCRA hazardous waste includes waste that is ignitable, corrosive, reactive (e.g., explosive) or contains certain amounts of toxic chemicals. EPA has developed a list of more than 500 specific hazardous wastes. Hazardous wastes are generated by businesses such as dry cleaners, automobile repair shops, hospitals, exterminators, photo processing centers, chemical manufacturers, electroplating companies, and oil refineries (www.epa.gov/osw//basic-hazard.htm). Information about hazardous waste handlers including generators, transporters, treatment, storage and disposal facilities, and more is available from EPA's RCRAInfo database through the Hazardous Waste Query Form (EPA 2009e): www.epa.gov/enviro/html/rcris/rcris_query_java.html.

Superfund: See CERCLA.

Underground storage tank: EPA defines an underground storage tank (UST) system as "a tank and any underground piping connected to the tank that has at least 10 percent of its combined volume underground" (EPA 2009f). Subtitle I of RCRA requires EPA to regulate USTs and to require owners and operators to prevent, detect, and clean up releases. The statute and regulations apply only to USTs storing either petroleum or hazardous substances as defined in CERCLA.

Vadose zone: The vadose zone is the zone between the land surface and the regional water table. The vadose zone is generally unsaturated, with pores containing a mixture of water and soil gas, except for the capillary fringe above the water table and any perched water tables within the vadose zone.

State Guidance

Many states have developed regulations, policies, or guidance for vapor intrusion investigations, while others are currently developing such documents or rely on the EPA (2002) draft guidance (Buonicore 2007; ITRC 2004). Screening and assessment of the potential for vapor intrusion must follow the regulations, policies, and guidance of the relevant jurisdiction. Obtaining guidance from the appropriate regulatory agency early in the process is the best way to avoid problems and ensure a successful project. The Interstate Technology & Regulatory Council (ITRC) maintains a list of vapor intrusion contacts for states and EPA regions on its Web site (www.itrcweb.org/vaporintrusion), and EnviroGroup maintains links to various state guidance documents on its Web site (www.envirogroup.com/links.php).

ASTM E2600: A National Standard for Assessment of Vapor Intrusion in Real Estate Transactions

In 2008, ASTM International developed a national standard (*ASTM E2600, Standard Practice for Assessment of Vapor Intrusion into Structures on Property Involved in Real Estate Transactions*) for assessment of vapor intrusion on properties involved in real estate transactions (ASTM 2008). This standard addresses vapor intrusion from USTs and landfills as well as CERCLA, RCRA, and brownfield sites. It defines straightforward and relatively low-cost approaches to screen sites for potential vapor intrusion conditions. It is anticipated that EPA and ASTM will work together to educate state regulatory agencies about the standard and seek to achieve consistency in regulatory response to assessments conducted using the standard as it becomes a routine part of property environmental due diligence (Buonicore 2008).

Based on extensive discussion with environmental consultants involved in Phase I assessments (from *ASTM E1527, Standard Practice for Environmental Site Assessments: Phase I Environmental Site Assessment Process* [ASTM 2005]), the task group that developed ASTM E2600 expects that the screening methodology laid out in Tiers 1 and 2 of the standard will eliminate vapor intrusion as a concern in the vast majority of real estate transactions (Buonicore 2008).

The standard uses a tiered approach to allow properties with a low risk of vapor intrusion to be screened out quickly and at relatively low cost. Tiers 1 and 2 are used to determine whether a potential vapor intrusion condition (pVIC) exists. If a pVIC does exist, Tier 3 is used to provide confirmation that a vapor intrusion condition (VIC) exists or to reduce the level of uncertainty. Tier 4 provides general mitigation alternatives. Users can conduct a Tier 3 investigation or preemptively mitigate a site (Tier 4) without conducting Tier 1 and 2 screenings if they choose to do so for reasons of timeliness, cost-effectiveness, or other considerations (ASTM 2008).

The standard requires that vapor intrusion assessments be performed by an environmental professional as defined in ASTM E1527 (ASTM 2005),[4] so in most cases this work will be contracted outside the primary design team. The steps are described here to give the design team an understanding of the process and how it may impact the schedule and the ultimate building design.

ASTM Tier 1 Screening

ASTM E2600 Tier 1 screening (ASTM 2008) uses information that is generally collected during an ASTM E1527 Phase I Environmental Site Assessment (ESA).[5] Phase I ESAs are conducted as a standard part of environmental due diligence in most commercial real estate transactions in the U.S. Information required for Tier 1 screening includes

- the existing or planned use of the property;
- existing and planned types of structures on the property;
- characteristics of the surrounding area;
- government records that identify known or suspected sources of chemicals of concern on the property itself and surrounding areas;
- historical records related to prior use of the property and surrounding areas;
- physical setting information including topographic, hydrologic, geologic, hydro-geologic, and soils data;
- natural and man-made features that may provide preferential paths for vapor movement;
- specialized knowledge that the user (typically the prospective purchaser) may have; and
- any other information from the Phase I ESA, if the vapor intrusion assessment is conducted in conjunction with an ESA.

This information is reviewed to evaluate whether a pVIC exists. The screening assesses

1. whether there are known or suspected contaminated sites within specified minimum search distances of the property,
2. whether chemicals of concern are likely to be present at these sites, and
3. whether the contaminated plume of groundwater, soil gas, or light non-aqueous phase liquid (LNAPL) from these sites is within the critical distance of the nearest existing or planned building on the property (or the nearest property boundary, if there are no existing or planned buildings), and, if it is, whether risk-based concentrations for vapor intrusion are exceeded.

The first two of these screening steps are mandatory, while the third is conducted only if data on the extent and depth of the contaminated plume are available at the time of the Tier 1 screening.

Contaminated Sites within Minimum Search Distance. ASTM E2600 specifies the approximate minimum search distances to which government records must be reviewed to identify known or suspect

[4] ASTM E 1527 references and repeats the requirements of 40 CFR §312.10(b). Under this regulation, a professional engineer or geologist must have the equivalent of three years of full-time relevant experience and others must have up to ten years of relevant experience to conduct these assessments. 40 CFR §312.10(b) states that "Relevant experience, as used in the definition of environmental professional in this section, means: participation in the performance of all appropriate inquiries investigations, environmental site assessments, or other site investigations that may include environmental analyses, investigations, and remediation which involve the understanding of surface and subsurface environmental conditions and the processes used to evaluate these conditions and for which professional judgment was used to develop opinions regarding conditions indicative of releases or threatened releases (see Sec. 312.1(c)) to the subject property" (GPO 2009).

[5] In the past, there was some ambiguity as to whether the Phase I ESA itself required investigation of the potential for vapor intrusion (Buonicore 2007), although the vast majority of Phase I ESAs did not include such an investigation. ASTM E2600-08 clarifies that vapor intrusion assessment is outside the scope of an ASTM E1527 ESA, though it may be conducted concurrently as a supplemental scope item.

contaminated sites. For some types of contaminant sources the search covers only the property itself, while for others it extends as far as a mile from the property's boundaries (Table 3.4-A). Historical records of past land uses must also be searched to the same distances. Standard historical sources that must be reviewed include fire insurance maps, local street directories, aerial photographs, U.S. Geologial Survey topographical maps, and other credible sources.

Likely Presence of Chemicals of Concern at These Sites. ASTM E2600 lists typical chemicals of concern for vapor intrusion in an informative appendix (see Table 3.4-B). (Many states have their own lists that must be used for sites in their jurisdiction.) The environmental professional uses existing records and data and familiarity with various types of contaminant sources (e.g., service stations, dry cleaners) to determine whether chemicals of concern are likely to be present.

Contaminated Plume within Critical Distance. If data on the location of the contaminated plume are available, the environmental professional can evaluate whether the plume is within the critical distance of the nearest existing or planned building on the property (or the nearest property boundary, if there are no existing or planned buildings). This is a "stretched-string" distance that takes into account the depth to the plume as well as its overland distance from the property. It is 100 ft (~30 m) for non-petroleum hydrocarbon chemicals of concern and LNAPL but only 30 ft (~9 m) for dissolved petroleum hydrocarbon chemicals of concern, since the latter are biodegraded in the vadose zone in the presence of oxygen.

Concentrations Exceeding Risk-Based Concentrations. If data are available on the concentrations of chemicals of concern in the contaminated plume, the environmental professional can evaluate whether these exceed risk-based concentrations (RBCs) for vapor intrusion. Some states use the RBCs from EPA (2002) while others have established their own generic RBCs for screening purposes.

- The EPA (2002) draft guidance sets target indoor air concentrations to satisfy both the prescribed risk level (for cancer risk) and the target hazard index (for non-cancer risk). It then establishes target shallow soil gas, deep soil gas, and groundwater concentrations corresponding to these target indoor air concentrations based on "reasonable worst case" attenuation factors from soil gas to indoor air and partitioning between the water table and soil gas governed by Henry's law. The EPA guidance allows the site risk manager to "choose to select media-specific target concentrations for screening at three cancer risk levels: 10^{-4}, 10^{-5}, and 10^{-6}, or a hazard quotient of 1 for non-cancer risk, whichever is appropriate" (p. 8) and thus provides three different tables of generic screening levels using the three different cancer risk levels. This provides latitude of as much as 100:1 in the RBCs to be used for screening.
- According to a survey of state regulators (ITRC 2004), over two-thirds of states now differentiate between residential and nonresidential occupancies in setting screening levels for chemicals of concern. The nonresidential screening levels are generally somewhat higher than the residential levels because the lifetime hours of exposure are assumed to be lower. In addition some jurisdictions use a child adjustment factor for carcinogens in residential settings but not in nonresidential settings (see, for example, NJDEP [2005]). Screening levels for schools, day-care facilities, hospitals, nursing homes, and other buildings with sensitive populations are typically lower than those for other workplaces and may be the same as those for residences. The target indoor air concentrations for vapor intrusion in workplaces are generally based on current estimates of cancer risk levels and non-cancer hazard quotients and are much lower than Occupational Safety and Health Administration (OSHA) occupational levels.

Table 3.4-A Approximate Minimum Search Distances* (ASTM 2008)

	Surrounding the Property Being Transacted		Hydrogeologically Up-Gradient of Property Being Transacted	
Environmental Record Sources	**Chemicals of Concern**	**Petroleum Hydrocarbon Chemicals of Concern****	**Chemicals of Concern**	**Petroleum Hydrocarbon Chemicals of Concern****
Federal Lists				
Federal NPL site list	1/3 mi (1/2 km)	1/10 (1/6 km)	1 (1.5 km)	1 (1.5 km)
Federal CERCLIS list	1/3 (1/2 km)	1/10 (1/6 km)	1/2 (1.25 km)	1/2 (1.25 km)
Federal RCRA CORRACTS facilities list	1/3 (1/2 km)	1/10 (1/6 km)	1 (1.5 km)	1 (1.5 km)
Federal RCRA non-CORRACTS TSD facilities list	1/3 (1/2 km)	1/10 (1/6 km)	1/2 (1.25 km)	1/2 (1.25 km)
Federal RCRA generators list	property only	property only	property only	property only
Federal institutional control/engineering control registries	property only	property only	property only	property only
Federal ERNS list	property only	property only	property only	property only
State and Tribal Lists of Hazardous Waste Sites Identified for Investigation or Remediation				
State and tribal equivalent NPL	1/3 (1/2 km)	1/10 (1/6 km)	1 (1.5 km)	1 (1.5 km)
State and tribal equivalent CERCLIS	1/3 (1/2 km)	1/10 (1/6 km)	1/2 (1.25 km)	1/2 (1.25 km)
State and tribal landfill and/or solid waste disposal site lists	1/3 (1/2 km)	1/10 (1/6 km)	1/2 (1.25 km)	1/2 (1.25 km)
State and tribal leaking storage tank lists	1/3 (1/2 km)	1/10 (1/6 km)	1/2 (1.25 km)	1/2 (1.25 km)
State and tribal registered storage tank lists	property only	property only	property only	property only
State and tribal institutional control/engineering control registries	property only	property only	property only	property only
State and tribal voluntary cleanup sites	1/3 (1/2 km)	1/10 (1/6 km)	1/2 (1.25 km)	1/2 (1.25 km)
State and tribal brownfield sites	1/3 (1/2 km)	1/10 (1/6 km)	1/2 (1.25 km)	1/2 (1.25 km)

*Distances are from the nearest boundary of the property undergoing transaction.

**Distances are shorter for petroleum chemicals because they tend to biodegrade in the vadose zone.

Notes: CERCLIS = Comprehensive Environmental Response, Compensation, and Liability Information System; CORRACTS = Corrective Action Sites; TSD facility = treatment, storage, or disposal facility; ERNS = Emergency Response Notification System; NPL = National Priorities List.

Table 3.4-B Typical Chemicals of Concern for Vapor Intrusion*+

CAS Regis. No.	Chemical	CAS Regis. No.	Chemical	CAS Regis. No.	Chemical	CAS Regis. No.	Chemical
83329	Acenaphthene	75003	Chloroethane (ethyl chloride)	86737	Fluorene	98953	Nitrobenzene
75070	Acetaldehyde	67663	Chloroform	110009	Furan	79469	2-Nitropropane
67641	Acetone	95578	2-Chlorophenol	58899	gamma-HCH (Lindane)	924163	N-Nitroso-di-n-butylamine
75058	Acetonitrile	75296	2-Chloropropane	76448	Heptachlor	103651	n-Propylbenzene
98862	Acetophenone	218019	Chrysene	87683	Hexachloro-1,3-butadiene	88722	o-Nitrotoluene
107028	Acrolein	156592	cis-1,2-Dichloroethylene	118741	Hexachlorobenzene	95476	o-Xylene
107131	Acrylonitrile	123739	Crotonaldehyde (2-butenal)	77474	Hexachlorocyclo-pentadiene	106423	p-Xylene
309002	Aldrin	98828	Cumene	67721	Hexachloroethane		Polychlorinated biphenyls (PCBs)
319846	alpha-HCH (alpha-BHC)	72559	DDE	110543	Hexane	129000	Pyrene
100527	Benzaldehyde	132649	Dibenzofuran	74908	Hydrogen cyanide	135988	sec-Butylbenzene
71432	Benzene	96128	1,2-Dibromo-3-chloropropane	78831	Isobutanol	100425	Styrene
205992	Benzo(b)fluoranthene	106934	1,2-Dibromoethane (ethylene dibromide)	7439976	Mercury (elemental)	98066	tert-Butylbenzene
100447	Benzylchloride	541731	1,3-Dichlorobenzene	126987	Methacrylonitrile	630206	1,1,1,2-Tetrachloroethane
91587	beta-Chloronaphthalene	95501	1,2-Dichlorobenzene	72435	Methoxychlor	79345	1,1,2,2-Tetrachloroethane
92524	Biphenyl	106467	1,4-Dichlorobenzene	79209	Methyl acetate	127184	Tetrachloroethylene (perchloroethylene)
111444	Bis(2-chloroethyl)ether	75718	Dichlorodifluo-romethane	96333	Methyl acrylate	108883	Toluene
108601	Bis(2-chloroiso-propyl)ether	75343	1,1-Dichloroethane	74839	Methyl bromide	156605	trans-1,2-Dichloroethylene
542881	Bis(chloromethyl)ether	107062	1,2-Dichloroethane	74873	Methyl chloride (chloromethane)	76131	1,1,2-Trichloro-1,2,2-trifluoroethane
75274	Bromodichloromethane	75354	1,1-Dichloroethylene	108872	Methylcyclohexane	120821	1,2,4-Trichlorobenzene
75252	Bromoform	78875	1,2-Dichloropropane	74953	Methylene bromide	79005	1,1,2-Trichloroethane
106990	1,3-Butadiene	542756	1,3-Dichloropropene	75092	Methylene chloride	71556	1,1,1-Trichloroethane
75150	Carbon disulfide	60571	Dieldrin	78933	Methylethylketone (2-butanone)	79016	Trichloroethylene
56235	Carbon tetrachloride	115297	Endosulfan	108101	Methylisobutylketone	75694	Trichlorofluoromethane
57749	Chlordane	106898	Epichlorohydrin	80626	Methylmethacrylate	96184	1,2,3-Trichloropropane
126998	2-Chloro-1,3-butadiene (chloroprene)	60297	Ethyl ether	91576	2-Methylnaphthalene	95636	1,2,4-Trimethylbenzene
108907	Chlorobenzene	141786	Ethylacetate	1634044	MTBE	108678	1,3,5-Trimethylbenzene
109693	1-Chlorobutane	100414	Ethylbenzene	108383	m-Xylene	108054	Vinyl acetate
124481	Chlorodibromomethane	75218	Ethylene oxide	91203	Naphthalene	75014	Vinyl chloride (chloroethane)
75456	Chlorodifluoromethane	97632	Ethylmethacrylate	104518	n-Butylbenzene		

*This ASTM (2008) list is drawn from *OSWER Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance)* (EPA 2002), deleting those chemicals that EPA indicated do not meet both the toxicity and volatility criteria and adding polychlorinated biphenyls. The approach used by EPA to develop the original list is described in Appendix D of the EPA document. Although EPA excludes petroleum releases from USTs from the scope of its guidance, many of the key chemicals of concern for petroleum leaks are nevertheless included in their list.

+As noted previously, intrusion of methane can create an explosion hazard. This is outside the scope of this Guide but needs to be considered when evaluating properties near contaminated sites that may be associated with subsurface methane.

Tier 1 Screening Outcomes. ASTM E2600 (ASTM 2008) defines those conditions under which a pVIC must be presumed to exist:

- If a known or suspect source of contamination exists within the specified minimum search distance and if chemicals of concern are suspected to be present at that site, the ASTM standard requires that a pVIC be presumed to exist if no further data are available.
- If data on the location and depth of the contaminated plume are available as well, a pVIC must be presumed to exist only if at least one plume or LNAPL is within the critical distance of existing or planned buildings on the property (or of the property boundary if there are no existing or planned buildings).
- If data on contaminant concentrations in the plume are also available and if the state allows use of RBCs, a pVIC must be presumed to exist only if at least one plume is within the critical distance and has concentrations at the closest point in the plume that exceed the RBCs.

If a pVIC is identified, the client working with his or her environmental consultant needs to decide how to proceed. In different circumstances it may make sense to proceed to a Tier 2 investigation or to proceed directly to pre-emptive mitigation (Tier 4).

If it can be determined that there are no known or suspect contaminated sites within the minimum search distance or, if there are such sites, that the distance to their contaminated plumes or LNAPL is greater than the critical distance, or if the contaminated plume is within the critical distance but the plume concentrations are lower than the applicable RBCs, then it can be presumed unlikely that a pVIC exists in an existing or planned building on the property. If no pVIC exists, no further action is required. However, the user might still decide to install pre-emptive mitigation if, for example, it appears possible that a migrating plume may reach the property at some time in the future or if there is a risk of future leaks or spills.

ASTM Tier 2 Screening

ASTM E2600 Tier 2 screening (ASTM 2008) may be based on existing or new data. If "extent of contamination" reports (Phase II reports) exist at the appropriate regulatory agency for all potentially contaminated sites within the minimum search distance, then the Tier 2 screening can be based on existing information alone. The reports are reviewed to determine the size and behavior of the contaminated plume, the specific contaminants and their concentrations, and the status of remediation. The environmental professional evaluates this information to determine whether the contaminated plume is within the critical distance and whether the concentrations at the nearest point exceed RBC levels, as described previously. It appears likely that in many cases environmental professionals will combine the Tier 1 screening and the portion of the Tier 2 screening based on existing data into a single scope of work (Buonicore 2008).

If there are known or suspect contaminated sites within the minimum search distance for which detailed plume data are not available, Tier 2 screening allows for sampling of soil, soil gas, and/or groundwater, if such sampling may prove useful in assessing the potential for a VIC.

Tier 2 Screening Outcomes. The criteria for deciding whether a pVIC exists or is not likely to exist at the property are essentially the same as described for the Tier 1 screening. While the decision at the Tier 1 stage is sometimes based only on the presence of known or suspect sources of contaminants within the minimum search distance (which in the worst case can be up to a mile), the more complete data available at the conclusion of a Tier 2 screening should at least allow the decision to be made based on whether a plume is within the critical distance (which at worst can be 100 ft [~30 m]) and may allow the decision to be based on whether contamination in those plumes exceeds RBCs.

ASTM Tier 3 Assessment

If the Tier 1 and Tier 2 screenings do not screen out the potential for a VIC, the prospective owner may choose to conduct a more sophisticated (and likely more expensive) Tier 3 assessment. Because current policies vary widely, ASTM E2600 (ASTM 2008) defines the assessment only in general terms and requires the environmental professional to review and consider applicable federal and state regulation, policy, or guidance. The standard suggests that in jurisdictions that do not provide vapor intrusion guidance, users should rely on the EPA (2002) draft guidance or the guidance prepared by the ITRC (2007a).[6] It also notes that the Tier 3 assessment requires specialized expertise and may be beyond the capability of the environmental professional conducting the Phase I ESA.

The specific investigative approach(es) selected for a Tier 3 assessment (see Table 3.4-C) may depend on regulatory requirements or on other considerations. ITRC (2007a) and ASTM (2008) provide considerable informative guidance and references on sampling design, sample collection and analysis methods, quality assurance (QA), and interpretation. Both recommend that multiple lines of evidence be used in drawing conclusions.

Use of Groundwater or Soil Gas Data. If groundwater or soil gas data are collected (e.g., in the case of new construction) and concentrations exceed generic screening levels, modeling is typically used to estimate indoor air concentrations. The EPA spreadsheet version of the Johnson and Ettinger model is most commonly used (see EPA [2004]).[7] This version includes a component programmed by EPA that calculates human health risk based on the estimated indoor concentrations. The Johnson and Ettinger model is based on certain assumptions that may not always be appropriate (ITRC 2007a):

- Steady-state conditions
- An infinite source of contamination
- Uniform air mixing in the building
- No preferential pathways
- No biodegradation of contaminants in the vadose zone
- Homogeneous lateral distribution of contaminants beneath the building
- Entry of contaminant vapors primarily through cracks in the foundation and walls
- Buildings constructed on slabs or with basements
- Constant ventilation rates and soil gas flow into the building

According to ITRC, the EPA version of the model is most suitable under homogeneous site conditions with uniform building construction features. Conversely, the model is weakest under variable conditions and cannot evaluate significant preferential pathways; wet basements; substantial lateral transport of soil gas; tall buildings in cold climates; large buildings with potential localized sources of vapors beneath them; and shallow, fractured-bedrock conditions. Each of these conditions has the potential to significantly increase the rate of vapor intrusion beyond the model's predictions. (ITRC 2007a, p. 37)

Obviously use of the model is appropriate when the assumptions implicit in it reasonably match the real-world conditions being modeled.

[6] ITRC is "a state-led, national coalition of personnel from the environmental regulatory agencies of some 46 states and the District of Columbia, three federal agencies, tribes, and public and industry stakeholders. The organization is devoted to reducing barriers to, and speeding interstate deployment of better, more cost-effective, innovative environmental techniques" (ITRC 2007a).

[7] Use of any model should be approved by the relevant regulatory agency. According to ITRC, regulatory agencies typically customize the EPA spreadsheet by changing some default values and limiting which parameters can be changed with site-specific data (ITRC 2007a).

Table 3.4-C Approaches for Vapor Intrusion Investigations (ITRC 2007a)

Medium Investigated	Evaluation Method*	Key Issues
Groundwater	Prediction of indoor air concentrations based on attenuation factor or site-specific modeling.	Lack of precision in attenuation factors or modeling requires use of very conservative assumptions. Henry's law must be corrected for groundwater temperature.
Soil gas	Prediction of indoor air concentrations based on attenuation factor or site-specific modeling.	Fewer pathway assumptions than for ground-water. More difficult to ensure accuracy and representativeness of measurements.
Sub-slab soil gas	Prediction of indoor air concentrations based on attenuation factor or site-specific model-ing. Attenuation factor may be measured using a naturally occurring tracer such as radon.	Fewest pathway assumptions. Intrusive. Attenuation factors may still be conservative for some buildings.
Indoor air	Direct measurement of indoor air concentrations.	Intrusive. Background sources may make it difficult to determine contribution of vapor intrusion. There may be seasonal variations in concentrations.

*In all cases the estimated indoor air concentration is used in a health risk assessment to determine whether a vapor intrusion condition exists.

Use of Indoor Air Samples. When indoor air samples are collected rather than groundwater or soil gas samples, determining the contribution due to vapor intrusion can be difficult because many of the chemicals of concern have other sources in building materials, heating fuels, consumer products, ambient outdoor air, and so on and because regulatory screening levels are close to background levels for many compounds. ITRC (2007a) therefore recommends that a) indoor air sampling be conducted only after identifying the buildings most likely to be affected in order to minimize false positives, b) background sources be eliminated prior to sampling whenever possible (e.g., cigarette smoke and recently dry-cleaned clothes), and c) outdoor ambient samples be taken whenever indoor samples are collected.

Tier 3 Assessment Outcomes. The conclusion of a Tier 3 assessment may be that 1) a VIC exists, 2) no VIC exists, or 3) there is not enough information to reach a clear conclusion. If there is insufficient information to reach a conclusion, a pVIC must be presumed to exist.

Site Remediation and Institutional Controls

Site Remediation

In the long term, the best remedy for contaminated sites is to remove the contaminant source or to perform treatments to reduce contaminant levels. Remediation technologies include such options as excavating and removing contaminated soil, pumping and treating contaminated groundwater, in situ chemical oxidation, in situ bioremediation, and soil vapor extraction and treatment. Detailed discussion of these measures is outside the scope of this Guide.

Removal of contaminated soil and soil vapor extraction have the potential to reduce or eliminate soil gas migration substantially in a relatively short time, rendering building mitigation measures unnecessary (ITRC 2007a). Some other technologies, such as groundwater pumping and treating, are longer-term strategies that may take many years to reduce the contaminant source to a level where vapor intrusion is no longer a concern, as at the Endicott, New York, site described in the Introduction of this Strategy. Where these longer-term cleanup strategies are used, institutional controls and/or building mitigation are necessary as interim strategies until cleanup is complete. In still other cases, cleanup may be on hold pending legal decisions regarding responsibility, availability of cleanup funds, or completion of investigations, feasibility studies, and remediation designs. In these cases, too, institutional controls and/or building mitigation are necessary as interim strategies.

Institutional Controls
Institutional controls are "legally enforceable conditions placed on a property to reduce the likelihood of exposure to unacceptable levels of contaminants" (ASTM 2008, p. 19). They may include such measures as zoning restrictions, prohibitions on excavation, advisories about groundwater contamination, requirements that vapor intrusion mitigation systems be preemptively installed in new construction, requirements that source remediation systems or building mitigation systems be periodically inspected, and/or requirements that contaminant levels be periodically monitored (ITRC 2007a).

Establishment of institutional controls is outside the scope of this Guide, but the design team needs to ensure that they are aware of and fully understand any institutional controls that may be in place on the property where a project is undertaken. In some circumstances an owner or developer could seek to incorporate institutional controls as an alternative to mitigation. For example, use restrictions that would ensure that a facility could not be used as a day care or school could allow higher action levels to be applied and possibly eliminate the need for a mitigation system.

Building Mitigation

Relationship to Radon Mitigation Techniques
The methods used to mitigate vapor intrusion are largely adapted from radon control strategies described and tested by EPA (1993, 1994a, 1994b, 1995b) and are therefore similar to those described in Strategy 3.3 – Control Entry of Radon.

This discussion mainly highlights differences in application to vapor intrusion, so Strategy 3.3 – Control Entry of Radon also needs to be reviewed in designing vapor intrusion mitigation systems. Note, however, that bringing indoor vapor concentrations below action levels commonly requires reductions of two or three orders of magnitude (and sometimes more), in contrast to the one to two orders of magnitude typically required to bring radon concentrations below action levels. To achieve these larger reductions, it may be necessary to combine several mitigation techniques or to design and install systems to exacting standards.

Note that the mitigation technologies described here are designed to reduce intrusion of contaminants in the vapor phase. If contaminants enter the building in contaminated groundwater or by capillary wicking, it is necessary to first solve the problem causing water entry and then address vapor migration.

Advantages of Mitigation as Part of Initial Design and Construction
Where the need to mitigate vapor intrusion is a possibility, it is cheaper and more effective to incorporate the system in the original design and construction rather than to retrofit it after the building is built and vapor concentrations are tested. The need for vapor intrusion control should therefore be considered early in design. During conceptual design, it may be possible to reduce the potential for vapor intrusion by changing the placement of a building on a property, the location of the portions of a building having basements, locations of elevator shafts, and the like (ITRC 2007a). Later design decisions may affect the cost of vapor intrusion mitigation systems or preclude some mitigation options. For example, the type and design of load-bearing elements may affect the number of subsurface vapor collection points required.

Regulatory Requirements
Requirements for design, installation, and performance testing of vapor intrusion mitigation systems vary widely by jurisdiction. It is therefore important to involve the appropriate regulatory agency early in the design process. Systems should be designed and installed by parties who meet the qualifications of the regulatory agency having jurisdiction and who have relevant expertise. Very few design teams or contractors have this expertise in-house, so most rely on specialized environmental consultants and mitigation contractors. Since vapor intrusion is a relatively new issue, the developer needs to review consultants' and contractors' experience carefully to ensure that they will be able to provide effective

solutions. Regulatory agencies may be able to provide information regarding environmental consultants and contractors who have worked on vapor intrusion within their jurisdiction.

Interstate Technology & Regulatory Council (ITRC) Guidance

ITRC's (2007a) vapor intrusion guideline summarizes available vapor intrusion mitigation technologies and their advantages and disadvantages (see Tables 3.4-D and 3.4-E). It was prepared by a team that included representatives of environmental agencies in 21 states, the EPA, the U.S. Army, the Navy, and a number of environmental consulting and industry groups.

Much of the ITRC (2007a) mitigation guidance is based on EPA research in single-family dwellings and on vapor intrusion experience in single-family dwellings. Some factors can make commercial buildings moderately less susceptible to vapor intrusion. These include somewhat higher outdoor air exchange rates in some commercial space types, somewhat greater indoor air dilution volumes in some cases, a larger footprint relative to the size of some vapor plumes, some degree of building pressurization in typical commercial designs, and higher action levels for some commercial space types. The impact of these differences on the suitability of various mitigation systems is likely to be greater for sites remote from the contaminant source (e.g., over a groundwater plume some distance away) than for contaminated sites themselves. In the latter case, where the projected indoor contaminant concentrations in an unmitigated building may be 1000 times the action level, modest differences in air change rates, etc., between commercial and residential buildings are not sufficient to affect the choice of mitigation techniques. In the former case, where projected concentrations in unmitigated buildings may be much lower, the normal differences between commercial and residential buildings may in some cases be sufficient to allow simpler mitigation techniques such as passive venting and barrier systems to succeed. As noted previously, however, passive systems always need to be designed to allow ready conversion to active systems if necessary.

Table 3.4-D Comparison of Vapor Intrusion Mitigation Methods (Adapted from ITRC [2007a])

Technology	Typical Applications	Challenges	Pros	Cons
Sub-slab depressurization (SSD)	• New and existing buildings. • In new construction, typically combined with venting layer and gas vapor barrier to maximize extent of sub-slab negative pressure field associated with each suction pit and reduce the number of pits required. • Can be designed to depressurize sumps, drain tiles, and block wall foundations, if present.	• Performance limited where soils are wet or have low permeability.	• Can be used in both existing and new buildings. • Most reliable, cost-effective, and efficient technique in the majority of cases. • Documented effectiveness in reducing vapor intrusion: 90% to 99% reduction typical in single-family homes (EPA 1993), with reductions of 99.5% or more possible with well-designed and constructed systems (Folkes 2002). • Adaptable to a wide range of site conditions and geology. • Variations in air temperature, wind, and atmospheric pressure do not influence effectiveness. • Performance can be monitored with simple pressure gauges. • Venting layers and gas vapor barriers do not need to be as robust as for passive systems.	• Requires periodic maintenance. • Higher operating and maintenance costs than passive systems. • In existing buildings, conditions may limit options for location of suction pits, risers, and fans. • More difficult to effectively depressurize large areas with each fan if soils are wet or have low permeability. • Will not work if the venting layer becomes saturated due to high water tables or flooding. • In some jurisdictions and situations, may require air emission permit or exhaust gas control.

Strategy 3.4

Technology	Typical Applications	Challenges	Pros	Cons
Sub-membrane depressurization (SMD)	• Crawlspaces. • Dirt or bedrock floors in existing building basements.	• Sealing to foundation wall, penetrations. • Potential for damage to membrane over time by tradespeople or maintenance staff accessing crawlspace.	• Similar to SSD. • Most effective mitigation system for crawlspaces. Properly installed SMD systems have resulted in concentration reductions of up to 99.5% in residences (Folkes and Kurz 2002). • Can be combined with SSD in buildings that have both slabs or basements and crawlspaces.	• Similar to SSD. • Membranes must be sealed well at foundation wall, footings, and penetrations to prevent leaks. • Membranes can easily be damaged by persons accessing crawlspace. • System needs to be inspected periodically to confirm that no significant leakage has developed due to damage or loss of seals. Monitoring, inspection, and repair costs may be higher than for SSD. • In some jurisdictions and situations, may require air emission permit or exhaust gas control.
Sealing joints, cracks, and penetrations in the building envelope	• Cracks and penetrations in existing buildings.	• Access to all openings for sealing. • Lack of permanence. • Low effectiveness by itself.		• In existing buildings sealing alone reduces levels only 0% to 50% (ITRC 2007a).
Gas vapor barriers	• New buildings. • Crawlspaces and dirt or bedrock floors in existing buildings. • Often combined with passive venting or SSD/SMD and with sealing of joints, cracks, penetrations, drains, etc. in foundation to increase effectiveness. Not generally recommended by itself.	• Preventing tears and holes. • Ensuring that seams, penetrations, etc. are effectively sealed. • May not be sufficient by itself unless only small reductions in vapor intrusion rates are needed. • Some states do not accept gas vapor barrier alone. • Lack of standard criteria for minimum thickness, puncture resistance, and tear strength of barrier materials.	• Low to moderate capital cost. • No mechanical parts. • Low operating and maintenance costs.	• Not easily applicable to existing buildings except for crawlspaces and dirt or bedrock floors. • Even small holes, tears, or incomplete sealings of seams or of edges at footings, walls, columns, or penetrations can render barrier alone ineffective. • Not likely to be effective by itself unless required reductions in intrusion rates are low. • In exposed applications (e.g., crawlspaces), tradespeople or maintenance staff may accidentally penetrate barrier during building maintenance work. • High concentrations of some chemicals could potentially degrade membrane or seam seals, so compatibility of the barrier with the contaminant vapor and other chemicals in the soil need to be assessed.
Passive venting	• New buildings. • Sites with low soil gas flux. • Should be combined with gas vapor barrier having no significant leaks. • Should be designed to enable conversion to active system if passive system performance is inadequate.	• Relies on airflow induced by wind and stack effects, which do not ensure venting at all times. • Airflow rates and suction usually much less than achieved by active systems. • Performance limited where soils are wet or have low permeability.	• Can be applied where vapor intrusion is a possibility but not yet certain to occur (e.g., new construction) and converted to an active SSD system later if determined necessary. • Low operating and maintenance costs.	• Not as effective as active SSD. EPA (1993) found variable performance for passive systems in new construction in single-family homes, with maximum reductions no greater than 90%. • Upgrade to active SSD likely to be required even in new construction if large concentration reductions are needed. • Not suitable for existing buildings unless the required reduction in contaminant concentrations is fairly small. EPA (1993) found reductions of 30% to 70% from passive systems in existing single-family homes. • Wind and stack effect do not ensure venting at all times. • Will not work if venting layer becomes saturated due to high water tables or flooding.

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Technology	Typical Applications	Challenges	Pros	Cons
Building pressurization	• New or existing large commercial buildings. • Buildings with sensitive occupants.	• Requires regular air balancing (and/or automated control) and maintenance. • Will not maintain positive pressure when air handlers are off. • Can increase energy costs due to need to bring in sufficient outdoor air to ensure pressurization.	• Applicable to both new and existing buildings. • May be the most effective technology at preventing vapor intrusion. • May be the most cost-effective option if existing HVAC system is capable of maintaining positive pressures. • Can be implemented in buildings with wet or very low-permeability soils that prevent SSD.	• Generally more costly than other techniques if existing system is not already capable of pressurization. • Incremental energy cost can be substantial. Automated control may minimize energy costs. • Typically keeps building pressurized only during occupied hours. Build-up of contaminants when HVAC system is off and length of time elevated concentrations persist after system comes on need to be evaluated in determining effectiveness. • Regular maintenance and air balancing required to ensure that positive pressure is reliably maintained. Pressure tests and monitoring need to be incorporated into the design to ensure sufficient positive pressure in all areas of building potentially subject to vapor intrusion. • Effective only if building is relatively tight (e.g., not in warehouses with large loading dock doors).
Indoor air treatment	• Specialized cases only. • Can be effective when combined with other techniques to achieve required concentration reductions in problem rooms.	• Can be difficult to effectively capture contaminants. • Energy intensive. Significant operating, maintenance, and monitoring burden. • Typically generates waste disposal stream.	• Removes and disposes of contaminants rather than simply redirecting them outside the building. • Less susceptible to malfunction or leaks than most other technologies. • Can be implemented in buildings with wet or very low-permeability soils that prevent SSD.	• Less effective than other control methods, where they are applicable. • Expensive compared to other methods. Costly to install and to operate. Annual operating expenses of $15,000 to $20,000 not uncommon (ITRC 2003). • Very maintenance-intensive. • Collects contaminant vapors within the building, so is dependent on uninterrupted performance to protect occupants. • If system leaks occur, they may result in higher exposures than if there were no control.
Sub-slab pressurization (SSP)	• Same as SSD. • Most applicable to highly permeable soils.	• Less effective than SSD. • Higher energy costs than SSD. • Potential for short-circuiting through cracks.	• Does not require soil gas to be collected within the building. • May be more efficient than SSD in highly permeable soils.	• Generally less effective than SSD. • Uses more energy than SSD. • Cracks or penetrations can allow air forced into sub-slab to re-enter building, carrying contaminants May not be appropriate for tight soils.

Table 3.4-E Key Elements of Vapor Intrusion Mitigation Systems (ITRC 2007a)

Sub-slab depressurization (SSD)	• Most widely applied and effective systems for vapor intrusion control. • Applicable to new and existing construction. • Typically combined with venting layer and passive barrier in new construction. • One or two suction pits adequate in most existing single-family homes. • Performance may be limited by low-permeability subsoils. • May be combined with drain tile or block wall depressurization.
Sub-membrane depressurization (SMD)	• Most widely applied and effective systems for crawlspaces. • Applicable to new and existing construction. • Suction field extension (e.g., perforated pipe) may be required for tight soils. • Liners should be sealed to foundation walls and footings. • Liners should be protected against damage where access is expected (e.g., to service furnaces or plumbing). • Performance may be limited by low-permeability subsoils. • May be combined with SSD, drain tile, and/or block wall systems.

Passive barrier (alone)	• Do not expect complete elimination of vapors. • Select barriers that are thick enough to withstand normal construction abuse. • Include thorough quality control procedures to minimize barrier damage. • Inspect barrier seals at all edges, penetrations, and seams. • Test barrier integrity and performance after installation. • Have contingencies to enhance passive barriers (with venting or other measures) if not adequate.
Passive venting	• Generally not adequate for existing structures (except crawlspaces). • Do not expect complete elimination of vapors. • Should be combined with sound passive barrier. • Venting layer must be highly permeable with distributed collection pipe system. • Allow for addition of fan if necessary to meet performance objectives. • Test system integrity and performance after installation.
Building pressurization	• Generally practicable only in commercial buildings. • Requires relatively "tight" buildings to limit airflow and energy costs. • Only the bottom floor (e.g., basement) requires pressurization. • May be cost-effective if existing HVAC equipment can be used without significant modifications. • Energy costs typically increased due to higher replacement airflow rates.
Sub-slab pressurization (SSP)	• Generally less effective than SSD systems. • May be appropriate in high-permeability subsoils. • Higher energy costs than SSD systems.

Active Soil Depressurization (ASD)

Active soil depressurization (ASD) systems (sub-slab depressurization [SSD] and sub-membrane depressurization [SMD]) are the most widely used, versatile, and effective systems to reduce vapor intrusion. ASD systems should be combined with sealing of joints, cracks, and penetrations, including sealing of below-grade walls. In new construction, ASD is typically combined with a gas-permeable venting layer and gas vapor barrier to further increase its effectiveness. Where the amount of vapor intrusion that will occur is uncertain, it can make sense to install a passive venting system with a gas vapor barrier (similar to ASD but without the fan) and add the fan(s) to upgrade to ASD if post-construction testing shows it to be necessary. Passive systems should always be designed to be readily converted to active systems. In general, use of barriers alone without passive venting is not recommended by ITRC (ITRC 2007a).

Existing Buildings. Folkes (2002) and Folkes and Kurz (2002) documented reductions in indoor vapor concentrations of 99.5% or more from carefully designed and installed ASD systems in residences in Redfield, Colorado. These systems were installed in existing homes and so did not include gas vapor barriers or sub-slab venting layers, but they did include sealing of accessible cracks and penetrations. About three-quarters of the SSD systems and two-thirds of the SMD systems were able to bring concentrations below action levels for the chemical of concern without modifications to the conventional radon mitigation system design. The remaining SSD systems required such modifications as enlargement of the suction pit, additional suction pits, and/or replacement of the fan with a larger fan. The remaining SMD systems required such modifications as sealing of small remaining gaps between the liner and foundation wall, addition of more perforated pipe to extend the suction field further under the liner, and/or installation of a larger fan.

New Construction. In new construction, use of venting layers and gas vapor barriers can increase the effectiveness of ASD systems, potentially allowing the number of vapor collection and venting points to be reduced or allowing a higher level of performance to be achieved with a given number of collection and venting points. A highly permeable venting layer facilitates lateral movement of soil gases to collection points. Where a gas vapor barrier (see the following "Gas Vapor Barriers" section) is used, the venting layer should consist of rounded materials that will reduce the risk of puncturing the barrier. ITRC (2007a) recommends sand or fine rounded gravel (pea gravel). These materials are finer than the ASTM #5 aggregate recommended in Strategy 3.3. – Control Entry of Radon and may have lower permeability, preventing suction pits from depressurizing as large an area. ITRC (2007a) notes that permeable non-woven geotextiles or geogrids can be used for the venting layer as long as care is taken to avoid clogging the pores with fine-grained soils or concrete.

ASD systems for radon mitigation in commercial buildings are described in Strategy 3.3. – Control Entry of Radon; it is recommended that these techniques be consulted when designing ASD systems for mitigation of vapor intrusion.

Sealing of Vapor Intrusion Routes

In existing buildings, ASD systems should be combined with sealing of joints, cracks, and penetrations, including sealing of below-grade walls. Sealing recommendations for radon mitigation in commercial buildings are described in Strategy 3.3 – Control Entry of Radon; it is recommended that these techniques be consulted when designing ASD systems for mitigation of vapor intrusion.

Gas Vapor Barriers

Gas vapor barriers are materials placed below a building to physically block the intrusion of vapors. They can increase the efficiency of ASD systems, reducing the number of collection points, vent risers, and fans required or providing greater concentration reductions for a given number of collection points. Gas vapor barriers should be used with ASD systems in new construction where vapor intrusion is a concern and in crawlspaces in existing construction. According to ITRC (2007a), they are unlikely to be effective by themselves unless only small reductions in vapor intrusion rates are needed, so their use alone is not generally recommended.

ITRC (2007a) recommends use of thick (e.g., 1/4 in. [~64 mm]) layers of spray-on rubberized asphalt emulsions or thick sheet membranes (e.g., 60–100 mil [~ 1.5–2.5 mm] high-density polyethylene or similar materials) (see Figure 3.4-D). ITRC recommends use of cushioning materials above and/or below the membrane, such as geotextiles, sand, or fine rounded gravel (pea gravel), to reduce the risk of puncturing the barrier and rendering it ineffective (see Figures 3.4-E and 3.4-F). ITRC cautions against use of thin polyethylene films or moderately thick (e.g., 10–20 mil [~0.25–0.5 mm]) polyvinyl chloride membranes below concrete slabs because experience has shown that they are too easily damaged during construction. ITRC further recommends that the chemicals of concern at a given site be evaluated to assess whether they could degrade the integrity of the gas vapor barrier material or seals.

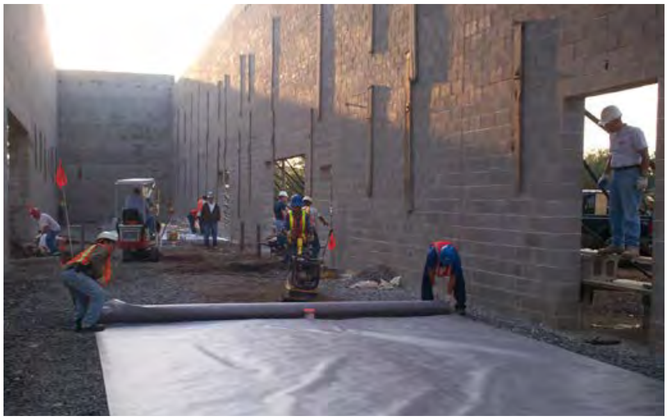

Figure 3.4-D Base Fabric (Non-Woven Geotextile) Installed to Protect Spray-Applied Gas Vapor Barrier Membrane from Underlying Aggregate, which Includes a Low-Profile Venting Network (see Figures 3.4-L and 3.4-M)
Photograph copyright CETCO.

Figure 3.4-E Gas Vapor Barrier Membrane Being Sprayed on Base Fabric
Photograph copyright CETCO.

Figure 3.4-F Protective Layer Laid Over Solidified Spray-Applied Membrane
Photograph copyright CETCO.

To create a gas-tight system, sheet membranes need to be welded at the seams and at penetration points. Penetration boots, attachment bars, and fasteners are needed to attach the liner to penetrations. Spray-applied membranes need to be sprayed onto a base carrier (e.g., a geotextile fabric) having at least a 6 in. (~150 mm) overlap at all seams. A cant strip needs to be installed around the base of each penetration and the membrane sprayed at least 3 in. (~80 mm) onto the penetrating components (piping, wiring, footings, posts, etc.) (Figure 3.4-G).

If a gas vapor barrier is to be effective, the project needs to include carefully planned and executed quality control procedures. These procedures need to ensure that the membrane is not damaged during installation and verify that it is carefully sealed at penetrations, seams, and edges (Figures 3.4-G, 3.4-H, 3.4-I, and 3.4-J). They need to ensure that it is not damaged during placement of the overlying rebar and concrete or other construction activities. They should also include testing of performance after the slab is placed, for example by smoke tests, pressure tests, or measurement of indoor vapor concentrations.

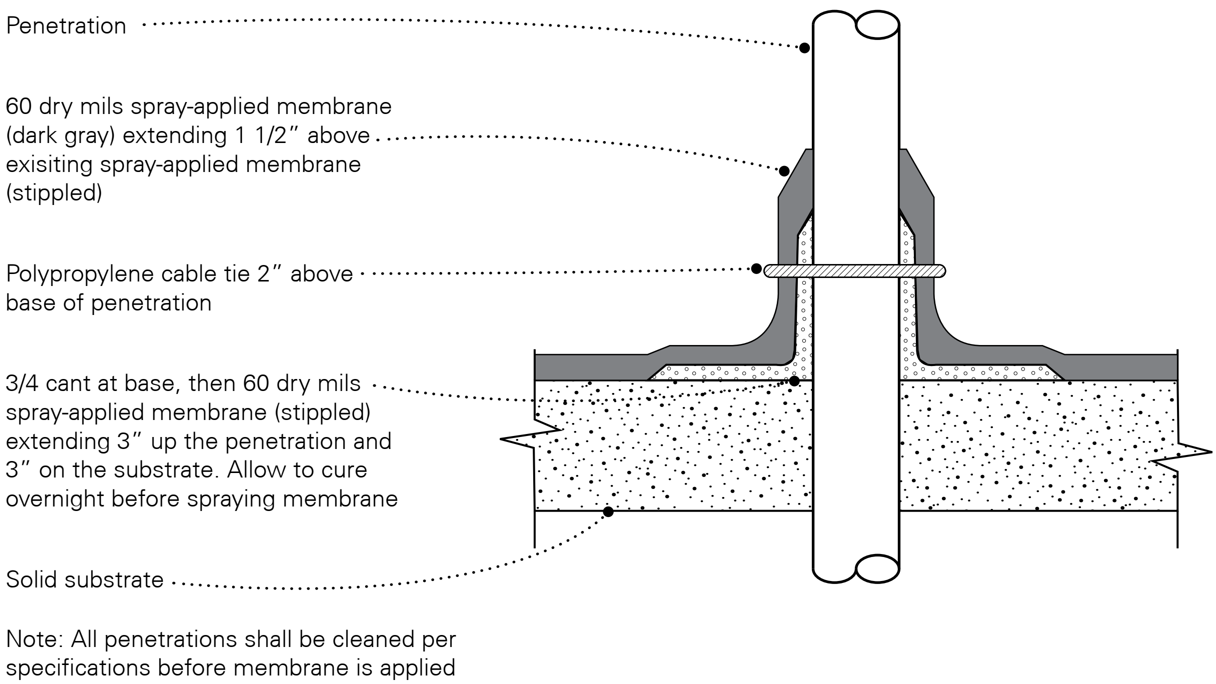

Figure 3.4-G Sealing of Spray-Applied Membrane at Penetrations
Adapted from CETCO (2008).

Figure 3.4-H Fan Injecting Smoke Under Membrane

Figure 3.4-I Smoke Escaping at a Leakage Point

Figure 3.4-J Spraying Over Leakage Point

Figure 3.4-K Leak Eliminated—No Smoke Escaping

Photographs copyright CETCO.

Figures 3.4-H, 3.4-I, 3.4-J, and 3.4-K show the smoke testing of a spray-applied membrane. The gas vapor barrier needs to be tested after installation of the slab as well to ensure that installation of rebar, the pouring of the slab, and other construction activities have not damaged the barrier.

The thick barrier and cushioning recommended for vapor intrusion go well beyond the recommendations for the sub-slab vapor retarder in radon mitigation systems (see Strategy 3.3 – Control Entry of Radon). The retarder recommended there is intended only to exclude wet concrete from the venting layer (aggregate), not to serve as a barrier against soil gas flow.

Gas vapor barriers used to reduce vapor intrusion need to be coordinated with vapor barrier requirements for moisture control (see Kanare [2005]).

Passive Venting

Passive venting consists of a venting layer below the slab and a passive vent stack to exhaust the soil gas. The primary driving forces for passive venting are wind and stack effect, and these may be low, zero, or reversed under some weather or mechanical system operating conditions, so a passive venting system needs to be combined with a highly effective gas vapor barrier with no significant leaks (ITRC 2007a).

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Passive venting is not as effective as ASD and may not be adequate where large reductions in indoor vapor concentrations are needed. Its first cost is generally higher than that of active systems for roughly comparable performance because of the need for a more highly permeable venting layer, more collection and venting points, a network of soil gas collection piping, and a highly effective gas vapor barrier. Moreover, some jurisdictions may not allow the use of passive systems. For all these reasons, it may be preferable to proceed directly to an active system.

However, in new construction where the amount of vapor intrusion that will occur is uncertain, it can make sense to install a passive system as a provisional strategy and later add the fan(s) required to upgrade to an active system if testing shows it to be necessary. Passive systems have lower operating and maintenance costs. In addition, they typically do not need a discharge permit, which is required for active systems in some jurisdictions.

Figures 3.4-L and 3.4-M show low-profile venting material being used as an alternative to a piping network. This material has a three-dimensional vent core wrapped with a needle-punched geotextile fabric that allows vapor to enter the core but keeps soil out. Fittings are used to attach the venting material to pipe risers for passive or active venting.

Building Pressurization

Building pressurization may be the best choice for sites with wet or low-permeability soils where ASD is unable to create large depressurization fields below the slab. It may also be a viable alternative to ASD for other buildings if the HVAC system has the capability to reliably maintain positive pressures in all ground-contact rooms (ITRC 2007a). EPA (1994b) reports that only small (<0.001 in. w.g. [<0.25 Pa]) positive pressures are required to prevent vapor intrusion. However, pressurization for vapor intrusion control requires a level of QA in design, construction, operation, and maintenance that goes beyond that associated with pressurization control for most other purposes. (Exceptions are cleanrooms and other spaces with exacting HVAC system performance requirements.) Building pressurization is also likely to increase energy use more than an ASD system. In cases where the building owner is not the party legally responsible for mitigation, the owner may be reluctant to employ the HVAC system for vapor intrusion mitigation control. For these reasons, building pressurization has not been widely used as a vapor intrusion mitigation strategy to date (Folkes 2008).

Figure 3.4-L Roll of Venting Material

Figure 3.4-M Venting Network

Photographs copyright CETCO.

Strategy 3.4

Strategy 2.3 – Maintain Proper Building Pressurization provides design guidance for building pressurization. Several additional considerations need to be taken into account when using building pressurization to mitigate vapor intrusion, as discussed in the following paragraphs.

Dilution of Contaminants that Accumulate when HVAC Systems are Off or No Outdoor Air is Introduced. HVAC systems can only maintain positive pressure when they are running and when outdoor air is being provided. When they are off (e.g., nights and weekends) or when the outdoor air dampers are closed, vapor intrusion may occur and allow contaminant concentrations to rise in indoor air. HVAC systems need to be started and outdoor air introduced long enough before occupancy to dilute accumulated contaminants, including those that may have sorbed onto building and furnishing surfaces. The time required to accomplish this needs to be evaluated on a building-specific basis.

Tight Control for Low Action Levels. Some chemicals of concern may have very low action levels, requiring more consistent and reliable pressure control than is needed to meet other objectives (such as control of condensation in building cavities, control of outdoor air contaminants, or control of drafts for occupant comfort).

Positive Pressurization under All Weather and Operating Conditions. Buildings and systems need to be designed, balanced, tested, operated, and maintained to provide positive pressure in all ground-contact rooms under all weather conditions and building operating conditions. Particular issues of concern may include, among others, the following:

- *Stack effect* in cold climates, including the potential need to compartmentalize the ground floor from higher floors and/or provide separate HVAC systems to enable efficient pressurization
- *Wind effect*
- *Balancing and control of outdoor airflows, relief flows, and exhaust fan flows* at the air handler level
- *Adequate allowance for building envelope leakage* in determining the excess of outdoor airflow over exhaust flow required for pressurization
- *Inability to pressurize buildings with large leakages*, such as warehouses with large doors that are frequently open
- *Zone-level balancing* of supply, return, and exhaust in ground-contact rooms, including zones (such as commercial kitchens) with large exhaust flows
- *Effects of demand-controlled ventilation (DCV), variable-volume operation, or other control strategies* on outdoor airflow and on building or zone-level pressurization
- *Pressure sensors* with proper location of indoor and outdoor taps, proper initial calibration, and periodic recalibration
- *Negative pressures* in return air systems in contact with the ground, including ducts, tunnels, plenums and mechanical rooms
- *Action of elevators* "pumping" soil gas into the building

Operation and Maintenance (O&M) Manuals and Training. It is critical that the design intent to use building pressurization to control vapor intrusion be clearly documented in the O&M manuals and addressed in operator training. Many future changes have the potential to undermine the effectiveness of this vapor intrusion mitigation strategy, including operator reductions in outdoor air volumes or shortening of morning purge times to reduce energy costs, addition of DCV, addition of exhausts, tenant turnover and fit-out, rebalancing by operators or contractors unfamiliar with the system design intent, and other actions. Because building pressurization is provided by the HVAC system, it may be more vulnerable to performance degradation by future O&M and remodeling changes than a dedicated vapor intrusion mitigation system such as an ASD system.

Energy Costs. Use of building pressurization to control vapor intrusion may entail higher equipment costs and energy costs to condition sufficient minimum outdoor air volumes and to purge contaminants each day before the first occupants arrive.

Unintended Contaminant Flows. Building pressurization could deflect contaminated soil gas into adjacent, unprotected spaces, such as other tenant spaces within a mall building—a situation that needs to be avoided.

Other Approaches

Positive sub-slab pressurization (SSP), indoor air treatment, and intrinsically safe building design may be viable alternative or supplemental mitigation techniques in certain circumstances.

Positive Sub-Slab Pressurization (SSP). In highly permeable soils where SSD systems are unable to adequately depressurize the area below the slab, use of positive SSP may be more effective (EPA 1993). In SSP, air (usually from indoors) is forced into the venting layer or the soil below the slab rather than being drawn out. This creates a zone of slightly elevated pressure, causing the vapor-laden soil gases below to flow to the sides of the building, where they are released into the ambient air. SSP systems use more energy than SSD systems. Moreover, cracks and penetrations in the slab or foundation wall may allow the air injected into the sub-slab to re-enter the building, potentially carrying vapors with it. Where SSP appears to be the appropriate choice, the injected air needs to be filtered to prevent clogging of the system. Pits need to be provided at the injection points (EPA 1993).

Indoor Air Treatment. Indoor air treatment is not widely used to reduce concentrations of intruding vapors because it is both less effective than other methods and more costly to install and operate. However, it can be useful to augment other mitigation technologies to further reduce concentrations in "problem rooms." Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives provides information on sorbent media, filter cartridge types, efficiencies, capacities, pressure drop, and selection criteria.

Intrinsically Safe Building Design. ASTM E2600 (ASTM 2008) suggests in multiple sections that vapor intrusion can be avoided through "intrinsically safe building design," such as use of open-air parking or well-ventilated underground parking between the ground and the first occupied floor. ITRC (2007a) does not discuss this alternative. Where this approach is consistent with the overall architectural design goals of a project, the effectiveness needs to be carefully evaluated. Considerations include, among others, the following:

- *Elevator Shafts.* The potential for elevator shafts serving underground parking garages or open air parking levels to provide a route for intrusion of vapors into the occupied floors.
- *Other Unintended Flow Paths.* The potential for other unintended airflow paths (e.g., around column enclosures) to allow vapors to be drawn into occupied floors.
- *Carbon Monoxide Control.* The potential for original or retrofit carbon monoxide control of parking exhaust to radically reduce garage ventilation and vapor dilution.
- *Stack Effect.* The potential for stack effect to overwhelm underground parking exhaust.
- *Unbalanced Parking Exhaust.* The potential for underground parking exhaust to increase soil gas flux if not properly balanced by make-up air.

Effect of Chemicals of Concern on Mitigation System Design

The particular chemicals of concern at a given site affect system design in three ways (ITRC 2007a):

1. Potentially combustible vapors require intrinsically safe blowers and monitoring or alarm systems.
2. Some vapors can degrade barrier membranes, pipes, or the solvents used to join pipes or seal membrane seams.
3. Contaminant action levels affect the concentration reductions required and the mitigation technologies likely to be successful. Passive systems may be able to achieve reductions of 80% or less, but greater percentage reductions will usually require ASD or pressurization systems (EPA 1993). Standard designs for radon control, if carefully executed, are generally sufficient for reductions of up to 95%, while enhancements may be required to achieve greater reductions (Folkes and Kurz 2002).

Quality Assurance of Vapor Intrusion Mitigation Systems

The environmental consultant is typically responsible for design verification, submittal review, and construction observation related to the mitigation system. The regulatory agency may also participate in these activities.

QA for passive barriers needs to include mechanisms to ensure gas-tight installation, protect the barrier during subsequent construction work, and test its effectiveness. All sealing of the barrier at seams, edges, and penetrations needs to be carefully inspected. Requirements placed in the specifications and observations made during construction should ensure that the integrity of the barrier is preserved. The general contractor and the rebar and concrete contractors who install the overlying slab need to understand the design intent of any gas vapor barrier and the importance of maintaining its integrity as well as the procedures for notification of the environmental consultant or barrier contractor if the barrier is punctured. The effectiveness of the barrier needs to be tested after installation of the slab.

The performance of vapor intrusion mitigation systems needs to be verified after construction is complete. Testing options include the following:

- Measuring the extent of the depressurization field created by an ASD system
- Injecting smoke or a tracer gas into the venting layer while depressurizing the building using the air-handling systems and watching for smoke or measuring tracer gas concentrations inside the building
- Measuring vapor concentrations in a monitoring layer above the barrier but below the slab and estimating indoor concentrations using conservative attenuation factors
- Measuring vapor concentrations in indoor air and adjusting for background concentrations

Most states that have regulations or policies related to vapor intrusion require at least one post-installation test to verify that mitigation systems meet performance objectives, and they specify which types of tests are acceptable. Tests typically need to be performed by a qualified environmental consultant.

If concentrations exceed action levels, performance of a passive barrier system may be improved by adding venting, assuming provisions for venting were made in design and construction. A passive venting system may be converted to an ASD system by adding a fan. Performance of ASD systems may be improved by increasing fan size, enlarging suction pits, installing additional suction pits and associated venting, performing additional sealing, or other strategies.

Operation, Maintenance, and Monitoring of Mitigation Systems

Most states that have regulations or policies related to vapor intrusion require a formal management plan to ensure that the mitigation system will be operated and maintained in a manner that provides ongoing, effective control of vapor intrusion. The management plan is a form of institutional control. Typically, O&M is the responsibility of the party responsible for the contamination.

Many states also require follow-up testing of indoor air and/or system indicators (e.g., sub-slab suction pressures) at some regular interval until such time as the mitigation system is no longer necessary. Regulators may allow the frequency of testing to be reduced over time if tests show that performance is consistently maintained. The testing requirement is also a form of institutional control.

Once long-term cleanup efforts reduce contamination to a degree that reduces vapor intrusion below action levels, systems can be deactivated with the approval of the regulatory agency, though some owners may choose to continue their operation.

Synergies and Conflicts

Many vapor intrusion mitigation techniques are relevant to other IAQ issues. Synergies and conflicts are summarized in Table 3.4-F.

Table 3.4-F Synergies and Conflicts between Vapor Intrusion Mitigation Techniques and Other IAQ Strategies

Vapor Intrusion Mitigation Techniques	Limit Penetration of Liquid Water into the Building Envelope	Limit Condensation within the Building Envelope	Maintain Proper Building Pressurization	Control Entry of Radon	Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives
	S = Synergy; C = Conflict				
Active soil depressurization (ASD)			C(2)	S(1)	
Sealing of vapor intrusion routes	S	S	S	S(1)	
• Gas vapor barriers	S	S	S	S(1)	
Passive venting				S(1)	
Building pressurization		S	S/C(2)	S	
Other approaches					
• Positive sub-slab pressurization (SSP)					
• Indoor air treatment					S
• Intrinsically safe building design					

Notes:

1. Although the general features of an ASD system are the same for radon and vapors from subsurface contaminants, specific requirements may be different. For a site where both vapor intrusion and radon are concerns, the more stringent requirements should be followed.

2. Some situations (e.g., natatoriums) require neutral or negative building pressurization to limit moisture transfer from the building into wall cavities. In these circumstances an ASD system needs to maintain the sub-slab at a lower pressure than the adjacent neutral or negative building areas, and a building pressurization system would not be suitable for vapor intrusion mitigation.

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Strategy 3.5

Provide Effective Track-Off Systems at Entrances

Introduction

Dirt tracked indoors on the footwear of building occupants and visitors carries with it a variety of contaminants and can represent an enormous burden on building maintenance and IAQ. Dislodged residues trapped in carpets will likely become resuspended into occupant breathing zones, while the contamination of indoor surfaces with nutrients and moisture may facilitate mold growth. Tracked-in dirt will contribute to increased wear of interior surfaces, leading to reduced service life and the need for more frequent replacement (potentially with associated early emissions of volatile contaminants). Higher dirt levels increase the need for cleaning and therefore elevate the release of indoor contaminants associated with cleaning agents and processes.

These negative impacts of tracked-*in* dirt can be minimized through careful design, installation, and maintenance of effective track-*off* systems at building access points. Design is highly specific to particular geographic regions, seasons, building sites, and functions. Aesthetic considerations may also guide design in certain cases. Building pressurization related to entranceway design must also be considered (see Strategy 2.3 – Maintain Proper Building Pressurization). For buildings with advanced requirements, such as cleanrooms in laboratory or medical environments, additional dirt-trapping techniques such as the use of "tacky" or "sticky" mats may also be required. A search for "track-off" or "walk-off" systems will reveal specific agencies that provide design solutions tailored to specific needs; some even list suggested specifications for entrance mat systems. General design principles for entranceway track-off systems will be discussed in this Strategy.

Contaminants Tracked into Building by Occupants

As stated in Objective 3, outdoor contaminants may include particles or gases in outdoor air, contaminants in the soil, and pesticides and landscaping chemicals applied around the building. These contaminants may be introduced into the building through a variety of pathways, including envelope penetrations (doors/windows), HVAC intakes, unintended infiltration due to negative building pressures, and occupant activities. Track-off systems can help control contaminant transport via building doorways.

According to Wilson (2001), many different pollutants are commonly found in indoor dust: lead, asbestos, pesticides, volatile organic compounds, non-volatile organic compounds (such as phthalates), polycyclic aromatic hydrocarbons, a wide range of allergens, bacteria (and associated endotoxins), and mold (and associated mycotoxins). There may be multiple sources for the settled dust found within buildings, but tracked-in dirt can be a significant contributor to many or all of these contaminants. Roberts et al. (1999) examined dust in nine homes and two small offices in Washington and found that carpet samples had average dust concentrations in excess of 1.9 oz/yd^2 (66 g/m^2), the vast majority of which was "deep dust loading" (typically not removed by standard vacuuming).

Mølhave et al. (2000a) resuspended dust that had been collected from seven Danish office buildings and exposed it to 24 healthy, nonsensitive volunteers. They found increased eye irritation as well as some influences on test performance, leading the investigators to conclude that the threshold level for acute and subacute (next-day) effects must be below the lowest concentration tested (140 $\mu g/m^3$) (Mølhave et al. 2000b). The Health Canada *Exposure Guidelines for Residential Indoor Air Quality* (1989) sets an acceptable long-term exposure range of ≤ 40 $\mu g/m^3$ for fine particulate matter (≤ 2.5 μm mass median aerodynamic diameter).

Landscaping and Building Approaches

Prevention of tracked-in dirt begins well before the first track-off mat is reached and includes careful design of pedestrian approaches to the building entrances. Sidewalks need to be thoughtfully laid out to anticipate traffic patterns (some designers advocate holding back a portion of the sidewalk budget until clear traffic patterns are revealed). This of course creates a high dirt burden during the initial period that needs to be controlled at the door.

Landscaping materials adjacent to walkway approaches ought to avoid plantings that will drop materials such as berries, flowers, or leaves that might be tracked or blown into the building. It is also important to use plant material that does not require application of pesticides that would subsequently be transported into the building (also see Strategy 2.6 – Consider Impacts of Landscaping and Indoor Plants on Moisture and Contaminant Levels). Watering of plant beds needs to be designed to prevent water accumulation on sidewalks. Walkway canopies can be provided to establish dry approaches to the building entry (and possibly heated during winter months where necessary to facilitate snow removal and clearing from footwear). It is important to keep the building approaches clean, dry, and, where necessary, cleared of snow. Ashkin (1998) recommends that approaches to the building should be of stone, brick, or concrete and textured so that soils are scraped from shoes prior to building entry. The entryway needs to also be pitched so that it will drain easily, and water spigots need to be installed to enable frequent washing of the exterior walks.

It is important that effective track-off systems be installed at all building entrances, since a significant proportion of track-in dirt may originate from relatively low traffic zones such as those associated with parking or service entrances.

Track-Off Systems

A general review by Wilson (2001) recommends that track-off systems extend at least 33 ft (10 m) and be comprised of three distinct sections: scraper, absorption, and finishing. Guidance provided by the EPA (2009) advocates 20 ft (6 m) total for a similar combination of surfaces, while Ashkin (1998) advocates the use of three 12 ft (3.7 m) sections based on a requirement that each foot hit each mat at least twice.

Systems installed in snowy climates typically require greater lengths of scraper mat, while rainy locations require longer adsorption portions. Muddy locations mandate the need for extended lengths of all three track-off zones.

Scraper Mats

The first mat segment is typically called the *scraper mat* and is located outside the building or inside the vestibule and is intended to remove as much dirt, mud, or snow as possible. It is typically constructed of fine mesh grate mounted over a pit appropriately sized to collect sufficient dirt that it need be cleaned only several times per year. If located within a vestibule, the pit needs to be drained and/or exhausted to the building exterior to control humidity. In less challenging climates/conditions, a simple mat material may suffice as the scraper zone.

Absorption Mats

The absorption mat is the building's next line of defense and is typically mounted inside the building entry doors or within a vestibule. It needs to be appropriately sized to meet its intended purpose of additional dirt scraping (of dirt loosened by the scraper mats) as well as moisture removal. These mats are commonly made of nylon or combinations of nylon and heavily textured piles of polypropylene.

Finishing Mats

The finishing mat is typically the final component of a three-zone track-off system. Its function is to complete the process of cleaning and drying the footwear of incoming building occupants. Designed properly, it captures and traps fine particulate material. Finishing mats are generally made from polypropylene with a course fiber surface (EPA 2009). As the last track-off component, often leading into a large foyer area,

Figure 3.5-B Ineffective Track-Off System
Photograph courtesy of Hal Levin.

Figure 3.5-C Inadequate Finishing Mat Length
Photograph courtesy of Hal Levin.

orientation of the finishing mat to coincide with traffic patterns and minimize bypass is critical if the design function is to be achieved.

To be effective, the finishing mat relies heavily on proper design and maintenance of the scraper and absorption zones. This is clearly not happening in the particular case illustrated in Figure 3.5-C.

Finishing mats typically terminate at a floor surface that can readily be damp-mopped or easily cleaned, providing additional protection for the building's primary flooring surfaces.

Maintenance
Proper maintenance and cleaning protocols for the track-off system components need to be included in maintenance documentation and manuals in order to preserve the components' intended functions as well as to prolong their useful life expectancy (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ). Failure to maintain/clean all components of the system may result in it becoming a source of IAQ contaminants rather than a preventative solution. Effective maintenance includes cleaning/replacement of mats as necessary, which will be dictated by daily/seasonal weather conditions and may require adjustment of absorption and finishing mat materials and lengths to suit conditions. Maintenance/cleaning of the collection pits beneath scraper mats is also important. The use of appropriate vacuum equipment is essential; thus, suitable electrical power conveniently located near track-off systems is also a necessary consideration of good building design. Selection of cleaning agents for track-off system mats needs to follow the guidance provided in Strategy 5.3 – Minimize IAQ Impacts Associated with Cleaning and Maintenance.

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Strategy 3.6

Design and Build to Exclude Pests

Introduction

Pest species that colonize buildings affect the indoor environment in several ways:

- The organisms may be the source or vector of environmental hazards. Mold, insects, and rodents may be sources of allergens (which can trigger asthma in some people) or disease-causing organisms.
- They may cause structural damage to the building. For example, termites, carpenter ants, and wood-decaying fungi can be very destructive.
- They may cause damage to material goods within the building, such as contamination of food and destruction of furniture.
- They may produce unpleasant noise or odors within the building.
- They may cause emotional distress to building's occupants.
- Their presence may trigger inappropriate use of pesticides, resulting in pesticide exposures to building occupants.

To colonize a building, creatures must somehow get inside, find food and water, and find a place (harborage) to meet and mate where they will be hidden from those occupants who will happily thump them or spray them with pesticide if they draw notice. Left to their own devices, a population of colonizing organisms will expand until they come into equilibrium with the available food, water, and harborage.

Pest Prevention Goals and Objectives

The pest prevention goal is to create an architectural intervention that reduces the probability of pests gaining access to the interior of a structure and, should infestation occur, to reduce the carrying capacity of the building for pests.

Think of a building as having a carrying capacity for a given species—enough food, shelter, and water at the right temperatures to sustain some maximum number. Colonized for long enough, the population will hover around the carrying capacity as shown in the left half of Figure 3.6-C. The use of pesticides or trapping activities may reduce populations temporarily but do not affect the carrying capacity of the building. Removing potential pest harborage, food, or water resources is the best way to lower a structure's pest carrying capacity. Reducing the ability of pests to spread throughout the structure can also be part of efforts to reduce a building's carrying capacity. The results of such efforts yield the reduced carrying capacity shown in the right half of Figure 3.6-C.

To reduce the probability of pest entry and lower the carrying capacity of the building, the specific objectives of the architectural interventions can be summarized as follows:

- Identify the pests of concern.
- Block, seal, or eliminate pest entry points.
- Reduce the risk of pest dispersal throughout building.
- Reduce pest access to food and water resources.
- Limit areas of potential harborage.

Pests of Concern

The first step toward designing and building a structure to exclude pests is to identify the particular pests of concern for the specific building location.

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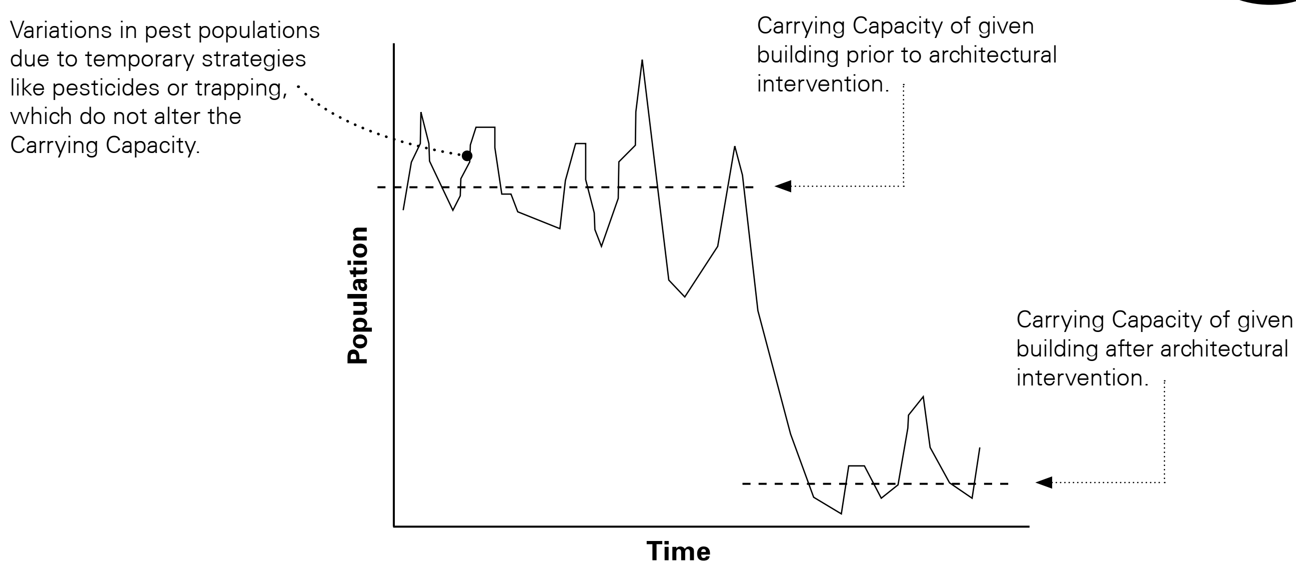

Figure 3.6-C Carrying Capacity of Building Changes with Architectural Pest Control Intervention

Some pest organisms are found in nearly all locations. For example, *Cladosporium*, *Aspergillus*, and *Penicillium* are molds that are found indoors in practically all U.S. climates. In addition, they are found in urban, suburban, and rural locations.

On the other hand, the presence (or absence) of some pests are dependent on the type of environment or on a specific climate. For instance, red squirrels and white-footed (deer) mice are more likely to be found in rural rather than in urban buildings. Other examples include scorpions, rattlesnakes, and Formosan termites, which are problems only over limited geographical areas.

Compile a list of the specific organisms that need to be managed at the building location. Local offices of the Cooperative Extension System of land-grant universities are good sources of information on vertebrates, insects, and fungi that are likely to colonize buildings in the area of the construction site (see www.extension.org [CES 2008]). Another good source is the county extension office for the building site (see www.csrees.usda.gov/Extension/index.html to locate a county extension office in the area [USDA 2009]). Building inspectors and vector control staff at local health departments can also provide additional information on identifying creatures of concern in the area.

The most common pest species include the following:

- Mammals
  - Rats
  - Mice
  - Squirrels
  - Bats
- Birds
  - English sparrows
  - Starlings
  - Pigeons
- Insects and Arthropods
  - Cockroaches

  - Ants
  - Termites
  - Bees and wasps
- Fungi
  - Wood-decaying fungi
  - Molds

General principles for controlling these pests are outlined in the sections of this Strategy. Detailed information on the identification, biology, habits, and control of specific organisms can be found in other sources, including Ebeling (1978), Olkowski et al. (1991), the CDPR (2007) Web site, and several EPA (2008a, 2008b, 2008c) Web sites, all of which are referenced at the end of this chapter.

Pest Entry Points

The entire surface of the building has been described as the "first structural line of defense against pest intrusion" (Franz 1988, p. 272) because most of the time pests such as rodents, insects, and birds enter through gaps and openings in the building enclosure.

Typical routes pest species use to enter buildings include the following:

- Open doors and windows
- Gaps around doors and windows
- Gaps between the foundation and the upper portion of the building
- Below-grade openings in crawlspaces and basements
- Drainage and sewer pipes
- Intermediate areas such as porches, sheds, basements, crawlspaces, attics, and attached garages
- In boxes, bags, or furnishings carried by people

To prevent entry of pests by design, examine a cross-section of the building and trace a continuous pest control barrier from the middle of the roof around the architectural section to the middle of the foundation floor. Whenever there is a hole or gap in this barrier, it is a potential entry point for pests. For instance, a dime-sized hole (0.7 in. [18 mm] in diameter) and a gap under a door of only 0.25 in. (6.4 mm) are adequate for an adult house mouse to enter a building. A hole of 0.25 × 1.5 in. (6.4 × 39 mm) will accommodate little brown bats, and a crack of 0.2 in. (5 mm) is large enough for adult cockroaches (Franz 1988; Smith and Whitman 2007).

Specific recommendations for blocking, sealing, or eliminating pest entry points as part of the design and build process include the following (Franz 1988; Merchant 2009; Simmons 2007a, 2007b; EPA 2008d):

- Eliminate gaps or flaws in foundations, slabs, or where wall framing meets foundation or slab floor.
- Install physical barriers beneath joints or other discontinuities in foundation.
- For termites, use a 3 in. (75 mm) basaltic sand barrier with 0.07 to 0.11 in. (1.7 to 2.8 mm) particle size under the foundation or on the floors of crawlspaces (especially in Hawaii). Use of sand barriers in other states is limited by availability of appropriate termite-barrier sand or limited applicators skilled in installation.
- Extend foundations below ground vertically at least 3 ft (0.9 m) with an L-shaped curtain wall about 2 ft (0.6 m) deep and a 1 ft (0.3 m) projection from the building.
- Use tight-fitting foundation vents and screens appropriately (0.25 in. [6.4 mm] hardware cloth for rodents and 1/16 in. [1.6 mm] or 10-14 mesh for most insects).

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- Seal utility entry points on the building exterior—pipes, cables, electrical conduit, ducts, exhaust vents, louvered vents, underground electrical lines, external meter boxes, etc. (See Figure 3.6-D.)
- Place screens over air intake and exhaust vents for HVAC systems to prevent insects and rodents from entering buildings. Whenever possible, use screens on doors, hatches, skylights, and other openings. Cover fan and vent openings with galvanized mesh with openings of 1/4 in. (6 mm) or smaller.
- Properly install doors and correct problems that interfere with close fit; use raised thresholds with 1/4 in. (6 mm) stops, nylon bristle door seals (properly installed), and self-closing doors.
- Ensure roll-up or overhead doors are well fitted, with no gaps between the track and the wall.
- Install close-fitting windows and screens.
- Use durable pest-proof exterior construction materials—e.g., solid brick or concrete is more durable than pre-fabricated panels.
- Minimize the use of rough finishes on the exterior that can provide footholds for rodents and other pests.
- Minimize the use of projections or ledges that provide nesting and roosting space for birds.
- Screen or otherwise eliminate animal access to decks, porches, and stairways—seal with 1/4 in. (6 mm) hardware cloth screen mesh to form a barrier, extending the barrier 12 in. (30 cm) into the ground with a 6 in. (152 mm) wide right-angled shelf away from the building.
- Specify guards on pipes and downspouts. (See Figure 3.6-E.)
- Design exteriors that have no access to wall cavities—no holes larger than 0.25 in. (6.4 mm) in diameter; modify weep holes with screening to prevent insect access.
- Eliminate gaps at bottoms of wall and corners of exterior siding—cover with metal flashing and stuff with copper mesh (rodents use the hollow outside corners of vinyl siding as stairways to attics).
- Eliminate rodent access under shingles—use vents with double roof jacks and/or heavy duty screen to prevent small animal access.
- Build a tight roof joist and protect with flashing on roof, wall joints, and edges.
- Make sure attic and soffit vents are properly screened using 1/4 in. (6 mm) hardware cloth screen mesh (especially where pitched roofs with different eave elevations meet in a valley).

Figure 3.6-D Sealing a Potential Pest Entry Route around the Refrigerant Lines for an Air Conditioner
Photograph courtesy of Terry Brennan.

Figure 3.6-E Example of a Pest Guard for a Downspout
Photograph copyright New Home Concepts.

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It is impractical to try to prevent entry of mold and wood-decaying fungi spores into buildings since spores are less than 10 μm in length and easily cling to surfaces or remain airborne. Prevention of colonization by fungi is largely a matter of moisture control—keeping things dry. Moisture- and mold-resistant materials are used for materials that are likely to get wet, e.g., foundations, siding, roofing, and the floors of entryways, shower rooms, bathrooms, and custodial closets. (Additional information is available in the Strategies of Objective 2 – Control Moisture in Building Assemblies.)

Pest Dispersal Throughout Building

Of equal importance to blocking entry into a building is preventing pest movement within a building, between nesting areas and sources of food and water. The same concepts for excluding pests from the building itself apply to restricting their movement within the interior structure of the building and need to include all vertical shafts, horizontal interconnecting subfloor trenches, electrical floor trunking, and gaps around pipes and cables (Franz 1988). This is especially important for urban buildings or sites with endemic rodent populations or in the case of multi-family buildings or hotels where the risk of the introduction of bed bug and cockroach infestations is greatest.

Specific recommendations for minimizing the risk of pest dispersal throughout a building as part of the design and build process include the following (Franz 1988; Simmons 2007a; EPA 2008d):

- Eliminate any gaps around floor joists and ceiling joists.
- Install wall cavity closures and avoid joist/rafter gaps.
- Eliminate gaps around wall, floor, and ceiling penetrations (drains, hoists, vents, pipes, conduits, ducts, utility shafts and tunnels, etc.).
- Equip storage areas with self-closing doors.
- Weather-strip interior doors where applicable (Figure 3.6-F).
- Eliminate cracks and crevices with sealant or metal wool (copper or steel).
- Seal floor penetrations surrounding shafts or chutes.
- Seal all internal partitioning walls and ceiling cavities.
- Seal utility entry points within the structure—electric lines, plumbing and heating pipes, fire wall sheathing, ducts, laundry drains—that penetrate through interior walls, ceilings, floors, the backs of cabinets, etc. to prevent rodents and insects from using electrical wires and conduits as a means to gain access to and travel throughout buildings.
- Eliminate pest access in plumbing systems by sealing around sillcocks, sewer lines, and other openings.
- Carefully review HVAC components, such as piping and ductwork, where they meet floors, walls, or ceilings and close openings pests could enter to prevent these from becoming runways for pests.
- Surround bases of elevators, conveyors, and machinery with a 2 ft (0.6 m) high smooth metal fence.

Figure 3.6-F Weather-Stripped Interior Corridor
Photograph courtesy of Terry Brennan.

Strategy 3.6

Compartmentalizing Individual Apartments to Prevent Unit-to-Unit Pest Migration

As part of a pest prevention strategy, individual apartments in a recently built multi-family building in New York City were compartmentalized as follows:

- Installed airtight interior gypsum board on all walls.
- Sealed all penetrations through the concrete plank floors.
- Sealed exterior CMU walls with continuous air barriers from footing to roof.
- Weather-stripped individual apartment doors (Figure 3.6-G).
- Installed an exhaust fan that vents directly through the exterior wall, eliminating duct risers within the apartment.

In addition, air sealing of common walls between apartments was completed to prevent unit-to-unit pest migration. Specific strategies included the following:

- Electrical boxes were sealed with duct mastic (Figure 3.6-H) and caulked to gypsum board.
- Gypsum was sealed to the top and bottom tracks.
- Top and bottom tracks were sealed to pre-cast plank deck.

To verify that compartmentalization was properly completed, each apartment was tested individually for airtightness using a blower door (Figure 3.6-I), and any openings found were sealed. (For additional information on this building see the case study "Adding Pest Control Features to Building Design without Adding Cost" in Part 1 of this Strategy.)

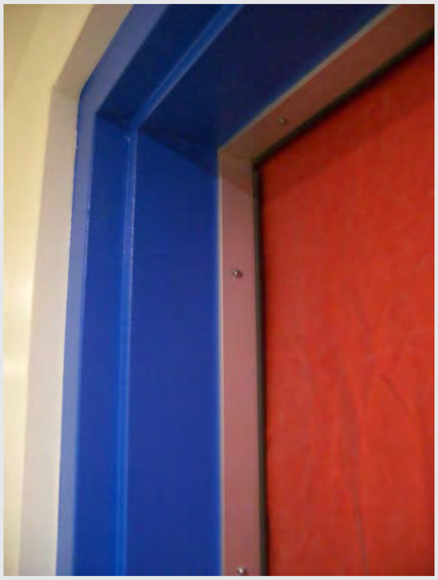

Figure 3.6-G Weather-Stripped Apartment Door
Photograph courtesy of Terry Brennan.

Figure 3.6-H Sealed Electrical Outlet in Common Wall between Apartments
Photograph courtesy of Terry Brennan.

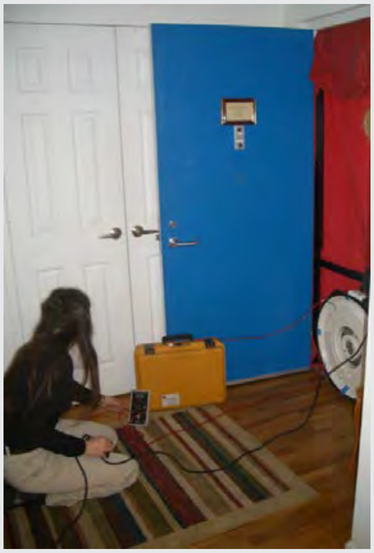

Figure 3.6-I Pressure Testing an Apartment for Tightness
Photograph courtesy of Terry Brennan.

STRATEGY OBJECTIVE 3.6

Strategy 3.6

Pest Access to Food and Water Resources

Identify the possible food resources that the building will contain. Since many pests like to eat what people like to eat, major food resources typically include the following:

- kitchens
- dining halls
- snack areas/vending machine areas
- restaurants
- food storage areas
- garbage and recycling collection, storage, and removal areas

Apply the exclusion methods used on the entire building to these specific areas within the building (i.e., block, seal, or eliminate entry). Draw details for and install continuous pest barriers around the sections that bound kitchens, food storage rooms, and trash handling areas. This includes the waste line side of the plumbing system—rodents and roaches often enter from the sewer side.

In designing kitchens, food handling areas, and trash/recycling areas, also consider ease of cleaning, inspection, and maintenance. Materials and designs that do not lend themselves to being easily cleaned, inspected, or maintained often encourage the proliferation of pests. In addition, make certain the design for these areas provides adequate storage space with pest-resistant fixtures (e.g., open designs with few or no hiding places or with portions that are freestanding and on casters for easy, thorough cleaning). As shown in Figure 3.6-J, a school kitchen in Florida installed expandable storage shelving in order to make the best use of limited storage space. The moveable shelves allow better use of space for more storage and also facilitate cleaning.

There are also food resources in and around buildings that are attractive to pests but not to people. For example, wooden materials are a food resource for termites and wood-decaying fungi. (Note: termites and wood-decaying fungi are the only pest species addressed in building codes. For example, foundation materials and the mudsills in contact with them are required to be made from materials that are resistant to attack by these organisms.) Similarly, there are a number of creatures that colonize buildings because there is mold growing inside the building (often inside wall cavities). Book lice and storage mites are examples. Colonization by these organisms is prevented by following the moisture control guidance in this Guide (see Objective 2 – Control Moisture in Building Assemblies).

Figure 3.6-J Expandable Shelving Designed with Pest Prevention in Mind
Photograph copyright Michael Merchant.

Figure 3.6-K Self-Closing, Pest-Resistant Trash Receptacle
Photograph copyright Michael Merchant.

Figure 3.6-K shows an example of a self-closing, pest-resistant trash receptacle. Such designs can greatly reduce problems with pests like rodents, birds, and bees and wasps.

Specific recommendations for reducing pest access to food and water resources as part of the design and build process include the following (Simmons 2007a, 2007b; EPA 2008d):

- Ensure that new kitchen appliances and fixtures are of pest-resistant design, e.g., an open design with few or no hiding places for roaches or with portions freestanding and on casters for easy, thorough cleaning.
- Provide space under and around appliances and equipment in kitchen areas to allow maximum ventilation and ease of (steam) cleaning; slope floors in kitchen areas to provide good drainage after cleaning.
- Use coving at floor-to-wall junctures to minimize build-up of debris and to facilitate cleaning. (Note: some cove moldings create a hidden cavity formed by the back of the cove, the floor, and the base of the wall. Avoid this by using molding that fills the corner or by filling the cavity with mortar or caulk, or in some instances consider dusting the cavity with boric acid. For more information about the use of boric acid, see the following section in this Strategy titled "Supplemental Pesticide Use.")
- In kitchen and other wet areas indoors, use sealed concrete or epoxy flooring instead of tile, which tends to crack and deteriorate over time, creating pest harborage.
- Do not install pegboard in kitchens, animal rooms, or laboratories.
- Ensure that all pipe insulation has a smooth surface and that there are no gaps between pieces.
- Place outdoor garbage containers, dumpsters, and compactors on hard, cleanable surfaces and away from building entrances (at least 50 ft [15 m] from doorways). Design the site with properly graded concrete or asphalt pads to help prevent rats from establishing burrows beneath them.
- Design the trash/recycling site with a solid enclosure that extends all the way to the ground. Use smooth metal or synthetic materials as opposed to chain-link, wood, etc. to prevent rodents from gnawing on and climbing the enclosure.
- If trash will be stored, design storage areas that can be closed off from the rest of the building.
- Equip storage areas with self-closing doors.
- Insulate pipes in areas that might be prone to condensation. Condensation is a significant source of water for pests.
- When specifying landscaping, give preference to plants that shed a minimum of seeds and fruits, since the seeds and fruit may attract and support insects, rodents, and undesired birds.

Areas of Potential Pest Harborage

Yellow jackets, honeybees, cluster flies, and solitary wasps often make nests behind brick veneers or horizontal or vertical sidings and panels. They can be excluded from the cavities behind brick veneers by using plastic insert vents in weep holes and by sealing window, door, and utility penetrations with mortar and caulks. It is more difficult to exclude them from spaces behind clapboards, vertical boards, and bat or panel sidings. For these siding types there are many linear feet of cracks and openings to be sealed; it is difficult to effectively seal some of them, and the cracks and joints are often an essential part of rainwater control. Effectively preventing insects from gaining entry to these spaces requires careful detailing and installation of barriers at joints.

Intermediate areas such as porches, sheds, basements, crawlspaces, attics, and attached garages often offer safe harborage for pests—they are often poorly sealed against entry and there are often hidden openings between such areas and the main part of the building. Pest species may find harborage as well as food and water resources in such ancillary spaces. For example, rats and mice, ants, roaches, snakes (attracted by the rodents), starlings and English sparrows, and bats may find homes in these spaces. They may venture into the building or outdoors for food. Bats will be out at night seeking flying insects as food, while the rodents and cockroaches may come out at night or during the day.

Lintels Designed to Discourage Pigeons Roosting on the Building

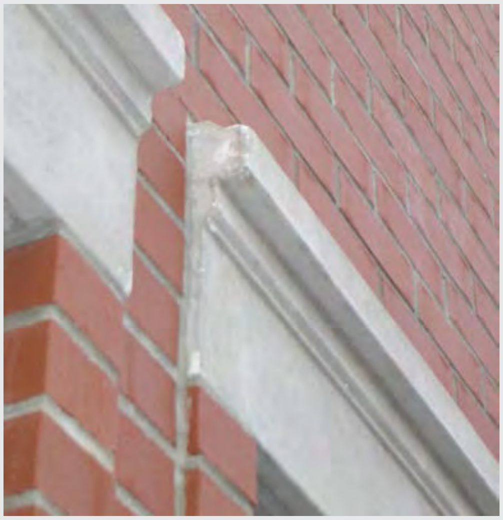

Figure 3.6-L Lintels Designed to Make it Uncomfortable for Pigeons to Roost
Photograph courtesy of Terry Brennan.

Figure 3.6-L shows the lintels used in a group of four multi-family buildings built in New York City that were designed to make it difficult for pigeons to roost. (Notice the drip edge cast into the bottom of the lintel.) From the street the lintel appears ordinary, but in reality only the front 0.5 in. (12 mm) is flat while the rest of the lintel slopes up at a 45° angle. This innovative design enables the architect to retain the architectural detail of lintels on the buildings, which helps them blend into the neighborhood, while at the same time discourages roosting pigeons. (For additional information on these buildings, see the case study “Adding Pest Control Features to Building Design without Adding Cost” in Part 1 of this Strategy.)

Clutter due to Lack of Adequate Storage Space

Figure 3.6-M Example of Inadequate Storage Space
Photograph copyright Michael Merchant.

Figure 3.6-M illustrates the problem that occurs when there is a lack of adequate storage space. In this instance, teachers in a school don’t have enough storage room. Clutter and lack of adequate storage space is one of the biggest problems in maintaining good pest control on school campuses (Merchant 2009). This issue is ideally dealt with during the planning phase for new campuses, when adequate storage can be designed into the building.

Strategy 3.6

An important design consideration within the building is to make certain there are adequate storage areas for all the functions of the building. Inadequate storage often results in areas that are disorderly and hard to keep clean, providing potential harborage and possibly food sources for pests.

In addition to considering the design of the building and its ancillary spaces, some attention needs to be directed at landscaping to discourage the harboring of pests (see Figure 3.6-N). The choice and placement of plantings can encourage pests by providing harborage, food sources, and/or access to otherwise unreachable parts of the building. On the other hand, there are choices that actually discourage pests. For example, leaving a 2 ft (0.6 m) plant-free zone around a building not only reduces pest harborage but also makes the landscape frightening to pest species, discouraging them from crossing the open area from the plantings to the building.

Specific recommendations for minimizing areas of potential pest harborage as part of the design and build process include the following (Merchant 2009; Simmons 2007a, 2007b; EPA 2008a):

- Slope window ledges 45° and provide a slick surface to discourage birds from perching and roosting.
- Avoid installation of exterior features that attract insects, rodents, birds, and bats (e.g., avoid light fixture designs that encourage perching, roosting, or nesting and avoid decorative lattices or other structural features that encourage nesting of birds or rodents, etc.).
- Use shielded outdoor lighting to reduce the attraction of night-flying insects. (Note: this has the further advantage of reducing light pollution. For a list of fixture options by application, consult the International Dark-Sky Association Web site, www.darksky.org.)
- Install bird-proof barriers (e.g., netting) that are designed to prevent nesting.
- Enclose fire escapes to eliminate bird perching and roosting as well as access for other pests.
- Fit eave roof tiles with bird stops (that will also exclude bats, bees, and wasps).
- Locate storage areas for boxes, paper supplies, and other materials in separate areas from where food or trash is stored. When stored together, these materials put food and shelter together, favoring pests.
- Eliminate dead spaces inside storage areas to restrict where rodents may hide (e.g., double walls, false ceilings, enclosed staircases, boxed pluming, voids under cabinets).
- Consider the potential for pest harborage when specifying interior wall coverings and built-in fixtures.

STRATEGY OBJECTIVE 3.6

Landscaping for Pest Management

Figure 3.6-N Example of Pest-Proofed Landscaping
Photograph copyright Michael Merchant.

For pest management reasons, the Richardson Independent School District (Richardson, Texas) deliberately chose to eliminate the foundation plantings on the side of a school building undergoing renovation. Instead they pest-proofed the side of the building by installing the sidewalk next to the building and moving the foundation plantings to the outside (Figure 3.6-N). This minor change is not noticeable from the street side and does not reduce campus aesthetics in any way.

- Install flush-fitting ventilation grilles tightly enough to eliminate openings around edges of grille.
- Use smooth surface insulation on all pipes with no gaps between pipes.
- Modify windows to prevent access for pests, with no clear passageways to inside.
- Modify weep holes in frames with copper or bronze wool to prevent access by insects.
- Correct structural features that provide opportunities for rodent harborage or burrowing.
- Design refuse and recycling areas with properly graded concrete or asphalt pads that prevent rats from establishing burrows beneath the areas.
- Maintain a 2 ft (0.6 m) wide vegetation-free access/inspection strip consisting of pea gravel, decomposed granite, or similar material around buildings to discourage insects and rodent entry into buildings.
- Select trees, shrubs, and other plant types that neither attract pest species nor provide easy access to structures. For example, avoid plants with berries that attract birds or choose trees whose mature heights (without pruning) will not allow pests access to the building roof.
- Give careful consideration to the placement of deciduous trees because leaves that accumulate along foundations provide harborage and sheltered runways for rodents.
- Avoid landscape use of vines (e.g., ivy) or dense ground coverings or shrubs touching or close to the foundation of buildings.

Note: if a species has a large population that is harboring near the building, a tiny fraction of them entering the building may seem to be a large infestation. For example, if the soil next to a building with a slab-on-grade foundation has several hundred springtails per cubic inch, hundreds or thousands of springtails a day may enter the building. And while there may be no possibility of such an infestation colonizing the building proper, it is still a pest species that needs to be dealt with.

The specific design objectives already discussed will reduce the probability of pest entry and lower the carrying capacity of the building. In addition to these design objectives, there are several related issues for the building designer or architect to consider when setting out to exclude pests:

- Access for maintenance and pest control activities
- Appropriate materials selection for sealing
- Supplemental pesticide use
- Construction site management

Access for Maintenance and Pest Control Activities

It is probably impossible to completely eliminate all voids, passageways, and potential pest harborage sites within a structure. As a result, all good building designs need to make areas of potential pest migration and harborage within the building accessible for maintenance, cleaning, and possible pest control activities.

Appropriate Materials Selection for Sealing

Specifying appropriate materials and sealing methods is a key component of successfully reducing or eliminating pests in buildings. A variety of materials are available that can be used to seal entry points, block potential passageways and routes of movement, limit access to food and water, and limit admittance to areas of harborage. Specific choices depend on sealant compatibility with materials surrounding the gap or hole that needs to be sealed as well as the capabilities of the target species and its size. For example, a rodent may enter a gap between two treated two by eights that form a mudsill on top of a foundation wall; a mouse may enter through a gap as small as 0.25 in. (6 mm) and a rat through a gap as small as 5/8 in. (16 mm). Another consideration is also the attractiveness of the food, water, and harborage resources inside the building itself.

Figure 3.6-O Steel Wool Used to Block the Entry of Rodents
Photograph courtesy of Terry Brennan

Figure 3.6-P Copper (or Stainless Steel) Wire Mesh Used to Block Entry of Rodents
Photograph courtesy of Terry Brennan.

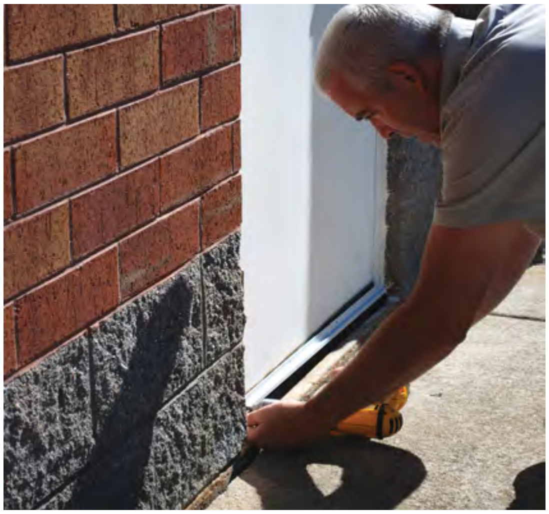

Figure 3.6-Q Brush-Type Door Sweep Being Installed
Photograph copyright Sealeze, A Unit of Jason Incorporated.

"[I]t is not always necessary for a material to be totally impervious to an animal so long as it can be very 'discouraging'" (Franz 1988, p. 274). For example, if the building offered entry to conditioned harborage with few food resources, these openings could be sealed using aluminum flashing or even pieces of wood, since that would be discouraging enough to the pest. However, if there are kitchens or if food is stored or eaten in the building, it would be better to use something more pest-resistant than wood or aluminum flashing. A better choice in such cases would be galvanized steel flashing stuffed with copper or stainless steel mesh or filled with concrete.

Building materials offer varying levels of protection from different creatures. Materials used to seal gaps and form the basis of pest exclusion need to be durable in the face of the creatures targeted for exclusion. Most building materials make good barriers to the entry of birds, bats, and many insects. While rodents are able to chew through plywood, oriented strand board (OSB), and even aluminum flashing, these materials generally provide a reasonable starting point for excluding them. As previously mentioned, special effort needs to be made to create pest species barriers around all potential food sites inside the building. (See the previous section titled "Reduce Pest Access to Food and Water Resources" for more information.)

As illustrated in Figure 3.6-O, steel wool can be used to block the entry of rodents through gaps around pipes and in foundations, but it has the disadvantage of being susceptible to rust. A better choice for blocking the entry of rodents through gaps around pipes and in foundations is copper (or stainless steel) wire mesh, which lasts much longer. It may need to be secured in place to prevent removal by determined pests (see Figure 3.6-P).

With the exception of termites, preventing insect entry to a building is at once easier and more difficult than dealing with rodents. It is easier because many common building materials—caulk, gypsum board, plywood, OSB—provide barriers to flies, wasps, roaches, beetles, and many species of ants. It is more difficult in that insects can squeeze through much smaller openings than the smallest of rodents. However, by careful sealing of joints and gaps with caulks, adhesive membranes, or high-rigid foams, many insects can be excluded from the building.

The good news is that most of the air sealing that is done for energy conservation is also useful in excluding pests from buildings. What is different is that air, unlike rodents and some insects, will not chew through sealants. Therefore, selecting products that can withstand potential attacks by likely pests is required when considering which products to specify for specific sealing applications.

Strategy 3.6

For gaps under doorways, most sources agree that among the best options is a raised threshold with a 1/4 in. (6 mm) stop or a brush-type door sweep. Figure 3.6-Q shows the installation of a brush-type door sweep for pest prevention.

Table 3.6-A summarizes information on materials used to exclude pest entry from the building enclosure. Table 3.6-B lists materials used for making loading dock doors resistant to pest entry.

Table 3.6-A Comparison of Materials for Sealing/Blocking Gaps and Holes
Sources: Franz (1988) and EPA (2008d).

Type	Target Pests	Gap Size it can Fill	Advantages	Considerations
Polyurethane foam sealant	Birds, bats; rodents if reinforced with metal mesh	Larger, irregular openings > 3 in. (75 mm)	Easy to use; cures to rigid plastic foam	Can provide harborage for insects if not protected; exposed use limited by code
Caulking	Insects, bats; rodents if reinforced with metal mesh	Smaller gaps—most types up to 0.4 in. (10 mm)	Flexible; easy to use; variety of materials and applications	Durability varies by caulking type
Corrugated plastic weep hole inserts or board stock	Insects, bats, birds; some rodent protection	Suitable for gaps 1/4 to 2 in. (6.4 to 50 mm).	Easy to use; does not corrode; maintains drainage and ventilation through weep holes; board stock can be used to provide rain wall cavity	No special considerations
Metal screening	Insects; birds, rodents, and bats	Relatively unlimited	Blocks openings but allows ventilation	Needs to be sized appropriately for specific pest; since screening restricts airflow, may require resizing of vents
Copper or stainless steel woven mesh louvers	Insects, birds, rodents, bats	Can be stuffed into gaps between 1/8 and 1 in. (3 and 25 mm); can be used for larger gaps if used in combination with caulk or foam; can be used to seal across openings up to 4 in. (102 mm) wide	Flexible, easy to use; allows ventilation; can be used to reinforce caulk or foam	May need to be secured or rodents may remove it; use corrosion-resistant metals; required on ventilation inlets and outlets
Sheet metal	Birds, rodents, bats; some insects	Used to cover openings, cracks from a fraction of an inch to several inches	Resists rodents well	May be steel or aluminum
Concrete, mortar, brick, cement masonry, mortared stone	Insects, birds, rodents, bats	1/4 inch (6 mm) to unlimited	Durable, structural materials; can fill large openings	Generally used to seal holes in concrete or masonry walls or floors; may be used to fill abandoned pipes
Plastic netting	Bats, birds	Relatively unlimited	Strong, ultraviolet stabilized, and durable for outdoor use	Can be installed in such a way that it can be removed for maintenance and inspection
Needle strips/wires	Bats, birds; rodents	n/a	Slightly more flexible uses than plastic netting	Can conflict with building aesthetics

Table 3.6-B Comparison of Materials for Sealing Loading Dock Doors
Source: Franz (1988).

Type	Target Pests	Best Application
Plastic strips for loading docks	Birds, bats, and flying insects	
Automatic doors for loading docks	Birds, bats, and flying insects	Better for heavily used doors
Air curtains for loading docks	Birds, bats, and flying insects	Less protective and less energy efficient but useful for dock doors that need to be kept fully open

Supplemental Pesticide Use

The end result of good architectural design will likely be a significant reduction in the need for pest control intervention over the lifetime of the structure. This reduces the need for insecticides that might impact IAQ. Common tools for integrated pest management, as shown in Figure 3.6-R, include a caulk gun, caulk, copper mesh, rubber gloves, an N-95 respirator, sticky traps, boric acid powder, and a duster.

Nevertheless, the use of certain pesticides during the construction phase may be appropriate and helpful (e.g., in cases where a persistent pest needs to be managed aggressively at the onset). Termites and cockroaches are two pests for which this approach may be worth considering and in some cases may be required by law.

In the U.S., termite control is usually a combination of exclusion, pre-emptive pesticide and bait application, ongoing monitoring for infestation, and treatment of the nest when infestation occurs. Low-toxicity boric-acid-based treatments that are effective against both termites and wood-decaying fungi have been developed to treat indoor wooden materials.

Termiticides have been developed that are effective in exterior soil treatments where the presence of water reduces the effectiveness of boric-acid-based treatment. Desirable characteristics for termiticides applied to soil are

- long-term effectiveness in below-grade conditions,
- more toxic to termites than to mammals and fish, and
- non-repellent to termites.

The term non-repellent needs further explanation to those outside pest control circles. First available in the late 1990s, non-repellent termiticides were found to provide superior control over older, highly repellent termiticides (Merchant 2009). Laboratory experiments at the University of Florida—Gainesville and elsewhere have confirmed that gaps in highly repellent termite barriers are easily found and exploited by foraging termites (Gahlhoff and Koehler 1999). Non-repellent products, on the other hand, allow termites to penetrate barriers but also kill them shortly thereafter (repellent termiticides rarely kill termites). In addition, termites that travel through these barriers pick up insecticide on their cuticles and pass it on to other nest mates, thus spreading the lethality to varying degrees. Finally, because there is no repellency to these new

Figure 3.6-R Common Tools for Integrated Pest Management
Photograph courtesy of Terry Brennan.

barriers, the termites are unable to locate and exploit gaps in the chemical barriers, making these products more forgiving of application error on soils that move and disrupt the barriers (Merchant 2009).

There are several effective termiticide products available on the market that meet the criteria listed in the previous bulleted list. The effective life of these products will vary according to manufacturer and active ingredient but generally range from 5 to 15 years. Of greater importance is the accuracy and honesty of the contractor making the application. Total gallons to be applied needs to be specified in contracts for pre-construction termite treatment, and honest and reputable pest control companies need to be used. Another issue is that older repellent termiticides are now significantly cheaper than the newer non-repellent variety. Unless the specifications clearly ask for the use of non-repellent termiticides or spell out acceptable products, contractors will more than likely use the cheaper, less effective product (Merchant 2009).

Because the effective life of a pre-construction treatment is typically much shorter than the anticipated life of the structure, other nonchemical tactics need to be considered. Use of corrosion-resistant stainless steel mesh in concrete expansion joints and around plumbing penetrations can provide lifetime protection of these entry points from termites. Such termite control systems have been developed in Australia and are now being sold in the U.S. To be considered, these systems need to have local and state building code approval and may also need to be acceptable to insurance parties. While such systems add cost to the project, they also provide significant value (especially in high termite-risk areas) by substantially reducing the possibility of termite entry.

In locations likely to have cockroaches infest food and garbage areas, a two-step approach can be very effective at preventing infestations. In step one, a qualified pesticide applicator is engaged to apply the lightest dusting of a low-toxicity pesticide (e.g., boric acid products) in the most vulnerable cavities. Only pesticides approved by the EPA for indoor use need to be considered. In step two, the cavities are carefully sealed. In this application only a tiny amount of low-toxicity pesticide needs to be used.

An example of this two-step approach follows. The kick space or wall cavities that contain the plumbing or gas lines running to kitchen sinks, dishwashers, and gas ranges can be dusted. Then all entries to the cavities (e.g., gaps around pipe and conduit, joints between gypsum board and wall framing) can be sealed using caulk. Copper mesh can be stuffed into gaps large enough for mice to get through and sealed with caulk. In this way there is a double defense and the creatures are unlikely to get in. In the case of cockroaches that do get in, they will have entered an attractive trap that will kill them in several days. (The long-term effectiveness of boric acid or boric salt dusts applied to wall voids may not be a panacea. Water, especially, can affect the availability of boric acid to the insects invading a wall void.)

Whenever possible, use the least-toxic pesticide option (see the sidebar titled "Pest Toxicity to People"). Make certain any supplemental pesticides utilized are approved for use in the locality of construction and for the purpose intended. Follow all regulations regarding the storing, application, and disposal of pesticides used at the site as well as regarding worker safety. More detailed information on pesticide and other treatment options can be found in Olkowski et al. (1991) and at the EPA (2008b) Web site.

Pesticide Toxicity to People

Pesticides are given a lethal dose (LD) rating, which is used to predict the hazard to people and other nontarget organisms. For example, LD50 refers to the dose of a given substance that kills 50% of the organisms exposed to it in tests. The rating is usually expressed in milligrams of poison per kilogram of body weight for the nontarget organism (mg/kg). For example, if a particular poison has an LD50 rating of 1.0 mg/kg and each individual in a group of 150 lb (68 kg) individuals consumes approximately 68 mg of the pesticide, half of the individuals could expect to die.

This measurement has some serious limitations. For one thing, the tests establishing the ratings are performed on nonhumans (primarily rats but to a lesser extent dogs, rabbits, monkeys, and a variety of birds and other animals), and it is important to remember that the effects on humans may be different than those on other animals. Another problem is that this rating system does not account for long-term or chronic effects of exposure to the pesticide being rated. Furthermore, individual responses to pesticides can vary considerably depending on age, physical condition, overall health, allergic reactions, and other unknown factors.

Source: Olkowski et al. (1991).

Strategy 3.6

3.6

Construction Site Management
Pest control needs to be integrated into construction site management for a number of reasons. New construction materials awaiting use as well as the by-products of construction can provide harborage for pests that move into the building as it is being constructed. During the construction process, new holes or cracks may appear as the structure settles or shifts. Construction errors can also cause unintended gaps or openings. In addition, changes in the building design, plumbing, heating, or electrical work will periodically require new pest management strategies to be implemented. Good construction management can greatly reduce pest infestations that start during the construction phase or contribute to pest infestations down the road.

Specific recommendations for construction site management harborage as part of the design and build process include the following (Franz 1988; Merchant 2009; Simmons 2007a):

- Keep job site organized and clean.
- Provide sealed metal waste containers at the job site for workers to use for food and other waste materials that might provide food resources to pests and establish policies that encourage workers to use them.
- Maintain a rodent control program around the job site, especially on large projects, to reduce the chance of rodents using the building for harborage before it is sealed.
- Avoid storing cellulose-containing materials (wood scraps, foam boards, cardboard, etc.) near the structure during construction.
- Enforce a no-burial policy for cellulose-containing materials on the construction site.
- Prior to foundation placement, remove all cellulose-containing material (tree roots, sumps, etc.) from the area encompassed by the foundation and within 1 ft (305 mm) of its perimeter and make sure fill material is free of vegetation and foreign material.
- Avoid use of cardboard void forms (void boxes) under slabs in high termite-risk areas.
- After all foundation work is complete, remove all loose wood and debris from the crawlspace and within 1 ft (305 mm) of the perimeter, including all wood forms, grade stakes, and supports.
- Systematically inspect construction work in progress to identify new gaps or openings as they occur and take appropriate action to seal them.
- Implement corresponding pest management strategies whenever changes in the building's design, plumbing, heating, or electrical specifications occur.

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Strategy 4.1

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).

STRATEGY OBJECTIVE 4.1

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.

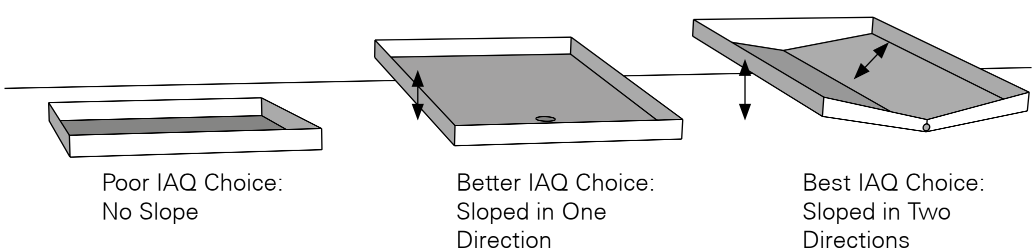

Figure 4.1-B Drain Pan Examples with and without Slope
Adapted from Stanke et al. (1998).

Strategy 4.1

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.

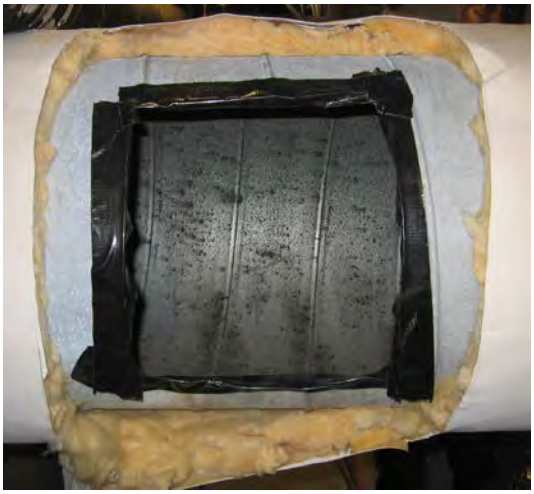

Figure 4.1-D Dust and Dirt Present on the Metallic Airstream Surface of Externally Insulated Supply Air Duct
Photograph courtesy of Phil Morey.

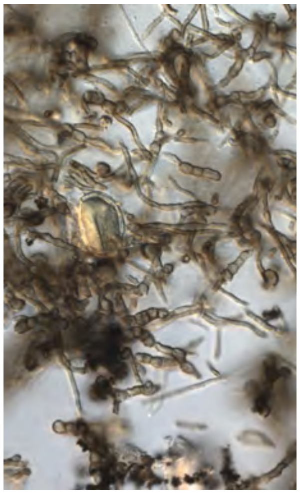

Figure 4.1-E Mold Growth (Spores and Hyphae) on the Dust and Dirt on a Metallic Airstream Surface
Photograph courtesy of Phil Morey.

Strategy 4.1

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.)

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Strategy 4.3

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

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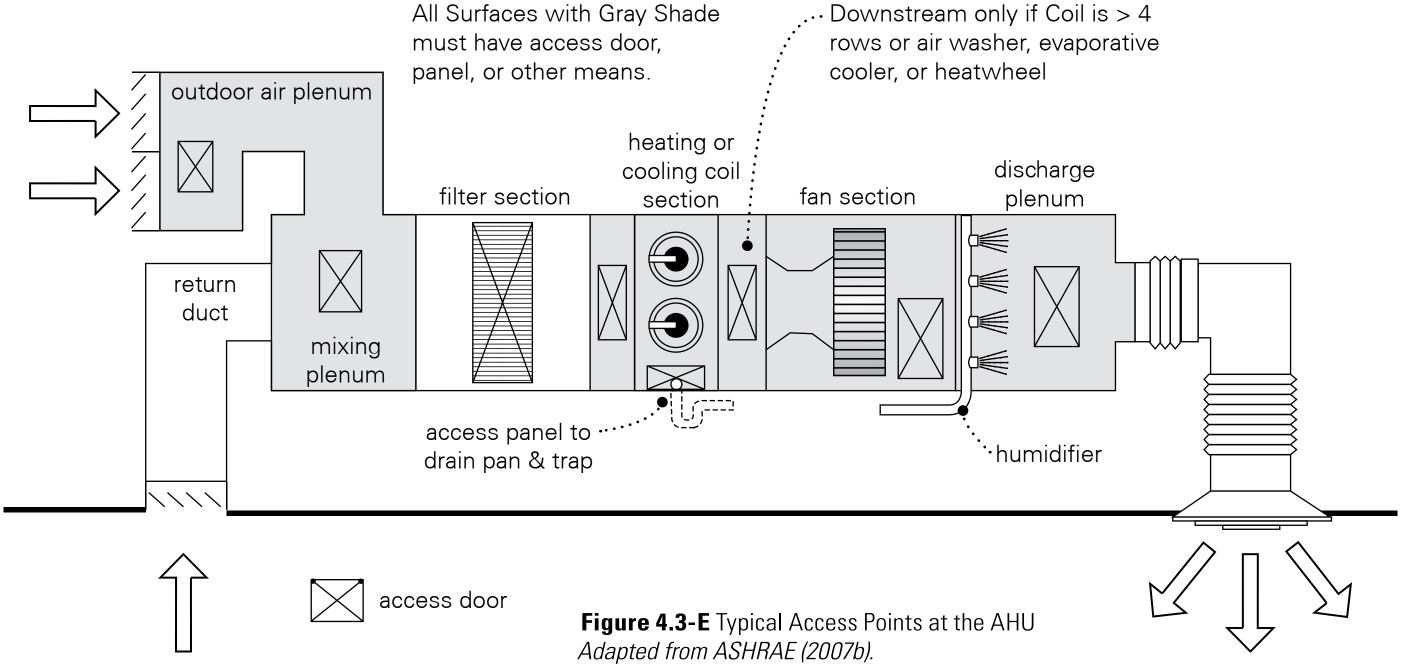

Figure 4.3-E Typical Access Points at the AHU
Adapted from ASHRAE (2007b).

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.

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.

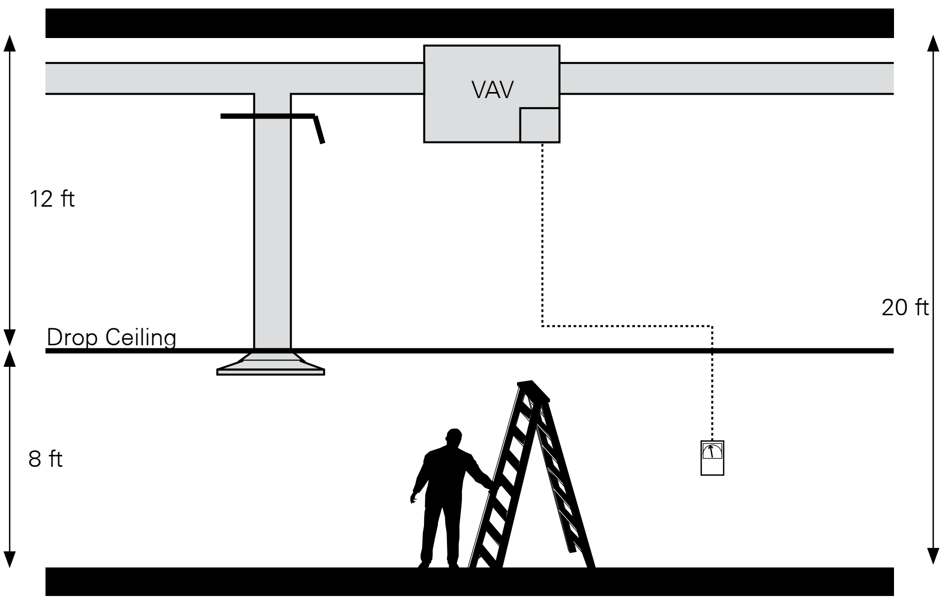

Figure 4.3-F Equipment Mounted High Above a Ceiling Can Be Impossible to Access

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.

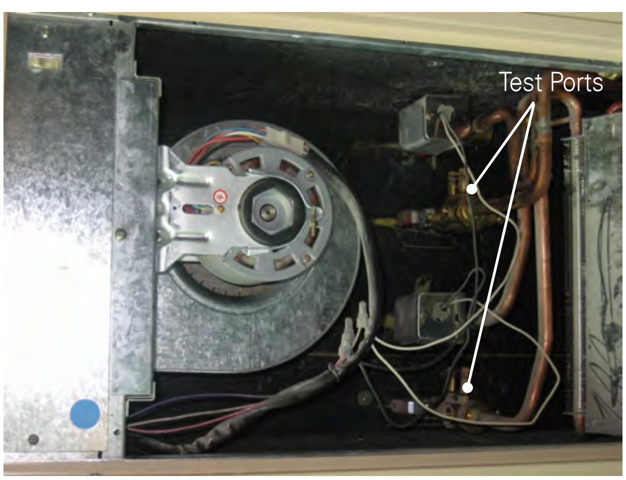

Figure 4.3-G Inaccessible Test Ports due to Balancing Valve Installation
Photograph courtesy of Jim Hall.

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).

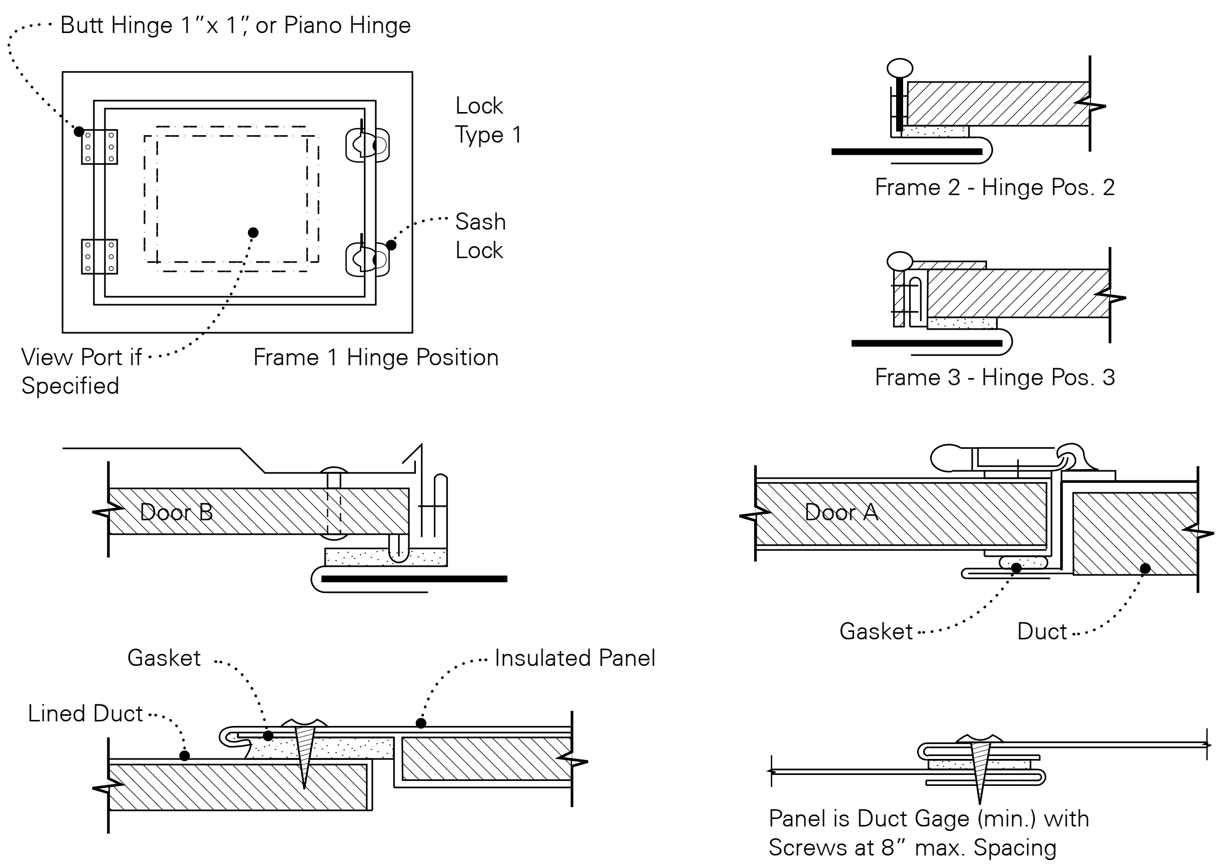

Figure 4.3-H Duct Access Doors and Panels
Adapted from SMACNA (1997).

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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.

unit being placed too close to a structural element and thus preventing adequate door swing at the access panels. Or, the AHU that is delivered may have a left-sided coils installation rather than the right-sided configuration specified in the design. Installation of this unit would necessitate changes in the numerous piping connections and might significantly change/compromise the intended access design.

The only effective way to control the potential impact of these field changes is to provide effective oversight and monitoring of the entire construction project.

Monitoring Installations

A project manager or field construction representative can provide effective oversight of the HVAC system installation. In fact, many projects now require such additional review to ensure compliance with plans, specifications, and applicable building codes. It is essential that this individual helps ensure that the design intent related to HVAC system access is preserved.

Unanticipated Access Requirements

Compliance with SMACNA HVAC Duct Construction Standards

Any modifications or additions of access doors may also impact long-term performance and IAQ if not properly installed. For example, if new access doors are required for cleaning or the remediation of mold growth within the system, these doors need to be installed in conformance with SMACNA requirements (SMACNA 2005) to ensure adequate prevention of leakage. In addition, all aspects of the installation need to be in conformance with new construction standards related to the insulation, vapor retarder, etc. Refer to the third edition of *HVAC Duct Construction Standards—Metal and Flexible* (SMACNA 2005) for detailed specifications for the construction and installation of access doors and panels.

Figure 4.3-K shows an example of an access door that was installed during a mold remediation project. The failure to ensure the integrity of the vapor retarder during installation places this system at risk for condensation and additional mold problems.

Figure 4.3-K Compromised Vapor Retarder at Access Door Installation
Photograph courtesy of Wayne Thomann.

Figure 4.3-L Multiple Reusable Access Panels Installed at a Supply Duct
Photograph courtesy of Wayne Thomann.

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Repeated Access

The potential need or benefit of providing future access to a particular location should always be considered before establishing new access points within any HVAC system. Future needs will help in deciding both the exact locations and the types of openings/closures for those access points. For example, some locations may only need to be accessed once for a very specific procedure such as duct cleaning. In such a case, a simple opening that can be easily plugged or sealed is typically going to be adequate. However, for openings where periodic inspecting or monitoring may be needed, an engineered opening that will accommodate the installation of an appropriate access door is preferred. This consideration is particularly important for systems that were installed with inadequate access during the original construction. For example, Figure 4.3-L shows new access doors that were installed in the supply ductwork just downstream of the cooling coils in a system that had experienced significant microbial growth because of inadequate inspection and maintenance. These new reusable access panels will allow routine monitoring and periodic inspection of this high-risk location in the HVAC system.

References

ASHRAE. 2007a. *ANSI/ASHRAE Standard 62.1-2007, Ventilation for Acceptable Indoor Air Quality*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 2007b. *62.1 User's Manual*. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

NFPA. 2008. Section 110.32, Work space about equipment. *NFPA 70: National Electrical Code*. Quincy, MA: National Fire Protection Association.

OSHA. 2008. CFR 1910.303 (h) (3). *29 CFR 1910*. Washington, DC: Occupational Safety and Health Administration.

SMACNA. 1997. *HVAC Duct Construction Standards—Metal and Flexible*, 2d ed. Chantilly, VA: Sheet Metal and Air Conditioning Contractors National Association.

SMACNA. 2005. *HVAC Duct Construction Standards—Metal and Flexible*, 3d ed. Chantilly, VA: Sheet Metal and Air Conditioning Contractors National Association.

Strategy 4.4

4.4

Control *Legionella* in Water Systems

Introduction

Lukewarm water (30°C–40°C [86°F–104°F]) in cooling towers, evaporative condensers, and potable water service systems provides places for the growth of *Legionella*, which are gram-negative bacteria. At present, there are approximately 48 species known in the genus *Legionella* (AIHA 2005), and many of the species have been associated with human illnesses. Some *Legionella* species can be distinguished into serogroups—approximately 70 serogroups are known (AIHA 2005). For example, *L. pneumophila* serogroups 1, 3, and 6 may be found in a water sample. *Legionella pneumophila* is the species that caused an outbreak of Legionnaires' Disease in Philadelphia, Pennsylvania, in 1976 in which 34 people died. Legionnaires' Disease is an infection (the lung of a susceptible person is the target organ) that results in pneumonia, which may be fatal. *Legionella* may also cause a milder form of illness known as Pontiac Fever, which is nonpneumonic and similar to a severe flu.

Figure 4.4-B shows the Bellevue-Stratford Hotel in Philadelphia, which was the site of an outbreak of Legionnaires' Disease in which 29 people died from exposure in the hotel and 5 people died from exposure outdoors in the vicinity of the hotel.

Legionnaires' Disease and Pontiac Fever differ in clinical reaction, incubation time, and attack rate (WHO 2007; ASTM 2008; Fields 1997). Legionnaires' Disease is a pneumonia with a 2–10 day incubation and occurs in about 5% of cases of community-acquired pneumonia. Further, there are specific risk factors for Legionnaires' Disease. For example, persons with immune deficiencies, underlying illnesses, or diabetes mellitus, those who smoke, and the elderly are at greater risk. Pontiac Fever is nonpneumonic, with symptoms that resemble influenza and onset about 36 hours after exposure. The reason for the differing health effects of *Legionella* exposure is unknown.

Legionella pneumophila is the species that most frequently causes Legionnaires' Disease, or legionellosis. Further, there are approximately 15 serotypes of *L. pneumophila* that are distinguished by their reactivity to diagnostic antibodies (Fields 1997). Identification of the environmental source of a legionellosis outbreak occurs when the species/serotype of *Legionella* from the infected person matches the species/serotype of *Legionella* in the environmental reservoir. Thus, it is important to determine the species and the serotype of both clinical and environmental isolates when attempting to identify the environmental source of an infection or outbreak. Molecular typing (alone or in combination with monocional antibody subtyping) is necessary to make a definitive match.

Figure 4.4-B Philadelphia Hotel—Site of a Legionnaires' Disease Outbreak
Photograph Courtesy of Hal Levin.

Strategy 4.4

4.4

Control of *Legionella* in Cooling Towers

Proper Siting (Building Siting, Mists, Building Openings)

Cooling towers should be located as far as possible from building openings, including HVAC system outdoor air inlets (see Section 7.6.5 of *ASHRAE Guideline 12, Minimizing the Risk of Legionellosis Associated with Building Water Systems* [ASHRAE 2000]). When choosing the location for cooling towers on or near buildings, consideration should be given to the direction of prevailing winds and the location of nearby areas where people may congregate. A minimum separation distance of 15 ft (4.6 m) is specified between cooling tower basins or intakes and building outdoor air inlets in *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007a). Additionally, a minimum distance of 25 ft (7.6 m) is required between cooling tower exhaust and outdoor air inlets (ASHRAE 2007a). However, the examples in the case studies "Drift from Cooling Tower Travels ~330 ft (~100 m)" in Part I of this Strategy and "Contaminated Cooling Tower" in Part II of this Strategy illustrate that aerosol containing *Legionella* can, under some conditions, traverse more than these minimal distances. Therefore, it is a good idea to choose cooling tower locations with an objective of reducing the carryover of drift or mist (from the tower) to outdoor occupancy areas as much as is feasible (see the case study text). In situations where cooling tower drift or mist is likely to impact populated outdoor areas, the designer needs to carefully evaluate the efficiency of drift eliminators (see Section 7.3 of ASHRAE Guideline 12 [ASHRAE 2000]).

HVAC outdoor air intakes and other building openings are best located as far as feasible from cooling towers. The HVAC inlet shown in Figure 4.4-C is located within 13 ft (4 m) of a double-cell cooling tower. Under certain atmospheric conditions, drift or mist from the towers can enter the outdoor air inlet.

Operation and Maintenance

The designer can help ensure that the cooling tower is well maintained to protect it against *Legionella* contamination by providing the owner/building operator with a complete set of operation and maintenance (O&M) information that includes appropriate biocide, scale, and corrosion control procedures (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ). This information includes cooling tower start-up procedures and procedures for start-up of undrained systems. Information on cooling tower system O&M needs to be placed in a secure location that is readily accessible to facilities O&M personnel as well as to building inspectors. Sections 7.6.1 through 7.6.3 of ASHRAE Guideline 12 (ASHRAE 2000) contain a helpful overview of cooling tower O&M procedures. Designers should also refer to Chapter 48 of the *2007 ASHRAE Handbook—HVAC Applications* (ASHRAE 2007b) for a review of scale, corrosion, and biological growth control procedures (see pages 48.5 through 48.6).

Section 5.4.1 of the World Health Organization (WHO) guide *Legionella and the Prevention of Legionellosis* (WHO 2007) provides designers with additional recommendations useful in upgrading the maintenance of cooling towers, namely designing cooling towers to be easy to clean (use nonporous materials) and easy to access (make interior surfaces readily accessible for purposes of cleaning).

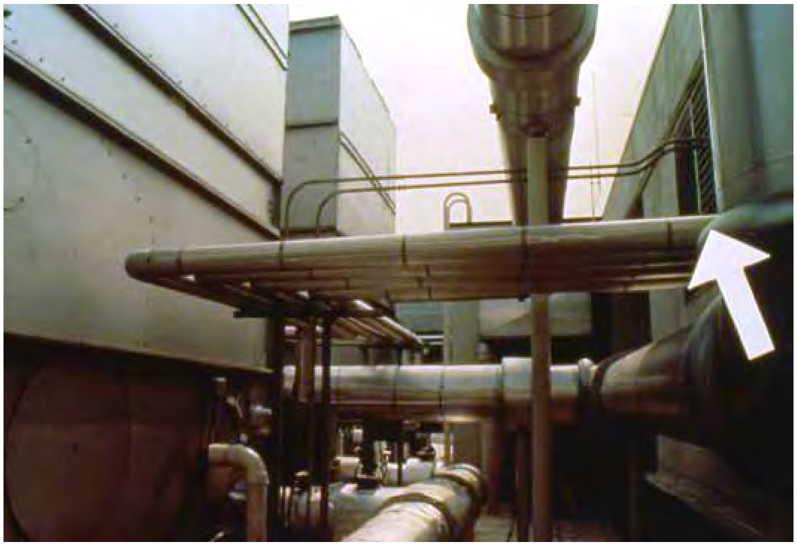

Figure 4.4-C HVAC Inlet Located within 13 ft (4 m) of a Double-Cell Cooling Tower
Photograph courtesy of Phil Morey.

STRATEGY OBJECTIVE 4.4

Strategy 4.4

4.4

Control of *Legionella* in Water Systems

Storage Temperatures in Hot Water Tanks

Table 1 in the Fields and Moore (2006) paper cited in the references section for this Strategy summarizes recommendations for storage and point-of-discharge temperatures in potable water systems (faucets, showerheads). There is general consensus that a hot water storage temperature of 140°F (60°C) and a point-of-discharge temperature of 122°F (50°C) are appropriate. Section 4.1.6 of ASHRAE Guideline 12 (ASHRAE 2000) and Section 4.4.1 of the WHO guidelines (WHO 2007) contain similar recommendations. However, maintaining such temperatures will not guarantee a *Legionella*-free system.

Design Considerations for Potable Water Systems

Sections 4.1.1 through 4.1.4 of ASHRAE Guideline 12 (ASHRAE 2000) provide information for designers on reducing the potential for *Legionella* amplification in potable water systems. These design considerations include the following: a) minimize the use of rubber washers and fittings in plumbing systems, b) reduce dead-end or stagnant plumbing lines, and c) reduce dirt and debris in water lines entering the buildings, as these materials provide nutrient for *Legionella* growth. Section 4.3 of the WHO guidelines (WHO 2007) includes a discussion of risk factors associated with construction materials used in plumbing systems.

Legionella *in Other Water Systems*

The growth of *Legionella* can occur in other water systems including heated spas, architectural fountains and waterfalls, misters, air washers, and humidifiers. ASHRAE Guideline 12 (ASHRAE 2000) provides a comprehensive review of this subject. As with cooling towers and potable water systems, the potential for *Legionella* growth is affected by water temperature (lukewarm water promotes growth) and the presence of nutrients and biofilms. The risk of disease is also affected by the amount of aerosol emitted from these water features.

Emergency Disinfection of Water Systems

Corrective actions to reduce *Legionella* amphilication in water systems, including thermal eradication, monochloramine treatment, hyperchlorination, copper-silver ionization, chlorine dioxide treatments, etc., are reviewed in the literature (WHO 2007; Stout 2007; ASHRAE 2000; Fields and Moore 2006; OSHA 2008; Flannery et al. 2006; Moore et al. 2006). Microorganisms including *Legionella* can be found embedded in the biofilm matrix present in water systems (Eboigbodin et al. 2008) and thus can be protected from disinfection by the biofilm. It is important, therefore, to advise O&M staff to minimize biofilm growth during maintenance of water systems (see Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ). In addition, during emergency disinfection, biofilm needs to be physically removed and disinfectant chemicals need to penetrate into residual biofilm matricies in order to inactivate microorganisms.

Section 7.6.4 of ASHRAE Guideline 12 (ASHRAE 2000) briefly mentions procedures for emergency disinfection of cooling towers. However, these procedures are highly corrosive and are not to be used routinely. The Cooling Technology Institute (CTI) provides an example of an emergency disinfection procedure for cooling towers (CTI 2000), as does the WHO *Legionella* guideline (WHO 2007, p. 82).

Section 4.1.6 of ASHRAE Guideline 12 (ASHRAE 2000) provides information on procedures for emergency thermal disinfection of hot water distribution systems. In order to carry out thermal disinfection, a hot water temperature of 160°F–170°F (71°C–77°C) is required with a minimum flush time of 5–30 min. Fields and Moore (2006) summarize emergency thermal disinfection recommendations for potable water systems based on other guidelines (see Table 1 of their paper). If thermal disinfection of a hot water system is not possible, then other means of emergency disinfection are available (see Section 4.1.6 of ASHRAE [2000]).

Personal protection equipment should be provided to workers involved in biofilm removal as part of normal cooling tower preventive maintenance as well as to inspectors and workers involved in emergency disinfection of water systems. Workers involved in cleaning and disinfection operations should be advised to wear a half-face respirator with a high-efficiency particulate air (HEPA) filter cartridge. This is especially important when removing biofilm from cooling tower surfaces because *Legionella*, other gram-negative bacteria, and other biofilm microorganisms may be aerosolized during the cleanup process. Gloves, goggles, and protective clothing should be used by workers to prevent exposure to chemicals used in the decontamination process. Section 6 of the ASHRAE Legionellosis position statement (ASHRAE 1998) contains a description safety procedures that should be followed during *Legionella* decontamination of water systems.

Environmental Monitoring for Culturable *Legionella*

Routine sampling of building water systems for culturable *Legionella* is considered controversial because disease may occur in the absence of positive sampling results and positive sampling results do not imply that disease has occurred or will occur.

In a recent review, Fields and Moore (2006) point out that the scientific basis for determining an "acceptable" number of *Legionella* in water systems does not currently exist for a number of reasons, including differences in occupant susceptibilities and building designs as well as variation in the virulence of *Legionella* species and serotypes. However, it has been suggested that *Legionella* risk is greatest when a high percentage of building water samples are positive for culturable *Legionella*, especially *Legionella pneumophila* serogroup 1 (Stout 2007).

Several documents review the microbial ecology of *Legionella* in cooling towers, hot water systems, and other water reservoirs (WHO 2007; ASTM 2008; Stout 2007; ASHRAE 2000; Fields and Moore 2006; OSHA 2008). Protocols for collection of *Legionella* from these sources are well known (AIHA 2005; ASTM 2008). Analysis of water samples for culturable *Legionella* is the preferred method used in field studies. Polymerase chain reaction methods, while providing a quick turnaround time for sample analysis in the laboratory, cannot distinguish between culturable and dead *Legionella*. Polymerase chain reaction methods for analysis are discouraged because only live (culturable) *Legionella* can cause infection. Table 4.4-A summarizes the resources available for the control of *Legionella*.

Contaminated Cooling Tower

Figure 4.4-D Relatively Clear Water in the Basin of the Cooling Tower on the Roof of Building B
Photograph copyright Janet Stout, Special Pathogens Laboratory.

Three office workers in building A developed Legionnaires' Disease caused by *Legionella pneumophila* serogroup 1. The implicated source of *L. pneumophila* was a three-celled cooling tower located about 330 ft (100 m) away on the roof of building B. The three workers took breaks located outside and at grade level around building A. Prevailing winds tended to blow drift (mist) from the cooling tower on the roof of building B toward the grade-level area at building A.

The water in the cooling tower appeared to be clean (see Figure 4.4-D) and had been treated with biocide. However, water samples from the tower contained about 3000 *Legionella pneumophila* serogroup 1 per milliliter. In this case study, "good maintenance" practices alone were insufficient to control *Legionella* amplification within this cooling tower. The only reliable way to determine if this or other water systems pose a risk for transmission of *Legionella* is culture sampling from the tower water basin.

Strategy 4.4

4.4

Table 4.4-A Legionella Resource Guide

Control of *Legionella* in Cooling Towers	
Proper siting	ASHRAE (2000), Sections 7.6.5 and 7.3
Proper O&M programs	ASHRAE (2000), Sections 7.6.1 through 7.6.3; WHO (2007), Section 5.3.2
Control of *Legionella* in Potable Water	
Proper storage temperatures in hot water tanks	ASHRAE (2000), Section 4.1.6; Fields and Moore (2006), p. 695; WHO (2007), Section 4.4.1
Design considerations	ASHRAE (2000), Sections 4.1.1 through 4.1.4; WHO (2007), Section 4.3
Control of *Legionella* in Other Water Systems	
Spas, fountains, misters, etc.	ASHRAE (2000)
Emergency Disinfection of Water Systems	
Cooling towers, potable water systems, etc.	ASHRAE (2000); CTI (2000); WHO (2007), p. 82; Fields and Moore (2006), p. 695

Strategy 4.4

4.4

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STRATEGY OBJECTIVE 4.4

Strategy 4.5

Consider Ultraviolet Germicidal Irradiation

Introduction

Ultraviolet germicidal irradiation (UVGI) inactivates airborne microorganisms by damaging the DNA necessary for replication and the initiation of the infection process. As such, irradiation does not physically remove the microbial agent, including its allergens and toxins; irradiation makes the agent unable to replicate and thus unable to cause infection. *Mycobacterium tuberculosis* and other agents such as the viruses that cause measles and influenza can enter the indoor air as droplet nuclei that are the residuals of respiratory droplets. These particles settle from the air very slowly and thus can be transmitted through a room or throughout a building. The greatest risk of exposure to infective agents such as *Mycobacterium tuberculosis* occurs in crowded rooms or buildings containing people with respiratory infections, such as homeless shelters and correctional facilities, especially when outdoor air ventilation is poor (First et al. 1999a, 1999b).

In the late 19th century and early 20th century, large amounts of outdoor air ventilation were recommended to reduce disease from infectious agents such as *Mycobacterium tuberculosis*. Approximately 15 cfm (7.5 L/s) of outdoor air per occupant appears to be near the minimum ventilation rate necessary to reduce transmission of infectious agents. Filtration can also capture droplet nuclei, but this intervention may not be practical in all cases (e.g., correctional facilities, homeless shelters). Adding UVGI to the upper-air space or in the ventilation airstream can increase the equivalent outdoor air change rate for infective bacterial (*M. tuberculosis*) and viral (e.g., measles and influenza) agents (Nardell and Macher 1999; Brickner et al. 2003).

Factors such as the type of microorganism and the relative humidity can also affect the ability of UVGI to damage microbial DNA. Thus, the corona virus is more susceptible to UVGI than the adenovirus (Walker and Ko 2007). UVGI is less effective against *Micrococcus luteus* (a human shed bacterium) at high relative humidity (Gorsuch et al. 1998). *Stachybotrys chartarum* appears more resistant to UVGI than *Aspergillus versicolor* (Green et al. 2005). UVGI has been shown to be effective in controlling the spread of *Mycobacterium tuberculosis* and measles in actual field studies in buildings (Nardell and Macher 1999; Nardell 2002).

Upper-air UVGI fixtures are typically installed 6.6 ft (2 m) or more above the floor in rooms where many people, including some occupants disseminating infectious microbial agents, may assemble and where outdoor air ventilation is inadequate (see First et al. [1999b]). The UVGI fixtures are installed above eye level along the upper portion of the room. Parallel louvers with nonreflective surfaces in the fixtures direct the irradiation in a slightly upward-tilted horizontal plane (Dumyahn and First 1999). Upper-air UVGI can lower exposure to *Mycobacterium tuberculosis* equivalent to 10 to 35 ach of outdoor air cleaning (LRC 2003; Brickener et al. 2003). Other factors such as irradiation intensity, time of droplet nuclei exposure, and relative humidity can affect the equivalent outdoor air cleaning achieved by UVGI.

The intensity of UVGI in modern upper-room systems, while adequate to inactivate vegetative bacterial cells, is generally inadequate to kill fungal spores (Kujundzic et al. 2007). Bacterial spores (e.g., *Bacillus subtilis*) are somewhat more resistant to UVGI than vegetative *Mycobacterium* species cells (Xu et al. 2003). See pages 16-7 and 16-8 of *2008 ASHRAE Handbook—HVAC Systems and Equipment* (ASHRAE 2008) for a comprehensive discussion of upper-air UVGI systems.

Upper-air UVGI using lamps that are shielded from occupants and located along upper-room walls may be used in combination with self-contained, fan-powered air cleaners containing ultraviolet (UV) lamps in order to inactivate airborne bacteria and viruses. In general, the inactivation caused by shielded upper-air lamps and fan-powered air cleaners is additive (Kujundzic et al. 2006). However, some fan-powered air cleaners with UVGI lamps were characterized as having the same air-cleaning rate whether the UV lamp was on or off (Kujundzic et al. 2006). It was also found that some air cleaners containing UV lamps generated ozone.

Multiple passes of room air through fan-powered air cleaners are thought to be necessary to inactivate bacterial spores (Scarpino et al. 1998).

UVGI in HVAC Systems

UV lamps placed in ductwork have been used for many years to inactivate *Mycobacterium* species and other microorganisms. The residence time of the microbe under UVGI illumination, as well as the intensity of the irradiation, are important factors for the inactivation of microorganisms. Kujundzic et al. (2007) reported that under low airflow conditions of 400 fpm (2.2 m/s), a substantial amount of vegetative bacteria and fungal spores were inactivated. At a higher flow rate of 1000 fpm (5.1 m/s), the same microorganisms were not inactivated.

VanOsdell and Foarde (2002) carried out a comprehensive study on the effect of UVGI on the inactivation of vegetative bacteria (*Staphyloccus epidermidis*), bacterial spores (*Bacillus subtilis*), and fungal spores (*Aspergillus versicolor*) in a mock-up supply air duct system. *Staphyloccus epidermidis* was most susceptible to UVGI. *Aspergillus versicolor* was most resistant to inactivation. Increased amounts of organic matter on the surface of the vegetative cell and higher relative humidity in the ductwork were protective against UVGI. Other factors that affect UVGI inactivation include the number and intensity of lamps in the ductwork, the operational temperature of the lamps in the ductwork (note that air conditioning cools the lamps and reduces UVGI intensity), the air velocity through the ductwork, and the reflectance of the airstream surface (e.g., the duct liner has a low reflectance). VanOsdell and Foarde (2002) appropriately point out that claims about inactivation of pathogenic microorganisms without substantial testing for that pathogenic bioaerosol are irresponsible.

UVGI lamps may be placed in air-handling units (AHUs), usually in air plenums where the irradiation directly falls on the coils and drain pans. However, UV light deteriorates many organic materials such as gaskets, rubber, plastic piping, and internal (airstream) insulation. Thus, UVGI needs to be directed away from the filter deck where it may cause deterioration of the filtration media. Highly efficient filtration (e.g., MERV 13 or better) of air passing through the AHU is necessary to remove airborne mold spores that are less susceptible to irradiation and to keep dust and dirt, which lessen the germicidal efficiency of the fixture, from accumulating on the lamp surface (Bernstein et al. 2006).

Culturable bacteria and fungi are inactivated on irradiated surfaces within the AHU (Menzies et al. 1999, 2003) (see Figure 4.5-B). Levels of culturable fungi on irradiated duct liner on AHU surfaces were also significantly lower than concentrations on non-irradiated duct liner (Levetin et al. 2001). However, culturable microorganisms cannot be inactivated from non-irradiated crevices and non-irradiated airstream surfaces in the AHU (Kowalski and Bahnfleth 2002).

Studies by Menzies et al (1999, 2003) have shown that UVGI on cooling coils and drain pan surfaces inactivates or prevents the growth of environmental fungi and bacteria. However, studies have not shown that UVGI of drain pans and coils results in reduction of culturable fungal and bacterial levels in indoor air in the office workplace.

UVGI and IAQ

Only a few studies have been simultaneously carried out on the efficacy of UVGI intervention on building-related symptoms and environmental microbiology parameters in the building and its HVAC system. The most comprehensive studies on the efficacy of UVGI on IAQ were those of Menzies et al. (1999, 2003).

In the Menzies et al. (2003) study, airborne endotoxin units (EU) were measured in AHUs immediately downstream of cooling coils/drain pans with the UVGI lamp turned on for 4 weeks and again in the same unit with the lamp turned off for 12 weeks. The results were as follows:

- Mean airborne endotoxins with UVGI on = 0.7 EU/ft^3 (0.02 EU/m^3)
- Mean airborne endotoxins with UVGI off = 2.3 EU/ft^3 (0.065 EU/m^3)

Thus, UVGI did cause a decline in airborne endotoxins in the air exiting the cooling coil section of the AHU. Because gram-negative bacteria (e.g., *Pseudomonas*, *Flavobacterium*, etc.) can grow on wet coil/drain pan surfaces, the decline in airborne endotoxin levels in air exiting the coil section is likely due to the significant reduction in bacterial growth on these wet coil and drain pan surfaces caused by UVGI.

The intervention studies carried out by Menzies et al. (2003) did not detect any differences in airborne fungi or endotoxins in the office workplace. However, the background levels of fungi and endotoxins in the outdoor and indoor air in the buildings studied were low, perhaps precluding the ability of UVGI or any other intervention in the AHU from having a significant effect on bioaerosols in the workplace.

Menzies et al. (2003) also determined that UVGI intervention in AHUs was associated with a slight but non-significant decline in levels of culturable bacteria in workplace air but not in air in supply air ducts, as follows:

- Workplace air, UVGI on = 3251 colony forming units (cfu) per ft^3 (92 cfu/m)^3
- Workplace air, UVGI off = 4488 cfu/ft^3 (127 cfu/m^3)
- Supply air, UVGI on = 636 cfu/ft^3 (18 cfu/m^3)
- Supply air, UVGI off = 636 cfu/ft^3 (18 cfu/m^3)

Figure 4.5-B Horizontal Lamp Placements for Coil Surface Disinfection
Source: ASHRAE (2008), Figure 8.

Thus, while Menzies et al. (2003) and others (Kuhn and Chaberny 2004) found that UVGI intervention reduced building-related symptoms, environmental causation of possible microbial origin remains elusive. A repetition of Menzies et al. (2003) studies using sampling and analytical procedures optional for the collection of environmental bacteria (AIHA 2005) and carried out in buildings with high background levels of microbial contaminants is urgently needed to determine the environmental basis for reduction in building-related symptoms associated with UVGI intervention.

Safety with UVGI

Nardell (2002) used the term *dangerous* to refer to the painful eye irritation and skin erythemia that can occur when people are exposed to unshielded UVGI. The American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) for 254 nanometers (NM) UVGI is 6.0 μJ/cm^2 (ACIGH 2007). Trevisan et al. (2006) reported a case where students in an autopsy room were exposed to 700 μJ/cm^2 (254 nm) UVGI irradiation for 90 minutes due to the absence of an interlock system to shut off the UV lights when occupants entered the room. In less than one minute, occupants were exposed to a dose of irradiation exceeding the ACGIH TLV, resulting in both ocular and skin symptoms. Talbot et al. (2002) described another case of occupant exposure to unshielded UVGI. These authors emphasized the need for fail-safe interlock devices to switch off the UVGI fixture when occupants enter any area where unshielded UV lamps may be present.

When UVGI lamps are installed in supply or return ducts, in AHU plenums, or in upper-air fixtures, the designers need to provide procedures that prevent accidental exposure of occupants and facilities maintenance personnel to unshielded UVGI (see Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ). The procedures need to include a lock out, tag out procedure for UVGI lamps in HVAC AHUs and ducts and a combination or keypad lock that prevents unauthorized persons from accessing electrical disconnect devices until it is safe to energize the UVGI lamp. Other safety issues associated with use of UVGI include a) procedures to be followed for safe disposal of UVGI lamps that contain mercury, b) procedures to be followed if accidental breakage of a UVGI lamp occurs, and c) training of facilities maintenance staff on hazards associated with the operation and maintenance of upper-air lamps and UVGI in HVAC systems. Pages 16.9 and 16.10 of the *2008 ASHRAE Handbook—HVAC Systems and Equipment* (ASHRAE 2008) contains detailed information on safety issues associated with UVGI.

Nevertheless, according to Nardell et al. (2008), upper air UVGI fixtures have been used safely in buildings for years. See Nardell et al. (2008) for review of upper-air UVGI safety procedures.

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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.

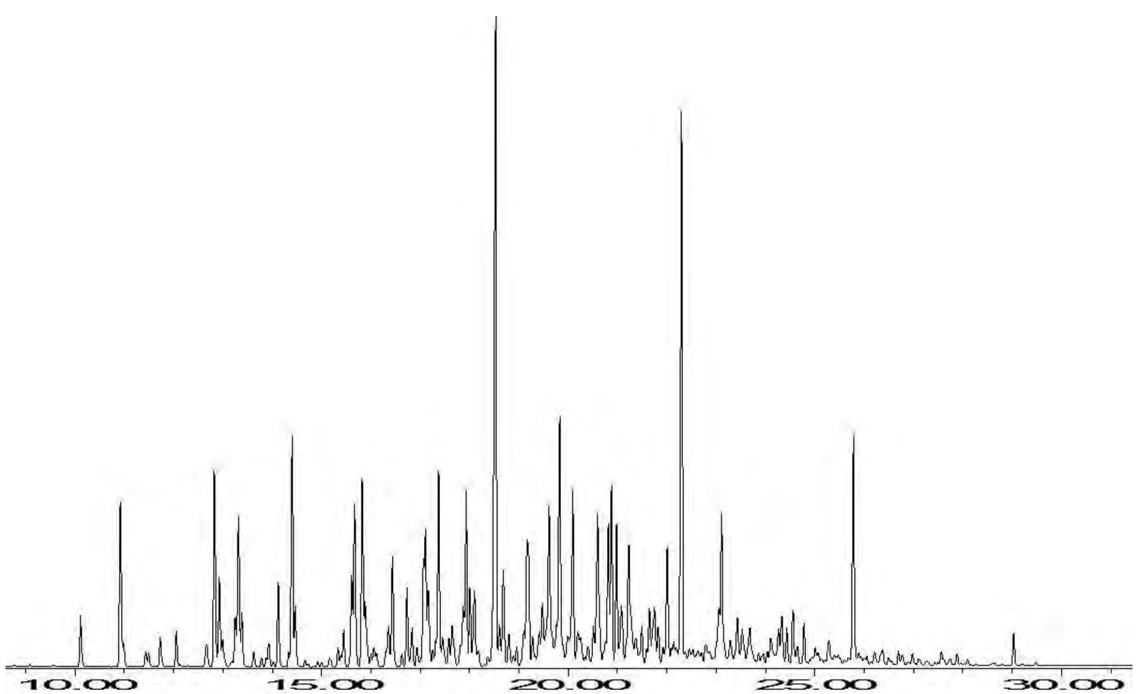

Figure 5.1-C Air Sample from Building Material Emissions Test: Each Peak Represents a Separate Compound
Image copyright NRC-IRC.

Strategy 5.1

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.

Strategy 5.1

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 ($\mu g/m^2/h$), 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.

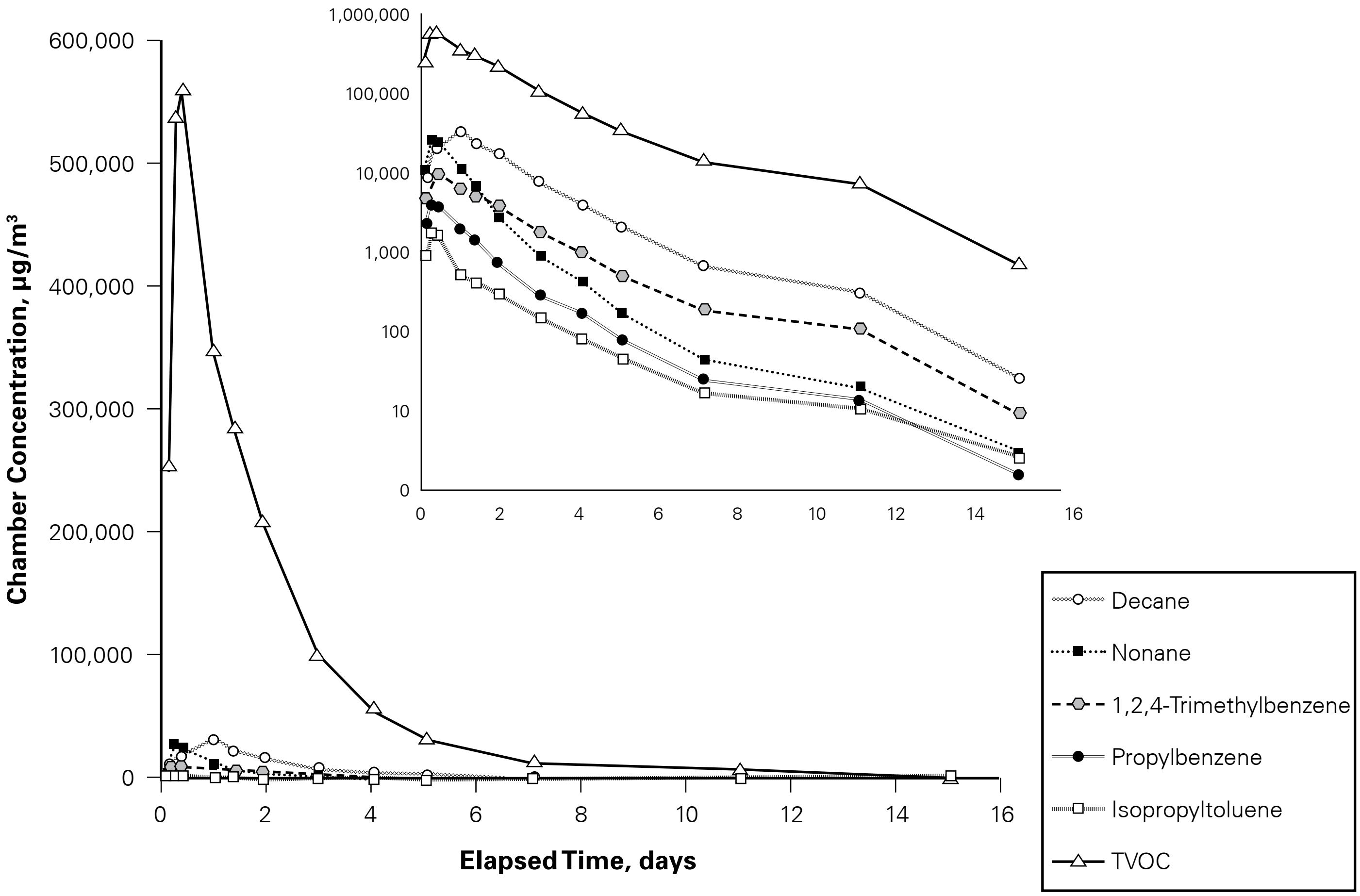

Figure 5.1-D Emissions Test for Glue-Down Carpet Assembly Showing High Initial VOC Concentrations and Rapid Decay
Adapted from data provided by NRC-IRC.

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.

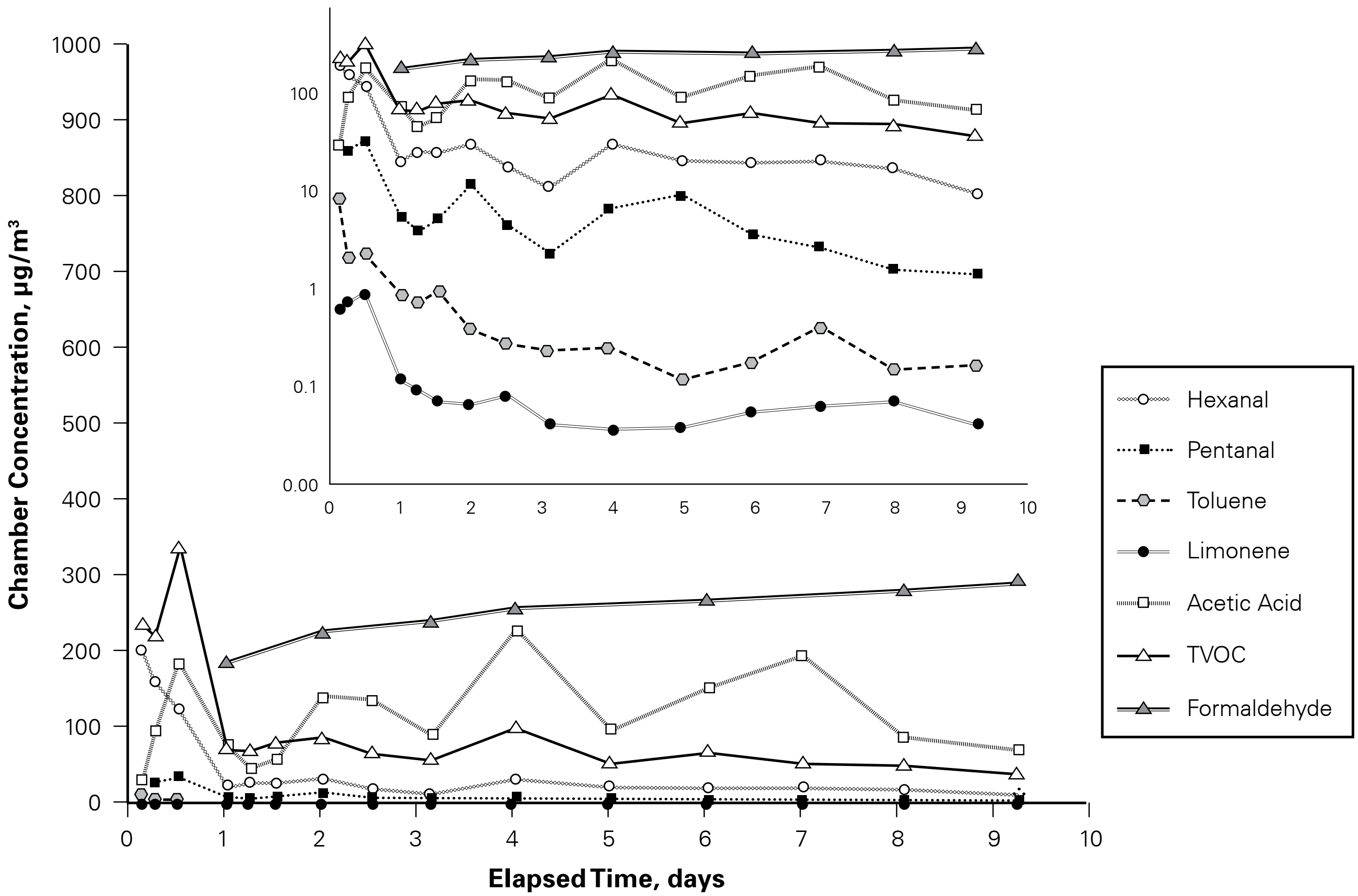

Figure 5.1-E Emissions Test for Engineered Wood Product Showing Slow Decay
Adapted from data provided by NRC-IRC.

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])

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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.

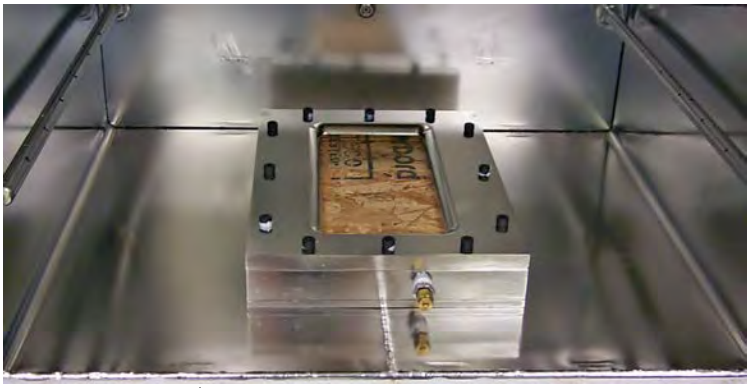

Figure 5.1-F Small (50L) Emissions Chamber
Photograph copyright National Research Council Canada (NRC).

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

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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/m³ (27 ppb)
	  • Acetaldehyde: no single product's modeled concentration can contribute more than 100% of a total maximum concentration limit of 9 µg/m³
	• 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.

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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

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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

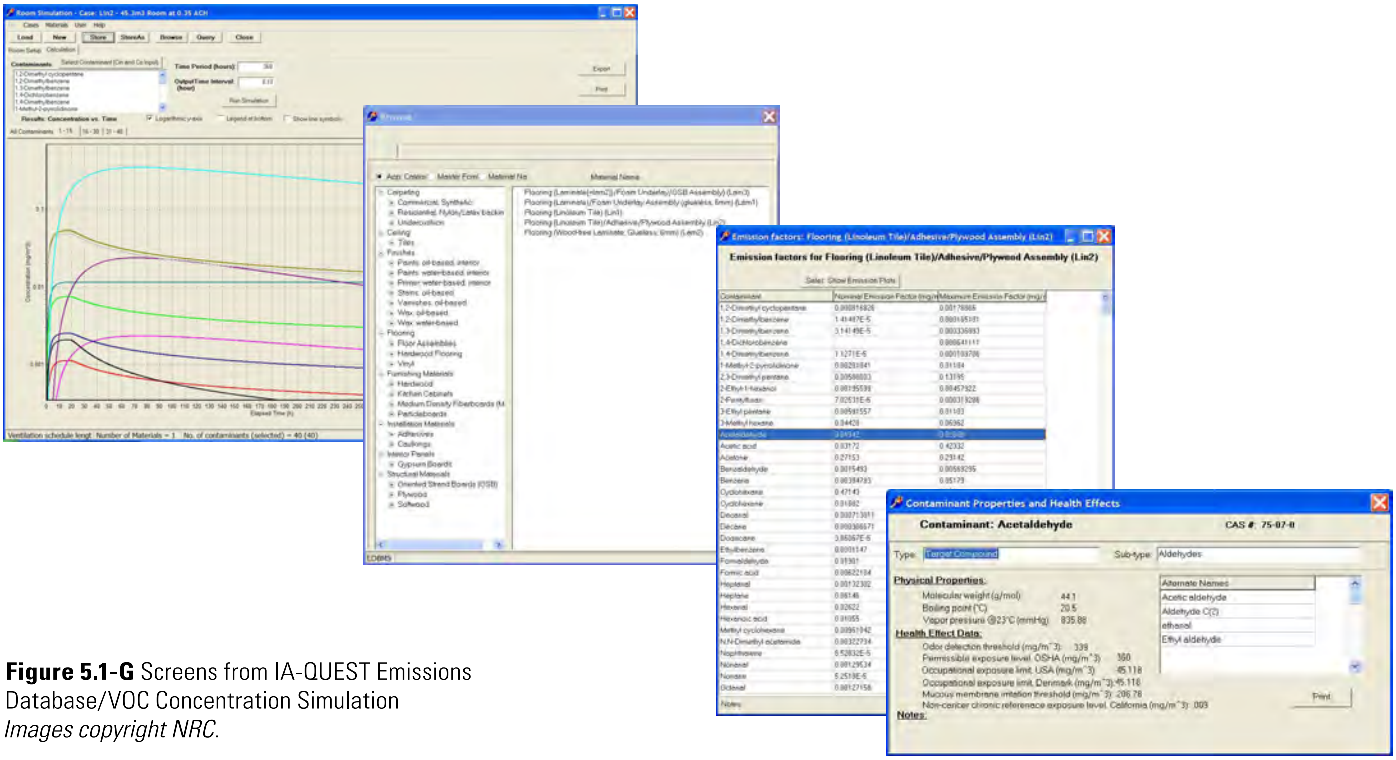

Figure 5.1-G Screens from IA-QUEST Emissions Database/VOC Concentration Simulation
Images copyright NRC.

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)

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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.

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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.

The EPA's *IAQ Design Tools for Schools* document (EPA 2009b) recommends that if specified,

- carpet needs to be selected that
  - has been tested for VOC emissions under the Green Label Plus testing program,
  - can be easily cleaned and maintained, and
  - is constructed to prevent liquids from penetrating the backing layer where moisture under the carpet can result in mold growth;
- new carpeting needs to be rolled out and conditioned in a clean, dry space prior to installation; and
- for glue-down carpet, the least toxic carpet adhesive system compatible with the selected carpet product needs to be specified and the installer instructed to use the minimum recommended quantities of adhesive.

Composite Wood/Agrifiber Materials

Composite wood products include plywood, hardwood plywood, medium density fiberboard (MDF), particleboard, oriented strand board (OSB), and hardboard. *Agrifiber* (agricultural fibre) refers to "waste" solid residue remaining from the harvesting and processing of agricultural crops (e.g., dried stalks of harvested grain). Agrifiber materials, including strawboard and wheatboard, utilize these waste feedstocks as raw materials when they are economically available. Composite wood and agrifiber products are commonly used for indoor trim and as core materials in the construction of furniture, cabinets, shelving, panels, and doors. Products within the composite wood/agrifiber category share significant diversity in the feedstock materials employed, in the surface laminations and treatments used for the final appearance, and in the adhesives used to bind them together. For these reasons, there is large variability common in the nature and extent of contaminant emissions from this group (see, for example, Magee et al. [2003] for an evaluation of the variable nature of emissions from OSB).

Historically, urea-formaldehyde resins have been widely used in the manufacture of composite wood/agrifiber materials, especially those for indoor applications. This is reflected in the dominant focus on formaldehyde emissions evident in Table 5.1-O. The case study titled "Formaldehyde Emissions from a School Textbook Storage Unit" provides an example of the impact of formaldehyde emissions.

There is little doubt that formaldehyde emission is an important consideration in materials selection, and significant improvement in composite materials through revision of the formulation of the resins employed has resulted from this focus. However, more attention to emissions from composite materials is still needed. Table 5.1-O shows that only *ASTM D 6330, Standard Practice for Determination of Volatile Organic Compounds (Excluding Formaldehyde) Emissions from Wood-Based Panels Using Small Environmental Chambers Under Defined Test Conditions* (ASTM 2008a), deals with non-formaldehyde emissions and that none of the specification documents look beyond this single compound. In this aspect, the specification of wood products lags significantly behind that of architectural coatings and flooring materials.

5.1

Table 5.1-O Labels, Test Methods, and Specifications—Composite Wood/Agrifiber Materials

Type	Agency/ Organization	Name and Details
Label—Content	TerraChoice Environmental Marketing Inc. (EcoLogo Program)	*CCD-019, Particleboard Manufactured from Agricultural Fibre* (www.terrachoice.com/images/ECP%20PDFs/CCD_019.pdf) • Specifies emission limits for formaldehyde and methylene diphenyl diisocyanate)

Label—Content	TerraChoice (EcoLogo Program)	*CCD-157, Resin for Engineered Wood Products* (www.ecologo.org/common/assets/criterias/ccd-157resinforengineeredwoodproducts(e).pdf)
		• Subcategories:
		  • Resin for OSB
		  • Resin for laminated veneer lumber/plywood

Test Method—Formaldehyde Emissions	ASTM International	*ASTM D 6007, Standard Test Method for Determining Formaldehyde Concentration in Air from Wood Products Using a Small Scale Chamber* (ASTM 2008b) • Specimens conditioned for a minimum of 1.75 hours; tested in emission chamber (0.02 to 1 m^3) at 25°C and 50% RH at 0.5 ach (sample until steady state achieved)
Test Method—Formaldehyde Emissions	ASTM International	*ASTM E 1333, Standard Test Method for Determining Formaldehyde Concentrations in Air and Emission Rates from Wood Products Using a Large Chamber* (ASTM 2002) • Specimens conditioned 7 days; tested in emission chamber (minimum 22 m^3) at 25°C and 50% RH at 0.5 ach (sample at 16-20 hours)
Test Method—VOC Emissions	ASTM International	*ASTM D 6330, Standard Practice for Determination of Volatile Organic Compounds (Excluding Formaldehyde) Emissions from Wood-Based Panels Using Small Environmental Chambers Under Defined Test Conditions* (ASTM 2008a) • Specimens stored in clean bag for a minimum of 48 hours; tested in emission chamber (0.05 m^3) at 23°C and 50% RH at 1.0 ach (sample at 24 and 72 hours)

Specification—Formaldehyde Emissions	American National Standards Institute (ANSI)	*ANSI A208.1, Standard for Wood Particleboard* (ANSI 1999)
		• Formaldehyde emission limits:
		  • Industrial particleboard: 0.30 ppm at 0.43m^2/m^3 loading
		  • Flooring grade particleboard: 0.20 ppm at 0.43m^2/m^3 loading

Specification—Formaldehyde Emissions	ANSI	*ANSI A208.2, Standard for Medium Density Fiberboard (MDF)* (ANSI 2002) • Formaldehyde emission limits: 0.30 ppm at 0.26m^2/m^3 loading

Specification—Formaldehyde Emissions	California Air Resources Board (CARB)	*Composite Wood Products Airborne Toxics Control Measure (ACTM)* (www.arb.ca.gov/toxics/compwood/compwood.htm)
		• Formaldehyde emission limits (via ASTM E1333):
		  • Particleboard: 0.18 ppm (reduced to 0.09 ppm for 2011)
		  • MDF: 0.21 ppm (reduced to 0.11 ppm for 2011)
		  • Hardwood plywood: 0.08 ppm (reduced to 0.05 ppm for 2010)

Specification—Formaldehyde Emissions	Composite Panel Association (CPA)	Environmentally Preferable Product (EPP) Grademark Program (www.pbmdf.com/Index.asp?bid=1087)
		• Formaldehyde emission limits (via ASTM E1333):
		  • Unfinished particleboard: 0.18 ppm at 0.43m^2/m^3 loading
		  • Unfinished MDF: 0.21 ppm at 0.26m^2/m^3 loading
		  • Hardboard: 0.20 ppm at 0.26m^2/m^3 loading

Specification—Formaldehyde Emissions	U.S. Department of Housing and Urban Development (HUD)	"Title 24, Part 3280, Manufactured Home Construction and Safety Standards" (http://ecfr.gpoaccess.gov/cgi/t/text/text-idx?c+edfr&rgn+div5&view+text&node=24:5.1.3.1.1&idno=24)
		• Formaldehyde emission limits (via ASTM E1333):
		  • Plywood: 0.2 ppm at 0.95m^2/m^3 loading
		  • Particleboard: 0.3 ppm at 0.43m^2/m^3 loading

Specification—Formaldehyde_ Emissions	Hardwood Plywood & Veneer Association (HPVA)	*ANSI/HPVA HP-1-2004, Hardwood and Decorative Plywood* (HPVA 2004) • Includes specification for formaldehyde emissions

Testing conducted by NRC-IRC and released through the IA-QUEST database program (NRC-IRC 2008) shows that a wide range of VOC emissions are characteristic of particleboard (see Figure 5.2-C in Strategy 5.2 – Employ Strategies to Limit the Impact of Emissions), OSB, MDF, and plywood, where the number of different VOCs emitted at levels sufficiently above detection limits to enable modeling were 36, 53, 47, and 33, respectively. Building designers need, therefore, to carefully specify composite materials that have been tested for VOC emissions beyond formaldehyde. In addition, techniques to control residual emissions are likely to be necessary with this class of product. Figure 5.1-J illustrates an example of untreated edges and hidden surfaces without barrier protection that may lead to higher emissions. (Refer to the section “Control of Emissions through Use of VOC Barriers” in Strategy 5.2 – Employ Strategies to Limit the Impact of Emissions for more information.)

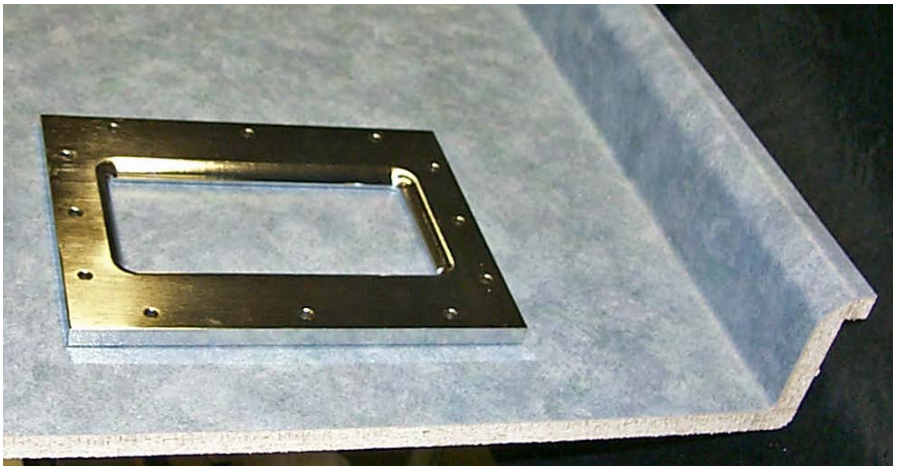

Figure 5.1-J Emitting Areas: Seal Hidden Surfaces
Photograph copyright NRC.

The following general guidance can be provided regarding the specification of composite wood/agrifiber materials:

- Use materials with non-formaldehyde emitting adhesives, ensuring that urea-formaldehyde resins have not been added as extenders.
- Specify materials that have been evaluated for VOC content/emissions in detail (not merely formaldehyde).
- Use barrier coatings/treatments to limit the emissions from cut edges and “hidden” surfaces.

Formaldehyde Emissions from a School Textbook Storage Unit

Figure 5.1-K School Textbook Storage Unit
Photograph courtesy of Hal Levin.

Particleboard shelving was used in a storage system for a school built in the late 1970s (see Figure 5.1-K). Combined with a building operation schedule that had the HVAC system running only between 7:30 a.m. and 3:30 p.m., the resulting formaldehyde levels in the room ranged from 2.3 to 2.7 ppm. At that time, OSHA limits on formaldehyde were 3.0 ppm (Schotland 1997), so this was deemed “safe.” At today’s limits, these levels would mandate the use of a respirator. Replacement of the shelving with pine boards resolved this particular problem.

- Be cautious regarding claims made about the effectiveness of formaldehyde "scavengers": they may reduce, but not eliminate, emissions and may extend the emissions period of the product.

Caulks, Sealants, and Adhesives

This diverse group of products has received considerable attention in terms of IAQ impact due to the products' potential to be strong indoor contaminants sources (Girman et al. 1984). Many are solvent based and may off-gas large amounts of VOCs (EPA 2009b).

Sealants include joint sealants (foam or caulk types) and duct mastic. Adhesives used indoors are numerous and include formulations used for acrylonitrile butadiene styrene (ABS) welding, carpet pads, ceramic tiles, cove bases, drywall and panels, indoor carpet, plastic cement welding, PVC welding, rubber floors, sheet-applied rubber, structural glazing, structural wood members, subfloors, top and trim, vinyl composite tile, asphalt tile, and wood flooring. The impact of adhesive selection on composite wood and agrifiber materials has been discussed in a previous section. As wet-applied materials, they represent strong initial evaporative sources of VOCs but may also show strong long-lasting emissions following skin formation (caulks and seals) or due to slow migration through overlying materials in the case of adhesives. Due to the evaporative nature of initial emissions, emissions testing requires carefully controlled conditions (including air velocity and exposed surface areas) if reliable product-product comparisons are to be made (Zhu et al. 1999). Because adhesives are employed with or between layers of materials, testing of material assemblies is a preferred means to accurately gauge emissions impacts on indoor environments. A summary of relevant test methods and specifications is provided in Table 5.1-P.

Table 5.1-P Labels, Test Methods, and Specifications—Caulks, Sealants, and Adhesives

Type	Agency/Organization	Name and Details
Label—Content	TerraChoice Environmental Marketing Inc. (EcoLogo Program)	*CCD-045, Sealants and Caulking Compounds* (www.ecologo.org/common/assets/criterias/CCD-045.pdf)
Label—Content	TerraChoice (EcoLogo Program)	*CCD-046, Adhesives* (www.ecologo.org/common/assets/criterias/CCD-046.pdf)
Label—Content	Green Seal	*Standard GS-36, Commercial Adhesives* (www.greenseal.org/certification/standards/commercial_adhesives_GS_36.cfm)
Test Method—Emissions	Underwriters' Laboratories of Canada (ULC)	*CAN/ULC-S774, Standard Laboratory Guide for the Determination of Volatile Organic Compound Emissions from Polyurethane Foam* (www.ulc.ca/Files/StandardsBulletin2004/Standards_Bulletin_2004-05_(S774-03)_EN.pdf)
Specification—Content	California Bay Area Air Quality Management District (BAAQMD)	*Regulation 8, Rule 51: Adhesive and Sealant Products* (www.baaqmd.gov/dst/regulations/rg0851.pdf) Note: the primary BAAQMD objective is not improved IAQ but reduction of outdoor smog, thus the VOC definition is the U.S. federal government definition (GPO 2009).
Specification—Content	California South Coast Air Quality Management District (SCAQMD)	*SCAQMD Rule 1168, Adhesive and Sealant Applications* (www.aqmd.gov/rules/reg/reg11/r1168.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).

The following general guidance can be provided regarding the specification and use of caulks, sealants, and adhesives:

- Specify the least toxic/lowest-VOC product suitable for the application.
- Specify that the installer use the smallest amount of adhesive necessary to fulfill the manufacturer's performance specifications for that product (where specified, employ recommended notched trowel to spread smallest permissible quantity of adhesive).
- Consider using mechanical fasteners as an alternative to adhesives.
- Increase ventilation rates in affected areas during and following application of caulks, sealants, and adhesives. Employ building flush-out where possible.

Ceiling Tiles

Ceiling tiles represent an extremely large surface area in building interiors (Figure 5.1-L). Thus, even with relatively low area-specific emission rates, their impact on IAQ can be significant. Ceiling tile types include those manufactured using fiberglass (which may emit formaldehyde); other designs include vinyl-coated tiles (which may be sources of various VOCs or SVOCs). Typically, one or more exposed surface of a ceiling tile is highly porous. This property leads to ceiling tiles becoming a large absorptive sink for capture and gradual re-emission of volatile contaminants from other indoor sources.

Consider the following general guidance on the subject of ceiling tiles:

- Consider ceiling tiles that are specified as having low formaldehyde and VOC emissions.
- Delay installation, when possible, until high-solvent generating operations (application of adhesives, painting, etc.) have been completed and a flush-out ventilation period has commenced.

PVC Materials

Polyvinyl chloride (PVC or vinyl) is found in thousands of common synthetic materials. Data from the American Plastics Council (APC 2002) indicate that approximately 75% of the annual North American PVC production (more than 14 billion pounds [6.4×10^9 kg]) is used in the manufacture of construction materials (including PVC-based flooring and vinyl-covered wallboards, shades and blinds, furniture, carpet backing, and moldings).

A wide range of VOCs and SVOCs are emitted from PVC, including plasticizers, solvent residues, unreacted monomers, and secondary degradation products (Järnström et al. 2008). Phthalates are added as plasticizers, primarily to give flexibility to the products. Di-n-butyl-phthalate, di-iso-butyl-phthalate, and DEHP were commonly used in PVC until ~2000; now di-iso-nonyl-phthalate is increasingly used (Pohle 1997; Lorz et al. 2002). Several phthalates, especially DEHP, are suspected to have significant adverse health impacts, including carcinogenic and teratogenic effects; soft PVC used in wall coverings may contain more than 30% phthalic acid esters (Wensing et al. 2005). Damp PVC flooring has been associated with asthma development in children (Bornehag et al. 2002), apparently due to phthalate hydrolysis (see the section in this Strategy titled "Indoor Chemistry—Secondary Emissions").

Increasingly, material specifications and labeling systems require strict limits or bans on the phthalate content of certified products. Commercial and residential formulations of vinyl flooring products vary significantly; care needs to be taken to ensure that the specification examined is for the precise material to be installed. Refer to the discussion on resilient flooring in this Strategy's "Flooring Materials" section and Table 5.1-N for test methods and specifications related to flooring products. PVC-free flooring materials are available from a number of manufacturers.

Strategy 5.1

Insulation Materials

Insulation may refer to thermal insulation (including fire-retardant materials) or acoustical insulation. This section reviews general aspects of insulation materials. For a more detailed discussion of acoustical ceiling tiles, acoustical insulation applied to HVAC ducting interiors, or acoustic panels incorporated into office partitions, refer to this Strategy's sections on ceiling tiles, HVAC components, and office furniture, respectively. Methods and specifications that target VOC content or emissions from insulation materials are relatively few (Table 5.1-Q).

Table 5.1-Q Labels, Test Methods, and Specifications—Insulation Materials

Type	Agency/Organization	Name and Details
Label—Content	TerraChoice Environmental Marketing Inc. (EcoLogo Program)	*CCD-016, Thermal Insulation Materials* (www.ecologo.org/common/assets/criterias/CCD-016.pdf)
Test Method—Emissions	Underwriters' Laboratories of Canada (ULC)	*CAN/ULC-S774.03, Standard Laboratory Guide for the Determination of Volatile Organic Compound Emissions from Polyurethane Foam* (www.ulc.ca/Files/StandardsBulletin2004/Standards_Bulletin_2004-05_(S774-03)_EN.pdf)
Specification—Emissions	ULC	*CAN/ULC-S705.1, Standard for Medium Density Closed Cell Spray Applied Rigid Polyurethane Foam—Material Specification* (ULC 2005) • Sets emission limits, when tested according to CAN/ULC-S774.03, for: • Acetaldehyde, dichlorofluoromethane, dichlorofluoroethane, trichlorofluoromethane, chloroform, α-methylstyrene, chlorobenzene, 1,4-dioxane, toluene, and 1,2,4-trimethylbenzene

The use of asbestos insulation is one of the classic examples of how building materials can have an adverse impact on IAQ. Initially valued for its properties as a good thermal and electrical insulator, as a material resistant to chemical attack and wear, and as a fireproofing material, these properties were eventually overshadowed by its adverse health impact on building occupants. Its use is now highly restricted.

In current building practice, insulation materials are installed as batts or blankets, as boards, or as loose-fill or spray-applied formulations (Figure 5.1-M). Insulation may be fibrous in nature (including fiberglass, rock wool, mineral wool, man-made mineral fiber, and ceramic fibers) or made from cellulosic materials. Plastic insulations, made from petrochemical-derived polymers, may be produced from styrene (extruded or expanded polystyrene), isocyanurate, or urethane feedstocks.

Figure 5.1-L Acoustical Ceiling Tiles
Photograph courtesy of Leon Alevantis.

Figure 5.1-M Insulated Surfaces: Wrapped HVAC Ducting, Structural Member Spray-On Insulation *Photograph courtesy of Leon Alevantis.*

Fiber-based insulations employ adhesive "binders" to hold the fibers together. Depending on the resin employed, various VOCs, including formaldehyde, may be released. Several manufacturers have modified production techniques and now market formaldehyde-free fibrous insulations. Care needs to be taken to verify claims of reduced emissions by selecting products that have been properly tested and certified. Simply switching to a phenol-based resin may not be sufficient, however, as urea-formaldehyde "extenders" are sometimes still used.

Insulation materials frequently incorporate flame-retardant properties (refer to the "Flame Retardant Materials" section in this Strategy), as insulation may be used to isolate hot components (e.g., for pot lighting systems) or to provide fire protection for building structural components. Cellulosic insulations are often treated with boric acid or borax pentahydrate to achieve fire-retardant properties. Air-blown cementitious foam insulations (made using magnesium oxide cement) provide fire retardancy. Manufacturers also report it to be non-toxic and chemically inert and as having zero formaldehyde emissions, though these claims have not been fully evaluated. For all insulation materials, as with any product, local building codes and regulations need to be observed.

Porous or Fleecy Materials

Porous materials used in buildings include unfinished drywall surfaces and ceiling tiles (perlite and cellulosic). Fleecy materials include certain insulation materials, textiles (upholstered furnishings, cloth-covered workstation partitions, and fabric wall coverings), carpets and underpads, and ceiling tiles (acoustic fiberglass) as well as sound-absorbing HVAC duct linings.

While they may be sources of indoor contaminants (for example, there may be VOC emissions, including formaldehyde from textiles and some fiberglass-based insulation materials), the main concern with these materials is that they can absorb contaminants from other sources (sink effect) then re-emit them over extended time periods (Levin 1989; Tichenor 1992). Typically, their exposed surface areas are large, thereby magnifying the problem.

Studies by Skov et al. (1990), confirmed by Norback (1995), found a correlation between airway and central-nervous-system-related symptoms and building "fleece factor" (the area of fleecy surface per room volume). Changes in room temperature or humidity were reported to trigger re-emission of sorbed pollutants. Won et al. (2001) found carpet to be a sorptive sink for non-polar VOCs while highly polar VOCs were absorbed by virgin gypsum board. Porous flooring materials such as carpeting may collect dirt and moisture, leading to mold formation (EPA 2008a).

In general, it is recommended to do the following:

- Limit the use of porous or fleecy materials to reduce the sink effects that can occur.
- Delay the entry within the building of porous or fleecy materials until strong solvent-generating activities have been completed (refer to the section titled "Staged Entry of Materials" in Strategy 5.2 – Employ Strategies to Limit the Impact of Emissions). In the case of glued-down carpeting, this is of course impossible without selecting adhesives with minimal VOC content/emissions properties.
- Avoid leaving gypsum wallboard unpainted longer than necessary and avoid high-VOC-emitting activities while unpainted wallboard is present (again, choose paint/primer with low VOC content and emissions to reduce the direct sink effect).

Flame-Retardant Materials

Flame retardancy (or *fire retardancy*) refers to any substance that prevents or delays combustion or that inhibits the spread of fire. Such materials are used extensively in buildings: on structural components, furnishings, and floor coverings as well as in office equipment such as computers, monitors, microwaves, etc. A 2004 summary by Wilson found that more than 175 flame-retardant compounds were being marketed (Wilson 2004). Representative examples of major types of flame retardants are listed in Table 5.1-R.

Table 5.1-R Flame-Retardant Material Classes

Flame-Retardant Class	Example Compounds
Chlorendic Acid Derivates	Dibutyl chlorendate
	Dimethyl chlorendate
Brominated Flame Retardants (BFRs)	Pentabromodiphenyl ether (penta BDE)
	Octabromodiphenyl ether (octa BDE)
	Decabromodiphenyl ether (deca BDE)
	Polybrominated biphenyls (PBB)
	Hexabromocyclododecane (HBCD)
	Tetrabromobisphenyl A (TBBPA)
	Polybrominated diphenyl ether (PBDE)
OrganoPhosphates	Bis(2,3-dibromopropyl) phosphate
	Tri-o-cresyl phosphate
	Tris(1-aziridinyl)-phosphine oxide (TEPA)
	Tris(2,3-dibromopropyl) phosphate (TRIS)

The safety benefits of such materials are obvious; however, there is growing concern about the health impact of certain classes of fire-retardant materials. Brominated flame retardants (BFRs), currently among the most common flame retardants due to their relatively low cost and high performance efficiency (Birnbaum and Staskal 2004), have been of particular concern. More than 75 distinct BFRs are produced as fire retardants. While polybrominated biphenyls are no longer produced, polybrominated dephenyl ethers are still in use and are suspected to cause serious health problems, including cancer, disruptions to the human endocrine system, and neurologic damage (AQS 2005). Concerns have also been raised regarding the release of harmful VOCs and chlorinated degradation products from polyurethane products for building and indoor use that have been treated with organophosphate flame retardants (Salthammer et al. 2003).

Caution needs to be exercised in specifying materials that require flame-retardant treatment or in the use of flame retardants on building components to avoid products with known IAQ impacts. Certain new products are available, including polyamides for protection of flammable components of indoor furnishings (Betts 2008), while boric acid/borax pentahydrate treatments of cellulosic insulation may be suitable alternatives, as may be cementitious fire retardants.

Structural Materials

Materials that are "hidden" structural components of the building may impact IAQ through chemical (or particulate) emissions if, via intended or unintended air pathways, they are in contact with air that reaches the indoor environment. These include materials used in the fabrication and sealing of the building envelope as well as in interior partitions and floor assemblies. Care needs to be exercised in the specification of these materials such that practical performance aspects also consider potential IAQ impacts.

HVAC Components

The ductwork and mechanical systems used in building HVAC systems can become sources of IAQ contaminants if not carefully specified, installed, and maintained. Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ recommends that HVAC components be protected during shipment and on-site storage to prevent contamination by dust and dirt. This can be accomplished using simple measures such as providing temporary seals on duct section ends. Residual oils from the manufacturing process remaining on duct interior surfaces need to be removed prior to installation according to SMACNA's *Duct Cleanliness for New Construction Guidelines* (SMACNA 2000). Additional guidance is provided in this Guide in Strategy 4.1 – Control Moisture and Dirt in Air-Handling Systems, Strategy 4.3 – Facilitate Access to HVAC Systems for Inspection, Cleaning, and Maintenance, and Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives.

Interior duct lining materials used primarily for controlling noise associated with HVAC supply air need to be used with care, as discussed in Strategy 4.1 – Control Moisture and Dirt in Air-Handling Systems, since they can increase risk of biocontamination of ductwork while also potentially emitting VOCs due to the breakdown of binding agents. As stated in Strategy 4.1, "sound" engineering practice to limit noise problems associated with HVAC ducting is the preferred approach.

Adhesives and sealant compounds used in the installation of ductwork and exterior duct insulation wrapping need to be specified to have low VOC emissions.

Office Furniture Systems

Modern office environments are dominated by open-plan designs (Figure 5.1-N). The components of a typical workstation or cubicle include panel systems, case goods (work surfaces, storage systems), and seating. Demand for efficient utilization of building space dictates that these office environments are tightly packed together.

Collectively, office furniture materials form large indoor surface areas. Often employing fleecy surfaces, insulation-filled partitions, composite wood materials, and painted or coated surfaces, office furniture materials have the potential to act both as sources and sinks of indoor contaminants. Since these materials surround individual office workers, any emissions they release are directly at the breathing zones of the occupants. For these reasons, considerable attention has thus been paid to characterizing and limiting the emissions associated with office furniture systems.

As with most aspects of building design, a balance needs to be achieved in specifying office furnishings. Veitch et al. (2003) examined 779 workstations in 9 buildings and determined that many factors are involved in worker satisfaction with office environments, including privacy issues, acoustics, lighting, and ventilation conditions. Developing materials and products that meet low emissions criteria in addition to other aspects of design is a significant challenge to the industry.

A summary of testing methods and specifications related to office furniture emissions is provided in Table 5.1-S. As "systems," office furniture groupings are often tested as full assemblies in large chambers (see Figure 5.1-O for an example): the Environmental Technology Verification (ETV) test protocol developed in the late 1990s for large chamber emissions testing (EPA 1999) focused on office furniture emissions. With the ETV protocol no longer maintained, BIFMA moved to develop independent methods that were recently

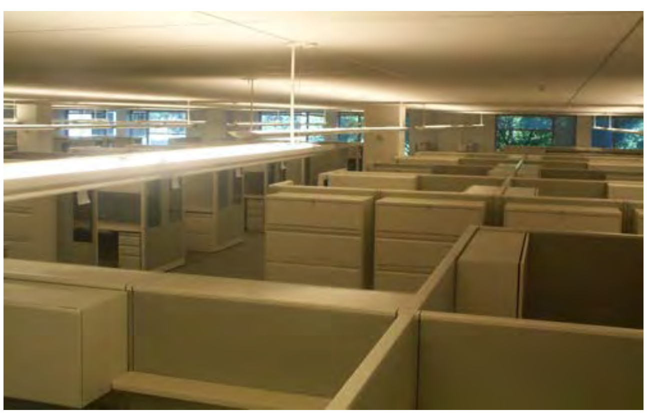

Figure 5.1-N Office Workstations
Photograph courtesy of Leon Alevantis.

Figure 5.1-O Office Workstation Test: 1942 ft^3 (55 m^3) Emissions Chamber
Photograph copyright NRC.

released as ANSI-approved standards (BIFMA 2007a, 2007b). In support of the BIFMA effort, Carter and Zhang (2007) defined standard, representative worst-case office environments and workstation layouts for use in modeling emissions of new office furniture used in North American office buildings. They developed both open-plan and private office configurations to provide manufacturers with bases for comparison for a broad variety of office furniture to relevant emissions requirements. Test methods that evaluate emissions from workstation components in small chambers then scale up the results to full-scale equivalents are under development.

Table 5.1-S Labels, Test Methods, and Specifications—Office Furniture Systems

Type	Agency/ Organization	Name and Details
Label—Content	TerraChoice Environmental Marketing Inc. (EcoLogo Program)	*CCD-032, Demountable Partitions* (www.ecologo.org/common/assets/criterias/CCD-032.pdf) • Issued in 1996 • Covers fully or partially prefabricated gypsum-board-based units whose primary functions are to restrict vision, sound, and passage • Specifies VOC emissions not to exceed 0.5 mg/m^3
Label—Content	TerraChoice (EcoLogo Program)	*CCD-033, Office Furniture and Panel Systems* (www.ecologo.org/common/assets/criterias/CCD-033.pdf) • Issued in 1996 • Specifies VOC emissions not to exceed 0.5 mg/m^3
Label—Emissions	Scientific Certification Systems (SCS)	Indoor Advantage (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)
Label—Emissions	SCS	Indoor Advantage Gold (www.scscertified.com/gbc/indooradvgold.php) • Designed to meet the indoor emissions limits required by the Section 01350 specification (CIWMB 2000). • Applies to systems furniture, case goods

Test Method—Emissions	Business and Institutional Furniture Manufacturer's Association (BIFMA)	*ANSI/BIFMA M7.1, Standard Test Method for Determining VOC Emissions From Office Furniture Systems, Components and Seating* (BIFMA 2007a)
		• Emissions at 72 hours (3 days) and 168 hours (7 days)
		• Conditions: 23°C, 50% RH, 1 m^2/m^3; 0.65–1.09 ach for complete workstations (33 m^3 chamber), 0.9–1.5 ach for workstation components (6 m^3 chamber), 1.0 ach for workstation materials (0.05–0.1 m^3 chamber); standardized workstation configurations
		• Required analysis:
		  • Formaldehyde and acetaldehyde (by HPLC)
		  • $C_6 – C_{16}$ VOCs (by GC-MS) reported according to chemical classes: Aliphatic hydrocarbons, Aromatic HCs, Halogenated HCs, Terpenes, Esters, Aldehydes, Ketones, Cycloalkanes, Glycols/glycol ethers, and Others
		  • Total concentration of each VOC class (calibrated using class-specific VOCs)
		  • Identification of any compounds representing >10% of the class peak area
		  • Identification of 10 most abundant compounds
		  • Quantification of any VOCs from ECA-TVOC list (EC 1997a)

Test Method—Emissions	Greenguard Environmental Institute (GEI)	*Standard Method for Measuring and Evaluating Chemical Emissions from Building Materials, Finishes and Furnishing Using Dynamic Environmental Chambers* (www.greenguard.org/uploads/TechDocs/GGTM.P066.pdf) • Attachment 2, *Office Furniture Test Requirement Specifications*
Test Method—Emissions	Research Triangle Institute (RTI)	Environmental Technology Verification Test Protocol: *Large Chamber Test Protocol for Measuring Emissions of VOCs and Aldehydes* (www.epa.gov/nrmrl/std/etv/pubs/07_vp_furniture.pdf) *Note*: this method is no longer maintained.

Specification—Emissions	BIFMA	*ANSI/BIFMA X7.1, Standard for Formaldehyde and TVOC Emissions of Low-emitting Office Furniture Systems and Seating* (BIFMA 2007b) • Defines acceptance criteria (based on LEED Commercial Interiors criteria) for low-emitting office furniture tested according to the BIFMA M7.1 test method (BIFMA 2007a) • Sets concentration limits for formaldehyde, 4-PC, total aldehydes, and TVOC emissions for a) workstation systems and b) office seating

Specification—Emissions	State of California Department of General Services (DGS)	"Open Office Panel Systems—Section 5.7, Indoor Air Quality (IAQ) Requirements" (www.cal-iaq.org/VOC/IAQ_Spec_from_080303143243710.pdf)
		• Sets emissions test requirements (testing procedures and maximum allowable VOC levels for standard office scenarios) for open office panel systems
		• References the following:
		  • BIFMA M7.1 (BIFMA 2007a) and BIFMA X7.1 (BIFMA 2007b) protocols
		  • OEHHA CREL limits (OEHHA 2008) (see Table 5.1-C of this Strategy)
		  • State of California Maximum Allowable iVOC Concentrations Limits (see Table F-5 in Appendix F – Additional Information on Material Emissions in this Guide for this list of 32 VOCs

Specification—Emissions	State of California DGS	"Final Environmental Specifications to be Included in the Bid Documents for Office Furniture Systems" (www.ciwmb.ca.gov/GreenBuilding/Specs/Furniture/DGSSpecs.pdf)
		• Office furniture specification established in 2000, set the following requirements:
		• VOC Emissions at 96 hours (4 days)
		• Environmental chamber conditions: 23°C, 50% RH, 1 ach
		• Required analysis/emission limits:
		  • Concentration limits for 7 classes of VOCs (μg/m^3) determined via GC-MS vs. pure standards from each individual class:
		    • Alkanes (100), aromatic hydrocarbons (50), terpenes (30), halocarbons (30), esters (20), aldehydes and ketones (excluding formaldehyde) (20), and other (50)
		  • Quantification of 63 individual VOCs via GC-MS using pure standards of each compound (according to EC [1997a])

As with specifications for other building materials, the level of detail in office furniture specifications has steadily matured. Greenguard certification of workstations, seating, and case goods sets allowable limits for VOCs (TLV/10), formaldehyde, 4-PC, TVOCs (detector response calibrated vs. toluene), and total aldehydes. Individual pieces of workstation components, seating, or case goods have allowable emission limits that are 50% lower than tested assemblies (except for individual VOCs). The Section 01350 specifications (CIWMB 2000; DGS 2000) required evaluation of emissions of formaldehyde, TVOCs (GC-FID as toluene), combined totals for seven separate classes of VOCs, plus quantification of 63 individual VOCs (if detected) from the list released by EC (1997a). In 2006, California updated this specification (revised in 2007) to include specific concentration limits for 32 individual VOCs (the complete list is provided in Appendix F – Additional Information on Material Emissions).

Office Equipment

In addition to the furniture systems that support and surround modern office workers, many varieties of devices and equipment are found in office environments. These include computers, monitors, copiers, printers, scanners, and fax machines, all of which can be significant sources of gaseous and particulate IAQ pollutants. These are relatively complex contaminant sources, having both resting and active operation modes (duty cycles) with corresponding variability in emission profiles and rates. Berrios et al. (2005) reported that VOC emissions from computers rose between 10-fold and 120-fold when turned on, with m-xylene, p-xylene, pentadecane, phenol, and toluene as common contaminants.

Electronic circuit boards within office equipment can be sources of chemical emissions. Those used in computer monitors, for example, can become very warm during use. Older models can reach internal temperatures of 140°F–158°F (60°C–70°C) according to a study conducted for the EPA (Cornstubble and Whitaker 1998). The authors showed that simply changing the composition of the laminates used to form the circuit boards could have a significant impact on reducing emissions.

Earlier generations of wet-process photocopiers, which utilized liquid solvents in the copying process, were an obvious source of IAQ contaminants and have been removed from most office environments. Their dry-process replacements, however, have been found to generate VOC contaminants as well as ultrafine particulates and ozone (Leovick et al. 1996; Brown 1999).

Laser printers may also emit ozone, which then participates in the formation of irritating secondary by-products (Weschler 2000). Lee et al. (2001) observed that ink-jet printers tend to have lower VOC and particulate emissions than laser printers and that poor maintenance of laser printers led to increased particulate emissions due to reduced transfer efficiency between the charged toner drum and paper surface.

Recent studies (Destaillats et al. 2008; McKone et al. 2009) have confirmed that the magnitude and nature of emissions from common office equipment can depend on both their stages of service life and the levels of diligence employed in their routine maintenance. The observed trend for reduction in VOC and SVOC emissions from computers as they age is an example of the former, while the impact of maintenance on laser printer emissions is an example of the latter. These authors found formaldehyde, organophosphate, and dibutylphthalate emissions from recent computer models. They did, however, observe a decline in the levels of BFRs emitted from newer computers, likely reflecting manufacturers' response to increased attention to this class of flame retardant (see the section in this Strategy titled "Flame-Retardant Materials").

Black (1998) described emissions testing of VOCs, ozone, and particulates from photocopiers, laser printers, and personal computers. Northeim et al. (1998) developed a method for the EPA for evaluating the emissions from dry-process photocopiers and conducted round-robin testing in four laboratories. McKone et al. (2009) utilized a 706 ft^3 (20 m^3) chamber operated at approximately 77°F (25°C) and 1–2 ach in their tests of office equipment emissions. For computers, they employed a 15-day test plan with a series of measurements starting with empty chamber, then chamber + computer off, then chamber + computer on, and ending with empty chamber following computer removal. For printers, a 60-hour test was conducted with a series of phases of operational and dormant printers.

Methods for assessing emissions from office equipment are listed in Table 5.1-T. The Blue Angel method was derived from *Standard ECMA-328, Determination of Chemical Emission Rates from Electronic Equipment* (ECMA 2007), which was first published in 2001. The third edition of this standard was harmonized with *ISO/IEC 28360, Information technology—Office equipment—Determination of chemical emission rates from electronic equipment,* which was released in 2007 (ISO 2007). The specifications listed in Table 5.1-T all reference these European standards.

The diversity in types, sizes, and operation modes of "office equipment" makes definition of a single test standard extremely challenging. Thus, the Table 5.1-T methods permit broad latitude in chamber sizes and air change rates (ranging from 0.5 to 5.0 h^{-1}), product loading factors (between 1:4 and 1:100), and specific test details and contaminant sampling. There is also considerable latitude in terms of equipment preparation, age, and usage prior to testing. While these conditions need to be documented in the assessment report, this means that results need to be interpreted carefully and make product-product comparisons difficult. Formation of ultrafine particulates is not assessed. An accepted standard methodology for the evaluation of office equipment emissions, perhaps on a product-by-product basis, with specific details related to chamber operation conditions, contaminant testing, and office equipment operation protocols, is needed to enable reliable product evaluations and comparisons.

Table 5.1-T Labels, Test Methods, and Specifications—Office Equipment

Type	Agency/ Organization	Name and Details
Label—Content	TerraChoice Environmental Marketing Inc. (EcoLogo Program)	*CCD-035, Office Machines* (www.ecologo.org/common/assets/criterias/ccd-035officemachines(nov282008).pdf) • Ozone, dust and TVOCs per The Blue Angel test method (RAL-UZ 122 [FME 2009]or Standard ECMA 328 [ECMA 2007]): • Ozone: 1.5 mg/h; dust: 4.0 mg/h (gravimetric using 0.7 µm filters); TVOC: 10 mg/h • Use of trace levels of cadmium, lead, mercury, and hexavalent chromium • Ban on PBB, PBDE, and chloroparaffin flame retardants (10-17 C) except for reused, remanufactured, or refurbished components
Method—Emissions	Federal Ministry for the Environment (FME; The Blue Angel Program)	*RAL-UZ 122, Office Equipment with Printing Function (Printers, Copiers, Multifunction Devices)*, Appendix 2, Test Guideline for Emission Rate Measurements (www.blauer-engel.de/en/products_brands/vergabegrundlage.php?id=147) • Based on Standard ECMA-328 (ECMA 2007)
Method—Emissions	European Computer Manufacturers Association (ECMA)	*Standard ECMA-328, Determination of Chemical Emission Rates from Electronic Equipment* (www.ecma-international.org/publications/files/ECMA-ST/ECMA-328.pdf) • Includes printers, personal computers, monitors • Emission rates of VOCs, other aldehydes and ketones, ozone, and particulate matter (gravimetric, 0.7 µm filter) from information and communication technology and consumer electronics equipment during intended operation in an emission test chamber
Method—Emissions	International Organization for Standardization (ISO)	*ISO/IEC 28360, Information technology—Office equipment—Determination of chemical emission rates from electronic equipment*
Specification—Content	FME (The Blue Angel Program)	*RAL-UZ 78, Computers* (www.blauer-engel.de/en/products_brands/vergabegrundlage.php?id=148) • No emissions testing
Specification—Emissions	FME (The Blue Angel Program)	*RAL-UZ 122, Office Equipment with Printing Function (Printers, Copiers, Multifunction Devices)* (www.blauer-engel.de/en/products_brands/vergabegrundlage.php?id=147) • Based on Standard ECMA-328 (ECMA 2007) • Specifies emission rates (mg/h) for benzene, styrene, ozone, dust, and TVOCs for printing phase of operation • For "ready" phase, only TVOC emission rate is specified
Specification—Emissions	Greenguard Environmental Institute (GEI)	Greenguard Emission Criteria—Office Equipment (Hardcopy Devices) (www.greenguard.org/uploads/EmissionsCriteria/GGPS.EC.015.R2.pdf) • Cites The Blue Angel RAL-UZ 122 specifications

In spite of the current limitations in emissions testing protocols for office equipment, certain general recommendations can be made regarding the selection and installation of office equipment, as follows:

- Seek office equipment that meets specifications such as those contained in Table 5.1-T.
- Select laser printers with lower energy utilization since emission rates tend to directly correspond with power consumption.
- Follow manufacturers' maintenance guidelines for laser printers to reduce emissions.
- Consider that ink-jet printers tend to have lower VOC and particulate emissions than laser printers.
- Consider laser printers that incorporate ozone scrubbing devices to reduce emissions.
- Consider that more recently manufactured office equipment may contain lower levels of phthalates.
- Emissions from office equipment tend to be highest during initial break-in periods. It may be advisable to run new devices during unoccupied periods (with adequate ventilation) in order to reduce impact on workers.
- Large-volume office devices such as photocopiers or large-format printers may be installed in separately exhausted locations (or with dedicated unit exhaust systems) as an effective strategy to limit IAQ impact (refer to Strategy 5.2 – Employ Strategies to Limit the Impact of Emissions and Strategy 6.2 – Provide Local Capture and Exhaust for Point Sources of Contaminants for more information).

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Strategy 5.2

5.2

Employ Strategies to Limit the Impact of Emissions

Introduction

As discussed in Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection, the preferred approach to limiting the impacts of indoor materials on IAQ is through source control (i.e., selecting low-emission materials for use within the building). This is not always possible, since other material properties may take precedence in certain cases. In spite of the best efforts to select low-emission materials, residual emissions will remain and can be significant; thus, additional strategies to deal with contaminants associated with building materials, interior finishes, and furnishings will be necessary. These strategies may take several general approaches.

Control of Emissions Through Use of VOC Barriers

Surface treatments can be effective in preventing emissions of volatile organic compounds (VOCs) from underlaying materials. In the case of products such as unpainted gypsum wallboard, these barrier coatings may prevent absorption of VOCs with subsequent re-emission. By reducing this reversible sink effect, such a barrier can reduce long-term exposure of occupants to VOCs. Exposed cut edges of materials such as compressed wood products have been shown to have higher normalized emission rates than their main surfaces. The use of barriers to cover these edges is thus an important means of controlling emissions.

Depending on the effectiveness of the barrier employed, it may in certain cases be preferable to leave surfaces in their original state. One example would be where a material has a limited reservoir of potential contaminant emissions that would normally be quickly emitted during the early life phase of the product. In such a case, it may be preferable to provide supplemental ventilation following building completion (see the section titled "Building Flush-Out") rather than use a partially effective barrier that will slow the emission rate and result in a net increase in occupant exposure. Evaluation of both the nature of potential emissions as well as the effectiveness of any barrier material for the particular emitted compounds is therefore needed.

Much of the work on evaluating barrier performance has focused on formaldehyde emissions from composite wood materials (e.g., Figley and Makohon [1993]). A review of barrier effectiveness in controlling emissions from composite wood materials including particleboard, medium density fiberboard (MDF), and hardboard is summarized in Table 5.2-A.

Certain barriers themselves may be sources of volatile contaminants, so the emission characteristics of the barrier material need to be carefully evaluated (per Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection). In addition, barriers may merely slow the rate of emission, resulting in prolonged impact of the underlaying material on IAQ. This can result in higher long-term exposure for building occupants.

A preliminary study by Barry and Corneau (2006) found that an epoxy powder coating reduced formaldehyde and total volatile organic compound emissions from MDF by more than 90%. This study also reported that phenolic, vinyl, and melamine paper reduced formaldehyde emissions from particleboard panels by more than 90% but were less effective on other VOC emissions, with reductions of 88%, 66%, and 85%, respectively.

The effectiveness of a melamine coating in controlling emissions from a particleboard-core countertop material was observed in tests conducted by the National Research Council of Canada Institute for Research in Construction (NRC-IRC). The results are included in NRC-IRC's *Indoor Air Quality Emission Simulation Tool* (*IA-QUEST*) (www.nrc-cnrc.gc.ca/eng/projects/irc/simulation.html). When tested with the melamine barrier intact, only trace levels of a few VOCs could be detected.[1] When the test was repeated

[1] Trace levels were detected below 1 μg/m³ in chamber at 1 ach and a material loading of 0.4 m²/m³.

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Table 5.2-A Barrier Types and Effectiveness for Controlling Formaldehyde Emissions from Particleboard, MDF, and Hardboard
Source: CPA (2003).

Barrier Type	Examples	Reported Barrier Effectiveness (Formaldehyde)
Laminates, Thick	High-pressure laminates	80%–95%
	Phenolic impregnated backer sheets (20 mils+)	80%–95%
	Vinyls (6 mils+)	80%–95%
Laminates, Thin	Melamine low-pressure laminates (thermally fused melamine)	80%–95%
	Polyester low-pressure laminates (polyester-saturated paper)	80%–95%
	Thin vinyls (2–5 mils)	80%–95%
	Vinyl-coated papers	70%–90%
	Foils	50%–70%
Coatings, Liquid-Applied	Acrylate (ultraviolet or electronic cured)	80%–95%
	Alcohol sealer	80%–95%
	Alkyd; alkyd and latex	80%–95%
	Alkyd primer sealer	70%–90%
	Polyurethane	70%–90%
	Polyurethane, two-component (water-based)	80%–95%
	Polyvinyl acetate	80%–95%
Coatings, Powder	Epoxy powder	80%–95%
Veneers	Wood veneers	"low to moderate"

with the particleboard edges exposed to the chamber air, more than 30 VOCs were detected, including various aldehydes, ketones, aliphatics, aromatics, and terpenes. Formaldehyde emissions were relatively high in the barrier-compromised specimen. These results are depicted in Figure 5.2-B.

"Hidden" surfaces, such as the backs or undersides of cabinet frames and shelving, are further examples where the application of barrier coatings can be effective in reducing VOC emissions into the indoor environment.

Material Conditioning and In-Place Curing

Newly manufactured materials typically exhibit relatively high emission rates. In most cases, as the materials age their emission rates decay significantly (see Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection). Delaying installation of materials within buildings can provide benefits in reducing contaminant emissions. Materials that are tightly wrapped when delivered to the building site in order to preserve their cleanliness will not have had a sufficient opportunity to off-gas prior to installation. Unwrapping such materials (for example, new partition panels typical of open office designs) and allowing them to air out in a clean, well-ventilated space prior to installation in their intended location within the building can be an effective strategy to reduce their IAQ impact.

The section of EPA's *IAQ Design Tools for Schools* called "Controlling Pollutants and Sources" (EPA 2009) explains:

> Air out is when completed products that produce objectionable emissions are removed from packaging and unrolled or spaced apart in a well-ventilated warehouse so that fresh air can easily flow in and around the products, thereby quickly removing any pollutants emitted from the products. Drawers and doors of cabinetry should also be open, and electrical products such as computers and printers should be turned on. Because the products are being aired out in a well-ventilated warehouse, the pollutants are not emitted within the school building, thus reducing the chances that the pollutants will be adsorbed onto other building materials or finishes, or that occupants will be affected. The types of products most applicable for air out include rolls or tiles of synthetic flooring

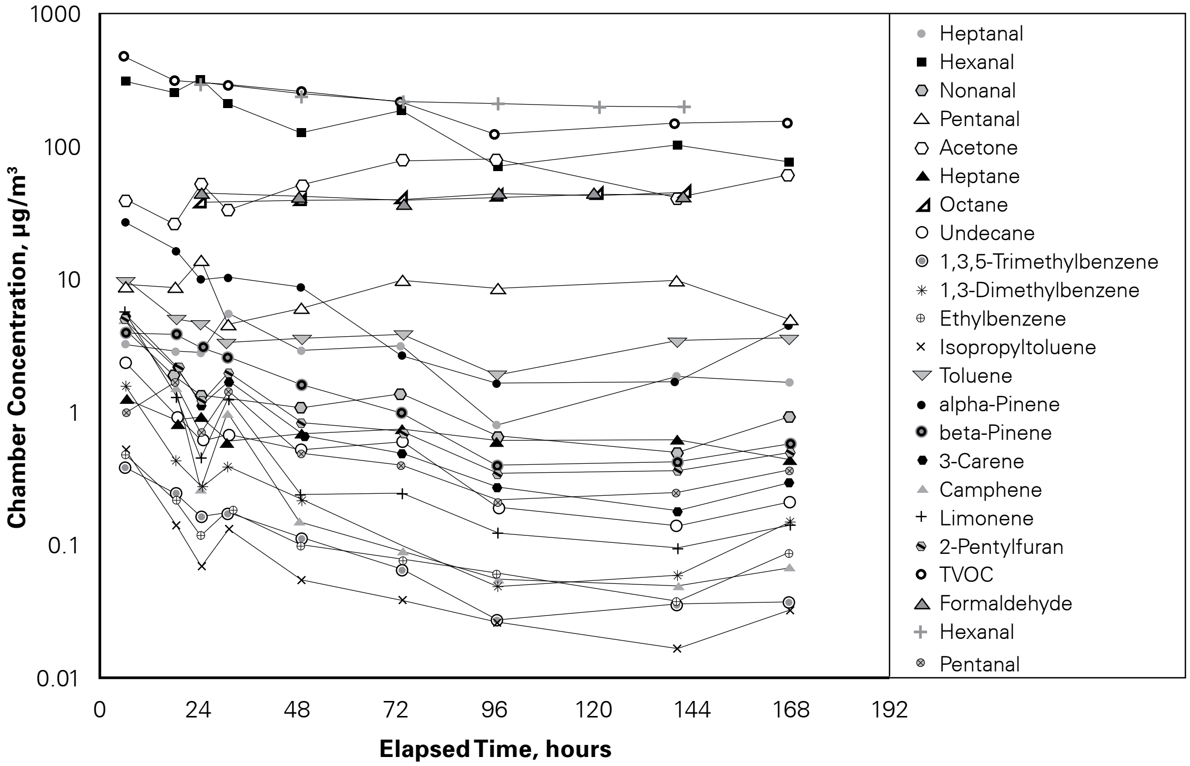

Figure 5.2-B Emissions from Barrier-Compromised Particleboard-Core Countertop
Adapted from data provided by NRC-IRC.

products, and products such as cabinets, shelving, desks, and work surfaces made from particle board, plywood, or medium density fiberboard (MDF).

Similarly, the Collaborative for High Performance Schools (CHPS) *Best Practices Manual, Vol. III—Criteria* (2006) for its pre-conditioning credit (EQ2.0.P10) recommends the following:

> Allow products that have odors and significant VOC emissions to off-gas in dry, well-ventilated space for a sufficient period to dissipate odors and emissions prior to delivery to the construction site or flush-out. Condition products without containers and packaging to maximize off-gassing of VOCs. Condition products in a ventilated warehouse or other building. (p. 80)

Curing is defined as the process during which a chemical reaction (such as polymerization) or physical action (such as evaporation) takes place, resulting in a harder, tougher, or more stable linkage (such as an adhesive bond) or substance (such as concrete) (BD 2009). In this context, in-place curing of building materials relates to intended formulation of products such that emissions are reduced through rapid evaporation and/or irreversible chemical binding within the aged product. This is particularly relevant in the case of wet-applied materials such as caulks, sealants, and adhesives or in the intended binding of free formaldehyde within compressed wood products. While the detailed chemistry is beyond the scope of building design, it is included here to the extent that it impacts material specification and interpretation of emissions test data.

Local Exhaust of Unavoidable Sources

Where known contaminant sources are unavoidable and present in localized clusters, it is appropriate to provide local exhaust systems to effectively capture and remove contaminant emissions (see Strategy 6.2 –

Provide Local Capture and Exhaust for Point Sources of Contaminants). This applies to high- and medium-use office equipment such as photocopiers and printers, to cafeteria and kitchen areas, and to school shop areas. (See Strategy 6.1 – Properly Vent Combustion Equipment for additional guidance related to local exhaust system design.)

Staged Entry of Materials

Installation of fleecy or absorptive materials within buildings need to be delayed until relatively high-emission activities such as painting/staining and using caulks, sealants, adhesives have been completed. Failure to do so will result in absorption of VOCs by these porous materials, with subsequent gradual re-emission and exposure to building occupants over extended periods of time. Refer to the section titled "Porous or Fleecy Materials" in Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection for further discussion.

Delayed Occupancy

New buildings need to remain unoccupied while pollutant-generating construction activities are going on or until building flush-out has been completed (see the section titled "Building Flush-Out") to reduce the impact of early-phase building material emissions. The IAQ Procedure (IAQP) from *ANSI/ASHRAE Standard 62.1-2007, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007) may be employed as a method of ensuring that target contaminant levels have been achieved prior to building occupancy (see Strategy 8.5 – Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate for more information).

Reasons to Avoid Use of Building Bake-Out

Building bake-out was proposed in the late 1980s (Girman et al. 1987) as a means of artificially aging new building materials and finishes by accelerating their emission rates. By increasing the indoor temperature to between 95°F and 102°F (35°C and 39°C), typically for two days while providing continuous ventilation, it was thought that stored reservoirs of volatile compounds within indoor materials could be substantially reduced, leading to lower contaminant levels once the building was occupied. Later studies by Girman and others, however, revealed significant weaknesses in this approach (Girman 1989; Girman et al. 1989, 1990; Bayer 1990, 1991; Hicks et al. 1990; Levin 1992; Offerman et al. 1993).

In its nonbinding guidelines related to office construction materials, the California Department of Health Services (CDHS) points to problems associated with building bake-outs, including

- technical difficulties associated with raising the temperatures of all VOC sources while providing sufficient ventilation,
- the questionable effectiveness of the procedure,
- potential material damage due to elevated temperatures,
- VOC (and semi-volatile organic compound) adsorption and subsequent re-emission by porous surfaces,
- the liability associated with the need to disable fire alarms and mechanical system safety points in order to reach bake-out conditions,
- the need to restrict access to the building due to health concerns, and
- the need to provide workers with respiratory protection (CDHS 1996).

Rather than conducting building bake-out, the CDHS guidelines recommend a combined approach involving

- selection of low-VOC-impact products and materials,
- employing a building flush-out strategy during and after construction (see the section titled "Building Flush-Out"), and
- delaying occupancy until VOC concentrations have been decreased to acceptable levels.

Strategy 5.2

5.2

Building Flush-Out

Recognizing that at completion of a new building contaminant emissions from building materials and interior surfaces are typically at their highest, it is generally recommended that building HVAC systems are operated to provide a higher-than-normal ventilation rate for a period of time. This contaminant dilution process is commonly referred to as *flush-out*. The guidance provided in this section supplements that described in Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ. It is not intended as an alternative to the priority strategy of selecting low-emission materials advocated in Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection.

Specific guidance related to building flush-out varies, as illustrated by the following.

- For new school construction, EPA (2009) recommends that the entire school be ventilated at a minimum of 1 air change per hour 24 hours a day/7 days a week for up to 90 days. At a minimum, all mechanical ventilation systems need to be set to provide the largest amount of outdoor air as practical from the final construction stages when floor products and paints are applied through the first few days of occupancy.
- In its *Best Practices Manual, Vol. III* (EQ2.0.P14), CHPS (2006) requires that following completion of construction, and with all interior finishes installed, the building be flushed with 100% outdoor air by supplying continuous ventilation with all air-handling units at their maximum outdoor air rate for at least 14 days while maintaining an internal temperature between 60°F and 78°F (15.6°C and 25.6°C) and relative humidity no higher than 60%. Occupancy may start after 7 days, provided flush-out continues for the full 14 days. Do not bake out the building by increasing the temperature of the space. (If continuous ventilation is not possible, flush-out must total the equivalent of 14 days of maximum outdoor air.)
- In its "Advisory on Relocatable and Renovated Classrooms," the California Interagency Working Group on Indoor Air Quality recommends that flush-out periods of 1–2 weeks be conducted prior to occupation (longer periods may be required) and that once occupied the HVAC systems continue to be operated at the maximum outdoor air setting for the first days to weeks of occupant use (CIWG-IAQ 1996).
- According to the EPA (2009), the State of Washington now requires a minimum 30-day flush-out period for all its new public buildings.
- Leadership in Energy and Environmental Design (LEED) (NC 2.2, EQ Credit 3.2: Construction IAQ Management Plan) (USGBC 2005) stipulates that after construction ends, prior to occupancy and with all interior finishes installed, a total air volume of 14,000 ft^3 of outdoor air per square foot of floor area (4267 m^3/m^2) be delivered while maintaining an internal temperature of at least 60°F (15.6°C) and relative humidity no higher than 60%. Assuming 10 ft (3 m) ceilings and 100% outdoor air at 1 air change per hour, this would require 58 days of continuous operation to achieve.
- The *High Performance Building Guidelines* prepared by the City of New York (NY 1999) specify that new buildings be flushed with 100% outdoor air for a period of not less than 30 days beginning as soon as systems are operable and continuing throughout installation of furniture, fittings, and equipment.

Note that if ASHRAE's IAQP (ASHRAE 2007) is employed, building flush-out could be discontinued if target contaminant levels are achieved upon return of the building to normal ventilation protocols (see Strategy 8.5 – Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate).

Several key issues need to be addressed if building flush-out is to be effective (or possible). These include the following:

- All post-construction cleaning within the building needs to be completed prior to flush-out and needs to avoid use of strong solvents.
- Flush-out needs to be conducted after the punch list to prevent re-introduction of contaminants associated with the completion of punch list items.

- Local outdoor environmental conditions including regional activities need to be considered in flush-out scheduling and operation. For example, HVAC operation with the maximum flow of outdoor air may not be appropriate during periods of high dirt/dust generation associated with grounds landscaping activities. Outdoor contaminants associated with rush hour traffic need to also be considered in specifying periods of peak outdoor air intake.
- In humid climates or conditions, 100% outdoor air intake may result in excessive intake of moisture (especially when drying of new construction materials is required). Damage to indoor materials may result.
- It is likely that 100% outdoor air will not be achievable if the flush-out timing coincides with cold winter conditions.
- Operation of HVAC systems for extended periods with high outdoor air intake rates may require additional filter capacity and/or maintenance as well as trigger fan warranty concerns.

The costs, delays, and difficulties associated with building flush-out highlight the merit of employing an effective strategy of selecting low-contaminant-emission building materials so that the length of time and the ventilation rate needed for flush-out can be reduced.

Ventilation Rates and HVAC Schedules
In this Guide, Strategy 7.1 – Provide Appropriate Outdoor Air Quantities for Each Room or Zone, Strategy 7.2 – Continuously Monitor and Control Outdoor Air Delivery, Strategy 7.3 – Effectively Distribute Ventilation Air to the Breathing Zone, and Strategy 7.4 – Effectively Distribute Ventilation Air to Multiple Spaces, which address the appropriate delivery of outdoor air to occupied zones in the building, need to be carefully adhered to. As discussed in Strategy 5.3 – Minimize IAQ Impacts Associated with Cleaning and Maintenance, ventilation schedules need to also consider the contaminant loads introduced within the building due to cleaning activities and adjust accordingly. In all cases, HVAC operation needs to include adequate outdoor airflow rates and be scheduled to enable dilution of residual contaminants prior to periods of building occupation.

Indoor Environmental Conditions
Emissions from building materials, finishes, and furnishings can exhibit significant dependence on local environmental conditions including temperature, humidity, and air change rate (Tichenor and Guo 1991; Wolkoff 1998). Control of local environmental conditions will therefore lead to improved control of indoor contaminant levels. Materials for surfaces anticipated to experience higher-than-normal ambient temperatures (for example, surfaces subject to significant solar gains or flooring materials in contact with radiant heating [Kim and Kim 2005]) need to be carefully selected for low-emission characteristics under these conditions.

Filtration and Air Cleaning
Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives provides guidance on selection and operation of HVAC filter systems aimed at both gas and particulate contaminants. When located in return airstreams, the filters may provide effective scrubbing of indoor contaminants. Ozone scrubbing of outdoor air, especially during daily peaks in ozone levels, can reduce the occurrence of irritating, reactive species formed indoors through secondary chemical interactions. During initial building construction, careful filtration measures need to be adopted for HVAC system protection as outlined in Strategy 1.4 – Employ Project Scheduling and Manage Construction Activities to Facilitate Good IAQ.

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Strategy 5.3

5.3

Minimize IAQ Impacts Associated with Cleaning and Maintenance

Introduction

Clean building interiors have a positive impact on IAQ and the health of building occupants. Skulberg et al. (2004) found that comprehensive cleaning reduces the airborne dust in offices and correspondingly reduces mucosal symptoms and nasal congestion. Franke et al. (1997) demonstrated that reduced airborne dust mass, volatile organic compounds (VOCs), and culturable bacteria and fungi resulted from adoption of an improved cleaning program in a four-story mixed-use building that included the use of entry mats, damp disposable dusting cloths, high-efficiency vacuum cleaners, and medium-speed floor machines in addition to careful screening of the harmful chemicals in cleaning supplies.

Cleaning agents and practices can, however, negatively impact IAQ due to associated releases of potentially large quantities of diverse chemicals into the indoor air (Wolkoff et al. 1998; Kildesø and Schneider 2001; CARB 2006, 2008a). The VOC emissions due to a single stripping/rewaxing of a resilient flooring material may exceed the emissions released during the initial installation phase of the material (when its emission rates are at their highest). Cleaning-related emissions can thus be a significant and ongoing factor in the IAQ performance of any building.

In addition, since building cleaning costs typically approach the energy costs to operate the building, efforts to reduce the required cleaning frequency and intensity through building design and material selection choices in design can be rewarding from both IAQ and financial perspectives (see Ashkin [1998] for an overview of cleaning costs and potential savings).

The simplest and most effective means of controlling the negative impact that cleaning products may have on the indoor environment is to reduce the need for their use. This is best accomplished by

- designing effective barriers to the entry of dirt into the building (see Strategy 3.5 – Provide Effective Track-Off Systems at Entrances and Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives) and
- choosing indoor surfaces that are easily cleaned with relatively benign agents.

Selecting Durable Materials and Finishes that are Simple to Clean and Maintain

While the chemical emission properties of building materials should not be neglected (see Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection), installing finishes/surfaces within the building that may be effectively and efficiently cleaned with relatively benign agents can also reduce the IAQ impact of cleaning. In this regard, the following approaches are recommended:

- Select materials with low dirt-trapping properties.
- Consider the use of terrazzo or decorative poured concrete as flooring options where appropriate.
- Consider any hard surface maintenance requirements such as polishing, stripping, or wet-process cleaning as well as the emissions characteristics of any products used in these activities.
    - Natural linoleum flooring products may not require stripping/waxing, but as with any flooring material, their emissions properties should be carefully examined prior to selection.
    - Note that VOC emissions from material surfaces may increase in response to wet cleaning processes.
- Specify an effective track-off system to reduce the requirement for carpet vacuuming, but in maintenance documentation, include recommendations for equipment with high-efficiency particulate air (HEPA) filtration to reduce fine particle resuspension.

- When specifying carpets, the following approaches are recommended:
  - Select styles that exhibit low dirt-trapping characteristics and that allow easy cleaning protocols.
  - Consider using carpet tiles instead of wall-to-wall carpeting to facilitate replacement of small areas as necessary.
  - Specify that during cleaning, operators need to be careful to avoid overwetting of carpet (which can lead to biocontamination) and that deep cleaning should be periodically implemented to effectively remove deep dust, thereby reducing exposure of building occupants to allergens and other pollutants (Roberts et al. 2004). (See Strategy 1.5 – Facilitate Effective Operation and Maintenance for IAQ for guidance related to the maintenance and cleaning of carpeted surfaces).
- For restrooms, the following approaches are recommended:
  - Specify large-dimension tile to reduce the amount of grout lines, which may be difficult to clean and require use of strong cleaning agents.
  - Avoid specifying white grout, which will show stains easily and thus require more frequent cleaning.
  - Specify non-staining surfaces that are easy to clean. Stainless steel may not in fact be "stainless" and often requires periodic application of polishing compounds that may release volatile contaminants. Polished granite, vitreous tiles, synthetic stones, and certain solid-surface plastics may be preferable materials (Wilson 2005).

Where possible, keep the number of different types of surfaces within a building to a minimum. This will reduce the number of distinct cleaning agents that must be used and also reduce the risk that cleaning products will be inappropriately used, leading to reduced longevity of interior finishes.

Microbial resistance of materials used indoors can be a consideration with regards to surface cleaning. In general, however, it is probably wise to focus on easily cleanable surfaces amenable to common disinfectant treatment where required (coupled with control of indoor/surface temperature and moisture conditions) rather than on utilization of specific microbial growth inhibitors.

Recommending Cleaning Products with Minimal Emissions

The volume of cleaning products used in commercial and institutional buildings can be extremely large. Efforts to reduce consumption and to select products with relatively low emissions of contaminants can thus have a significant impact on IAQ. The classes of cleaning agents used indoors are diverse and include general-purpose cleaners, bathroom cleaners (including disinfectants, sanitizers, antiseptics, and disinfectant-cleaners), drain cleaners, carpet cleaners, glass cleaners, degreasers, stain removers, deodorizers (including air "fresheners"), polishes, waxes, and sealers.

Cleaning products used indoors include caustic acids and alkalis, antimicrobial agents, and assorted solvents of organic nature (including hydrocarbons, glycols, and glycol ethers). Aerosol-based cleaners typically contain light hydrocarbon gases. Disinfectants contain alcohols and aldehydes. Degreasers and spot cleaners may release chlorinated hydrocarbons into indoor air.

According to the EPA (2000), "Traditional cleaning products can contain chemicals associated with cancer, reproductive disorders, eye or skin irritation, and other human health issues" (p. 4). Table 5.3-A summarizes the potential health impacts due to compounds commonly found in cleaning agents. There are a number of sources of information on selection of cleaning agents that will have minimal IAQ impact; Table 5.3-B provides a summary of available information.

Table 5.3-A Chemicals Found in Cleaning Products

Compound	Cleaning Agent	Potential Health Impact
Alcohols • Ethanol • Isopropanol	Disinfectants	• Frequently combined with phenolic compounds or ammonium quats, the health risks of which are listed in this table
Aldehydes • Glutaraldehyde • Formaldehyde	Sterilizers, some disinfectants	• Formaldehyde is a carcinogen • Can cause severe skin, eye, and respiratory irritation and headache, nausea, and/or vomiting • Skin allergies or sensitization with repeated use
Ammonia	Household cleaners, especially for glass	• Extremely irritating to respiratory passages at 5%–10% weight per weight
Antimicrobial Agents • Triclosan	Disinfectants, detergents	• May bioaccumulate; overuse may lead to resistant strains
Oxidizers • Chlorine	Disinfectants	• Bleach is highly toxic when mixed with ammonia or ammonium quaternary compounds, forming chloramine gas • Can produce chlorine gas when mixed with or used in conjunction with strong acids, such as those found in toilet bowl cleaners
Glycol ethers • Ethylene glycol monomethyl ether (and acetates of) • Ethylene glycol monoethyl ether (and acetates of) • Ethylene glycol monobutyl ether (butoxyethanol) • Ethylene glycol monopropyl ether	Solvents	• Reproductive toxins • Some are haemolytic • Classified by CARB as Toxic Air Contaminants (CARB 2009)
Phenols • Ortho-phenylphenol • O-benzyl-p-chlorophenol • P-tert-amylphenol • Alkylphenol ethoxylates (APEs or APEOs)	Detergents	• Irritating to the eyes and skin • Ortho-phenylphenol listed as carcinogen
Phthalates	Polishes, fragrances for cleaning products	• Linked to reproductive abnormalities, liver cancer, and asthma
Quaternary ammonium compounds • Benzalkonium chloride • Alkyl dimethylzylammonium chloride	Disinfectants or sanitizers	• Repeated exposure can lead to occupational asthma, allergies, or skin sensitization • Suspected gastrointestinal and liver toxicant
Terpenes	Pine oil cleaners	• React with ozone to form irritants such as formaldehyde, hydroxyl radicals, and secondary organic aerosols

Table 5.3-B Sources of Information Regarding Cleaning Agent Properties and Cleaning Practices

Agency/ Organization	Document/Database	Guidance
ASTM International (formerly American Society for Testing and Materials)	*ASTM E1971-05, Standard Guide for Stewardship for the Cleaning of Commercial and Institutional Buildings* (www.astm.org/Standards/E1971.htm)	Includes assessment of cleaning processes, product selection, storage, usage, disposal, equipment, training of cleaning personnel, and communication throughout the chain of commerce. Operation and maintenance of HVAC systems to provide adequate ventilation to lower risk to cleaning personnel, building occupants, and the environment during or as a result of the cleaning process.
State of California Department of General Services (DGS)	*Technical Specification For the Evaluation of Environmentally Preferable Janitorial Chemicals* (www.ciwmb.ca.gov/GreenBuilding/Specs/Janitorial/Janitorial.doc)	
TerraChoice Environmental Marketing Inc. (EcoLogo Program)	*CCD-146, Hard Surface Cleaners* (www.ecologo.org/common/assets/criterias/CCD-146.pdf)	Institutional and industrial: general purpose cleaners, degreasers, bathroom cleaners, odor eliminators, spot and stain removers, glass cleaners, neutral floor cleaners, hand soap, dish liquid soap
TerraChoice (EcoLogo Program)	*CCD-148, Carpet and Upholstery Care Products* (www.ecologo.org/common/assets/criterias/CCD-148.pdf)	Cleaners and shampoos designed to remove soil from carpet fibers and fabric
TerraChoice (Environmental Choice Program)	*CCD-166, Disinfectants and Disinfectant-Cleaners* (www.ecologo.org/common/assets/criterias/CCD-166.pdf)	Disinfectants and disinfectant-cleaners
Green Seal	*GS-37, Green Seal Environmental Standard for General-Purpose, Bathroom, Glass, and Carpet Cleaners Used for Industrial and Institutional Purposes* (www.greenseal.org/certification/standards/industrial_institutional_cleaners_general_bathroom_glass_carpet_GS_37.pdf)	General purpose cleaners, bathroom cleaners (excluding toilet bowl cleaners, disinfectants, and sanitizers), glass cleaners
Green Seal	*GS-40,Green Seal Environmental Standard for Industrial and Institutional Floor-Care Products* (www.greenseal.org/certification/standards/industrial_institutional_floor_care_GS_40.pdf)	Floor finishes (or floor polishes): any product designed to polish, protect, or enhance floor surfaces by leaving a protective wax, polymer, or resin coating that is designed to be periodically removed (stripped) and reapplied Floor finish strippers (or floor finish removers): products designed to remove floor finishes through breakdown of the finish polymers or by dissolving or emulsifying the finish, polish, or wax
Green Seal	*GS-08, Environmental Standard for General-Purpose, Bathroom, Glass, and Carpet Cleaners Used for Household Purposes* (www.greenseal.org/certification/standards/household_cleaners_general_bathroom_glass_carpet_GS_08.pdf)	Designed for household cleaning products, but many items have general usage
U.S. Environmental Protection Agency (EPA)	"Greening Your Purchase of Cleaning Products: A Guide For Federal Purchasers" (www.epa.gov/opptintr/epp/pubs/cleaning.htm)	General information and links to resources for clean products
EPA	Database of Environmental Information for Products and Services (http://yosemite1.epa.gov/oppt/eppstand2.nsf/Pages/ListTables.html?Open&Hardware%20Store&Cleaning%20Supplies%20and%20Equipment&Type=A)	Links to cleaning product information and a database of environmental information on over 600 products, including janitorial and pest-control products
Western Sustainability and Pollution Prevention Network (WSPPN)	Janitorial Products Pollution Prevention Project (Private project with sponsors including EPA and the State of California) (www.wrppn.org/Janitorial/jp4.cfm)	Governmental and nonprofit project, includes factsheets on cleaning products

Strategy 5.3

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Certain cleaning agents contain compounds that, when exposed to ozone at levels that can occur indoors, react to form irritating contaminants (see the section titled "Indoor Chemistry—Secondary Emissions" in Strategy 5.1 – Control Indoor Contaminant Sources through Appropriate Material Selection). Pine oil cleaners, for example, are sources of terpenoids including α-terpinene, d-limonene, terpinolene, and α-terpineol (Singer et al. 2006a; CARB 2006) that have been shown to interact with ozone to create secondary products including formaldehyde, hydroxyl radicals, and secondary organic aerosols.

In a survey of commonly available cleaning products, Nazaroff et al. (2006) found that many contained ethylene-based glycol ethers (primarily 2-butoxyethanol) at levels up to 10% (mass fraction), while 12 out of 21 products tested contained terpenes and other ozone-reactive compounds at levels up to 26%. When tested in realistic room-cleaning scenarios in the presence of typical indoor ozone levels, in some cases the use of these products resulted in the formation of both formaldehyde and fine particulates at levels exceeding California Ambient Air Quality Standards (CAAQS) (CARB 2008b; OEHHA 2008). Hydroxy radical formation was also noted. Concentrations of glycol ethers could reach levels of concern with use of some products. Careful selection of cleaning products thus needs to be addressed in operation and maintenance (O&M) documentation, including explicit discussion of these concerns.

Air fresheners have been associated with the formation of irritating secondary emissions (Singer et al. 2006b), and their use should be discouraged. Products containing fragrances may emit various VOCs, some of which may by toxic or hazardous (Steinemann 2009). In general, indoor O&M documentation ought to recommend that use of cleaning agents containing fragrances and/or terpenes be avoided. Test methods to examine the indoor environmental impact of cleaning products are beginning to be developed (see, for example GEI [2008]).

Providing Appropriate Storage for Cleaning Products

Even with careful selection of appropriate cleaning products for use indoors, janitorial closets need to be properly vented. Direct exhaust to the outdoors with no recirculation will result in negative pressurization of these spaces and is recommended practice. These storage locations also need to be well lit (to facilitate proper preparation of cleaning agents/equipment) and contain hot water taps, appropriate mop sinks, and properly sloped floor drains that are designed to capture any chemical spills and simplify subsequent cleanup. Flooring materials in janitorial closets can be vinyl composite tile or concrete coated with a durable chemical-resistant coating (Ashkin 1998). As a general recommendation, one janitor closet should be provided for every ~14,000 to 18,000 ft (~1300 to 1700 m^2) of building floor area.

Specify in O&M documentation that easy-to-use dispensers be installed for all concentrated cleaning agent stock solutions. Also explain that while it is important to purchase cleaning agents as concentrates in order to reduce packaging requirements, care must be taken to ensure correct preparation of cleaning solutions while also reducing the risk of spills, excessive use, waste, and staff injury. Recommend that clear instructions for cleaning agent preparation and use should be posted along with available material safety data sheet (MSDS) information on cleaning products and clear warnings regarding any hazards associated with their use. Providing detailed training of custodial staff regarding preparation of cleaning solutions at proper concentrations is essential.

Recommending Cleaning Protocols that Will Have Minimal IAQ Impact

In O&M documentation, explain that

- cleaning strategies focused on the efficient use of relatively benign cleaning products should be adopted as part of building O&M practices,
- damp wiping of surfaces generates fewer IAQ contaminants than does spraying,
- hot water (within safe limits) reduces the required concentrations of cleaning agents, and

- two-bucket mopping with frequent changes to rinse bucket results in reduced cleaning agent residues on indoor surfaces.

In O&M documentation, provide instructions regarding the selection, preparation, handling, usage, and storage of cleaning agents, coupled with suggestions for ongoing training of custodial staff. The dangers associated with the use of improperly diluted agents or with mixing of cleaning product classes should be clearly identified and included in this training.

An energy-IAQ balance must be achieved in terms of cleaning activity scheduling. Appropriate selection of easily cleaned surfaces will reduce the time requirement for effective cleaning. Design choices that permit cleaning during hours when the building is occupied will similarly have a positive energy impact, but this is achievable only through the use of cleaning materials and protocols that do not generate irritants. Terpene-containing agents need to be avoided as a general practice, but their use is particularly discouraged during late afternoon periods when ambient ozone levels typically peak. This is because elevated indoor ozone levels via building ventilation coupled with the emission of terpenes from cleaning agents may lead to formation of strong irritants via secondary chemistry reactions. Building ventilation rates should be adjusted to meet any requirements due to cleaning activities (refer to ASTM E1971 [ASTM 2005] for guidance). The advice of custodial/janitorial staff regarding optimal cleaning protocols should be sought early in the design process in order to facilitate engagement and successful adoption of best cleaning practices.

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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.

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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.

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Figure 6.2-B Exhaust Vent Embedded in Nail Care Workstation
Source: EPA (2007).

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.

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.

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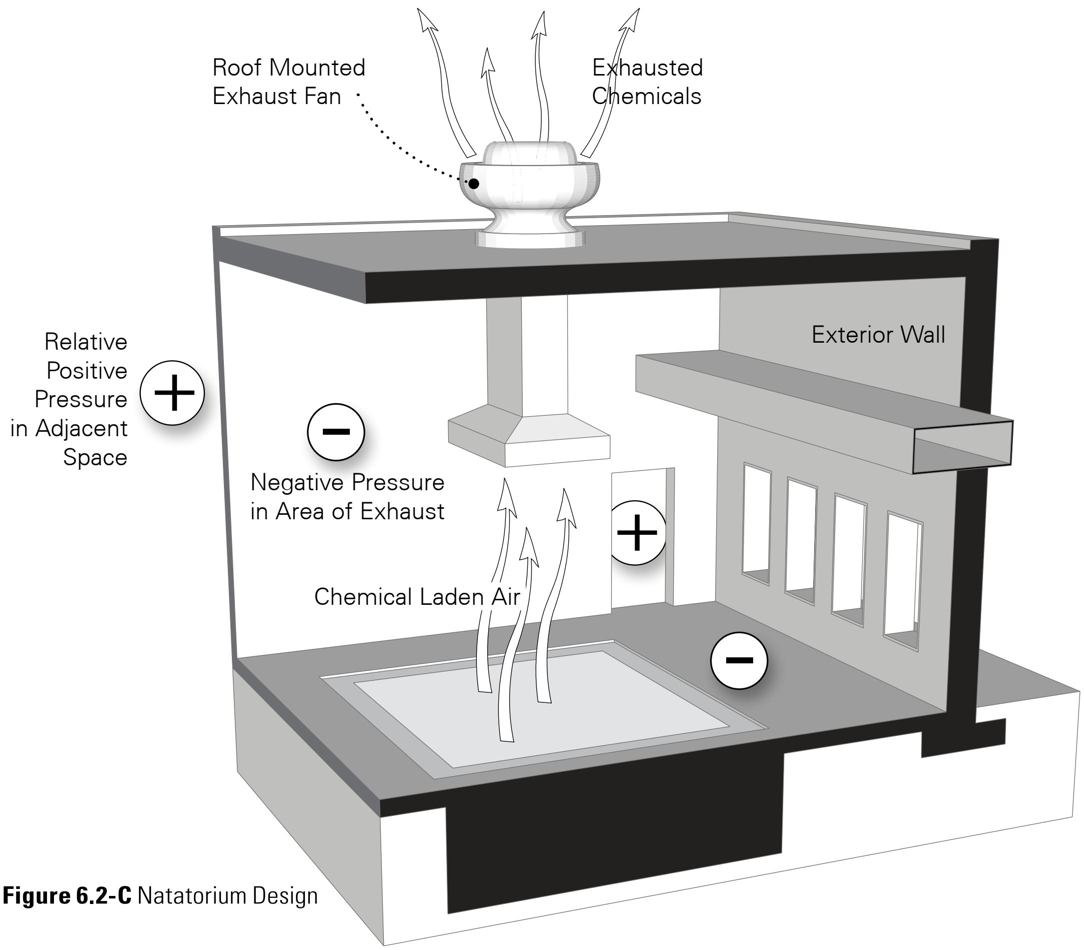

Figure 6.2-C Natatorium Design

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

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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).

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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.

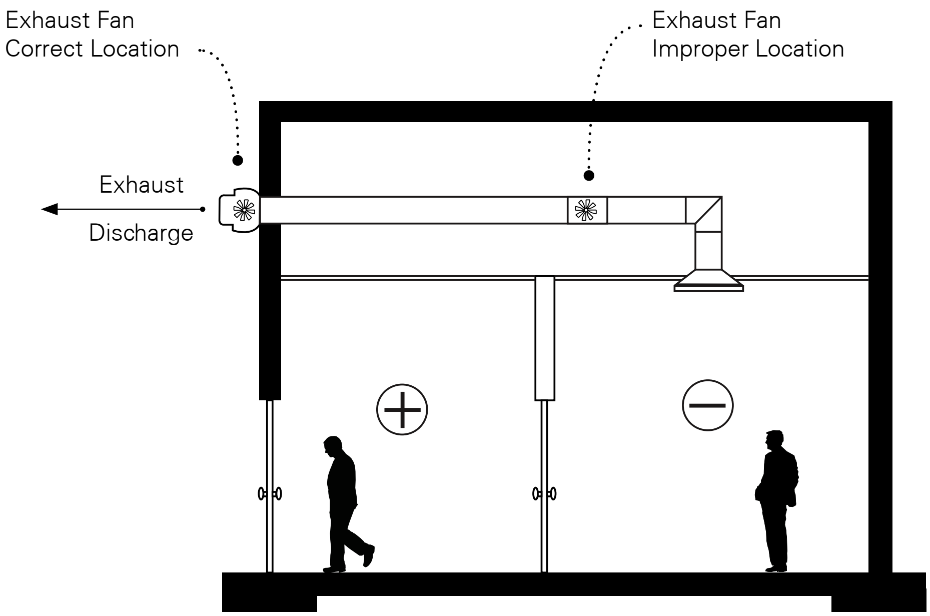

Figure 6.3-D Correct Location of Exhaust Fan to Maintain Exhaust Ducts in Plenum Spaces under Negative Pressure

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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.

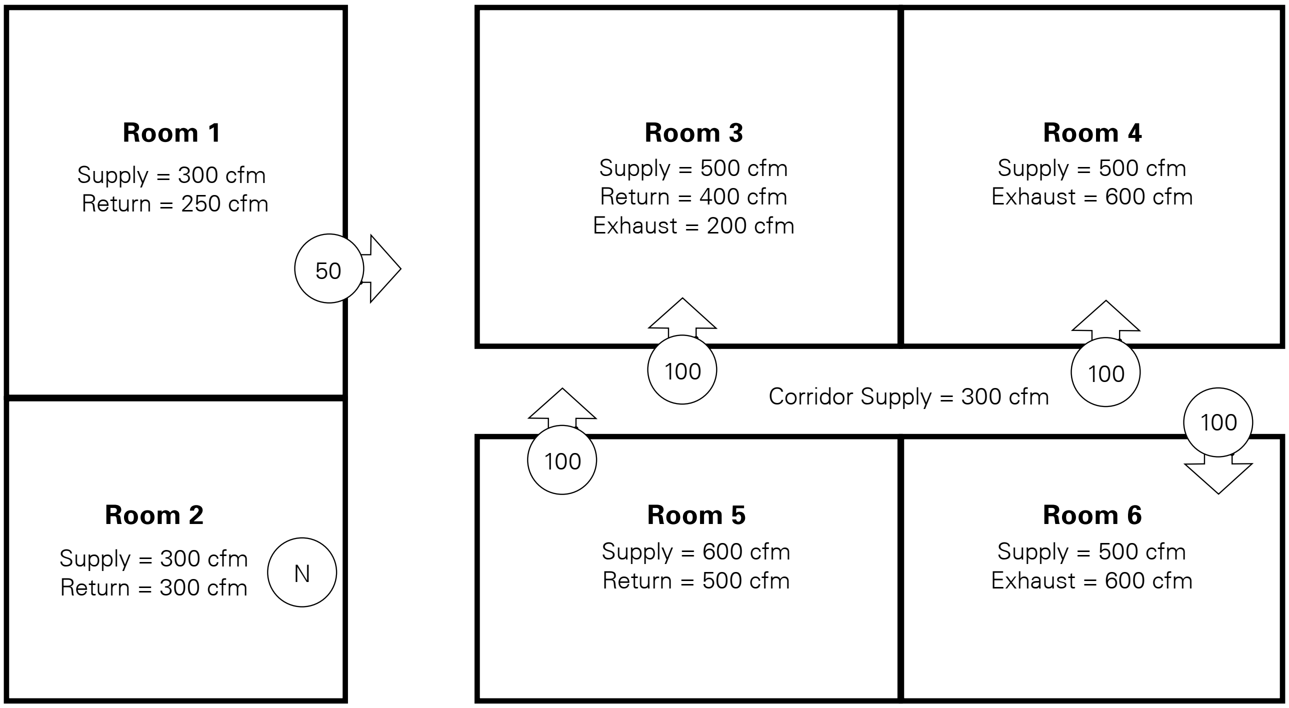
In some space layout arrangements an anteroom might be required. An anteroom is a transition room between areas of substantially different pressures or a space that is used to gain access to a room that needs to maintain its pressure even during disturbances such door openings. The use of anterooms provides 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).

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.

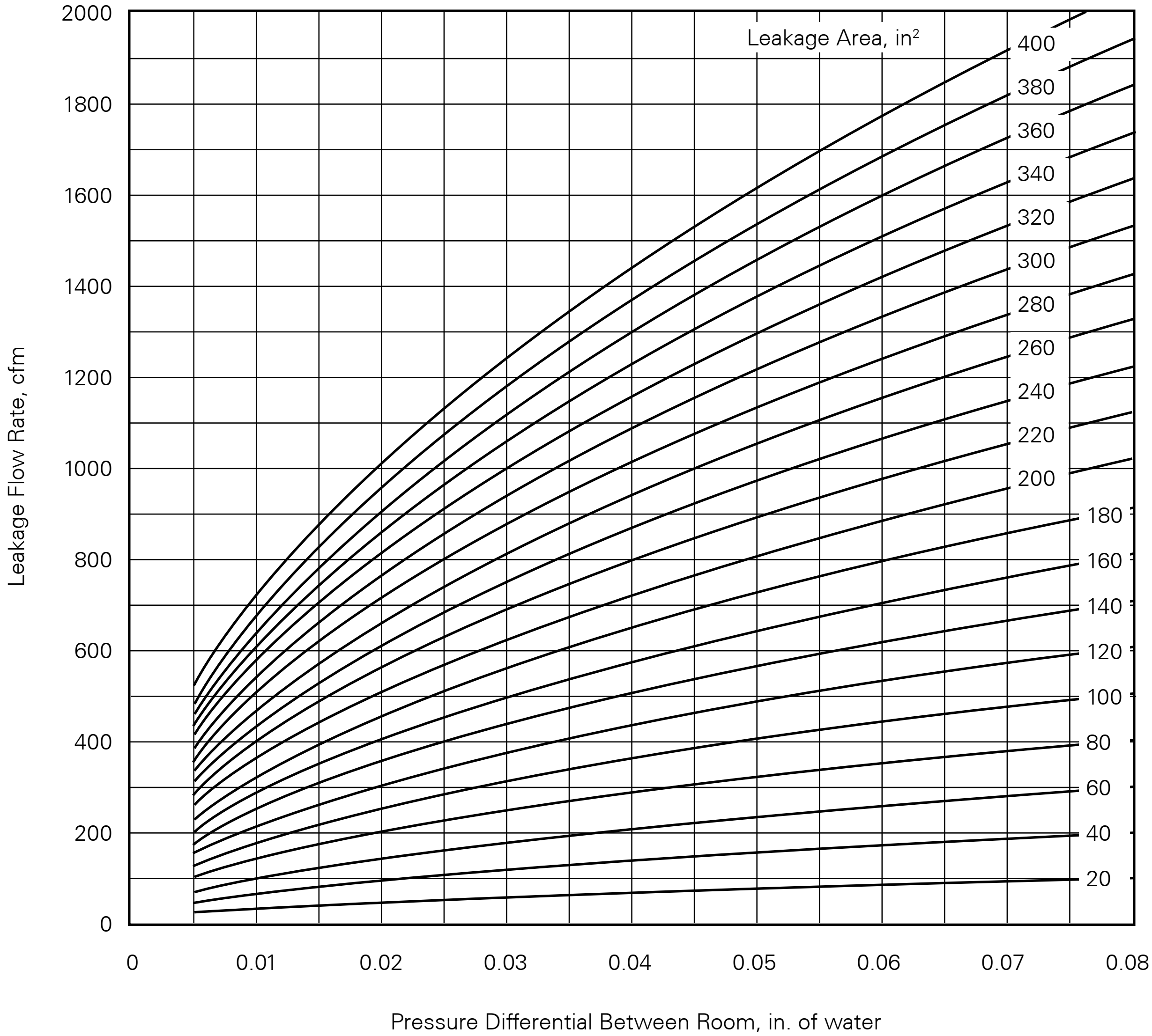


Figure 6.4-D Flow Rate through Leakage Area under Differential Pressure
Adapted from ASHRAE (2007b), p. 16.6.

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

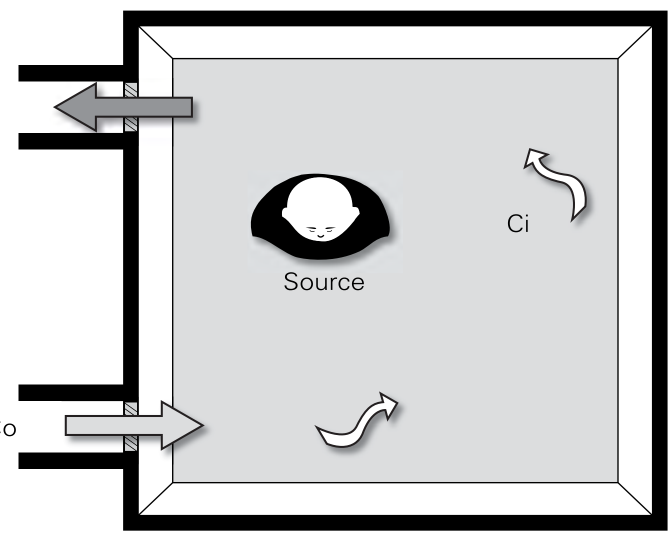

Figure 7.1-B Steady State, where V = Ventilation Rate (Volume/Time), C = Concentration (Mass/volume), and S = Emission Generation Rate (Mass/Time)

- 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):

Strategy 7.1

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

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.

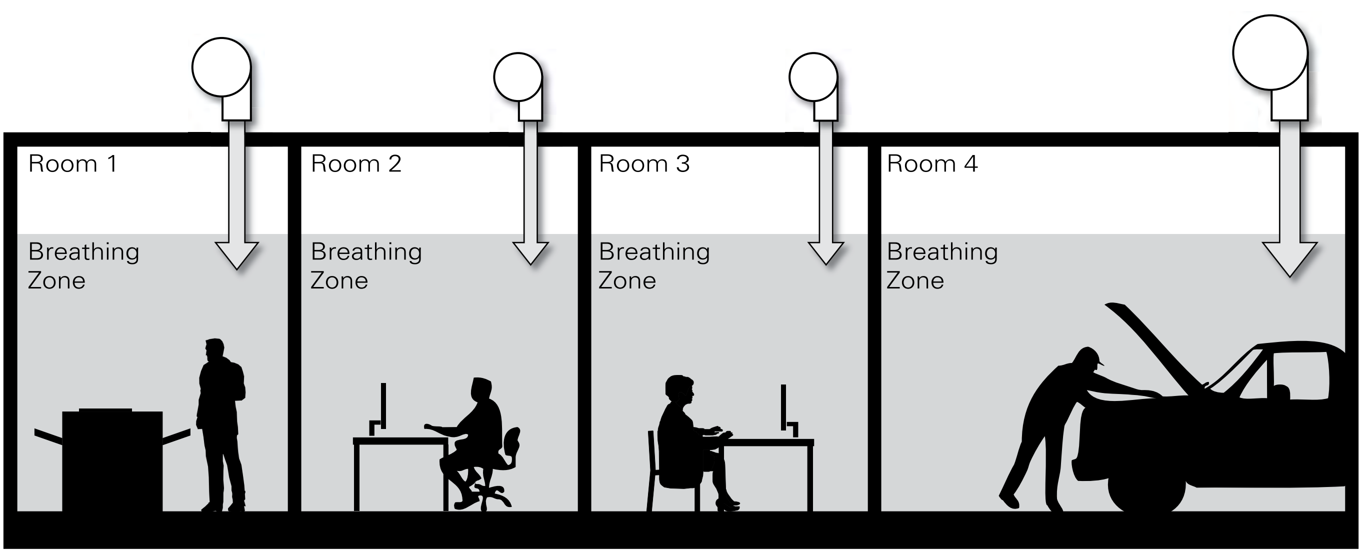

Figure 7.1-C Occupancy Category Examples

STRATEGY OBJECTIVE 7.1

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.

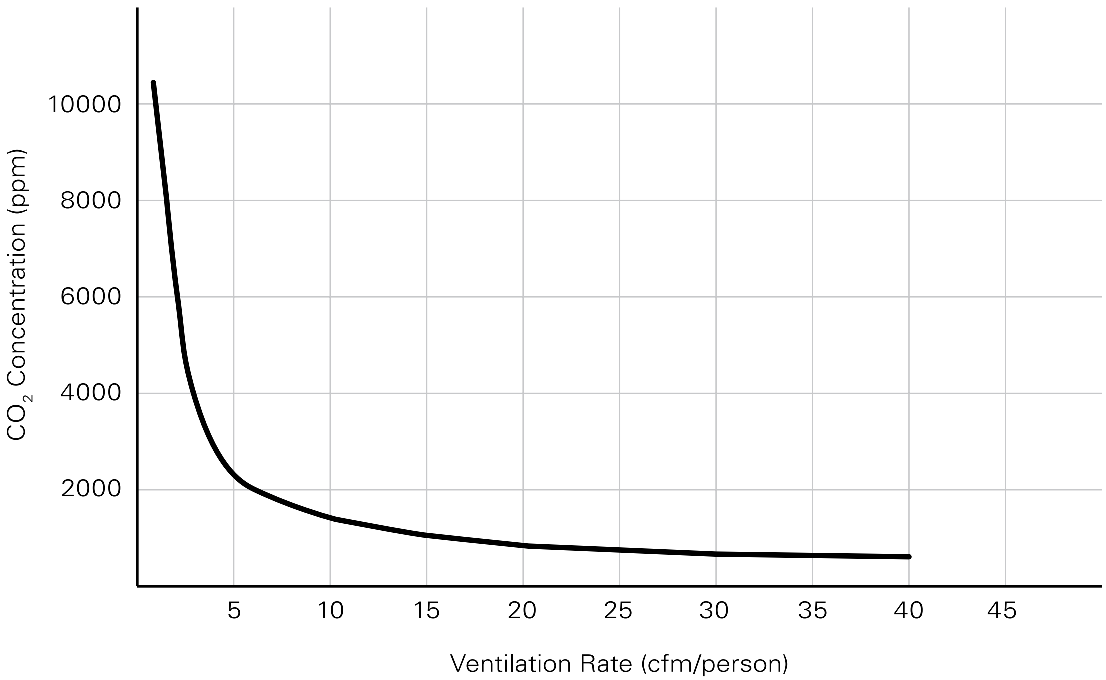

Figure 7.1-D Ventilation vs. CO_2 Concentration

- *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.

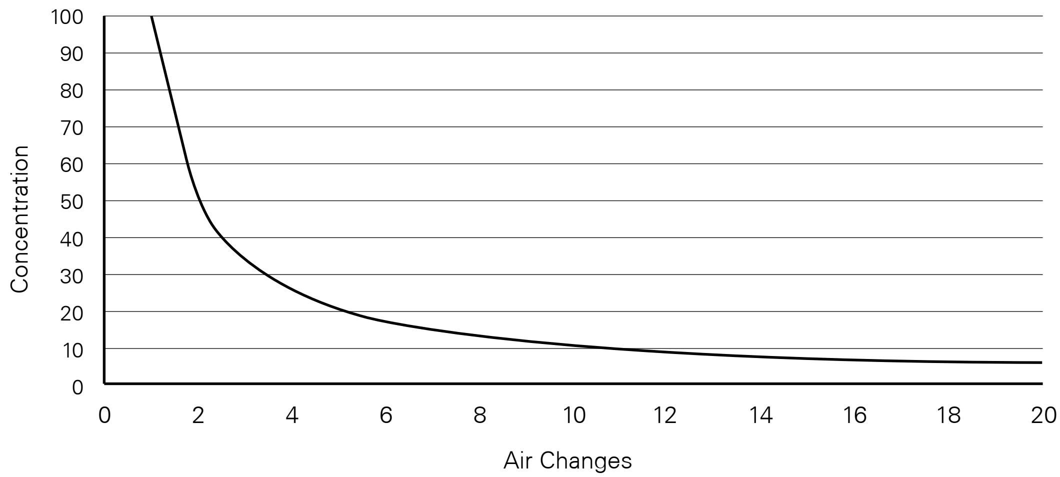

Figure 7.1-E Steady-State Ventilation vs. Concentration Curve

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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.

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.

Strategy 7.2

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)

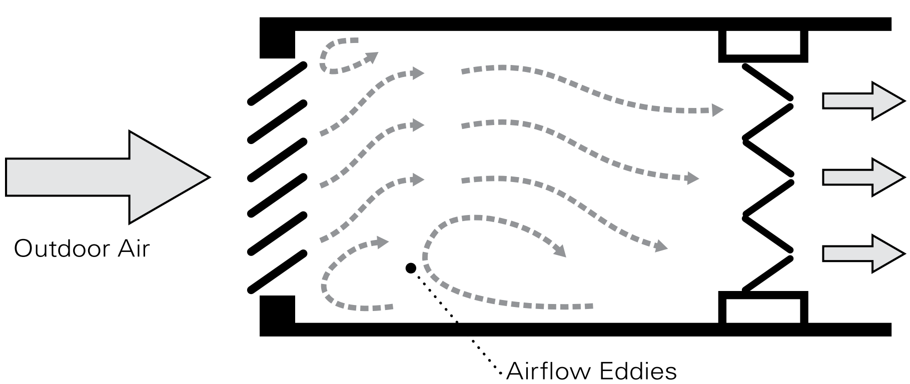

Figure 7.2-E Illustration of Airflow Patterns at the Outdoor Air Intake
Adapted from Fisk et al. (2005b).

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.

Strategy 7.2

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

Strategy 7.2

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):

$$\%\ OA = (CO_{2\text{-}RA} - CO_{2\text{-}MA}) / (CO_{2\text{-}RA} - CO_{2\text{-}OA}) \times 100$$

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.

$$\%\ OA = (t_{RA} - t_{MA}) / (t_{RA} - t_{OA}) \times 100$$

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

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).	

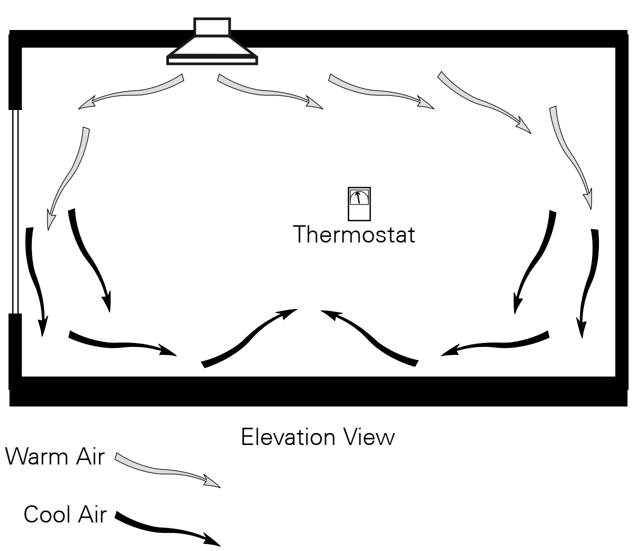

Figure 7.3-C Proper Overhead Heating Design
Adapted from Int-Hout (2007).

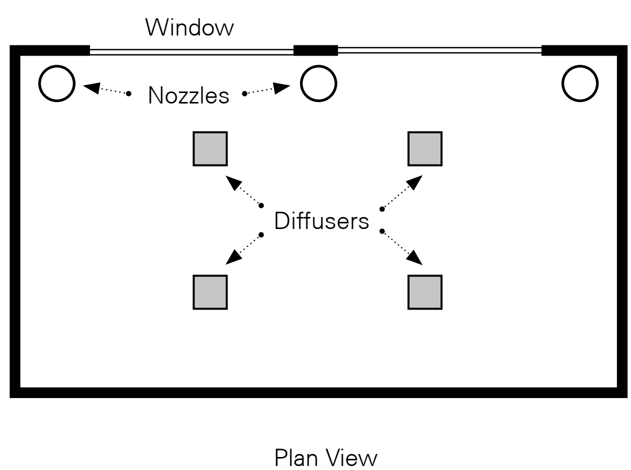

Figure 7.3-D Alternate Overhead Heating Design
Adapted from Int-Hout (2007).

Strategy 7.3

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.

Once the maximum Z_p is determined, E_v can be determined by looking it up in Table 6.3 of ASHRAE Standard 62.1, which is duplicated in Table 7.4-A in this Guide.

Table 7.4-A System Ventilation Efficiency
Source: ASHRAE (2007a), Table 6.3.

Max (Z_p)	E_v
≤0.15	1.0
≤0.25	0.9
≤0.35	0.8
≤0.45	0.7
≤0.55	0.6
>0.55	Use Appendix A of ASHRAE Standard 62.1

Notes:

Max (Z_p) refers to the largest value of Z_p, calculated using Equation 6-5 of ASHRAE Standard 62.1, among all the zones served by the system.

For values of Z_p between 0.15 and 0.55, one may determine the corresponding value of E_v by interpolating the values in the table.

The values of E_v in this table are based on a 0.15 average outdoor air fraction for the system (i.e., the ratio of the uncorrected outdoor air intake V_{ou} to the total zone primary airflow for all the zones served by the air handler). For systems with higher values of the average outdoor air fraction, this table may result in unrealistically low values of E_v, and the use of Appendix A of ASHRAE Standard 62.1 may yield more practical results.

Variable-Air-Volume (VAV)

A variable-air-volume (VAV) system provides a variable amount of air to each room or zone. Thermal comfort is usually maintained by varying the supply airflow rate. For all multiple-zone systems, including VAV, the system ventilation efficiency (E_z) determines the minimum outdoor airflow rate required at the outdoor air intake (V_{ot}).

The difference in VAV and CV systems is that in VAV systems, the airflow varies depending on the load. Reducing the volume of air reduces the load on the fan and saves energy. For VAV systems, the zone primary airflow (V_{pz}) is the minimum expected primary airflow for design purposes (sometimes noted as V_{pzmin}). Often airflow during heating is different from airflow during cooling. If this is the case, then both conditions (heating and cooling) need to be calculated.

In general, a VAV system will require more outdoor air at the intake because as the primary airflow (V_{pz}) decreases, the value of Z_p increases (Stanke 2004, 2005a). An article providing an example of how to calculate E_z and V_{ot} for a single-path multiple-zone recirculating system with VAV is included in this Guide in Appendix G – Single-Path Multiple-Zone System Design. The article assumes the worst-case VAV box conditions. Experienced designers may be able to make more accurate predictions of the behaviors of the systems that they design. With either extensive field experience or a realistic simulation of the system's dynamic behavior, the outdoor air requirements may approach those of a CV system. Lacking such information, the method shown in the article provides a conservative design approach.

Secondary Recirculation

Some systems have fans that create additional recirculation beyond that of the primary air handler. The efficiency of these systems can be dramatically better than "single supply" systems. The calculation of the system efficiency using the following equation is more complex because of the multiple recirculation paths (ASHRAE 2007a):

$$V_{ot} = V_{ou}/E_v$$

where

$$E_v = \text{minimum } (E_{vz})$$

general case $E_{vz} = (F_a + X_s \cdot F_b - Z_d \cdot F_c)/F_a$

Relevant nomenclature provided by ASHRAE Standard 62.1 (ASHRAE 2007a) is:

A_z = zone floor area (the net occupiable floor area of the zone), ft² (m²)

D = occupant diversity (the ratio of the system population to the sum of the zone populations): $D = P_s / \sum P_z$

E_p = primary air fraction to the zone: $E_p = V_{pz}/V_{dz}$ (E_p = 1.0 for single-duct and single-zone systems)

E_r = in systems with secondary recirculation of return air, fraction of secondary recirculated air to the zone that is representative of average system return air rather than air directly recirculated from the zone—Note: For plenum return systems with local secondary recirculation (e.g., fan-powered VAV with plenum return), $E_r \leq 1.0$. For ducted return systems with local secondary recirculation (e.g., fan-powered VAV with ducted return), typically $E_r = 0.0$.

E_v = system ventilation efficiency (the efficiency with which the system distributes air from the outdoor air intake to the breathing zone in the ventilation-critical zone, which requires the largest fraction of outdoor air in the primary air stream); determined from Table 6-3 or Equation A-3 of ASHRAE Standard 62.1

E_{vz} = zone ventilation efficiency (the efficiency with which the system distributes air from the outdoor air intake to the breathing zone in a particular zone); determined from Equations A-1 or A-2 of ASHRAE Standard 62.1

E_z = zone air distribution effectiveness (a measure of how effectively the zone air distribution uses its supply air to maintain acceptable air quality in the breathing zone); determined from Table 6-2 of ASHRAE Standard 62.1

F_a = fraction of supply air to the zone from sources outside the zone: $F_a = E_p + (1 - E_p) \cdot E_r$

F_b = fraction of supply air to the zone from fully mixed primary air: $F_b = E_p$

F_c = fraction of outdoor air to the zone from sources outside the zone: $F_c = 1 - (1 - E_z) \cdot (1 - E_r) \cdot (1 - E_p)$

P_s = system population (the maximum simultaneous number of occupants in the area served by the system); where population fluctuates, it may be averaged as described in Section 6.2.6.2 of ASHRAE Standard 62.1

P_z = zone population (the largest number of people expected to occupy the zone during typical usage); if P_z is not known, it is determined from the default occupant densities listed in Table 6-1 of ASHRAE Standard 62.1; where population fluctuates, it may be averaged as described in Section 6.2.6.2 of ASHRAE Standard 62.1

R_a = area outdoor air rate (the outdoor airflow rate per unit area to be provided in the breathing zone to dilute contaminants that are emitted at a rate that is related more to floor area than to population); determined from Table 6-1 of ASHRAE Standard 62.1

R_p = people outdoor air rate (the outdoor airflow rate per person to be provided in the breathing zone to dilute contaminants that are emitted at a rate that is related more to population than to floor area); determined from Table 6-1 of ASHRAE Standard 62.1

V_{bz} = breathing zone outdoor airflow (the outdoor airflow required in the breathing zone of an occupiable space): $V_{bz} = R_p \cdot P_z + R_a \cdot A_z$

V_{dz} = zone discharge airflow (the expected discharge [supply] airflow to the zone that includes primary airflow and locally recirculated airflow), cfm (L/s)

V_{ot} = outdoor air intake flow (the design outdoor airflow required at the ventilation system outdoor air intake)

V_{ou} = uncorrected outdoor air intake (the outdoor air intake flow required if the system ventilation efficiency E_v were 1.0): $V_{ou} = D \cdot \sum R_p \cdot P_z + \sum R_a \cdot A_z$

V_{oz} = zone outdoor airflow (the design outdoor airflow required in the zone): $V_{oz} = V_{bz}/E_z$

V_{ps} = system primary airflow (the total primary airflow supplied to all zones served by the system from the air-handling unit [AHU] at which the outdoor air intake is located): $V_{ps} = \sum V_{pz}$, cfm (L/s)

V_{pz} = zone primary airflow (the primary airflow supplied to the zone from the AHU at which the outdoor air intake is located), L/s (cfm); includes outdoor intake air and recirculated air from that AHU but does not include air transferred or air recirculated to the zone by other means

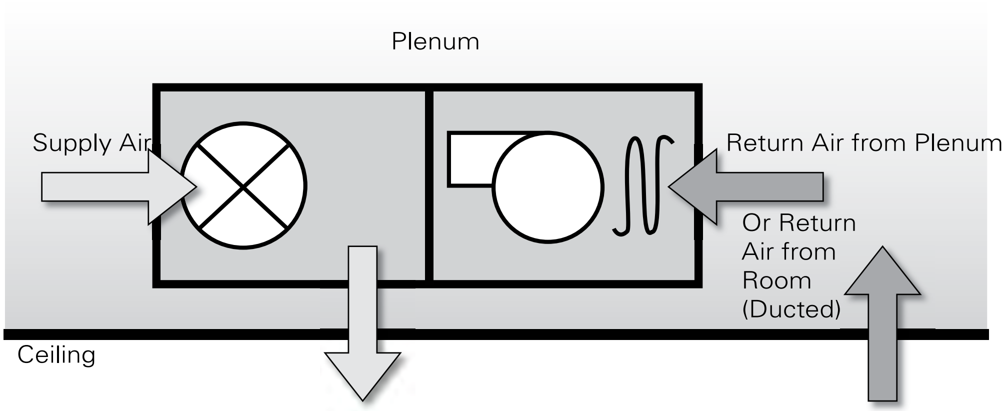
X_s = average outdoor air fraction (at the primary air handler, the fraction of outdoor air intake flow in the system primary airflow): $X_s = V_{ou}/V_{ps}$

Z_d = discharge outdoor air fraction (the outdoor air fraction required in air discharged to the zone): $Z_d = V_{oz}/V_{dz}$—Note: For VAV systems, V_{dz} is the minimum expected discharge airflow for design purposes.

Explanation of applications and use of the equation $E_{vz} = (F_a + X_s \cdot F_b - Z_d \cdot F_c)/F_a$ for all of the possible combinations of secondary recirculation systems is beyond the scope of this Guide. The reader is referred to ASHRAE for additional resources, including the *62.1 User's Manual* (ASHRAE 2007b), archives of the *ASHRAE Journal* (Stanke 2005b), and several courses offered by the ASHRAE Learning Institute (www.ashrae.org/ALI). The types of systems for which this approach needs to be used are listed in the following subsections.

Parallel Fan-Powered Box

The parallel fan-powered box system is a VAV system for cooling. When heat is required, a fan turns on and pulls tempered air from the plenum and/or provides heat from heating strips or coils. Since this system



operates in two modes, there will be at least two calculations required for system efficiency and a potential for multiple operating conditions. (See Figure 7.4-B.)

Figure 7.4-B Parallel Fan-Powered Box

Series Fan-Powered Box

The series fan-powered box system is a VAV system for cooling that also recirculates air from the room (ducted return) or the plenum (plenum return). This system provides better mixing in the zone than not having a fan and may improve comfort. The box may or may not provide heating. If this system operates in two modes, there will be at least two calculations required for system efficiency. (See Figure 7.4-C.)

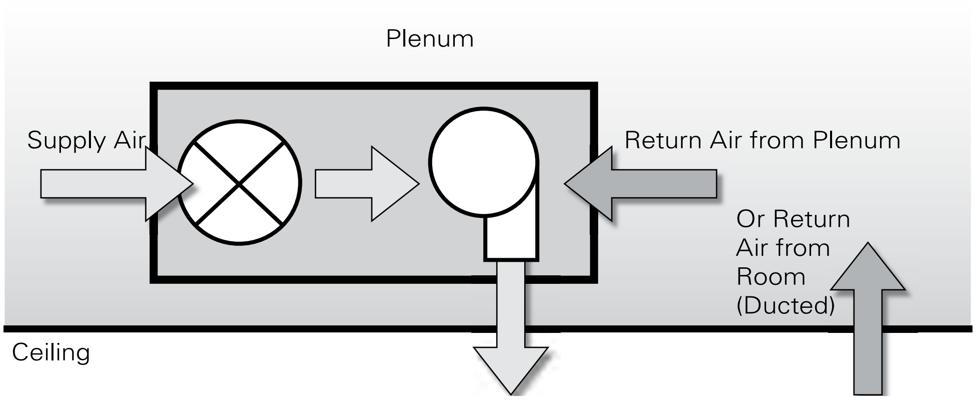


Figure 7.4-C Series Fan-Powered Box

Ducted vs. Plenum Return

Depending on the configuration, a ducted return may perform as a "single supply" system. There are several important IAQ advantages to ducted returns with regard to building pressurization and other concerns, but the plenum return may have a ventilation system efficiency advantage.

Transfer Fan

In some cases a fan may be used to transfer air from an adjacent (or nearby) space to increase the airflow in a room such as a conference room. This can improve system ventilation efficiency depending on the quality of the air from the transfer space. (See Figure 7.4-D.)

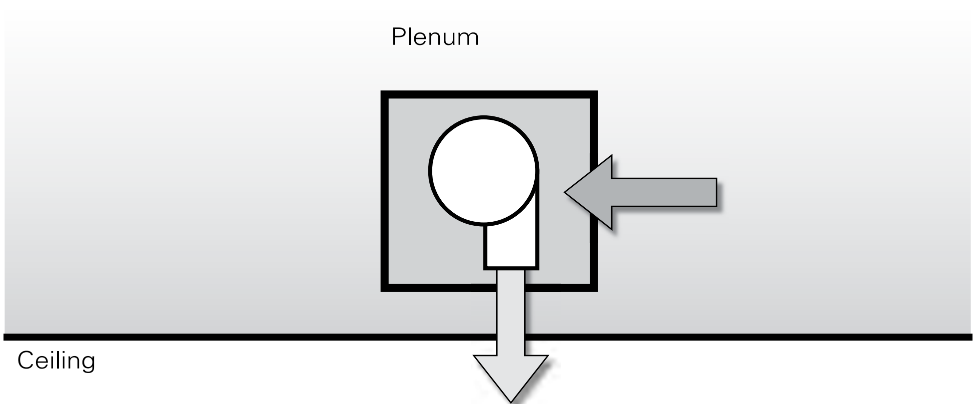


Figure 7.4-D Transfer Fan

Other Systems (Less Commonly Used)

Changeover Bypass VAV

Changeover bypass VAV is a special case where the primary fan airflow is constant and the zone airflow varies.

Dual Duct Dual Fan

As the name implies, there are two ducts and two primary fans in a dual duct dual fan system—one for cooling and one for heating. Outdoor air is usually provided through the cooling system. In this case the primary heating fan recirculates some unused outdoor air, improving the system efficiency. Temperature is controlled in the zone by mixing air from the two ducts to provide the temperature needed to offset the heating or cooling load.

Induction Unit

An induction unit system uses high-pressure primary air to "induce" a secondary airflow in the room across heating or cooling coils. There are many different designs and one should reference manufacturers' literature for unit performance data.

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Strategy 7.5

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

Introduction

The three fundamental methods of controlling indoor air pollution are source control, ventilation, and air cleaning (including filtration). In one form or another, most of the other Strategies in this Guide address source control and ventilation strategies (e.g., controlling sources inside and outside the building, moisture control , pest control, HVAC systems and outdoor air ventilation, exhaust and pressurization strategies, etc). This Strategy addresses particle filtration and air cleaning. Filtration and gas-phase air cleaning (FAC) strategies are important because they can provide means of removing contaminants that other strategies are either unable to control or do not control as effectively or efficiently. In this way, filtration and air cleaning can help reduce occupant exposure to a variety of contaminants and thus improve occupant health, comfort, and productivity.

This discussion provides in a more complete understanding of filtration and air cleaning equipment evaluation, selection, and application processes than is currently available. It is intended to provide the designer with a basic working understanding of extraction efficiency, testing methods, equipment selection, life-cycle costing, and application of filtration and air cleaning. However, it is not intended to inform the reader about the fundamentals of filtration and gaseous air cleaning (such as the mechanics, physics, and chemistry of particle arrestance and molecular adsorption), as these subjects are well covered in ASHRAE Handbook chapters (see Chapters 11 and 12 in *ASHRAE Handbook—Fundamentals* [2009], Chapter 24 in *ASHRAE Handbook—HVAC Systems and Equipment* [2008a], and Chapter 45 in *ASHRAE Handbook—HVAC Applications* [2007a]). The *NAFA Guide to Air Filtration* (NAFA 2006) also serves as an excellent resource for this fundamental information.

FAC Equipment Selection and Specification Guidance

Table 7.5-A provides broad general selection guidance that combines and balances the project need or strategy with appropriate extraction efficiency requirements and limitations, contaminants of concern (CoC), and life-cycle cost/value. The design strategies in the table have been assigned numbers to easily refer to them in later sections of this Strategy. The terms and acronyms employed are briefly described in the table footnote and discussed more fully in later detailed discussions of each of the strategies. Since the general performance characteristics of FAC equipment are incremental as efficiency is increased, the recommendations provide a range of options that give the designer flexibility of selection dependent upon the constraints of space, pressure drop, and cost. Thus, the resulting outcomes can be attained incrementally without the necessity for “cleanroom” performance levels when they are unwarranted. Table 7.5-A denotes suggested efficiencies that span from “good”—at the lower end of the spectrum, which represents enhanced IAQ performance over code minimum levels—to “best.” The latter represents substantially improved performance, benefit, and/or value for that specific strategy over normal code minimum levels.

The reader is cautioned that these general selection recommendations are based on efficiency consideration only and that there is wide variation within efficiency classes as to pressure drop and flow rates, dust holding capacity and life cycle, and overall value. This is why these elements (especially pressure drop) are not included in this generalized guidance. These elements are, however, discussed in more detail in the following sections of this Strategy.

Strategy 7.5

Table 7.5-A General Selection Guidance Based on Efficiency

Design Strategy	Problem or Situation	Recommendation/ Solution Range	Outcome/Benefit
7.5.1	Keep heat exchange and distribution system surfaces cleaner	Apply MERV 8–13	Reduces excessive coil fouling; maintains heat exchange efficiency; reduces energy losses; lowers cleaning and maintenance costs; maintains system performance; lessens opportunities for mold growth by reducing nutrient and moisture retention
7.5.2	Keep conditioned space cleaner	Apply MERV 8–13	Reduces nuisance dust; lowers housekeeping costs
7.5.3	Control viable and/or pathogenic particles	Apply MERV 14–16	Lowers occupant exposure to airborne pathogens; decreases negative health effects; decreases absenteeism (Milam 1992) and related productivity costs
7.5.4	Treat excessively polluted outdoor air	Apply MERV 11–14 Apply Gas Phase ME	Ensures acceptability when outdoor air is non-compliant; lowers occupant exposure to external sources of particles, odors, and irritants; lowers risk of cross-contamination from building exhausts; reduces undesirable products of chemical reaction between ozone and indoor chemicals
7.5.5	Control specific CoC, including those associated with criminal intent or accident	Apply MERV 13–16 Apply HE-HEGA	Reduces risk of accidental spills or criminal incidents of particulate or gas-phase contamination that are detrimental to processes, products, people, or their related activities
7.5.6	Augment outdoor air ventilation rates using the IAQ Procedure from ASHRAE Standard 62.1 (ASHRAE 2007b)	Apply MERV 11–13 Apply ME-HE	Can reduce excessive latent load from outdoor air in certain regions; reduces contaminant load from polluted outdoor air; can result in reduced HVAC capacity and related capital cost, energy consumption, and operating cost

Notes:
MERV = Minimum Efficiency Reporting Value
HEPA = high-efficiency particulate air
ME = medium-efficiency range partial bypass gas-phase air cleaner
HE = high-efficiency solid bed gas-phase air cleaner
HEGA = high-efficiency gas deep bed adsorber

A full range of particulate and gas-phase filters is available from a wide selection of manufacturers (see the sections in this Strategy titled "Selection Guidance: Particulate Filters" and "Selection Guidance: Gas-Phase Air Cleaners" for more detailed descriptions of the various filter types). The filters vary widely in frame methodology and quality, seal mechanism, filter/sorption media type, cartridge depth and size, loading characteristics and capacity, surface area configuration, airflow and pressure drop, and cost. The efficiency or removal performance represents only one of these final selection criteria. Of these factors, pressure drop is the most important cost factor because energy usage dominates the operating life-cycle costs of all FAC equipment.

Pressure drop characteristics can vary widely within a specific efficiency class as well as over the life cycle of the FAC cartridge, which is why this factor is not included in the general guidance in Table 7.5-A. Recommendations for minimizing pressure drop as well as discussion of other factors that influence the overall performance and total value of the FAC system are included in the following sections and need to be included in the FAC selection and specification process.

The application of filtration and air cleaning is a balance of extraction requirements with the physical/mechanical limitations of the air-handling system, the characteristics of the CoC, and the features of the FAC equipment. Generally, the higher the efficiency requirements, the greater will be the space requirements and energy, operating, and maintenance cost requirements of the FAC system. Because of the latter constraints, the final selection of equipment needs to go beyond removal efficiency to include capacity and life cycle, maintenance requirements, and life-long pressure drop factors (see the section in this Strategy titled "Maximizing the Value and Performance of FAC"). Because of these factors, life-cycle cost, including energy requirements, rather than just first cost need to drive the selection. In the case of multiple strategies, the more stringent selection will prevail and satisfy the lesser requirements.

Selection Guidance: Particulate Filters

In filter selection guidance, the Minimum Efficiency Reporting Value (MERV) designation is employed to describe the efficiency level of the filter. MERV is derived from *ANSI/ASHRAE Standard 52.2, Method of Testing General Ventilation Air-Cleaning Devices for Removal Efficiency by Particle Size* (ASHRAE 2007c), which is discussed in detail in this Strategy in the section "Performance Evaluation and Consideration of FAC Alternatives." See Table 7.5-B for MERV designations.

In the following paragraphs, the design strategy numbers listed correspond to the numbers assigned to the strategies in Table 7.5-A.

Table 7.5-B Comparison of MERV Data, Filter Type, and Prior Designations

MERV Level	Dust Spot %	Typical Particulate Filter Type	% 0.3–1 μm	% 1–3 μm	% 3–10 μm
1	N/A	Low-efficiency fiberglass and synthetic media disposable panels, cleanable filters, and electrostatic charged media panels	Too low efficiency to be applicable to ASHRAE Standard 52.2 (ASHRAE 2007) determination		
2	N/A				
3	N/A				
4	N/A				
5	N/A	Pleated filters, cartridge/cube filters, and disposable multi-density synthetic link panels			20–35
6*	N/A				36–50
7	25%–30%				50–70
8	30%–35%				>70
9	35%–40%	Enhanced media pleated filters, bag filters of either fiberglass or synthetic media, rigid box filters using lofted or paper media		>50	>85
10	50%–55%			50–65	>85
11	60%–65%			65–85	>85
12	70%–75%			>80	>90
13	80%–85%	Bag filters, rigid box filters, minipleat cartridge filters	>75	>90	>90
14	90%–95%		75–85	>90	>90
15	>95%		85–95	>90	>90
16	98%		>95	>95	>95
The following classes are determined by a different methodology than that of ASHRAE Standard 52.2 (ASHRAE 2007).					
NA	N/A	HEPA/ULPA filters evaluated using IEST Recommended Practice CC001.3 (IEST 1993). Types A through D yield efficiencies at 0.3 mm and Type F at 0.1 mm	99.97% IEST Type A		
NA	N/A		99.99% IEST Type C		
NA	N/A		99.999% IEST Type D		
NA	N/A		>99.999% IEST Type F		

* MERV 6 is prescribed by ASHRAE Standard 62-2001 (ASHRAE 2001) for minimum protection of HVAC systems.

Particulate Filter Design Strategies 7.5.1 and 7.5.2—MERV 8–13. These strategies are important because they address advanced air quality application to a broad application segment of building indoor environments. Both anecdotal and applied field research (Burroughs 2004, 2005) indicate that the minimum filtration requirement of *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007b), MERV 6, is a substantial improvement over the previously used fiberglass disposable panel filters. However, this same research indicates that the MERV 6 filter does not keep coils or systems sufficiently clean to avoid downstream accumulation and related coil and duct cleaning and maintenance. It also verifies that the degree of visual system cleanliness increases and downstream accumulation decreases as the MERV efficiency increases. The reason that the MERV 6 filter is not adequate comes mainly from its inability to control the fine particulate matter contained in polluted outdoor air that accumulates in the distribution system pathway and components.

Figure 7.5-B illustrates the difference between mass and particle counts. Although the larger particles in outdoor air are the major segment of the airborne mass, the smaller submicron-sized particles dominate, consisting of over 98% of the count. These superfine particles are very small and difficult to filter out and are the cause of the black soot-like smudging accumulation on wet surfaces and air pathway surfaces.

Field research (Burroughs 2004) has found that the best selection for these target areas is MERV 13 extended media filters, as illustrated in Figure 7.5-C, applied in gasketed front-loading filter retainers. This efficiency selection provides a good balance of efficiency, capacity, pressure drop, and both first and operating costs. In higher MERV filters, the efficiency increases incrementally but with disproportionately more increase in pressure drop. When space or pressure drop limits prevail and restrict this selection, the lower MERV levels of 8–12 provide good improvement and are available in 2 and 4 in. (50 and 100 mm) filters that can be accommodated by unitary equipment having integral filter racks. Though it has higher pressure drops, the MERV 13 filter is now also available in 2 and 4 in. pleated versions. All these are substantial improvements over the minimal MERV 6 filter with only marginal increases in cost and pressure drop.

Cleaner HVAC systems are critical to sustaining good air quality because particulate accumulation results in odor or volatile organic compound (VOC) retention, nutrient buildup, and moisture retention that enables microbial growth in the air handler and distribution system. This same MERV 13 efficiency level provides adequate extraction to generally improve space cleanliness, and the enhanced extraction efficiency

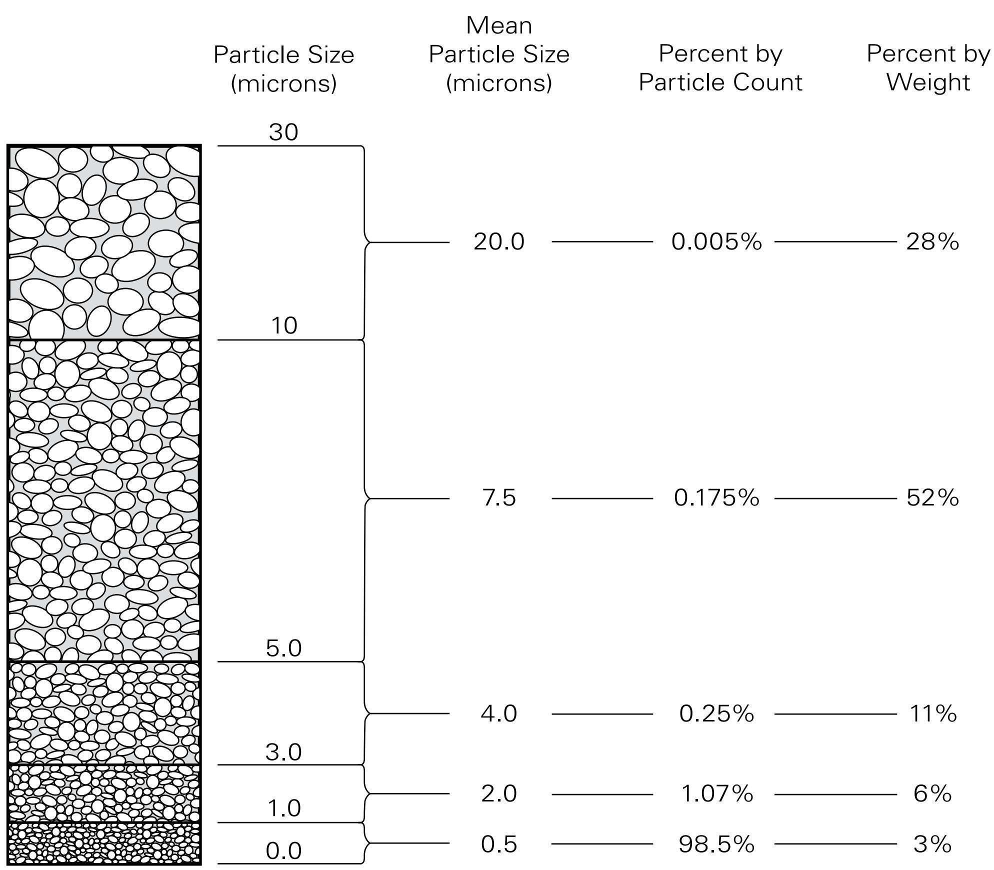


Figure 7.5-B Particle Size Distribution in the Atmosphere
Adapted from NAFA (2006), Figure 1.4.

enables the designer to consider the appropriateness of the IAQ Procedure (IAQP) from ASHRAE Standard 62.1 (ASHRAE 2007b) (see Strategy 8.5 – Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate for more information).

Particulate Filter Design Strategies 7.5.3—MERV 13–16. Because of their relatively small size (0.3 to 1 μm) and higher related exposure risk, the control of viable, pathogenic, toxic, or respirable particles requires higher efficiency control, greater than MERV 13. Dependent upon virulence or toxicity, concentration, and dosage limitations, MERV 14 is normally applied. However, up to and beyond MERV 16 may be required, though this level is not normally applied except in health-care and high-risk settings. The MERV 15 and 16 levels offer very high efficiencies at the submicron size range and operate with acceptable velocities and pressure drops for commercial equipment, yet they impose higher first cost, higher pressure drops, and higher operating costs. These result in higher life-cycle costs and may lead to diminishing return of value in particle reduction in the space, unless ultra-high reduction is required by the risks involved. Therefore, the design team needs to consider both the appropriate particle size and required extraction efficiencies as they select the higher-efficiency filter for optimized life cycle and value. (See Figure 7.5-D.)

When installing the higher MERV level filters, seals and gasketing as well as special retainer systems are extremely critical to successful performance and fulfillment of the MERV efficiency expectation. However, this design selection area is highly particle-size dependent, and the final MERV selection needs to be driven by the target particle size of concern and the reduction targets required.

The designer needs to also be aware that the outdoor air is a primary source of smaller respirable-sized particles (less than 2.5 μm), primarily because of condensation nuclei from internal combustion engines, chemical reactions, or phase changes (evaporation of aerosols). The range of commercial filters through MERV 16 will accommodate most accidental and naturally occurring contaminants. However, the heightened risk of criminal- or terrorist-induced threats may require greater than MERV 16 or high-efficiency particulate air (HEPA) filtration.

Originally, *HEPA* was an acronym for *high-efficiency particulate arrestor*, which was created as a generic noun to describe the cartridge that was developed as part of the Manhattan Project and patented and marketed under the registered trade name Absolute. It was defined as having 99.97% efficiency of 0.3 micron-sized particles (comparable to 0.03% penetration) and was created for ultimate life-safety protection in atmospheres contaminated with radioactive condensation nuclei. More recently, *HEPA* has been altered

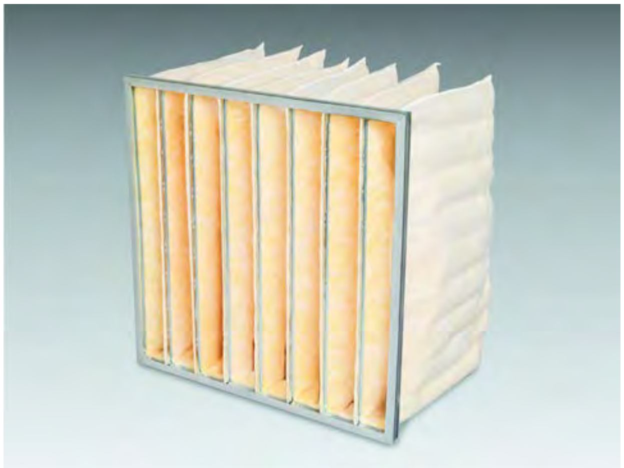


Figure 7.5-C Typical Extended Media Pocket Filter of MERV 13 Efficiency
Photograph courtesy of The Filtration Group and Filtrair.

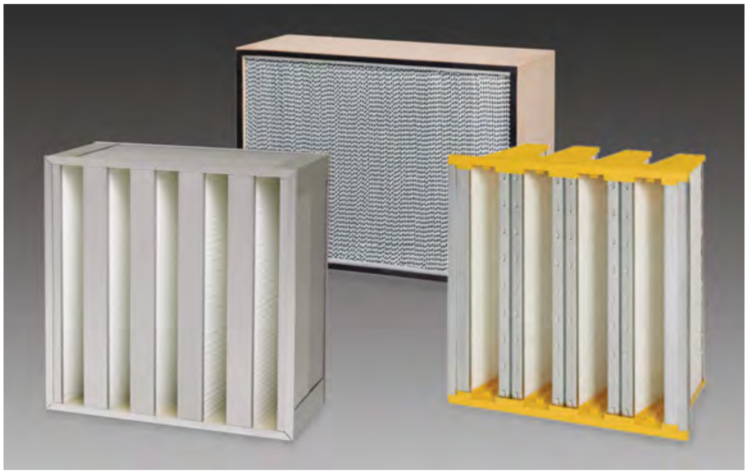


Figure 7.5-D Typical High-Capacity HEPA Cartridges
Photograph courtesy of The Filtration Group and Filtrair.

to use "air" instead of "arrestor" and has become a modifier of "filter," but it still retains its original efficiency level. Phrases such as "HEPA-like" are misstatements and misuses of the describer. *ULPA*, which stands for ultra low penetration air filter, is a recent coinage used to describe filters having even higher efficiencies than HEPA filters, up to 99.999% at even smaller sizes down to 0.1 µm. When progressing into the HEPA levels of filtration, an entirely different class of mechanical and space requirements are imposed, including reduced airflow (250 fpm [1.3 m/s] approach velocity), increased pressure drop (up to 3 in. w.g. [750 Pa] at termination change point), increased seal requirement, increased monitoring, and increased footprint space for access and service. These equate to increased first cost, increased service cost, and increased energy requirements.

When filters at the higher end of the MERV spectrum are applied, and since the investment in filtration and related operating capacity is already funded, the optimal conditions for using the IAQP need to be examined and considered because of the potential payback in energy savings (ASHRAE 2007b). (See Table 8.5-C in Strategy 8.5 – Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate for information on when to apply the IAQP.)

Caution: At higher MERV levels, both pressure drop and life cycle can vary dramatically within a MERV class. This variance between filters depends upon surface area, media selection, airflow rating, and filter configuration. The designer needs to carefully compare, select, and specify the preferable cartridge configuration in addition to the desired MERV level.

Selection Guidance: Gas-Phase Air Cleaners

This section provides guidance for gas-phase air cleaner selection. In the following paragraphs, the design strategy numbers listed correspond to the numbers assigned to the strategies in Table 7.5-A.

Gas-Phase Air Cleaner Design Strategies 7.5.4 and 7.5.6. These general strategies can be fulfilled by a medium-efficiency (ME) range of gas-phase filters (see Figure 7.5-E). Dependent upon the air cleaner selection, MERV particulate control requirements may also be fulfilled in a single combination filter stage using a common retainer. This type of gas-phase cleaner combines the function of sorption and particulate filtration. The sorption media is imbedded within a fibrous matrix that retains the sorption media particles without binders or other techniques that negate sorption capacity. Because of the fabric component, filter modules can exhibit MERV 6–12 particulate filtration capabilities, and some gaseous filters carry MERV testing designations. Most gas-phase air cleaners in this efficiency range (50%–80%) include pleated chemical media filters from 1 to 4 in. in depth and solid bed flat panels and V-cells with bed depth of less than 1 in. or that are partially filled. Filters with greater depth (e.g., 12 in. in depth) require appropriate tracking, access depth, and/or special filter retainer banks or side-load units similar to extended media particulate cartridges.

There are various filtration sorption pelletized media options available in 12 in. filters, such as either carbon or alumina/potassium permanganate ($KMnO_4$) or both. These options enable the designer to respond to varying requirements. However, ME filters are normally applied for light odor loads and, in such settings, the ME-type cartridge is serviced and changed out on a timed routine. This is because the limited sorbent content combined with the particulate accumulation yields limited life cycle, usually three to four months in a typical office space. This life-cycle is consistent with the change cycle of the particulate control component.

One particularly useful application of ME gas-phase cartridges is the treatment of outdoor air contaminated with ozone in nonattainment areas. The change cycle of these filters is difficult to predict or measure because carbon does not have a good life expended analysis protocol. Thus, the change-out regime needs to follow experience and/or the manufacturer's recommendations. If the media contains a reagent, such as $KMnO_4$, precise "life remaining" can be determined by commercial laboratories or the manufacturer to determine the change cycle.

Gas-Phase Air Cleaner Design Strategies 7.5.5 and 7.5.6—HE-HEGA. When dealing with critical gas-phase CoC, the designer needs to be cognizant of the full nature of the contaminant, including identity and chemical properties of the CoC, concentration and source generation rate, and targeted control attainment levels of the chemical CoC. Control at this molecular level is relatively high-tech and requires knowledgeable selection of the appropriate sorbent, the sorbent air cleaner cartridge, and the retainer system. These high-efficiency (HE) air cleaner systems require higher levels of pressure drop capacity, space for installation and service, accommodation for weight, and rigorous maintenance attention. Because of varying operating conditions and concentration exposures, most sorbent air cleaners are unpredictable in their life cycles. Thus, they need to be monitored rigorously using either gas-phase monitoring equipment, testing coupons, or sorbent sampling for factory analysis to determine precise change cycle. (See Figure 7.5-F.)

The HE air cleaner typically employs deep pleats of media-loaded nonwoven fiber beds (6–12 in. or deeper) or solid media beds or trays varying from 1–3 in. in depth that are filled with pelletized sorption media. These containers are then configured into an extended-surface V-cell that both lowers the pressure drop and controls the velocity of the air through the media bed.

Much higher single-pass efficiencies and longer service life are attained by these air cleaners as compared to the ME lighter duty versions. However, some of the deeper 12 in. pleat versions of the ME air cleaners can achieve efficiencies similar to the 1 and 2 in. V-cells and have been reported to last 6–12 months to 2 years depending on the application. The higher performance level is achieved because of the total weight of sorbent content as well as the longer dwell time that is engineered into the cartridge. The designer can also select the appropriate sorption media dependent upon the requirements and properties of the CoC. Specific sorbents can be selected for specific chemical control properties, such as carbon for high-molecular-weight VOCs; alumina/ $KMnO_4$ for acid gases, formaldehyde, and other reactive lower-molecular-weight compounds; zeolite molecular sieves for ammonia; and treated carbons for specialized needs such as the war gases and toxic industrial chemicals. Physical blends of sorbent pellets can also be employed for general mixed airstreams, such as occupancy odors.

The high-efficiency gas adsorber (HEGA; historically coined such by federal agencies) gas-phase filter cartridge is designed to maximize single-pass efficiency and minimize breakthrough, thus providing optimal control of hazardous chemicals with life-threatening risks. The unit employs deeper media beds, longer

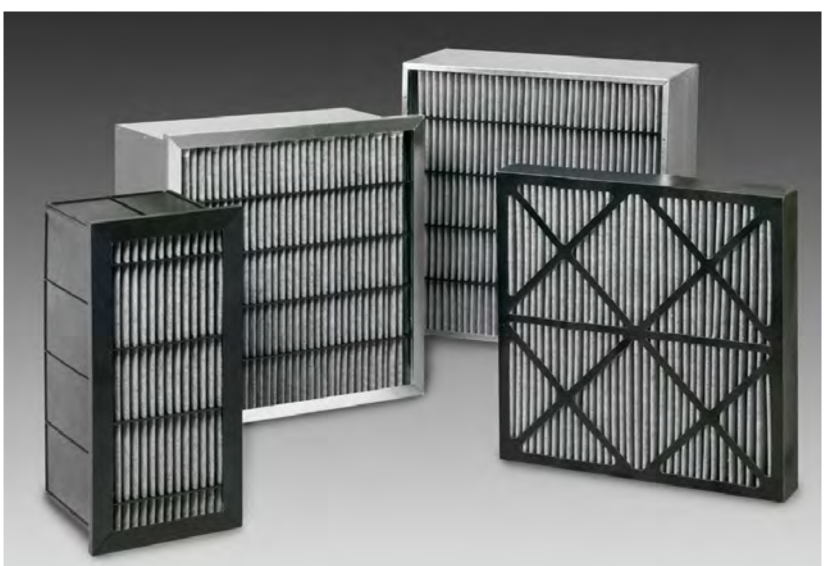


Figure 7.5-E Typical ME Lighter-Duty Gas-Phase Cartridges
Photograph courtesy of The Filtration Group and Filtrair.

Figure 7.5-F Typical High-Capacity HEGA Cartridge
Photograph courtesy of CamFil Farr Company.

dwell times, greater media weight content, deeper pleats, and specialized reagent treated media selected to control specific known toxic gases. Multiple-pass systems using lighter-duty filters and/or multiple media selections may also attain similar heightened performance levels. These air cleaners are applied in commercial buildings that are considered to be vulnerable to criminal/terrorist acts of war or in commercial spaces where highly toxic airborne contaminants are health threats to occupants. This area of application is a specialized technical art form and requires the designer to seek experience and dedicated expertise to properly select, design, and apply HEGA systems.

The service life of gas-phase air cleaners is highly dependent upon contaminant concentration and operating exposure time. Unlike that of particulate filters, gas-phase air cleaner life cycle cannot be monitored in situ or in real time, unless by specialized chemical sensing equipment that is not currently practical for most commercial applications. However, if the CoC are odorous or irritating, then recurring occupant complaints provide an indicator of service life termination. Test coupons can be installed concurrently in the airstream and can provide useful guidance when analyzed by the equipment manufacturer. In the case of pelletized media, especially alumina/$KMnO_4$, small bulk samples can be periodically withdrawn for laboratory analysis by the manufacturer to provide indication of remaining service life. Remaining service life can also be estimated by the manufacturer from tests on bulk samples of nonwoven media from a pleated filter. This is most practical when considering a large bank of filters.

Air Capture and Seals

A number of factors influence the performance, efficiency, and overall effectiveness of a FAC system. The most significant and often overwhelming factor is air bypass. For the air filtration or extraction system to perform, the air must pass through the filter media. Thus, the first and most important step in attaining properly filtered air is control of air capture and bypass.

Bypass can occur in multiple ways:

- Outdoor air can infiltrate into the conditioned space through the building envelope because of pressure imbalance and envelope flaws, thus bypassing the entire air-handling system. This is also an issue regarding moisture control and is discussed more fully in Strategy 2.3 – Maintain Proper Building Pressurization. Air can bypass the filter section in the air handler because of openings in the air-handling system housings or flawed, inadequate, or failed seals and gaskets in the doors, access panels, and fabrication seams.
- Air may bypass the filter cartridge because of flawed seals within and between the retainers or the tracking system.
- Air can bypass the filter around the frame of the filter because of a lack of or inadequate or failed gasketing and seals between filters, between the filter and the retainer, between the filter and the access door, or between the filter and the access tracking.

Recent research (field research, modeling, and in-duct laboratory measurement) have demonstrated that even small visible gaps on a single plane of the filter can result in significant loss of efficiency. In field evaluation, Burroughs (2006) demonstrated that adding 1/8 in. neoprene gasketing between the mating vertical header frames of MERV 13 bag filters mounted in side-load tracking increased measured efficiency by 17% at 1 μm particle size (see Table 7.5-C). Ward and Siegel (2005) modeled the bypass phenomenon based on the crack infiltration formula in *ASHRAE Handbook—Fundamentals* (2009). In controlled laboratory research, Chojinowski et al. (2009) demonstrated similar impact of bypass measured in a ASHRAE Standard 52.2 test rig (ASHRAE 2007c). This amount of bypass (see Figure 7.5-G) can equate to the effective loss of two to three MERV levels of efficiency.

Table 7.5-C Efficiency Increase Results from Intervention Evaluation Applying 1/8 in. Neoprene Gasket Tape on Vertical Mating Surfaces of MERV 13 Frames (Ward and Siegel 2005)

Particle Count Comparison	Particle Size Band		
	0.3 μm	0.5 μm	1 μm
Count prior to intervention	1177633	26862	2347
Count subsequent to gasketing	1000824	21637	1941
Average increase in efficiency	15.0%	19.5%	17.3%

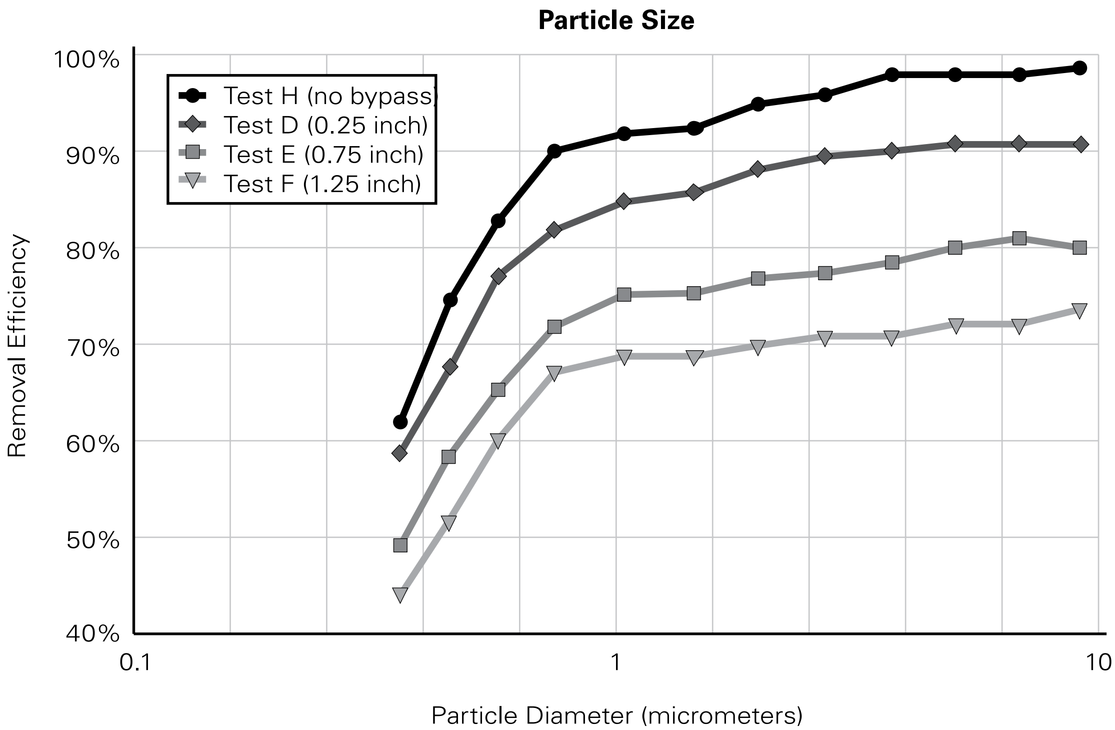


Figure 7.5-G Reduction of Efficiency at Various Gap Dimensions—Laboratory In-Duct Research Performed by University of Illinois–Chicago
Adapted from Kosar (2007), Graph 5.

Thus, to optimize the performance of any enhanced FAC system, the following guidance is recommended.

- Properly balance the building to avoid unfiltered air infiltrating into the conditioned space; see Strategy 2.3 – Maintain Proper Building Pressurization for more information.
- Apply line-of-sight or light-penetration inspection to avoid visually obvious bypass pathways around the FAC system, around filter frames and retainer systems, and at access doors.
- Seal all mating metal surfaces with caulk or appropriate mastic, including ductwork joints, adjoining frames, and air-handling unit (AHU) seams.
- Gasket the seal planes of filter frames or headers with resilient, nonporous gasketing, such as neoprene foam.
- Gasket all filter frame mating surfaces with resilient, nonporous gasketing, such as neoprene foam. (Suggestion: specify desired gasketing as factory installed on the filter cartridge at the appropriate or desired seal plane.)

Examples of Filter Failures

Figure 7.5-H Fallen Filter with Substantial Visible Gap

This case study highlights examples of filter failures.

The filter shown in Figure 7.5-H, which serves a health-care surgery staff facility, fell because of a poorly sized filter track, resulting in more than 2 in. (50.8 mm) of visible gap. The MERV 14 filter is now behaving as a MERV 8 filter.

The gasketing on the filter access door in Figure 7.5-I has eroded and disappeared. Thus, the door to the filter compartment no longer seals properly.

The corrosion penetration within the air handler shown in Figure 7.5-J allows outdoor air to bypass the filter bank.

Figure 7.5-I Eroded Gasketing on Filter Access Door

Figure 7.5-J Corrosion Penetration within an Air Handler

Photographs courtesy of H.E. Burroughs.

FAC System Location

Figure 7.5-K illustrates the various locations (labeled as Alternatives 1 through 8) that can be employed for a filtration bank. The location alternatives provide the designer with the versatility to locate the filtration function where it best suits the specific needs of the project for performance, access, and life-cycle cost.

Optional locations of the filter bank depend upon the needs and intent of the design strategies, contaminant sources, and space usage. As shown in Figure 7.5-K, the return air (ALT 1) and outdoor air (ALT 2) can be filtered independently allowing for different filter selection; can be combined (ALT 3); can be located upstream with or without prefiltration (ALTs 4 and 4a), downstream of the coil with or without prefiltration (ALTs 5 and 5a), downstream of the blower (ALT 6), or terminal to the distribution system (ALT 7); or can treat the exhaust air to avoid atmospheric pollution or cross-contamination occurrences (ALT 8).

Using the IAQ Procedure

The IAQ Procedure (IAQP) of ASHRAE Standard 62.1 (ASHRAE 2007b) provides the designer an opportunity to provide enhanced IAQ conditions as well as energy savings. When using this performance procedure,

Strategy 7.5

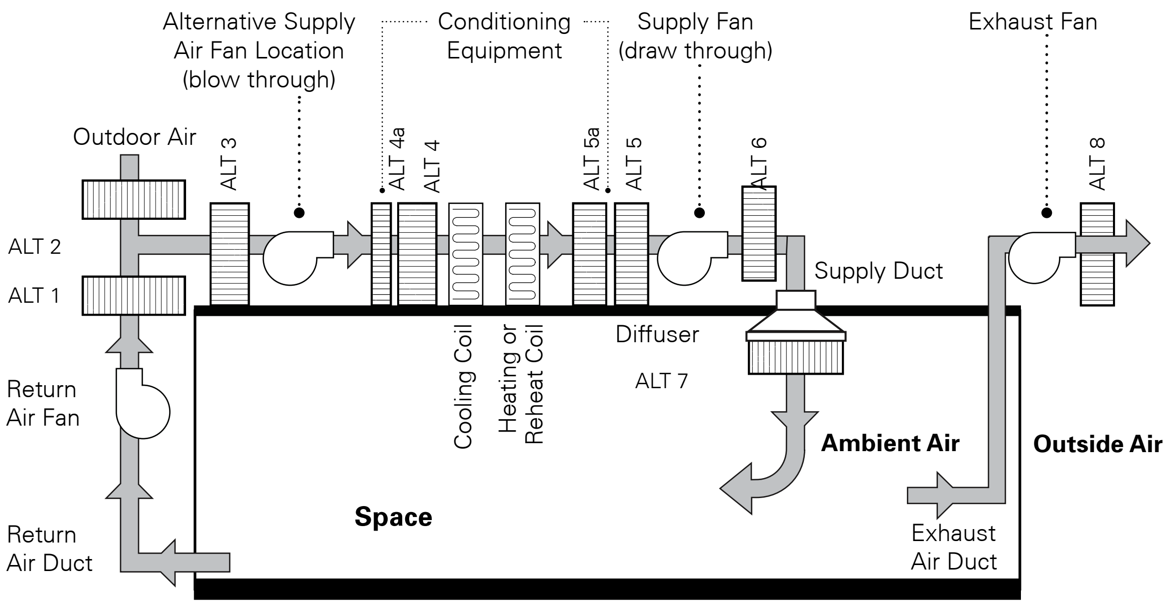


Figure 7.5-K Optional Locations for a Filter Bank
Adapted from NIOSH(2003).

FAC can be employed to achieve contaminant control through contaminant removal (extraction) rather than dilution (ventilation). Both strategies are fractional in the amount of delivered clean air, with FAC being more cost-effective during hot and humid outdoor conditions because of the capacity and operating cost of treating the high latent content of outdoor air. Once the makeup air and pressurization requirements are met, the remaining dilution equivalency may be provided by FAC dependent upon the considerations listed in the bulleted list that follows. Since a significant portion of the HVAC energy demand can be for treating the outdoor air ventilation component, the IAQP this approach can provide the owner with compelling incentive to consider the IAQP pathway.

The IAQP using FAC to fulfill ventilation compliance is best considered when the following conditions are met.

- *When outdoor air is polluted, of low quality, and/or in nonattainment of the U.S. Environmental Protection Agency (EPA) National Ambient Air Quality Standards (NAAQS).* The IAQP can lower the introduction of contaminated outdoor air that is not acceptable for dilution purposes. This is particularly applicable in ozone nonattainment areas.
- *When CoC are known or can be identified and quantifiable, both in outdoor air and return air.* This enables the determination of targets of acceptability and attainment and the selection of appropriate filtration and/or gaseous air-cleaning tactics and equipment, and it helps in choosing the methodology of measuring and monitoring the systems during operation.
- *When the condition of the outdoor ambient air is designated as "hot and humid" or when outdoor air is seasonally hot and humid.* This enables the potential reduction of outdoor latent load, which can also reduce design capacity, first cost, and operating costs.
- *When enhanced filtration is already a design component, which may be because of known contaminant generation or advanced requirements for the conditioned space.* Once the investment is made in filtration that exceeds minimum requirements, the enhancement may be sufficient to satisfy the IAQP requirements and also yield related operating energy savings from ventilation reduction.

- *When the building occupant population density is high and/or widely diverse, requiring large quantities of outdoor ventilation air during relatively short peak occupancy.* This is particularly applicable in public assembly and conference spaces. The FAC thereby avoids the excess capacity that occupancy-driven ventilation rates require when in fact the space is transiently occupied and vacant for a high percentage of operating times.
- *When the economic value of the IAQP in first cost, operating cost, and positive environmental impact warrant and the owner is willing to support the conscientious monitoring and maintenance of the HVAC system to sustain its effectiveness.*

A fuller discussion of the overall requirements and limitations of the IAQP is contained in Strategy 8.5 – Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate.

Though not widely applied in commercial buildings, a number of installations in selected markets that have successfully employed the IAQP since its incorporation into ASHRAE Standard 62-1981 have been reported by Burroughs (2004).

Caution: Most code bodies have not accepted the IAQP in the current version of ASHRAE Standard 62.1 (ASHRAE 2007). Thus, the use of the IAQP requires additional rigor from the designer to provide mass balance calculations or other compliance measures, including air testing, to demonstrate the control of CoC and to attain code variance. Verification of attainment must also be obtained and can be provided by FAC suppliers or IAQ consultants through air testing to demonstrate control. This is an additional first cost to demonstrate attainment; the operation and maintenance of the filtration equipment adds to operational cost as well. However, dependent upon the specific circumstances, the return on investment ratios in energy can far outweigh the cost of filtration and additional engineering rigor. (See also Strategy 8.5 – Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate.)

Design Process Protocol

The application of enhanced FAC is a well-established technology in industrial process control, cleanrooms, health care, pharmaceuticals, and special usage buildings, such as museums and laboratories. However, it has not been widely used in general commercial buildings. Table 7.5-D therefore provides a regime to familiarize the designer to the routine of applying enhanced FAC.

Performance Evaluation and Consideration of FAC Alternatives

Particulate Filter Efficiency Evaluation—MERV

In particulate filtration selection, specific efficiency guidance is based upon the minimum efficiency determination using ASHRAE Standard 52.2 and its related MERV designations. *MERV* stands for *Minimum Efficiency Reporting Value* and is a derivative of the composite efficiency curve, which is the full data product of ASHRAE Standard 52.2 (ASHRAE 2007c).[1]

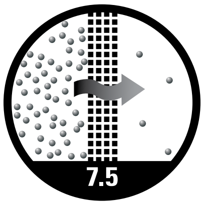
ASHRAE Standard 52.2 with its MERV reporting system provides the designer with comparative efficiency data for filters under laboratory conditions using a controlled test aerosol over their entire loading cycle. The test is run using a full range of 12 particle size fractions from 0.3 to 10 μm that is provided by the test aerosol using potassium chloride (KCl) salt. This size spectrum covers the range of particle sizes that are considered to be important in providing high-quality indoor environmental conditions. Filter efficiency is dependent upon particle size, increasing with larger particles (see Figure 7.5-L for the particle sizes of common airborne agents).

[1] This Method of Test (MOT) was first published in 1999 and has since superseded the archaic Average Atmospheric Dust Spot Test Method of ASHRAE Standard 52.1 (ASHRAE 1992). The 2007 edition incorporates errata but does not change the MOT.

Table 7.5-D Design Process Protocol

Task	Rationale and Explanation of Process
Investigate and characterize ambient (external) CoC	Establishes quality and reliability of outdoor air as a diluent. Identifies external sources of odor, particulates, pollutants, and potential chemical risks for exposure or reaction. Predicts need and timing for outdoor air treatment/avoidance. Guides the selection of control methods and efficiency requirements.
Identify and characterize internal CoC	Provides basis for quality of return air for determining class and reuse options. Predicts needs and levels of air treatment. Contaminant identity guides selection of proper control method—particulate or gas-phase—and efficiency targets.
Select FAC efficiency and methods to control identified CoC	Determines efficiency selection (MERV level) and gas-phase filter type. Establishes targets of contaminant reduction and control.
Perform life-cycle analysis and select filter cartridge within efficiency bracket	Considers life cycle, capacity, durability, labor, space, pressure drop, and factors beyond efficiency and cost in final selection.
Based upon filter selection and ambient air condition, evaluate IAQP as energy management option	When enhanced filtration is specified, the investment in first cost and operating cost is covered. Dependent on outdoor air contamination and seasonal latent load, the IAQP may be indicated for operating cost savings and favorable payback.
Determine location of filter banks	Guides the need and specific treatment requirements of different air sources—outdoor air vs. return air vs. mixed air.
Establish seal, gasketing, and retainer needs	Specify seal and gasket requirements in AHU, distribution, and filter bank. Specify retainer system. Without guidance, this critical element may be neglected by installers.
Select air filter cartridge and framing to maximize life cycle and durability	Provides for maximum life cycle, lowest operating cost, and lowest life-cycle cost. Ensures that the filter frame will sustain the filter media throughout an extended life-cycle period.
Provide appropriate monitoring instrumentation	Filters need to be monitored and serviced based upon a designated pressure drop. Provide for proper sensors, read-out, and linkage to building automation systems.
Specify filtration requirements during construction	Most systems become pre-contaminated during the start-up procedures due to inadequate filtration. Specified FAC equipment needs to be installed upon start-up to protect systems during this high contaminant generation period.
Carefully evaluate the need for prefiltration	With filters of MERV 13 and lower, prefiltration may add cost, labor, and energy demand without compensating added value to final filter life cycle. Consider pre-filtering only MERV 14 or greater filters and only high-efficiency HE-HEGA cartridges unless heavy lint or visible dirt load is expected.
Provide for additional changes of specified filters for post construction	Without this, the change-out may be purchased and supplied on price alone.
Provide for compliance verification of IAQP as component of commissioning	Establishes conformity and attainment of target CoC concentrations through air testing or subjective evaluation of panel of observers. (See "Applying the IAQP" in Strategy 8.5 – Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate.)
Provide the owner with filter selection rationale and specifications along with full documentation, as well as training for operations personnel	Without guidance, maintenance personnel may buy on habit, prior knowledge, or ignorance. Training is especially important for performance and value, especially when filtration is fulfillment of the IAQP.

Filter efficiency changes over the loading cycle, generally increasing as the filter loads with an accumulated layer of particulate matter, although some types of media can lose efficiency during loading. ASHRAE Standard 52.2 provides minimum efficiency data during loading while providing minimum levels at specific particle sizes. These data are combined and reported as the composite efficiency curve that indicates this minimum efficiency for each of 12 size fractions at whatever loading stage that it occurs. Figure 7.5-M illustrates the data from multiple stages of loading with ASHRAE test dust (ASHRAE 2007c), including an initial stage that serves as a conditioning step intended to relieve static charge in media types that rely on this vehicle for efficiency enhancement.



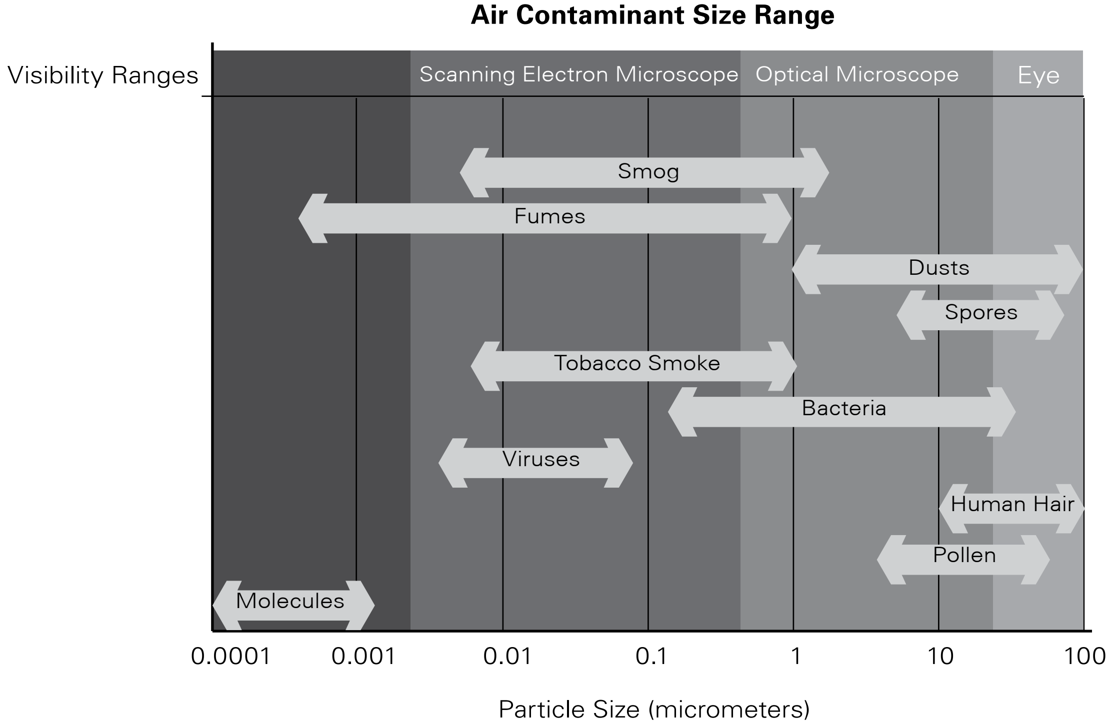


Figure 7.5-L Particle Size Range of Common Airborne Agents
Adapted from NIOSH(2003).

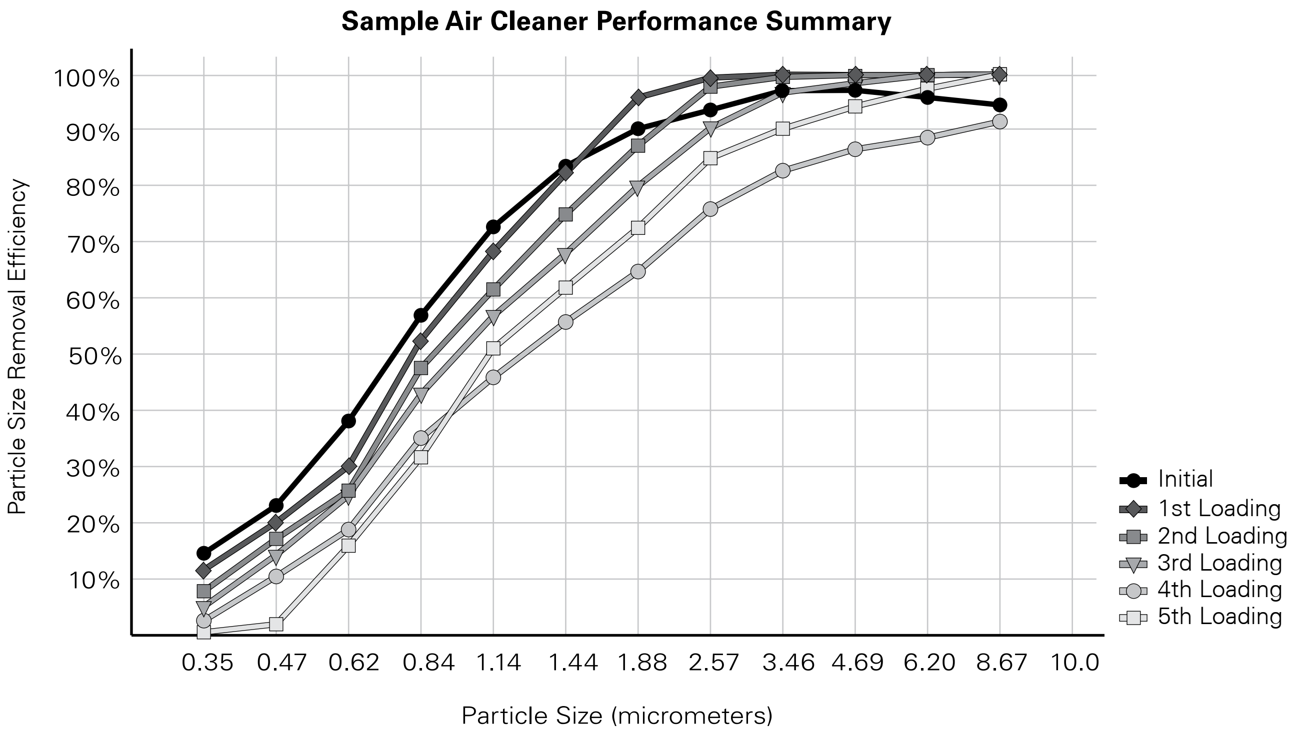


Figure 7.5-M Sample Air Cleaner Performance Summary
Adapted from ASHRAE (2007c), Figure C-2b.

The composite efficiency curve is then integrated into three micron-size bands (E_1 = 0.3 to 1; E_2 = 1.0 to 3.0; E_3 = 3.0 to 10.0) and the efficiencies in each band are averaged and bracketed with minimum thresholds to derive the MERV designation. Because it is simpler, easier, and quicker to interpret than the composite efficiency curve, the MERV can be used for broad screening and category selections.

Nevertheless, the composite efficiency curve needs to be examined by the designer for precise minimum efficiencies at specific size fractions of concern for critical applications, especially in the higher MERV designations when minimum performance is more critical. Upon request, most filter equipment manufacturers will furnish third-party test reports showing the composite efficiency curve and related MERV designations on their products.

For quick screening, increasingly higher MERV levels indicate improved minimums and improved efficiencies at smaller particle sizes (see Table 7.5-B). For example, MERV 6 has a measured efficiency of not less than 35% in the 3.0 to 10 μm size range, and its efficiency against <1 μm particles is not even reported. On the high end, MERV 16 has a measured efficiency of not less than 95% against the 0.3 to 1 μm size range. The MERV designation progresses upward through this efficiency spectrum, allowing the designer to select the desired bracket of efficiency at the smallest particle size of concern.

After several years of experience with the then new method of test (MOT), the Standing Standard Project Committee (SSPC) for ASHRAE Standard 52.2 determined that the conditioning step in the procedure was not sufficiently rigorous to replicate the efficiency drop experienced by certain media, specifically synthetic "electret" media that demonstrates an inherent initial charge. When exposed to ambient pollution constituents, such as ultrafine particles or diesel exhaust, this charge can be relieved, bringing about a dip in the performance curve that is not predicted by the original conditioning step. Research sponsored by SSPC 52.2 has yielded guidance on an enhanced conditioning loading procedure that employs a KCl aerosol replacing the ASHRAE dust previously used. This revised conditioning method is published as Appendix J in the standard, providing an optional alternate conditioning step. Thus, designers and owners desiring the more robust conditioning criterion need to specify the desired MERV designated with "KCl conditioning" and iterate the specific targeted minimum efficiency from the composite efficiency curve and the testing velocity. For example, a specification could read: "MERV 14 (KCl conditioned per Appendix J) 95% @ 1.0 μm @ 0.93m^3/s."

Caution: Efficiencies and related MERV designations are only one aspect of final filter selection. See the section titled "Maximizing the Value and Performance of FAC" in this Strategy for guidance on other performance criteria such as life cycle or pressure drop.

The curves shown in Figure 7.5-N represent an array of composite efficiency curves indicating precise minimum efficiency data points at each of 12 particle sizes. The three bands (E_1 = 0.3 to 1; E_2 = 1.0 to 3.0; E_3 = 3.0 to 10.0) are merged to create the MERV designations represented here by Filter A (MERV 14), Filter B (MERV 11), Filter C (MERV 9), Filter D (MERV 8), and Filter E, which is a disposable panel filter with insufficient efficiency to be qualified by the ASHRAE Standard 52.2 MOT.

Gas-Phase Air Cleaner Efficiency Evaluation

The testing of gas-phase air cleaners is much more of an art form than the particulate testing, since there has been no published industry consensus standard for the testing of gas-phase filters. However, ASHRAE Standard Project Committee 145P was successful in developing a standard MOT that was published in 2008: *ANSI/ASHRAE Standard 145.1, Method of Testing Gaseous Contaminant Air Cleaning Media for Removal Efficiency* (ASHRAE 2008b). This standard MOT covers the testing of sorbent media at laboratory-bench scale. A forthcoming companion standard, ASHRAE Standard 145.2, will establish the efficiency performance of a full-sized cartridge in a laboratory test duct that is adapted from the ASHRAE Standard 52.2 duct. The standard is expected to be published in 2010, but in the meantime there is no

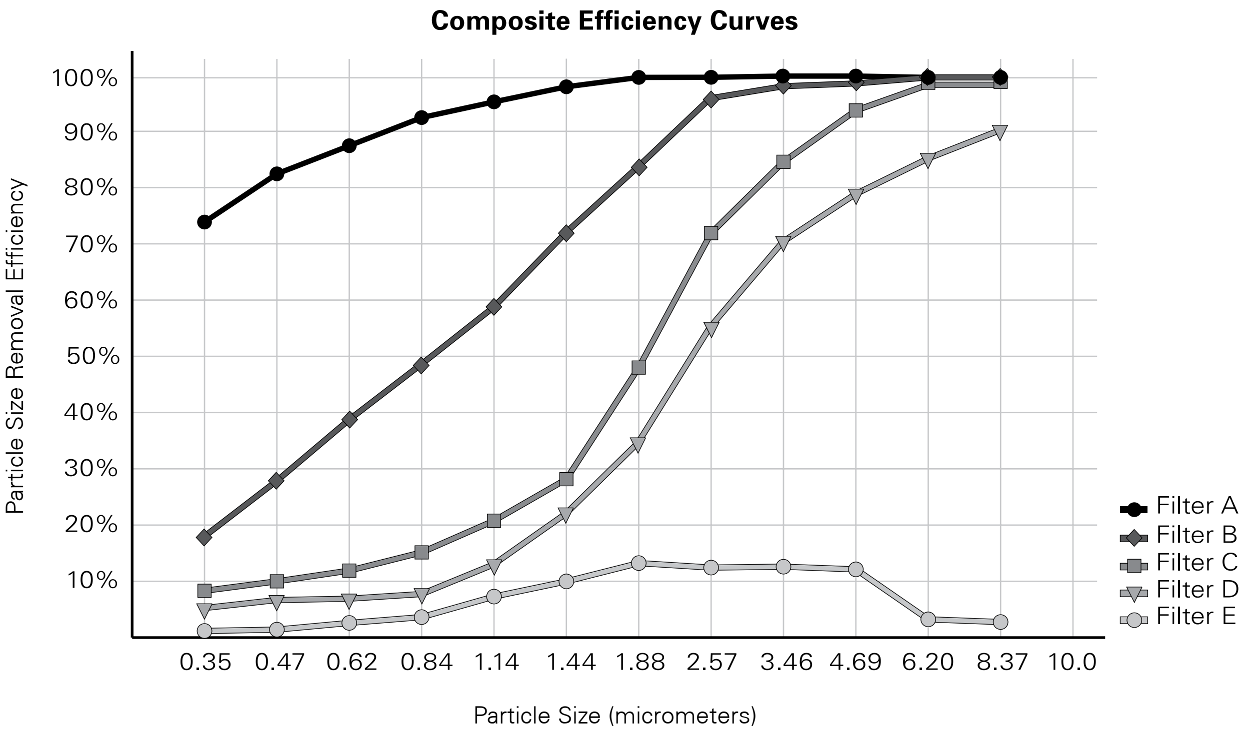


Figure 7.5-N Composite Efficiency Curves
Adapted from ASHRAE (2007c).

industry standard for testing gaseous air cleaner cartridges and no established efficiency labeling system comparable to the MERV system.

Currently, however, performance data is available from manufacturers who have established proprietary test methods that are generally based upon or are similar to the pending ASHRAE Standard 145.2. The efficiency data is generally reported using a variety of metrics: single-pass efficiency for specific contaminants under defined conditions, time to breakthrough, micrograms/mol of contaminant retained vs. unit mass of sorbent, or some combination of these. The performance data can be performed on single gas challenges or may employ blended gases to represent typical chemical profiles of airstreams of concern.

Caution: A number of influences can affect the selection of the appropriate gas-phase air cleaning, because efficiency is influenced by several factors having to do with chemical properties of the sorbent and the CoC as well as the behavior of molecules in the gaseous state.

Maximizing the Value and Performance of FAC

Life-Cycle Analysis

The dominant factor influencing life-cycle cost of filtration has little to do with the first cost of the filter, although this is often the prevailing purchasing criterion. The real cost to the owner is related to *how long it lasts* and *how much it costs to operate*. To illustrate, the entire life-cycle analysis of FAC includes all of the following (these can apply equally to both particulate and gas-phase filtration):

- *Filter Delivered Cost.* The cost of freight is a significant factor in shipping filters because of bulk and rate penalty.

Energy Savings with Acceptable IAQ in Renovated Office Space

Figure 7.5-O High-Rise Office Building
Photograph courtesy of H.E. Burroughs.

The 20-story building shown in Figure 7.5-O is located within a high-rise office complex that is a typical tenant-leased property that contains predominantly state agency departments. It is approximately 35 years old, with its original air-handling equipment. Each floor is an autonomous zone served by a single air handler. Outdoor air is supplied from a common shaft from the roof to each mechanical room, which serves as the return plenum from the ceiling plenum return system. At the beginning of a new lease term, the tenant entity required the landlord's management company to bring the property up to the then-current ASHRAE Standard 62 version, which imposed outdoor air levels beyond the capacity of the existing air handlers. The mechanical rooms are central to the building with no external access and, further, have no extra space to accommodate unit replacements or upgrades. The management team applied the IAQP of ASHRAE Standard 62.1 (ASHRAE 2007b) to replicate the improvement of indoor environmental acceptability through FAC rather than additional ventilation air. This avoided the introduction of additional outdoor air that would have overwhelmed the existing system with hot and humid air during summer cooling conditions. The unit was limited to side-access 2 in. (50.8 mm) filter tracks previously devoted to 2 in. (50.8 mm) disposable fibrous glass prefilters. The upgrade and fulfillment of the IAQP was accomplished through the usage of special ME gas-phase pleated air cleaners. These combination filter cartridges employ a MERV 8 rated particulate filter media imbedded with sorption pellets of $KMnO_4$/alumina that are retained within the strata of filter media. The upgraded filtration system has demonstrated a three-month life cycle that was established by capacity analysis by the filter manufacturer.

Based on site testing in 2007, the system efficiency for reduction of particles was documented at greater than 85% and total volatile organic compound concentration in the space was determined to be no greater than 325 $\mu g/m^3$. The energy savings experienced by the building manager equals $26,409 less the cost of the filtration maintenance of $16,747 for net savings of $9,662 per year over the comparable cost of treating an equivalent amount of outdoor air. The installation of the filtration equipment did not require further capital expenditure beyond the filter cost; thus, the payback was virtually immediate and the tenant has been completely satisfied with the IAQ conditions. Thus, the filtration upgrades not only fulfilled the compliance requirement of ASHRAE Standard 62.1, they also facilitated the completion of a long-term lease opportunity in an older building.

- *Warehousing, Handling, and Storage*. The cubage of filtration requires disproportionate warehouse space.
- *Labor of Installation/Replacement.* Ease of access, gasketing, and location of units influence man-hours expended.
- *Use of Prefilters to Protect Downstream Filters*. Prefilters can extend the life of more expensive final filters of higher efficiency and cost but require additional space, labor, cost, and energy.
- *Life Cycle of Filters.* The change cycle dictates the cost per unit time.
- *Pressure Drop.* This includes initial pressure drop requirement and characteristic pressure drop curve over loading.
- *Disposal of Expended Cartridges.* The disposal of cartridges includes the labor, handling, and freight cost of solid waste disposal; in some cases, the filters are considered hazardous waste.

This entire life-cycle cost analysis is dominated by two factors—the life cycle of the filter and the pressure drop loss during installation. For example, if the life service cycle of the final filter is doubled, then first cost, freight, labor, handling and storage, and disposal costs are halved automatically. In the case of pressure drop, the cost of an additional 0.25 in. w.g. (62 Pa) pressure drop over one year with an air handler running

24/7 with a moderately efficient motor with power costing 6 cents/kWh will be approximately $64/year. If a typical MERV 14 cartridge filter requires 0.6 in. w.g. (150 Pa) initial pressure drop, it is obvious that the energy cost of $153 far exceeds the first cost of any MERV 14 filter. If a minipleat filter with an identical MERV designation operates at 0.25 in. w.g. (62 Pa) less and lasts longer, then the energy savings over its life cycle will pay for the filter regardless of its first cost. (See Table 7.5-E for an illustration of a typical filter operating cost comparison.)

Table 7.5-E Comparison of Identical MERV Filters with Differing Surface Areas/Media Velocities

Filter Description	First Cost	Life Cycle Expectation*	Pressure Drop, in. w.g. (Pa) **	Cost/Year Total Operation***
MERV 8 2 in. pleat	$6.00	3 months	0.25 (62.5)	$88.00
MERV 8 4 in. pleat	$11.00	8 months	0.15 (37.5)	$45.73
MERV 14 cartridge	$115.00	2 years	0.60 (150)	$211.10
MERV 14 minipleat	$145.00	3 years	0.35 (87.5)	$137.93

* Life cycle based on manufacturer's recommendation and field experience.

** Energy calculations based on 24/7 operation, moderate efficiency motor, and $0.6/kWh.

*** Combined annualized filter cost plus energy cost.

How to Maximize the Life Cycle and Performance of FAC

Since life cycle and pressure drop are the critical cost factors in FAC, the designer has the opportunity to design into the building long-term life-cycle operating advantages that will provide the owner with lifetime return on investment. The following recommendations provide insight into the control of life cycle and operating cost.

Examine the Initial and Final Pressure Drop Features of Filter Selections. As illustrated in Table 7.5-E, the same MERV filter in a different configuration can provide a totally different energy demand. Select the filter of the required MERV having the lowest initial pressure drop—regardless of the initial cost of the filter.

Specify High-Quality Cartridge Framing Materials that Are Sturdy and Moisture Resistant. Sturdy, moisture-resistant framing materials are needed because extended media filters have a longer installed life—years as opposed to months. Low-grade pasteboard or light-duty beverage board typically used in less expensive filter frames will not retain integrity, hold dimensions, or properly support the filter media over its potential life cycle. Low-quality framing will degrade before the capacity of the filter media is fully exploited, resulting in shorter life cycles than are possible with quality framing materials.

Understand the Role of Approach or Duct Velocity. When applied to filtration equipment, the rule of squares is not precisely applicable to approach or duct velocity because of turbulence factors at the faces of extended media filters. However, the influence is far greater than a linear relationship—disproportionate gains can be attained by derating filters. Most manufacturers publish pressure drop data over various approach velocities. The role of velocity is illustrated with the rating curves in Figure 7.5-P. When filters are underrated by as little as 20%, the gain can be more than 50% increased life cycle, with reduction of up to one half in operating pressure drop. The figure illustrates that a 20% reduction in approach velocity can drop the initial pressure drop by one half and also increase the operating life cycle by 50% to 200%. To attain this reduction within engineered systems, simply increase the duct cross section by oversizing the filter bank. For example, increase a 4 × 5 configuration to a 5 × 5 configuration. There is no impact on floor space and the reduction in pressure drop is significant. When this is not possible, consider media velocity as discussed in the next paragraph.

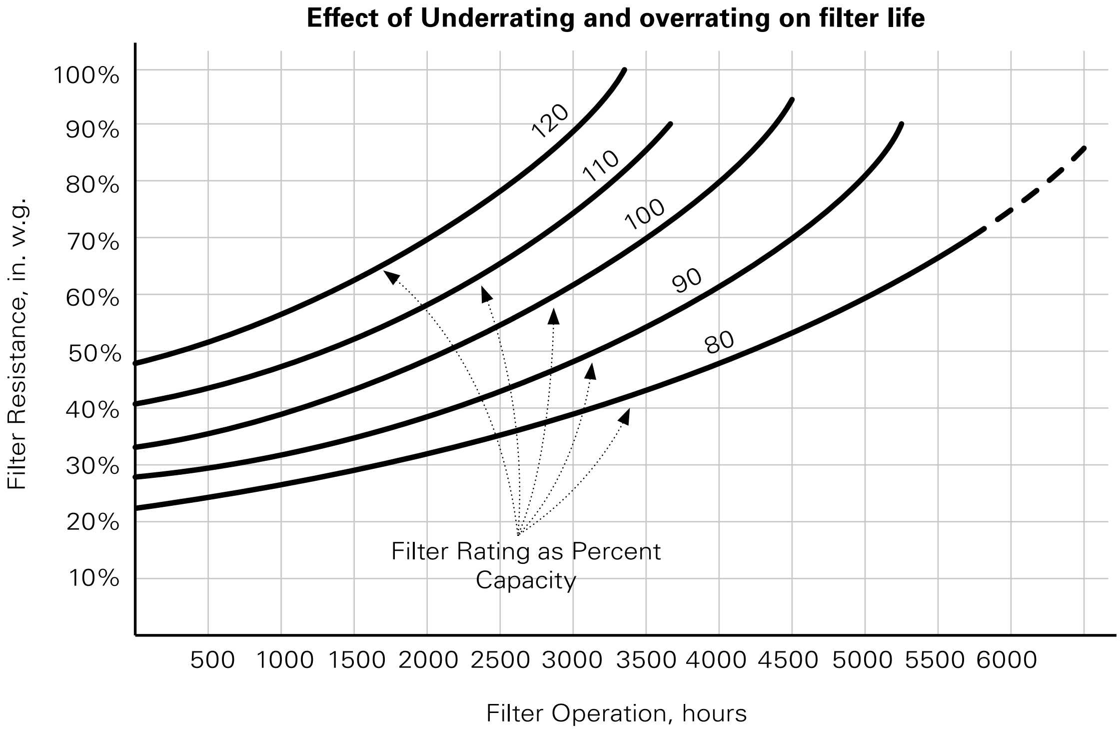


Figure 7.5-P Effect of Underrating and Overrating Filter
Adapted from NAFA (2006), Figure 13.1.

Understand the Role of Media Velocity or Dwell Time within the Media. The rule of squares likewise does not apply precisely with media velocity, but lowering media velocity also yields disproportionate gain in pressure drop. This is done within the filter by selecting filters with higher surface area, attainable with higher pleat count with pleated filters, deeper pleat depth (from 2 to 4 in. for example), deeper pockets in the case of bag filters, and filter configurations such as V-banks that provide enhanced surface area. Within the targeted MERV level, select the filter with the most surface area possible, consistent with the physical constraints of the system, and select equipment that can support installation and access of higher-surface-area FAC. The reduction of velocity also yields increased performance in other ways. Especially in gas-phase filters, the lower media velocity increases single-pass efficiency. In particulate filters, the dirt-holding capacity is enhanced and the life cycle is extended from the standpoint of both dirt holding as well as lower pressure drop and extended time before attaining change points due to diminished airflow.

Table 7.5-E provides analysis comparing two different filter types having the same MERV designation with different initial pressure drops due to surface area variations. When pressure drop and related energy expense is combined with life-cycle expectation, the lower-initial-cost filter is the poor decision from a long-term life-cycle perspective. Within a MERV range, the best-value filter is the one with the most surface area and the lowest pressure drop, regardless of first cost.

Monitor the Pressure Drop Progression of Particulate Filter Systems Using Precise Manometer Equipment. Most modern air-handling equipment is equipped with variable-speed drives (VSDs), meaning that the system operates at part-load condition much of the time. This effectively lowers the pressure drop and enables even greater life-cycle extension if monitored, and change-out is not on an arbitrary time schedule. This also allows the prescription of the change-out point, which ought to be no greater than twice the original rated initial pressure drop. Although this is contrary to most suppliers' literature that denotes the failure point or final test point of the filter, it does represent the most economical range of the filter life cycle.

Strategy 7.5

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Most extended media filters exhibit a relatively flat pressure drop performance curve for most of their life cycle, until the final fraction of loading when most curves abruptly rise and terminate. By changing ahead of this rise, most of the filter life cycle will have been attained at the lowest possible range of energy demand.

Avoid Prefiltration when Applied Solely to Protect Downstream Final Filters. The prefilter adds life-cycle cost and energy demand and seldom proportionately extends the life-cycle value of the final filter, as is illustrated in Table 7.5 F. Exceptions apply for downstream MERV 14 and greater level particulate filters, HE-HEGA gas-phase filtration, or when there are unusual loads of large mass particles, such as blowing sand.

Historically, filter suppliers have recommended prefiltration protection of higher-efficiency, higher-cost final filters using less expensive "sacrificial" prefilters. The theory was that prefilters keep larger particles from flooding the final filter, yielding longer life for the more costly final filter. Table 7.5-F debunks this myth and compares the impact of the life-cycle cost of two typical prefilters with the savings through life-cycle extension of the final filter being prefiltered. For this analysis, energy is ignored and only filter cost is compared for simplicity. Energy cost would make the comparison even more extreme.

The "First Cost" column of Table 7.5-F denotes the master list price of the filter type for comparison purposes (prior to routine discounts for volume or customer contracts). The next column adds a nominal labor fee for change-out labor and handling and reports the annual cost of the filter based on factory-recommended annualized change cycles. In the case of the higher MERV filters, one-year life was assumed as the baseline. Assume the addition of prefiltration to attain life extension beyond this one-year baseline. From the simple math, it is easy to see that the cheap disposable filter is one of the most expensive annual costs because of short life and related labor costs. To illustrate the point, when the MERV 6 pleat is used to prefilter the MERV 13 pocket filter, the resulting cost is $56 for prefiltration to gain one additional year on the final filter with a value of $20.43. If even longer life is attained, the multi-year cost of prefiltration exceeds the annual value gain of life extension by a multiplier of 6 ($84 vs. $13.62). It is likely that only the more expensive filters, MERV 14 and higher, warrant prefiltration consideration. The final determination needs to be made only after careful consideration of the nature of the prefiltered air, the additional energy demand of the prefilter, and the related gain of life in the final filter. (Remember, if energy were also considered in this comparison, a 0.25 in. w.g. [62.5 Pa] pressure drop [typical of prefilters] costs up to $64/year at $0.06/kWh, which is more than double the annual cost of the pleat prefilter.)

Table 7.5-F Cost Benefit ($) Analysis of the Use of Prefiltration on Final Filters, Excluding Energy

Filter Type and Efficiency	First Cost (price)	Cost 1st Year	Cost 2nd Year	Cost 3rd Year
Fiberglass panel prefilter	2.86	46.32	46.32	46.32
MERV 6 pleat 2 in. prefilter	6.00	28.00	28.00	28.00
MERV 12 pocket	36.25	37.25	18.62	12.41
MERV 13 pocket	39.86	40.86	20.43	13.62
MERV 13 rigid cartridge	105.63	106.63	53.32	35.54
MERV 14 bag 6 pocket	43.79	44.79	22.40	14.93
MERV 14 bag 8 pocket	77.80	78.80	38.90	26.27
MERV 14 minipleat	145.00	146.00	72.50	48.67

This table compares the annualized cost of two typical prefilters as compared to the potential gain in life-cycle cost of final filters through life extension beyond one year. Prices are master list and will vary downward with discounts. Labor is added nominally at $1.00 per filter per change. Only the most expensive of the final filters with provide annual positive payback for prefiltration, but this may also be eroded by the energy operating cost of the prefilters.

7.5

Energetic Filters

The previous discussions in this Strategy refer to FAC that have reported efficiencies using the industry consensus ASHRAE Standard 52.2. There are other filtration or air-cleaning devices that employ variations of active electrical fields, including ionization, surface irradiation, and catalytic activation, that are claimed to provide enhanced particle and molecular capture. Many of these tactics provide the tantalizing prospect of low pressure drop. Unfortunately, many of these claims cannot be tested or validated using ASHRAE Standard 52.2 (ASHRAE 2007) or ASHRAE Standard 145.1 (ASHRAE 2008). Thus, there is no recognized industry standard or MOT to evaluate or rate these devices that claim contaminant control or extraction through this energetic means. The second and perhaps more important concern regarding energetic devices is that electrical fields generally create ozone as a by-product. Ozone is a CoC in the indoor environment because of potential irritation from direct exposure as well as potential by-products of reaction with indoor pollutants. Even those products that demonstrate control of ozone discharge within allowed limits beg the question of potentially harmful by-products of ozone exposure and reaction within the device.

Electronic Air Cleaner (EAC). The most established and best known energetic device is the electrostatic precipitator, also called an *electronic air cleaner* (*EAC*). This device employs an electrical field to charge the small airborne particles and incorporates a deposition plate that attracts and captures the particles, extracting them from the airstream. The deposition plate is periodically cleaned to renew the capture efficacy. This device is especially effective against small micron-sized particulate matter that responds well to electron charging and deposition. The EAC category of air cleaner is not tested using the ASHRAE Standard 52.2 MOT because there is no declared “end point” for filter service, which negates the ability to predict minimum efficiency. Unlike arrestance filters, the efficiency of this device is best when totally clean and drops over time to an end point of zero efficiency. The inability to predict efficiency drop-off and appropriate cleaning/service cycles impairs the usability of this device in critical commercial applications. More recent research sponsored by EPA (Hanely 2002) has shown that the charging wires of the EAC can also become blinded with depositions of airborne silicates. Over time, these depositions sheath the wires and decay the ability of the unit to be sufficiently cleaned, thus reducing its ability to return to original efficiency levels after the cleaning process.

Emerging Technologies. Some newer devices employ various combinations of energetic sources with both particulate and gaseous components and make strong claims regarding enhanced air cleaning or purifying through ionization, surface irradiation, catalytic activity, or other electron manipulation. Many of these devices are residential in marketing motivation, but they are appearing in the commercial market. Generally speaking, if a claim sounds too good to be true, then it probably isn’t. Even if the system or device is based on sound technology, if the claims are based upon anecdotal testimonies lacking credible third-party research or documentation, then the claims can be suspect.

In general, even if the device does not lend itself to the full ASHRAE Standard 52.2 MOT, the performance can still be verified. For example, upstream versus downstream particle counts or contaminant concentration comparisons performed by a credible third-party researcher can provide an accurate indicator of performance. However, if the full ASHRAE Standard 52.2 regime cannot be performed on the product for whatever reason, then it is inappropriate for MERV designations in any form to be claimed by the supplier. The evaluation needs to contain a life-cycle or capacity evaluation as well as efficiency determination for full consideration in comparison to established products. If the device is claimed to act upon the space rather than upstream/downstream of the controller, then in situ site or chamber testing under controlled conditions over time can provide an indication of performance under actual operating conditions.

Combination Devices or Clean Air Devices. A number of products manufactured and marketed primarily for the residential marketplace are being used in commercial applications. These devices combine one or more of the previously described extraction techniques within a self-contained blower and housing. This category of products is referred to as *clean air devices*. These air cleaners range from small relatively ineffectual appliances to larger engineered machines that can effectively deliver over 1000 cfm (472 L/s) of relatively clean filtered air. The higher-end machines can incorporate competent gas-phase and HEPA levels of filtration as well as the more exotic energetic technologies. The better units are rated using a chamber-type test administered by American Home Appliance Manufacturers (AHAM) that provides a rating called the *Clean Air Delivery Rate* (*CADR*). This rating provides an indication of an equivalent amount of clean air delivered by the unit that is derived from its tested extraction efficiency combined with the related airflow volume. The CADR rating provides the user with an ability to select and size equipment to treat a known volume of space, such as a meeting room or print room. The advantage to the designer in using a unitary clean air device is that it can provide high-end extraction on a localized basis without involving the central air handler. It also can be managed on an as-needed basis to extend the service life of the air-cleaning components. Because of the relatively high pressure drop of the air-cleaning components, the units can be noisy. They also require the routine maintenance of most filtration system components, which may be of specialized configuration, making replacement more expensive than routine filter cartridges.

Ultraviolet Germicidal Irradiation (UVGI). The use of ultraviolet germicidal irradiation (UVGI) as an energetic device for airborne pathogen control in upper-room air is well-established in health-care facilities, especially tuburculosis wards. The more recent IAQ concerns about microbial growth, especially mold in HVAC systems, as well as terrorist-related concerns for microbiological-based weapons of mass destruction, have reawakened interest in this time-proven technology. Though claimed as an “air purifier,” UVGI is not a filter, per se, because no extraction or retention of the affected particles occurs. However, the technology has merit for preventing fungal amplification in wet areas of the HVAC system. More pertinent to FAC is the use of UVGI irradiation to activate a catalytic substrate, such as titanium dioxide, that can potentially chemically convert airborne reactive VOCs as well as reactive inorganic gasses into more innocuous or benign compounds. Though demonstrated on a laboratory scale, this technology lacks commercialization in readily available commercial systems. For more information on UVGI, see Strategy 4.5 – Consider Ultraviolet Germicidal Irradiation.

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Strategy 7.6

7.6

Provide Comfort Conditions that Enhance Occupant Satisfaction

Introduction

Thermal conditions indoors, combined with occupant activity and clothing, determine occupant thermal comfort, which in turn impacts occupant productivity and perceptions of air quality. Thermal conditions affect chemical and biological contaminant levels and/or the intensity of occupants' reactions to these contaminants, but our knowledge of these effects and their mechanisms is very limited. Despite this limited knowledge, achieving high performance in thermal comfort is likely to result in lower contaminant levels and better occupant perceptions of IAQ.

Dry-bulb temperature is only one physical parameter out of many that interact in a complex manner to produce occupant satisfaction. Others include humidity, radiant temperature, air movement (including dynamic elements that mimic natural breezes), and factors even more remote from thermal conditions, such as occupant proximity to windows, sight lines to windows, and the control offered to occupants, whether they use it or not.

Occupant expectations play a large role as well. For instance, occupants generally accept a much wider range of thermal conditions in spaces that are naturally rather than mechanically conditioned or in spaces that give individuals greater control over their own environment.

In traditional designs, the HVAC designer's role in achieving comfort conditions often begins and ends at the selection of indoor design conditions and the sizing of a system to provide these conditions at peak load. This is certainly a prerequisite in mechanically conditioned buildings, yet it leaves very little latitude to designers to improve thermal comfort control beyond the norm. Depending upon the particular design, there are several additional considerations and actions available to a designer beyond this prerequisite that can enhance occupant satisfaction.

Basic Thermal Comfort

Thermal comfort is highly individual and cannot be predicted with accuracy even for a particular person. Nevertheless, there are tools for calculating the proportion of people likely to be satisfied by the combination of air temperature, humidity, air velocity, and radiant temperature. The most commonly known tool in the U.S. is *ASHRAE Thermal Comfort Tool* (ASHRAE 1997), a computer program that is part of *ANSI/ASHRAE Standard 55, Thermal Environmental Conditions for Human Occupancy* (ASHRAE 2004).[1] In order to use this tool, the amount of clothing worn by occupants and their levels of metabolic activity must be provided, in units of clo (clothing level) and met (metabolic rate), respectively. Accounting for variations among individuals in clothing and activity is not part of automatic temperature control systems; this is one reason for providing, when possible, more zones and greater individual control by occupants. One aspect of individual control that occupants may have, depending on their work environment, is the ability to add or remove clothing to adapt to their thermal comfort sensations. To the extent that this can be allowed, it will enhance thermal comfort and reduce energy consumption.

STRATEGY OBJECTIVE 7.6

Zoning and Occupant Control

It is wise to select zones carefully and consider using as many as needed to create sufficient homogeneity within each zone to improve the chances of satisfying the comfort needs of occupants in the zone. Rooms and areas having loads that vary over time in patterns that are significantly different from areas that surround them should have their own conditioning control loops and thermostats. Each person in control over his or her own environment (e.g., personalized ventilation and conditioning, as provided in many

[1] The program code is published in Normative Appendix D of ASHRAE Standard 55-2004 in C++/BASIC. A user-friendly version on CD, *ASHRAE Thermal Comfort Tool*, is available for purchase from ASHRAE.

automobiles and airplanes) is the ideal situation in that personal control has been shown to increase satisfaction and reduce sick building syndrome symptoms. However, this is not always possible due to limitations such as first cost, architectural layout, and system complexity. When quantities of zones are limited by such considerations, strategic distribution of zones can improve their impact. For example, ten single-occupancy offices with similar glazing on the same facade of a building can be in one zone, but the conference room with variable occupancy or a corner office exposed to two compass directions would likely need to be designed as separate zones. The sales area of an in-line store with glazing and frequent door openings generally warrants a different zone from the stock and merchandise preparation area with equipment such as steamers.

It is expected that individual occupants in the same temperature control zone will have different thermal comfort needs. They should be encouraged, therefore, to adjust their clothing to fit their own needs. However, if occupants have an adjustable thermostat in the space, then so-called "thermostat wars" may sometimes occur where occupants frequently re-adjust the thermostat that others have set. This situation can reduce both the efficiency and the effectiveness of the comfort system. For example, a person who feels warm may set the cooling setpoint 10° lower than normal, which can result in significant subcooling of some systems. If another individual changes the setting to an unusually high temperature, this can consume excessive energy and not satisfy anyone's thermal needs. The solution in some cases may be giving control to a neutral party, such as the building operator or office manager, or in other cases it may be using thermostats in which temperature change is limited.

Dummy thermostats that are not connected to the automatic control have sometimes been installed on the theory that mere thermostat twiddling will satisfy occupants. This strategy, however, risks further alienating and frustrating occupants, creating an atmosphere of mistrust between system operators and occupants and distancing occupants from the reality of what HVAC systems can and cannot do.

Part-Load Humidity and Velocity Control

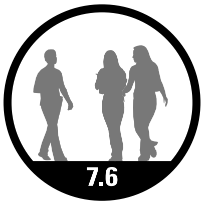
The control of humidity at part load is important for thermal comfort and also for reducing the potential for condensation. For more information on part-load control of humidity, see Strategy 2.4 – Control Indoor Humidity.

Systems that vary the air volume in response to changes in thermal load can have advantages in energy conservation and humidity control at part load. However, air diffusion devices need to be selected so that minimum air velocity conditions in occupied zones are maintained at low airflow. Selecting diffusers that achieve this over the entire range of airflow, using fan-powered variable-volume boxes, or otherwise enhancing air movement can do this.

Operational Strategy and Design Implications

Most automatic temperature control systems respond only to dry-bulb temperature and not to other thermal parameters such as humidity, radiation, or air movement. Many building operators have discovered by trial and error that the ideal dry-bulb conditions for occupant satisfaction are about 70°F (21°C) in the winter and 72°F (22°C) in the summer, which is different from the typical indoor design condition of 75°F (24°C). Lower temperatures, such as 68°F (20°C), have been shown to improve occupant satisfaction with IAQ, independent of perceived thermal comfort.

Designers can take this information into account in their designs by avoiding thermostats that have fixed rather than variable setpoints and sometimes by allowing sufficient system capacity to achieve the "ideal" temperatures. If this results in excess capacity, then part-load control and efficiency considerations are important. In addition, it is important to choose thermostat locations that best represent the conditions that occupants will experience and that are not confounded by solar radiation or other heat sources. When no single location meets this criterion, one can consider providing multiple averaging temperature-sensing locations. For more information on the potential benefits of radiant heating and cooling, tight humidity



control, and separating the thermal conditioning and ventilation functions, see Strategy 1.3 – Select HVAC Systems to Improve IAQ and Reduce the Energy Impacts of Ventilation.

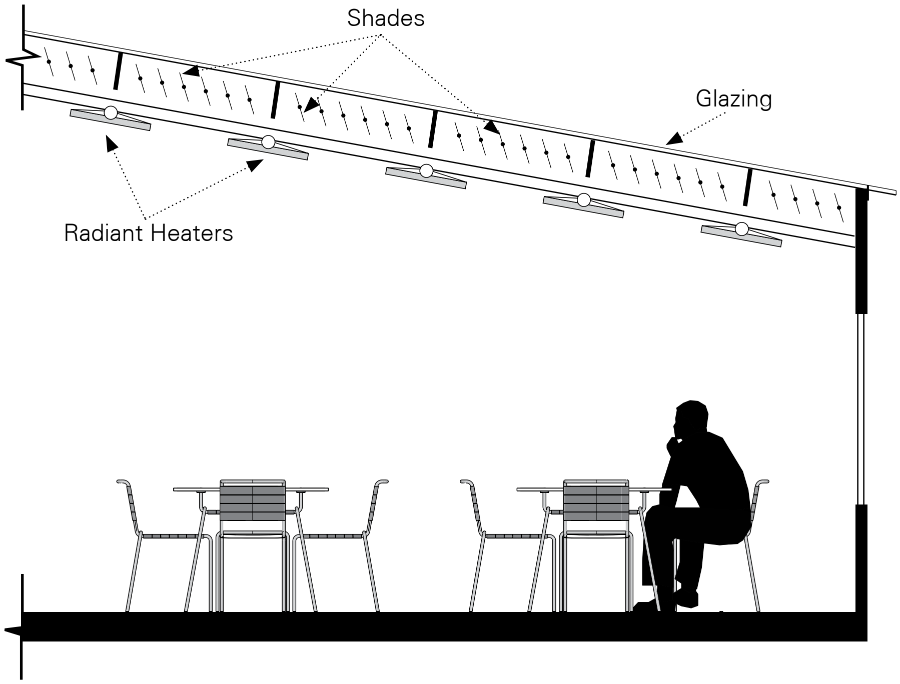


Figure 7.6-B Radiant Heating and Cooling Can be Used to Enhance Comfort in an Expanded Temperature Envelope

Thermal Radiation

The design team that considers the significant role thermal radiation can play in thermal comfort can 1) mitigate the negative impacts of radiation, 2) take these impacts into account in system capacity and control, and 3) utilize the beneficial contributions to comfort that radiation can make. For example, glazing introduces natural light and gives people a visual connection to the outdoor environment, but it can also degrade thermal comfort by exposing occupants to direct radiation from the sun as well as create drafts in winter. Selecting glazing that transmits visible light but not thermal radiation can mitigate these effects. In addition, cooking equipment that is close to customer areas can be a significant source of thermal radiation that can degrade occupant comfort. ASHRAE Standard 55 (ASHRAE 2004) provides useful guidance for these and similar situations and also for other parameters such as radiation asymmetry. (See Figure 7.6-B.)

If radiant heating is used, be aware that an unintended side effect can be increased off-gassing of contaminants from the heated materials, including those surfaces that receive radiant heat from the primary heated surface. If radiant cooling is used, consider the potential for condensation (see Strategy 2.4 – Control Indoor Humidity).

Air Movement

Air distribution systems should be designed to achieve an appropriate air velocity near the occupants (sometimes referred to as *terminal velocity*), which is often about 50 fpm (0.25 m/s). Air diffusion selected so that required air velocity conditions in occupied zones are maintained both at full load and at low airflow will reduce complaints, such as those that would normally occur with a variable-air-volume system. Design velocities for underfloor air distribution (UFAD) and displacement-type systems are often lower to avoid the cold sensation on occupants' lower extremities.

The use of supplemental fans can expand the thermal comfort envelope and may be considered in cases where full conditioning is not practical or to improve energy efficiency. See the case study titled "Vehicle Maintenance Shop" for an example of this application.

In the heating mode, drafts can occur under windows and at other significant sources of heat loss. This can be counteracted by heat sources under windows or by overhead forced air or radiant heating. Overhead forced air for heating can be low in cost, but if it is delivered from a very high ceiling or if the air is much

Vehicle Maintenance Shop

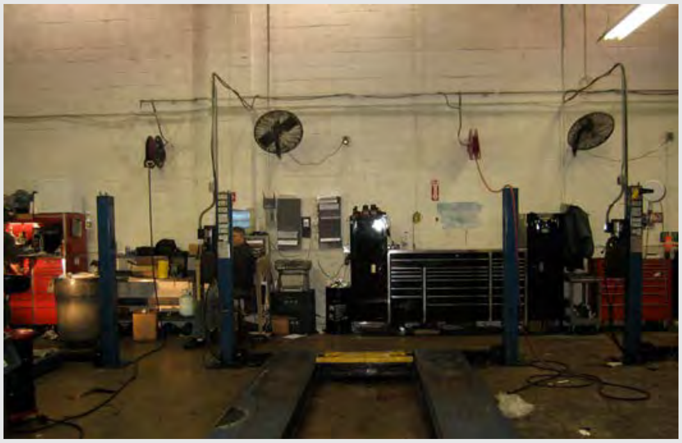


Figure 7.6-C Wall Fans in Vehicle Maintenance Shop
Photograph courtesy of Larry Schoen.

Figure 7.6-D Doors to Vehicle Maintenance Shop
Photograph courtesy of Larry Schoen.

The automobile service area shown in Figures 7.6-C and 7.6-D presents a good application for overhead gas-fired radiant heating to enhance comfort and save energy.

In this vehicle maintenance shop, wall fans for occupant-controlled air movement have been successfully used to enhance thermal comfort while making higher temperatures acceptable (Figure 7.6-C).

Since the doors to the maintenance shop frequently remain open, heating by thermal radiation is more effective than heating the air inside the shop (Figure 7.6-D).

hotter than the room temperature, the air will not reach the occupied level and will not counteract the drafts. It will also not mix sufficiently to be an effective source of ventilation air (See the related sections of *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* [ASHRAE 2007], including Table 6-2).

A checklist is provided in Table 7.6-A that can be used for providing comfort conditions that enhance occupant satisfaction.

Table 7.6-A Comfort Conditions Checklist

Conditions that Enhance Occupant Satisfaction	✓
Basic Thermal Comfort	
• Consider humidity, air velocity, radiation	
• Consider occupant clothing and metabolic rate	
• Use *ASHRAE Thermal Comfort Tool* (ASHRAE 1997) or equivalent to select indoor design	
• Design for part-load conditions	
• Select thermostat locations carefully	
• Educate occupants regarding clothing adaptation	
Zoning and Occupant Control	
• Use separate zone for each unique microenvironment	
• Educate occupants about thermostat settings and HVAC operation	
• Expand comfort envelope using personal cooling/ventilation	

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Conditions that Enhance Occupant Satisfaction	✓
• Expand comfort by occupant control over natural conditioning	
• Use operator control in case of "thermostat wars"	
Thermal Radiation	
• Use radiation (hot or cool) to expand the thermal comfort envelope	
• Shade excessive solar radiation	
Air Movement	
• Achieve the minimum velocity (see Basic Thermal Comfort items above)	
• Expand the upper thermal limits using air movement	
• Address drafts by selection of diffusers and heat location	
Part-Load Control	
• Maintain air velocity	
• Control humidity	
Operation Capabilities	
• Design to allow flexibility that can retain satisfaction levels	
• Adjustable setpoints allow response to occupant expectations	

Illustration of the Many Factors Affecting Thermal Comfort

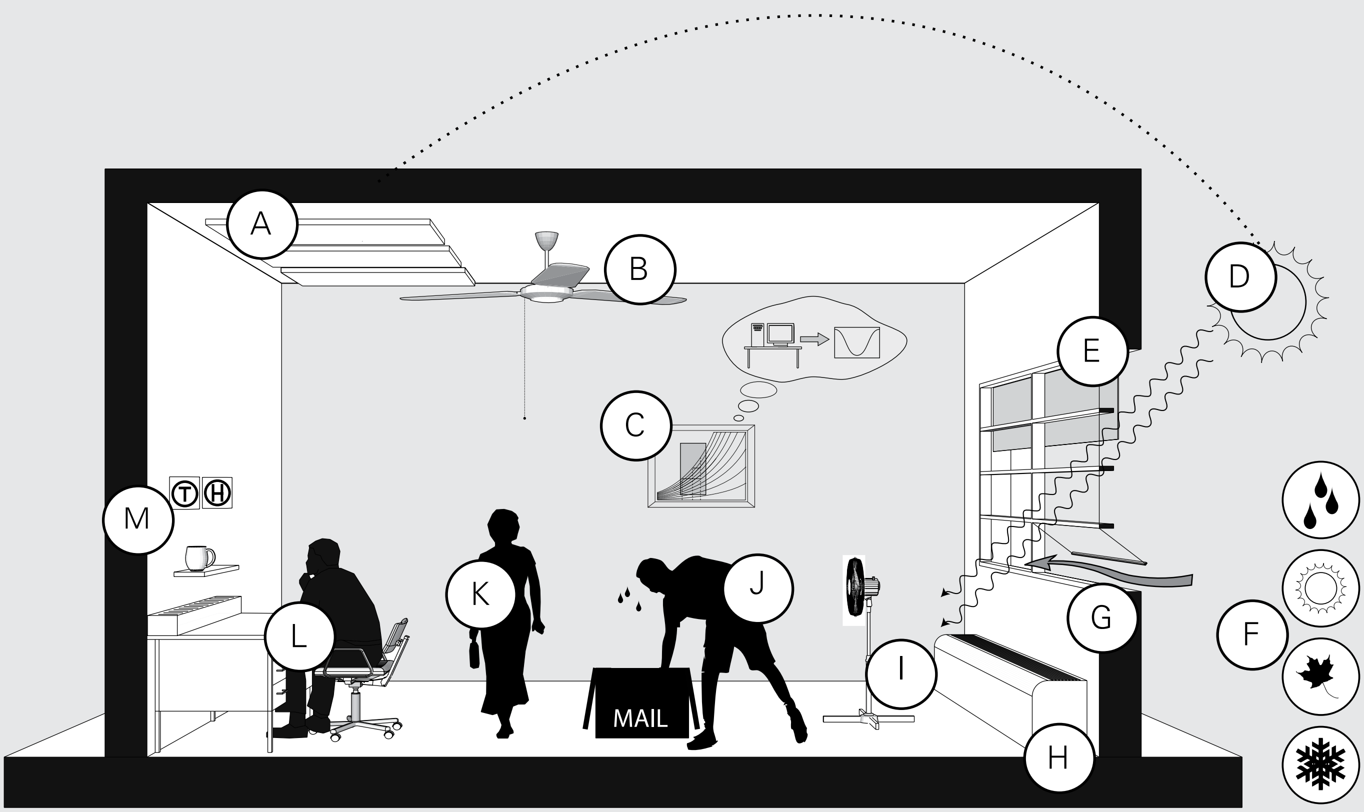

Figure 7.6-E Tools to Maintain Thermal Comfort

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Figure 7.6-E demonstrates some tools for maintaining thermal comfort. The following details explain the labeled elements in the figure as indicated.

A. The heavy line on the ceiling is a radiant ceiling panel, which may be cool or hot. A cool surface, in addition to cooling the air in the room, provides the ability to accept some radiant heat directly from the occupants and can allow for a somewhat higher room temperature. This could be called a *cooled ceiling*; some systems incorporate chilled beams. This type of system can be used with lower amounts of supply air, often displacement ventilation from below, that a) supply all the ventilation to the room, b) handle the latent (humidity) load, and c) provide the air movement portion of thermal comfort. This type of system requires close dew-point temperature control and has attracted greater interest in Europe and Asia than in North America. The higher room temperatures allowed could have the undesirable effect of increasing material contaminant emissions and further compound this by increasing subjective occupant sensitivity to these contaminants and other aspects of the air. Generally, IAQ comfort is greater at the lower end of the thermal comfort temperature range.

   The ceiling panel could also be used for heating purposes, in which case the inverse would be true: it would allow lower room temperatures to achieve the same thermal conditions.

B. The ceiling fan is one way to enhance air movement, which allows for higher room temperatures to achieve the same thermal comfort. This concept of expanding the thermal comfort window is quantified in the *ASHRAE Thermal Comfort Tool* (ASHRAE 1997), which is part of ASHRAE Standard 55 (ASHRAE 2004). The pull string represents occupant control, which further enhances the benefit of this feature.

C. The framed picture on the wall represents what most people think of as the thermal comfort envelope on the psychrometric chart from ASHRAE Standard 55. However, this is not the whole story, as the thought bubble shows. The fixed envelope on the chart is always for a particular amount of clothing (clo), metabolic activity (met), radiant temperature, and air velocity. Proper use of the chart requires the computer-based *ASHRAE Thermal Comfort Tool*. The arrow to the right from the computer shows a graph representing the mean predicted vote that is the basis for the *ASHRAE Thermal Comfort Tool*: there are conditions that minimize the thermal discomfort (and, conversely, maximize the thermal neutrality), but they do not please everyone all the time. This is where the concept of user control can enhance thermal comfort even beyond what the tool predicts.

D. The sun coming in through the window not only impacts the temperature of the room but also shows the thermal radiation impact directly on occupants. It can also cause photochemical reactions on building materials and furnishings that impact the chemical content of the indoor air (and the longevity of the materials). Ultraviolet and thermally protective glazing that selectively passes only the visible light range can mitigate these effects, while retaining the aesthetic effects of natural light and the potential for energy savings by allowing electric lighting to be dimmed. The sun can also be a source of glare that impedes visually dependent work activities, but features such as light shelves can mitigate this effect and preserve the value of daylighting. The increased radiation load on the occupants requires a lower temperature to achieve the same thermal comfort, which uses more energy in the cooling season but less energy in the heating season.

E. The shade on the window shows once again that user-controlled features have even further benefits for enhancing thermal comfort. The advantages and disadvantages of the solar radiation may change over time as surrounding buildings are erected, demolished, or modified. While this is out of the control of the designer, the flexibility of the system to meet these potentially changing conditions—which is within the designer's control—is worth considering. With manually operable window shades, occupants play a role in controlling their own thermal comfort.

F. The four seasons shown outside the room represent the changing impact that outdoor conditions have on elements such as windows and walls and their results for indoor conditions. They also represent the changing thermal comfort expectations that people have in the different seasons, both because they wear different clothing and because they acclimate to different outdoor conditions.

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G. The user-operable window can be used both for thermal comfort and for ventilation when occupants think that outdoor air conditions are better than those indoors. The window can save energy and provide greater IAQ comfort. This may be because occupants can respond to temporary episodes of indoor emissions and achieve greater dilution ventilation and also because of the human desire for control over one's environment. The downside of depending on operable windows is the potential for outdoor noise or contaminants to enter.

The fact that the operable window is directly over a perimeter unit shows the interplay between the automatic, thermostatically controlled systems and user-controlled natural ventilation. These two systems can be coordinated using occupant education and interlocks that limit operation of the mechanical system when windows are open. Failing to coordinate the systems can waste energy and create moisture problems.

H. The perimeter unit itself shows another form of occupant-controlled conditioning. However, it can also have the disadvantage of taking up useful and desirable space under the window. Occupants may also use it for storage of books and other items that may impede airflow and degrade comfort.

I. The pedestal fan shows another type of occupant-controlled enhanced velocity air movement that can allow higher temperatures and still achieve the equivalent thermal comfort. It can also enhance the effectiveness of the operable window and allow expansion of the range of outdoor conditions during which natural conditioning can be used. Fans that match the décor of the room are available. Fans in the space can also introduce unwanted noise, but occupants may be willing to tolerate this extra noise if their thermal comfort is improved.

J. The worker handling the box is active and has a high metabolic rate compared to the seated worker. Thus, he requires lower temperature, humidity, radiant temperature, and/or higher air velocity to be comfortable. The fan is therefore directed right at him.

K. The standing worker is unhappy because she is wearing more clothing than any of the other workers and has a higher metabolic rate than the seated worker (though not as high as that of the worker lifting the box) and thus is not thermally comfortable. She pays the energy bill and wishes that the occupants would better coordinate the use of the fan, the operable windows, and all of the other occupant-controllable features so that greater comfort could be provided using less mechanical heating and cooling. However, since the occupants do not have any incentive or information on energy costs, as they do in their own homes, they may err on the side of greater comfort and lax operation and use more energy than they would if they had incentives and information.

The standing worker is also not happy with her job, which is beyond the control of the room designers but is a factor that compounds thermal discomfort as well air quality discomfort.

L. The seated worker is happiest because he has control over ventilation right at his desk, has the most direct benefit of the cool ceiling panel above, has his coffee right at hand, and has control over the room thermostat. In addition, his metabolic rate and clothing are appropriate to the thermal conditions. However, this may not last, as the coffee is right under the thermostat, and the heat rising from the coffee might cause the thermostat to call for subcooling of the room. This is not something the designer can control; although the designer may have considered workspace placement in the design of the space, sometimes the furniture layout is unknown or changes after selection of the thermostat location.

M. The humidity sensor that is next to the thermostat indicates moisture sources in the room: the hot coffee, the occupants, the open window, and other sources of humid outdoor air. The interior humidity is part of the thermal comfort complex that needs to be taken into account in system design. In many cases, the system can effectively control humidity conditions without special dehumidification sequences (see Strategy 2.4 – Control Indoor Humidity).

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In a high-performance building, effective communication and coordination among the building operator, the tenant, the interior designers, and the occupants will allow them to coordinate all aspects of space modification such as relocating thermostats and adjusting ventilation rates, redistributing heating/cooling loads, and rebalancing of airflow.

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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.

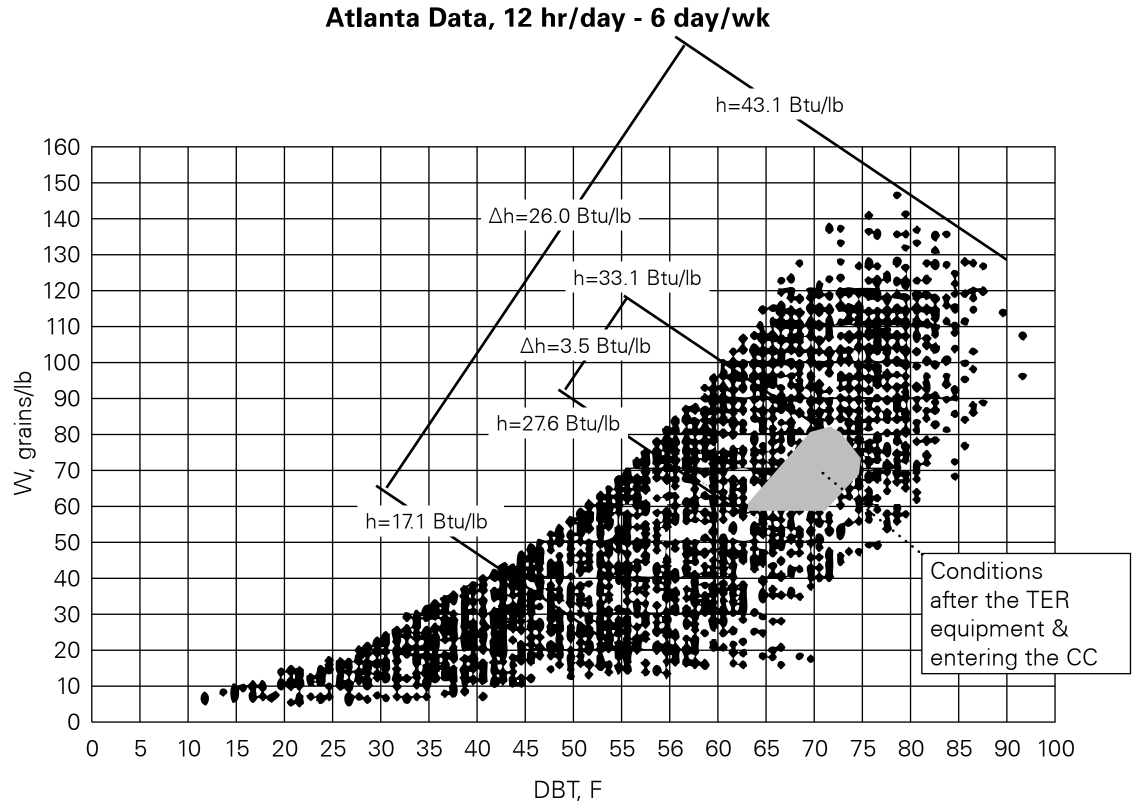

Figure 8.1-D Cooling Coil Conditions with Total Energy Recovery
Adapted from data provided by Stanley Mumma.

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.

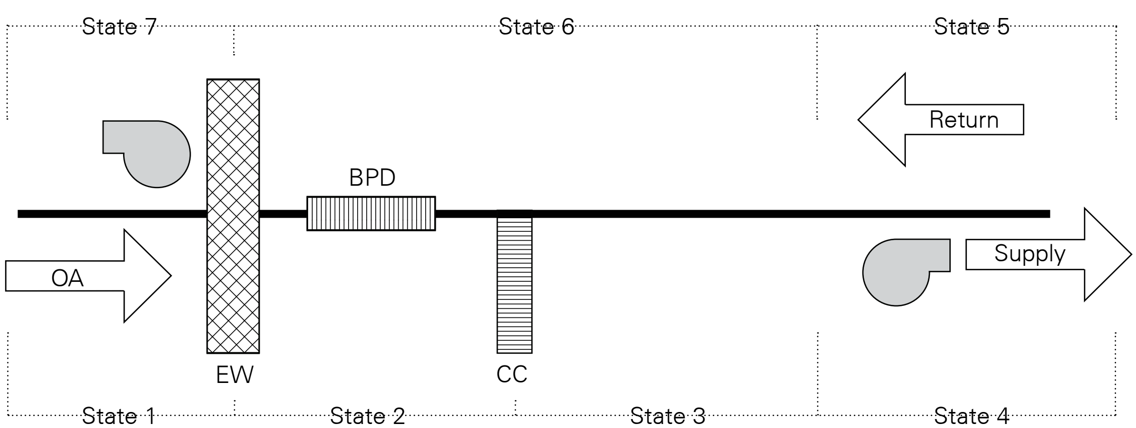

Figure 8.1-E DOAS with Enthalpy Wheel and Cooling Coil

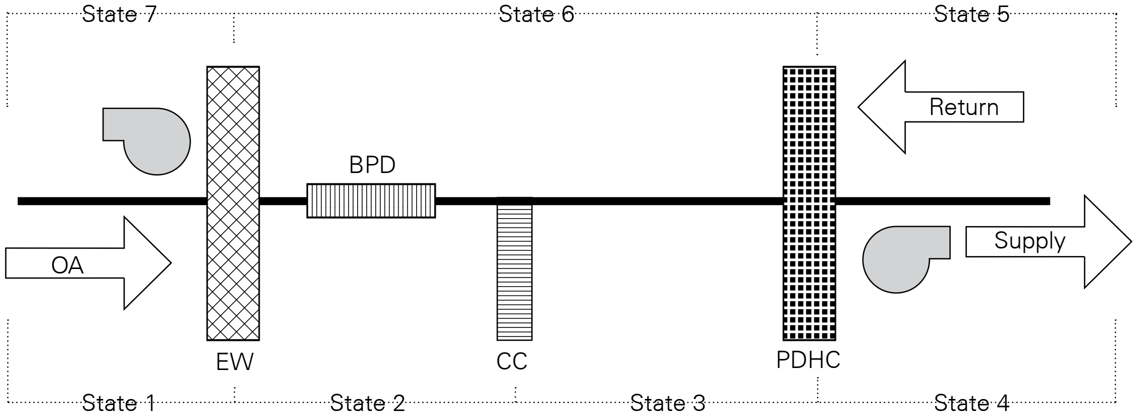

Figure 8.1-F DOAS with Enthalpy Wheel, Cooling Coil, and Passive Dehumidification Component

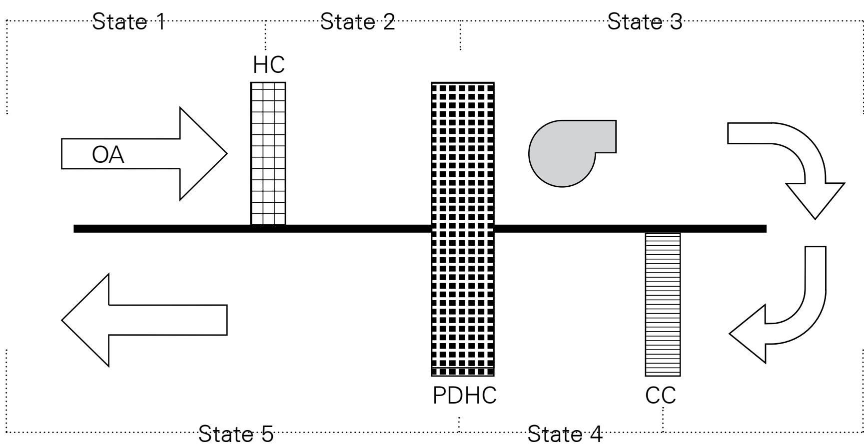

Figure 8.1-G DOAS Configuration without Energy Recovery

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Strategy 8.2

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	—	—	—	—

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	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

[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.

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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)

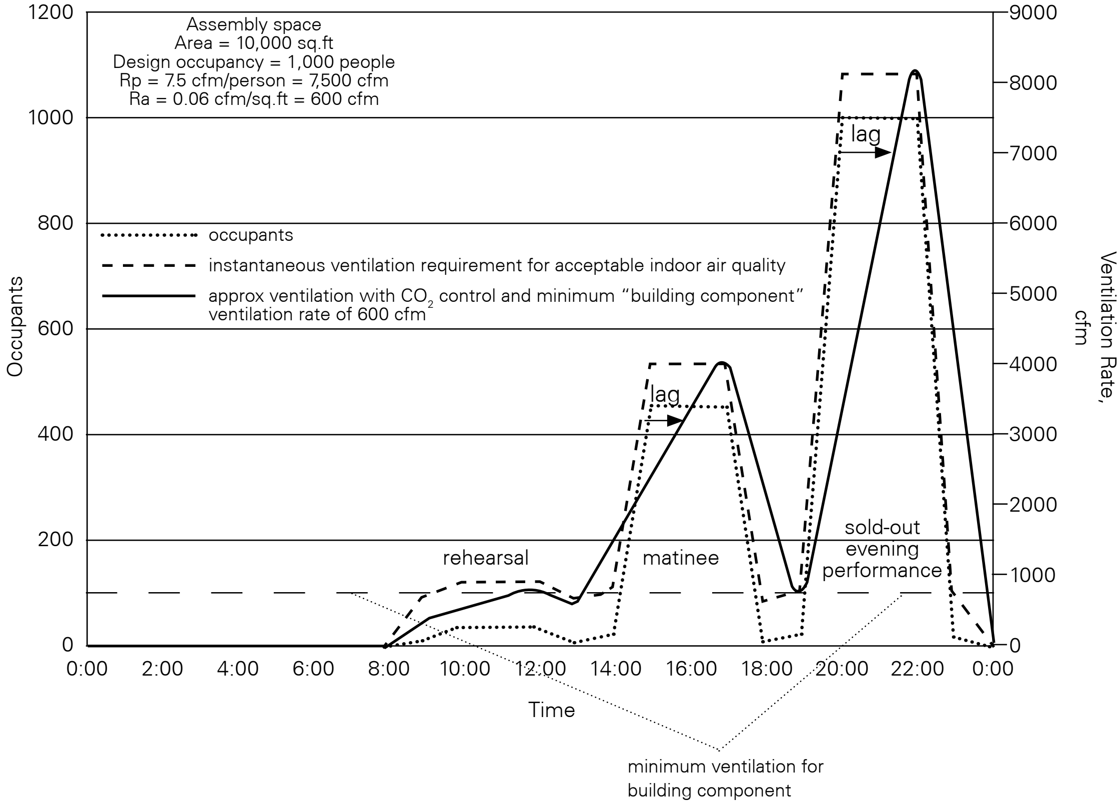

Figure 8.3-D Illustration of the Lag between Occupancy and Minimum Ventilation Rate in CO_2-Based DCV

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 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

> 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.

Strategy 8.4

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.

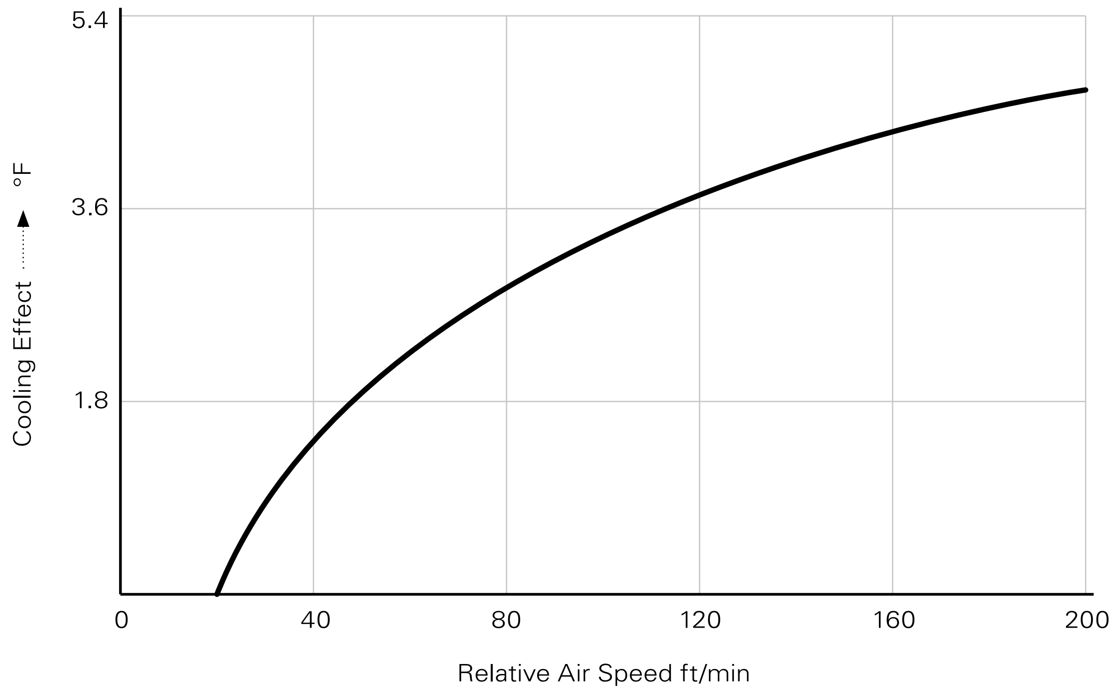


Figure 8.4-G Effect of Air Speed on Thermal Comfort
Adapted from CIBSE (2005), Figure 2.4.

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.

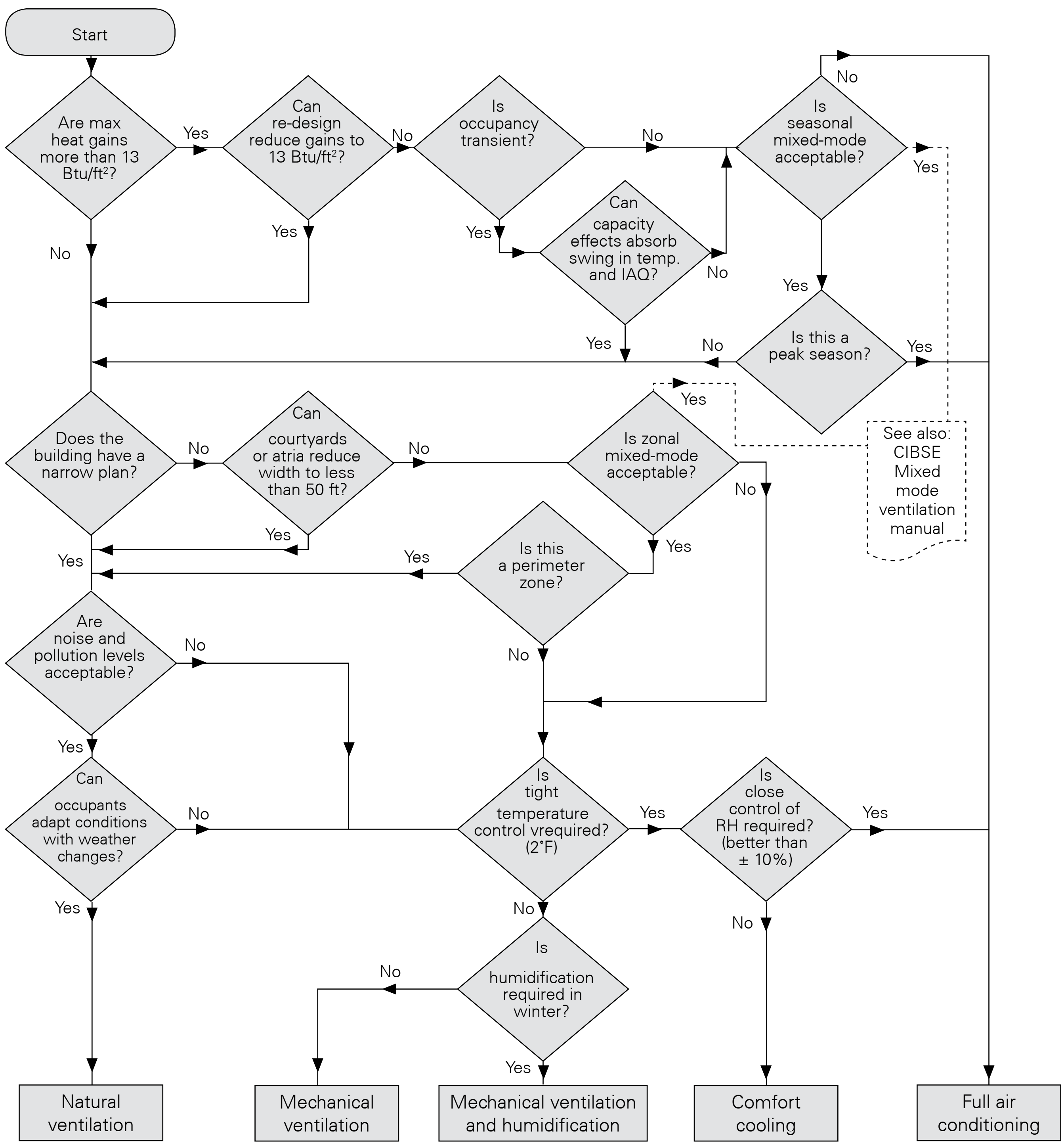


Figure 8.4-H Selecting a Ventilation Strategy
Adapted from CIBSE (2005), Figure 2.8.

Strategy 8.4

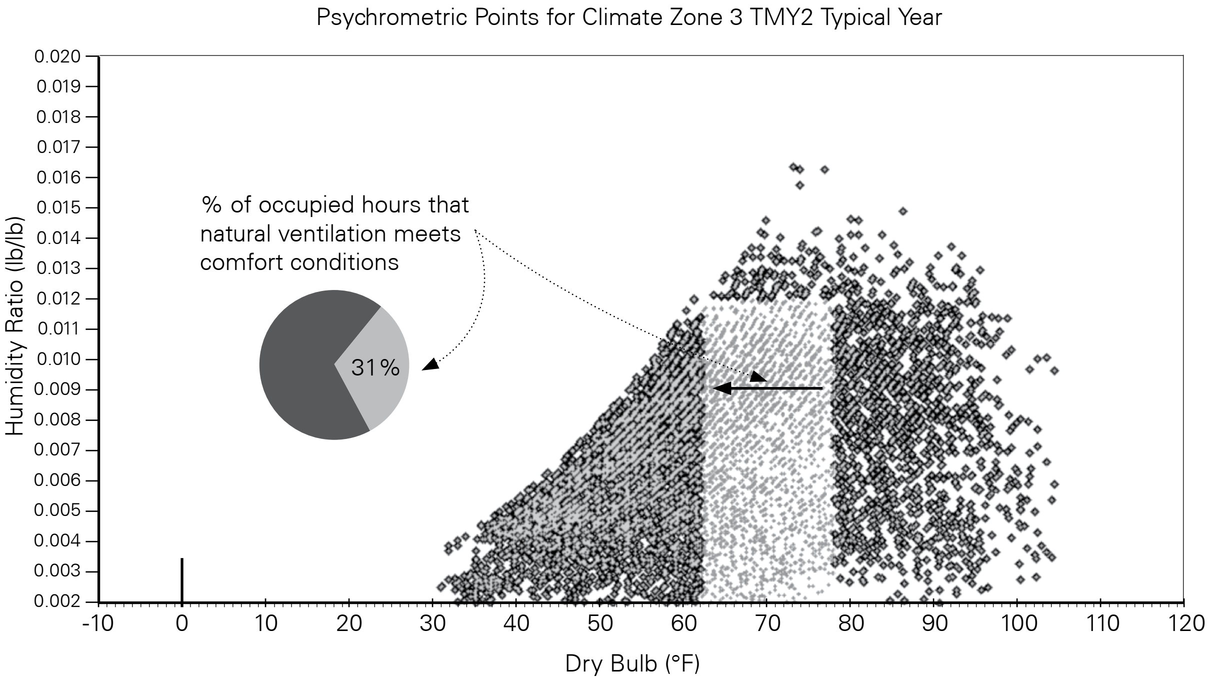


Figure 8.4-I Psychrometric Points for Climate Zone 3
Adapted from Stantec (2009).

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.

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)

Strategy 8.4

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.

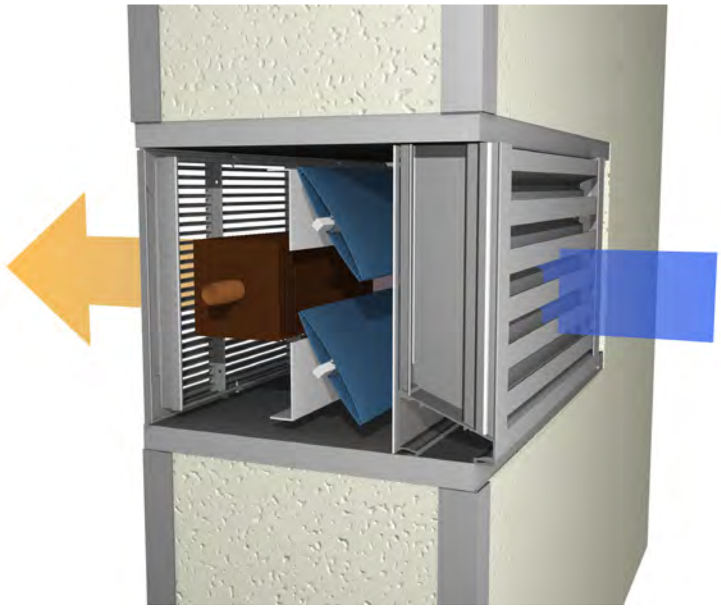


Figure 8.4-J Trickle Vent Example

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.

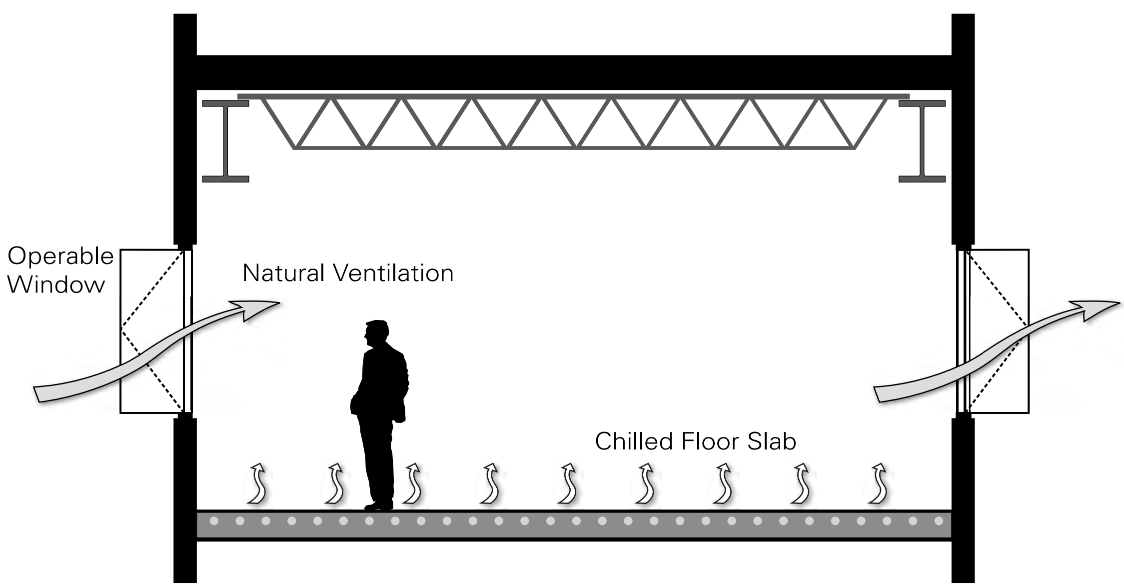
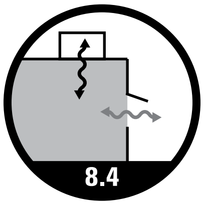


Figure 8.4-K Mixed-Mode/Hybrid System Combining Natural Ventilation with Chilled Slab

Strategy 8.4



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

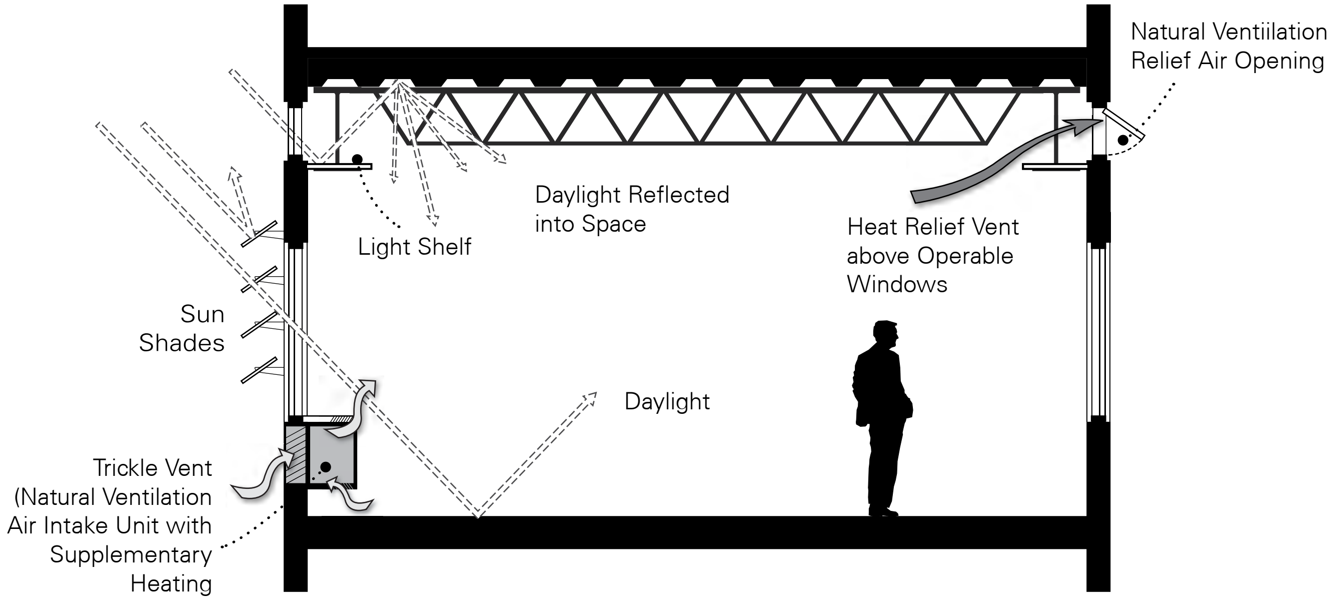


Figure 8.4-L Daylighting Used in Combination with Shading and Natural/Mixed-Mode Ventilation

> 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).

Strategy 8.4

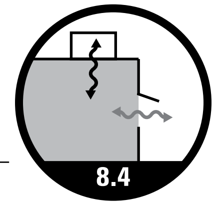


Table 8.4-A Ventilation and Cooling Design Options
Data source: Stantec.

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.

$$Q = 60 \times K \times A \times \sqrt{(2g \times H \times (T_i - T_o)/T_i)}$$

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)

Strategy 8.4

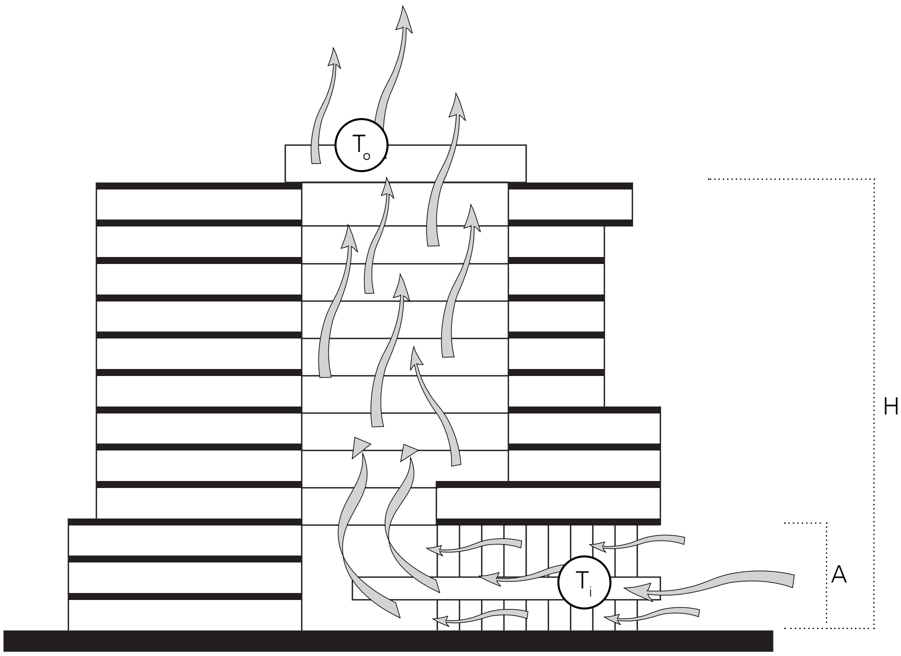


Figure 8.4-M Stack Ventilation

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

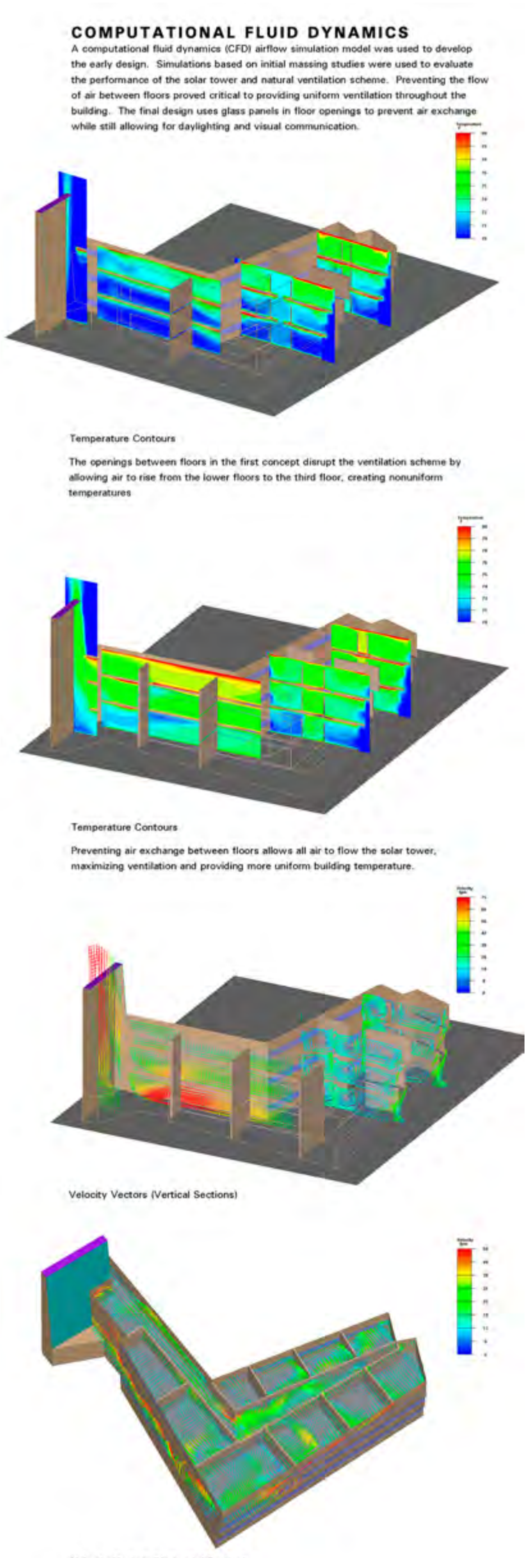


Figure 8.4-N CFD Modeling of Temperature Distribution and Airflow in a Building Addition

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.

Strategy 8.4

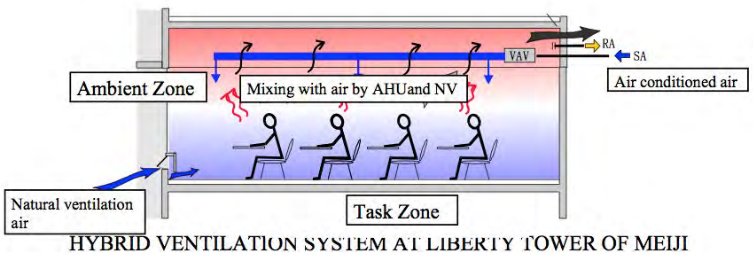
Table 8.4-B Sample Capital Cost ($/ft2 [$/m2]) Comparison of Passive Natural Ventilation and Cooling vs. Hybrid (Including Automated Window Control) vs. Traditional Systems for a Pacific Northwest Building
Source: Stantec (2009).

	Passive Natural Ventilation and Cooling Design (Perimeter Baseboard Heat)	Hybrid Natural Ventilation and Cooling Design (Heated/Chilled Radiant Slab)	Traditional Ducted VAV System
Architectural Items			
Windows	$4.90 ($52.74)	$4.90 ($52.74)	$2.40 ($25.83)
Window actuators and wiring	—	$6.30 ($67.81)	—
Window security and wiring	$1.50 ($16.15)	Covered by direct digital control	$0.90 ($9.69)
External blinds	$5.06 ($54.47)	$5.06 ($54.47)	—
Internal blinds	—	—	$2.16 ($23.25)
Wiring for blinds	$1.60 ($17.22)	$1.60 ($17.22)	—
Relief chimneys	$3.50 ($37.67)	$3.50 ($37.67)	—
Ceilings	$0.50 ($5.38)	$0.50 ($5.38)	$1.50 ($16.15)
Architectural Subtotal, $/ft^2 ($/m^2)	**$17.06 ($183.63)**	**$21.86 ($235.30)**	**$6.96 ($74.92)**
Mechanical Items			
Central plant (heat)	$3.00 ($32.29)	$3.00 ($32.29)	$3.00 ($32.29)
Central plant (cool)	—	$3.00 ($32.29)	$3.00 ($32.29)
Perimeter baseboards	$2.00 ($21.52)	—	—
Radiant slab piping	-	$6.00 ($64.58)	—
Ventilation air fin-tube units	$0.15 ($1.61)	$0.15 ($1.61)	—
VAV boxes and ductwork	—	—	$6.60 ($71.04)
Air-handling unit	—	—	$3.50 ($37.67)
Hydronic piping and pumping system	$2.50 ($26.91)	$2.50 ($26.91)	$5.00 ($53.82)
Terminal unit controls	$2.50 ($26.91)	$2.50 ($26.91)	$5.50 ($59.20)
Balancing	$0.06 ($0.65)	$0.06 ($0.65)	$0.18 ($1.94)
Commissioning	$0.50 ($5.38)	$1.00 ($10.76)	$1.00 ($10.76)
Mechanical Subtotal, $/ft^2 ($/m^2)	**$10.26 ($110.44)**	**$18.21 ($196.01)**	**$27.78 ($299.02)**
Total Cost per ft^2 (m^2)	**$27.32 ($294.07)**	**$40.07 ($431.31)**	**$34.74 ($373.94)**

Natural Ventilation Project Lessons Learned

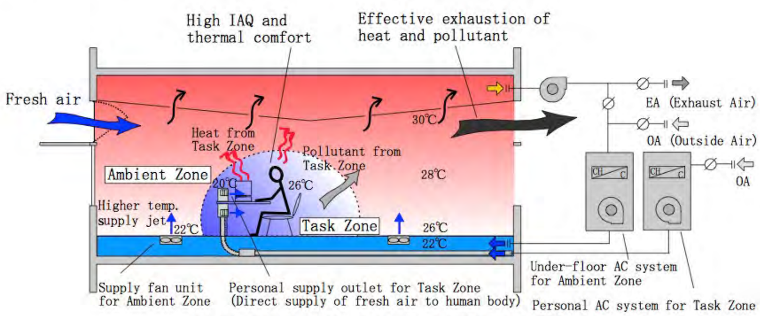
3.14 Lessons Learned

The most significant problem of the system was that inlet located under the glazed windows along perimeter zone. It leads the uncomfort for the occupant sitting near the window, because occupants' feet become cold. In addition, the air induced by natural ventilation came to occupant zone directly, then it was mixed with the air supplied from ceiling inlet by air conditioning system. With this condition, the air by natural ventilation, which is a little high and humid, will revolt the occupant.



HYBRID VENTILATION SYSTEM AT LIBERTY TOWER OF MEIJI

To remove this problem, a new type of hybrid ventilation system was proposed at IDE (Institute of Developing Economies, JETRO) by us (contact person: Dr. Tomoyuki Chikamoto, chikamoto@nikken.co.jp).



HYBRID VENTILATION SYSTEM AT IDE

With this system, excess cooling load and pollutant from task zone are exhausted by natural ventilation effectively. And task zone is amended for the comfort by conditioned air supplied from the floor and personal inlet unit.

Another major problem at this building is pressure loss between the room and corridor (that is wind core). The air from room to wind core is led through return path ducts in which conditioned air also passes through to return. In these pass duct, smoke and fire dumpers, which prevent smoke and fire extension, are set. The limitation of the size of pass duct and these smoke and fire dumpers lead to large loss of pressure and lead to decrease of air flow rate.

Figure 8.4-O Excerpt from the Pilot Study Report by Kato and Chikamoto (2002)

Great care must be taken in the design of natural ventilation systems to ensure that the system and building configuration can maintain acceptable thermal comfort and IAQ under all operating conditions. The following should be taking into consideration when designing natural and mixed-mode ventilation systems.

- Energy savings from daylighting depend on skylights and windows and electric lighting controls that need to be properly designed, commissioned, and maintained.
- Energy savings from natural cooling require that supplementary air-conditioning systems are turned off when windows are open.

The excerpt shown in Figure 8.4-O comes directly from the pilot study report on the Liberty Tower of Meiji University in Tokyo (Kato and Chikamoto 2002) and details the lessons learned as a result of monitoring the natural and hybrid ventilation systems employed in the building.

Strategy 8.4

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Strategy 8.5

IAQ 62.1

8.5

Use the ASHRAE Standard 62.1 IAQ Procedure Where Appropriate

Introduction

The IAQ Procedure (IAQP) provides designers with an important option or adjunct to the prescriptive Ventilation Rate Procedure (VRP) in *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (ASHRAE 2007a), thereby increasing the potential for good IAQ control. The IAQP has the potential to add additional protection against occupant exposure to harmful contaminants and to do so efficiently, thereby also saving energy.

The main approaches to controlling contaminant levels in indoor air are source control, ventilation, and filtration and gas-phase air cleaning (FAC). The IAQP generally employs all three of these basic control methods, allowing the realization of the combined strengths of each to yield the following potential benefits.

- It provides a methodology for documenting and predicting the outcome of source control tactics and rewards reduction tactics by potentially lowering ventilation requirements.
- It can lower the heat, moisture, and pollutant burden of outdoor air and reduce the outdoor airflow rate to the conditioned space.
- The use of enhanced FAC lowers the constituent contaminant concentrations of contaminants of concern (CoC) contained in the outdoor air.
- The use of enhanced FAC can lower the constituent concentrations of CoC created and recirculated within the conditioned space.
- Enhanced FAC can result in cleaner heat exchange surfaces and more sustainable energy-efficient HVAC systems.
- Lessening outdoor air can lower system capacity and operating costs by substituting lower-cost source control and/or FAC to replicate a portion of the outdoor air component.

History of the IAQP

The IAQP was first introduced in the original 1973 edition of ASHRAE Standard 62 and discussed again in 1981 as a portion of the recirculation discussion. In these early editions, the standard allowed the treatment of recirculated conditioned air using enhanced FAC to reduce the outdoor air ventilation requirement to as low as 5 cfm (2.5 L/s) per person, which was cited as the lowest acceptable rate. Because the 1981 edition of ASHRAE Standard 62 was not ANSI approved, the procedure was not widely applied or adopted into building codes, other than in a limited number of local jurisdictions such as Atlanta and Seattle.

The VRP was formalized in ASHRAE Standard 62-1989 as the prescriptive pathway using tables of rates-based space usage and occupancy. The IAQP was formalized at the same time as an alternate path to attain acceptable IAQ. However, the IAQP has not been widely used by designers because of its lack of acceptance by code-writing authorities, its complexity, and the additional engineering rigor required as compared to that needed for the VRP, including more calculations, analyses, and testing or retesting. The occasional usage of the procedure was predominately focused in the South, because of the high outdoor humidity and heat loads, or in buildings having high concentrations of contaminants from indoor sources, such as volatile organic compounds. Further, the procedure has been applied mostly in buildings having high density and wide diversity of occupancy, such as arenas, schools, auditoriums, theaters, convention centers, and hotels. In these spaces, the economic advantages can provide compelling returns on the additional design and equipment investment.

The 2007 edition of ASHRAE Standard 62.1 (ASHRAE 2007a) was written in code-enforceable language and is therefore somewhat more complex than previous versions. The VRP requires an engineering calculation for minimum ventilation values for both occupancy pollutant sources and building-derived sources. It establishes a minimum filtration efficiency of MERV 6 for both of the VRP and IAQP pathways. It requires assessment of the outdoor air pollutant levels and application of enhanced FAC of outdoor air when the site is in a nonattainment zone for PM10 or ozone. It includes requirements on start-up and maintenance, which implies additional attention in those areas that concern system access, cleanability, and operating efficiency that apply to both pathways. These additional levels of engineering attention combined with spiraling energy costs have created a much more attractive economic platform for considering the application of the IAQP.

When to Use the IAQP

The IAQP is most effectively applied under one or more of the conditions identified in Table 8.5-A. The overwhelming driver of the IAQP is economic because of the compelling potential savings in large, high-occupancy projects. However, several of the denoted conditions impose additional requirements upon the design team when employing the simpler VRP. Thus, in several conditions (marked with asterisks), this additional engineering rigor is already expended to meet the current level of compliance to the VRP of ASHRAE Standard 62.1-2007 (ASHRAE 2007a). This reduces the additional requirements necessary to evaluate and apply the IAQP alternative.

Table 8.5-A Optimal Conditions Indicating Consideration for IAQP Usage in Single-Zone Systems

Condition	Outcome
*Outdoor air is nonattainment for National Ambient Air Quality Standards (NAAQS) or otherwise polluted	Reduces burden of external ambient sources of particulate and gaseous pollutants
*Components selected for low out-gassing source contribution	Allows outdoor reduction through use of mass balance equations to document comparability to dilution
CoC are known or readily identifiable	Once identified, CoC concentrations can be evaluated and verified through mass balance equations and/or testing
*Identified CoC concentrations are high, requiring additional ventilation	Enables control of contaminants through FAC in conjunction with normal VRP rates, eliminating peak excess ventilation
*Supplemental ventilation required by code, standard, authority, or influencing document	Through FAC, excess component of ventilation is provided for attainment of points or compliance, while avoiding the energy burden of excessive outdoor air
Acceptable concentrations of CoC are established by cognizant authorities	Allows establishment of attainment targets of CoC to guide control/filtration requirements and to enable verification of attainment
Similar successful buildings are available for citation	Provides verification of success of IAQP in similar circumstances and guidance as to successful application.
Outdoor air is hot and humid	Allows reduction of latent heat load in hot and humid climates or during hot and humid peaks, resulting in potentially lowered capacity and operating energy demand
*FAC is already required for other considerations	Once enhanced FAC is a system component, no additional equipment investment is required to apply the IAQP
High population density and wide diversity prevail in building usage	With occupancy odor being the dominant CoC concurrent with widely varying space usage, the use of FAC allows substantial reduction of ventilation rates
Renovation of existing property	Implies contact with owner/tenant and greater awareness of CoC and potential establishment of targets of acceptability
Properties with existing capacity limitations	Enables compliance with current standards/codes using existing equipment relying on IAQP for supplemental contaminant control without additional HVAC capacity to treat added outdoor air
Involvement of motivated and knowledgeable owner	Involves owner who appreciates and gains from the economic advantages of the IAQP and is committed to maintenance of FAC

Applying the IAQP

Table 8.5-B outlines the design steps related to the application of the IAQP. The discussion in this section provides further information and guidance on the alternative criteria for application and compliance to the IAQP as cited from ASHRAE Standard 62.1 (ASHRAE 2007a). (See the *62.1 User's Manual* [ASHRAE 2007b] for more information.)

Table 8.5-B Applying the IAQP

Design Step	Application
Select IAQP alternative compliance method	Refer to Table 8.5-A for discussion of when it is potentially advisable and advantageous to employ the IAQP.
Determine and select CoC	Investigate and/or select CoC applicable for the project. Requires input from owner/occupant regarding weather and environment data; materials selection; and space usage, occupancy, and activity. May require air testing to determine.
Establish CoC sources and strengths	Determine the existing or expected sources, concentrations, and out-gassing rates of CoC to guide material selection tactics, control strategies, and efficiency and location requirements of control equipment. (See Appendix B of ASHRAE Standard 62.1 [ASHRAE 2007a] for assistance and guidance.) May require air testing to determine.
Determine cognizant authorities for CoC	Based upon CoC, determine and select the appropriate authority to support the targets of acceptability, such as EPA, NIOSH, WHO, etc. May include owners having cognizant experience with proprietary CoC used at their site.
Select method(s) for determining acceptability	See the discussion in the subsections under the heading "Applying the IAQP" in this Strategy for details on methods of establishing compliance and acceptability to occupants.
Determine targets of acceptability	Select the concentration levels determined to be acceptable and select the percentages perceived to be acceptable by an occupant observer panel.
Determine if excess ventilation is required	Based upon the CoC and their concentrations, determine whether excessive ventilation beyond normal VRP rates is required. Employ the IAQP to comply with "excess" ventilation requirements imposed by the owner, codes, or other standards.
Apply appropriate source control tactics	Apply source control tactics (see the Strategies in Objective 5 – Limit Contaminants from Indoor Sources) prior to employing FAC. Elimination or avoidance of contaminants is usually more cost-effective than FAC.
Determine FAC requirement	Dependent upon CoC nature, source, concentration, and out-gassing generation rate, select, apply, and locate the appropriate FAC control methodology. (See the discussion on filtration selection in Strategy 7.5 – Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives).
Evaluate IAQP for supplemental needs	Apply FAC to treat selected zones for compliance, to treat the total building to attain improved IAQ acceptability, or to supplement the ventilation effectiveness beyond the VRP rate.
Determine availability of similar successful buildings	If this is the selected method of compliance, investigate and document similar building experiences and performance.
Perform mass balance calculations	If the selected method, perform the appropriate mass equations as detailed in Appendix D of ASHRAE Standard 62.1 (ASHRAE 2007a) to determine that the attained results from source reduction or FAC replicate the normal VRP dilution rate.
Perform compliance methods	Use testing and monitoring of CoC or the acceptability panel to evaluate the treated space to establish acceptability and compliance. May require air testing to determine.
Provide documentation	Document each step of the IAQP design process, including the selection rationale, the CoC with sources and strengths, the reduction or control methodology, the compliance method, and the compliance data.

Mass Balance

Mass balance equations are provided by ASHRAE Standard 62.1 in its Appendix D (ASHRAE 2007a).

Figure 8.5-B provides eight different single-zone system arrangements to enable the determination of steady-state conditions applicable to each. These calculations provide the outdoor airflow and resulting

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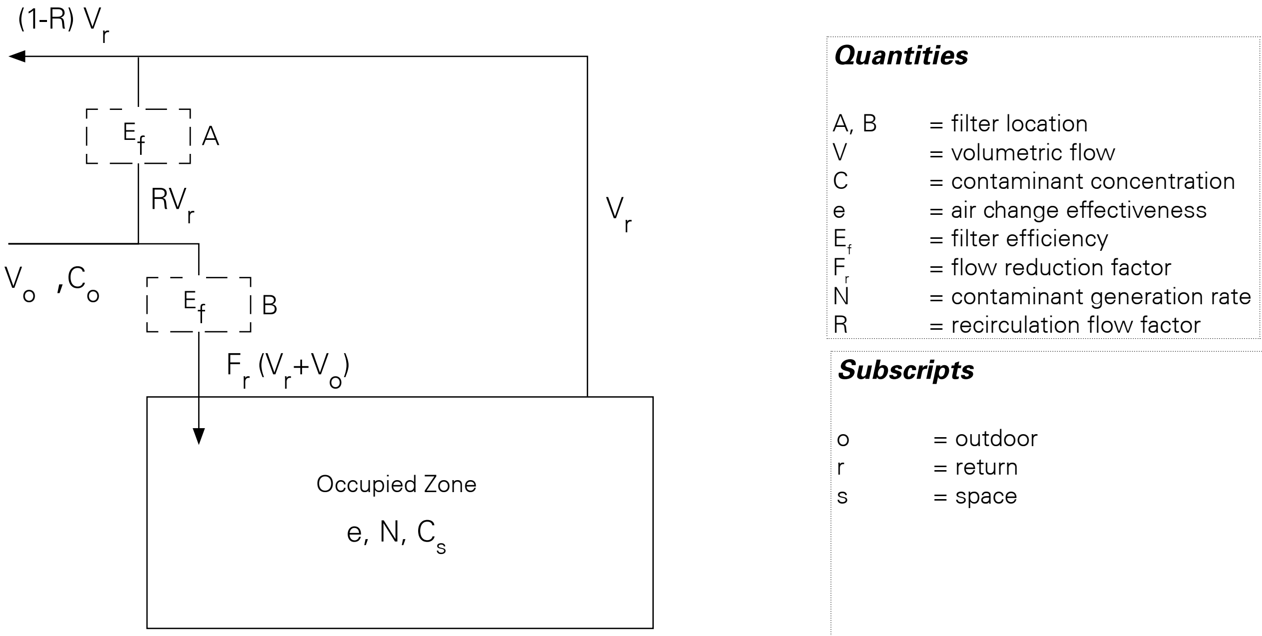

Figure 8.5-B Required Outdoor Air or Space Contaminant Concentration with Recirculation and Filtration
Adapted from ASHRAE (2007a), Figure D-1, with code quantities and subscripts.

space contaminant concentration comparing the effect of dilution with filtration removal or extraction efficiency. Other tools are also available to the designer to provide similar data, for example, contaminant modeling programs such as CONTAM (NIST 2008).

Successful Buildings

Successful buildings provide local authorities assurance of the successful history of the application of the IAQP under similar conditions. Although there are a number of buildings that have successfully employed the IAQP, they tend to fall into the classes of buildings in hot and humid climates and/or those experiencing high occupancy and/or wide diversity of occupancy density and/or activity and, thus, represent a small percentage of the building stock. Yet, the energy savings and related air quality improvements from the successful usage of the IAQP provide powerful incentives and benefits, as illustrated in the case study in this Strategy titled "Using the IAQP in a Southeastern High-Rise Hotel." Because of the recurring surge of energy prices, the stories of these buildings are emerging along with the reports of their energy savings (Burroughs 2006). Their influence provides high value in supporting the usage of the IAQP and warrants the effort to seek out the justification of this method.

Contaminant Air Monitoring and Testing

Contaminant air monitoring and testing is required during the evaluation period when the CoC are not easily determined or, if known, when their concentrations or source strengths or generation rates are not known. Other than this initial usage of air testing, monitoring and air testing may also be used to verify the delivered concentration after treatment with FAC. This process verifies that the product of the IAQP is equal to or better than the expectation of the VRP. The process of air testing can be costly because it requires trained operating personnel and specialized monitoring equipment. Thus, care needs to be taken to be precise and focused in the selection of critical CoC for testing and evaluation to reduce the testing costs. This alternate also contains a requirement for the setting and verification of acceptability limits for the perceived IAQ. For example, if the acceptance level is set at 80%, then an untrained panel of occupants must be used to

Using the IAQP in a Southeastern High-Rise Hotel

Figure 8.5-C Southeastern High-Rise Hotel
Photograph courtesy of H.E. Burroughs.

The system shown in Figure 8.5-C is in a high-rise hotel in a major Southeastern city and was built using an atrium-style tower. The structure is approximately 40 years old and has been subjected to increasing heat loads and increased numbers of occupant complaints due to a combination of aging mechanical equipment and the additional load of solar reflections from more recently constructed high-rise office buildings surrounding the glass tower of the hotel. The hotel operating personnel experienced increasing difficulty sustaining comfort and humidity conditions in the upper strata of the tower atrium.

As an energy conservation measure and to enhance cooling capacity, four recirculation units were installed on each quadrant of the hotel roof. The four recirculation air handlers collect exhaust air from the hotel tower rooms and treat the air with high-efficiency solid-bed gas-phase filtration equipment. The filter systems are also equipped with MERV 6 filters installed upstream and downstream of the gas filter cartridges. Two of the 20,000 cfm (9440 L/s) air handlers (south and west units) are also equipped with cooling coils to augment the cooling capacity of the building. All of the units free-blow into the top of the tower atrium to replace a total of 80,000 cfm (37,760 L/s) of previously required outdoor makeup air.

The calculated cost savings to replace this amount of makeup air totals $111,909 per annum, less the annual FAC maintenance and operating cost of $6,808, yielding a net saving of $105,101 per year. Air testing performed in 2007 indicated an average system efficiency of 62% for reduction of 1 µm sized particles. Measured total volatile organic compounds (TVOCs) averaged 376 $\mu g/m^3$ in the supply air, with return air from the space measured in excess of 1000 $\mu g/m^3$.

Data source: H.E. Burroughs.

verify that more than 80% of the group affirms the acceptability of the IAQ after no more than a 15-second exposure to the subject space. Either the air testing or the perceived air quality evaluation can be performed as an alternate method of compliance.

Combination with VRP

Combining the IAQP with the VRP makes sense in certain situations. For example, if the change of usage of a space converts a low-density office into a high-density conference room, the IAQP can be applied to this particular space to provide acceptable IAQ in this subzone without increasing the outdoor air quantity to the entire space. In another example, when specific CoC would require additional outdoor air to create sufficient dilution, the IAQP can be employed through the addition of enhanced filtration to control those CoC in conjunction with the normal VRP rate. Other programs and influences, such as the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) Green Buildings Rating System (USGBC 2008), may encourage the general premise of up to 30% outdoor air additional to the normal VRP rate to meet their performance criteria. The IAQP can also provide contaminant removal, which may result in a similar reduction in contaminant concentration without increasing dilution ventilation, attaining this additional increment through FAC rather than additional outdoor air.

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IAQ
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8.5

Use of the IAQP in the Texas School District

Figure 8.5-D Texas School Building
Photograph courtesy of Gerald Lamping.

A Southwestern Texas school district applied the IAQP to a high school that was experiencing high humidity, IAQ complaints, and high energy costs (Figure 8.5-D). After the selection of CoC and related air testing, the selection of concentration limits, and setting of the perceived IAQ acceptance level, the IAQP was implemented. The system employed enhanced particulate air filters (MERV 8) and medium-efficiency gas-phase filtration to reduce the outdoor air component by 9760 cfm (4607 L/s). Annual energy savings were measured at 68,897 kWh of electricity, 4,091 therms of natural gas, and $11,900 in cost. Concurrently, the school reported elimination of IAQ complaints from teachers and has documented a reduction of student usage of asthma inhalers by 50%. Tested CoC and target concentrations are noted in Tables 8.5-C and 8.5-D of this Strategy.

Process for Applying the IAQP

IAQP Design Process Flowchart

Figure 8.5-E is a visual description of the process taken from the *62.1 User's Manual* (ASHRAE 2007b) that illustrates the IAQP design process.

Selection of Contaminants of Concern (CoC)

The selection of the appropriate CoC has been the primary area of discomfort to designers in the consideration of the IAQP and, thus, deserves further elaboration. In new construction projects, designers have traditionally been wary of the IAQP because of potential liability as well as the cost of additional engineering effort. This fear regarding risk is well founded when the base building design is a generic and/or speculative office building and the designer does not have full knowledge of the environmental conditions or the intended occupant density or activity. This situation does not allow the design team sufficient knowledge to develop the CoC or definitive target acceptability criteria, since the occupancy is unknown. These open questions expose the designer to greater risk because of vague information and the need to make too many assumptions.

However, when the project is a building renovation with an existing and known owner, having an existing operating history, located in an established site setting with environmental history data, and having an established occupancy quantity and activity, it is more feasible to consider and apply the IAQP.

In some instances, the IAQP is far more cost-effective than the VRP for design, construction, and operation. As an example, a building may have been built to prior (lower) ventilation standards and bringing the facility to comply with current code would require substantially increased HVAC capacity. If replacement of this equipment is not required as part of the renovation, then compliance to current improved IAQ acceptability may be attained using the IAQP without upgrading or replacing the existing HVAC equipment. The only equipment modification that is required is to accommodate for the addition of enhanced particulate and/or gas-phase filtration.

Direct contact between the designer and the owner/occupant of a project facilitates the designation and selection of the CoC, their concentration strengths, and acceptability targets for both the specific CoC targets

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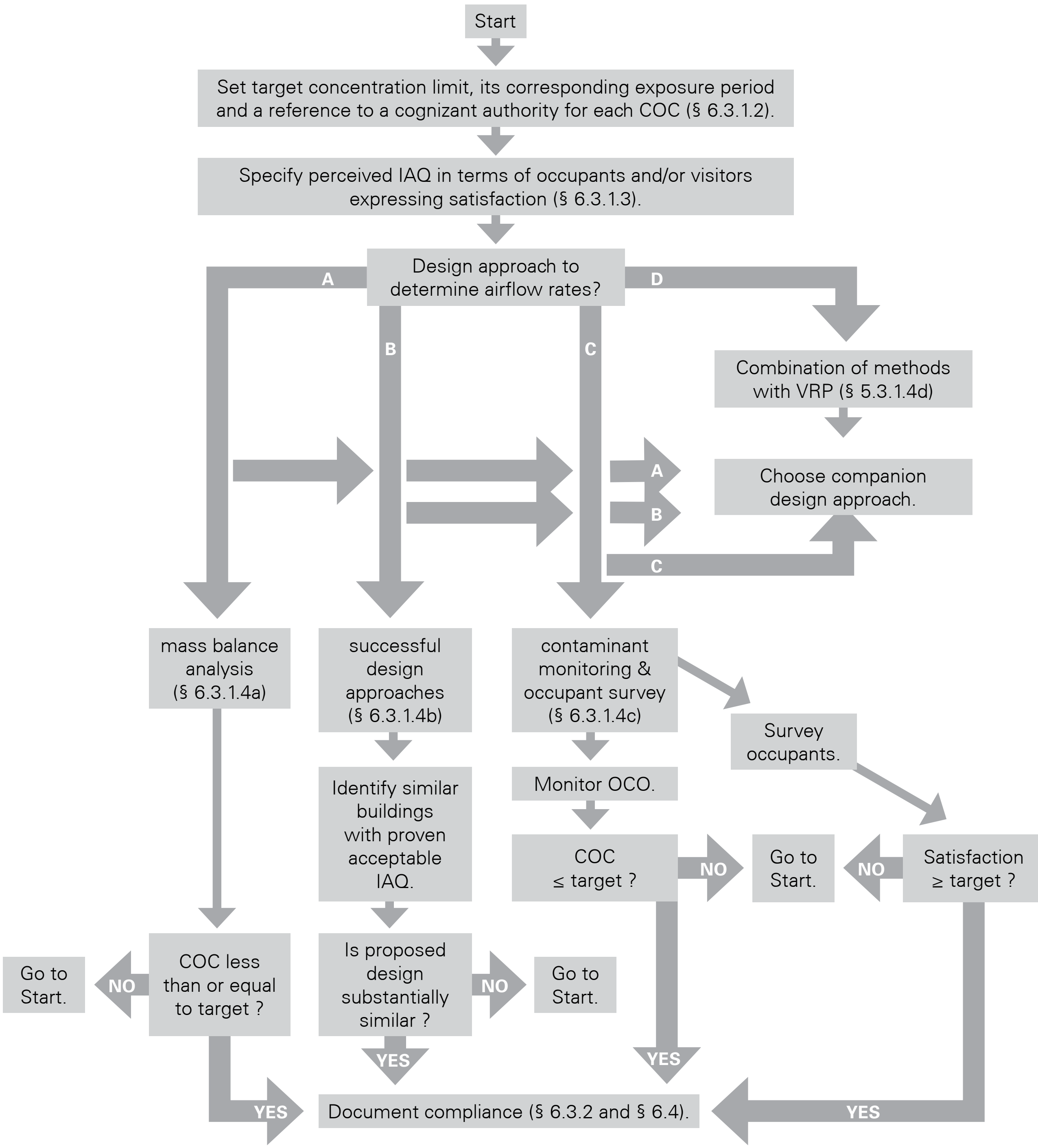

Figure 8.5-E IAQP Design Flowchart
Adapted from ASHRAE (2007).

as well as the perceived air quality. Tables 8.5-C and 8.5-D illustrate the technique of CoC selection that was performed during the project described in the case study in this Strategy titled "Use of the IAQP in the Texas School District." The school district staff designated as potential contaminant sources the building, the occupants, and the outdoor air and then selected specific contaminants to profile and replicate these sources.

Table 8.5-C illustrates the selected contaminants and Table 8.5-D (Stanley and Lamping 2007) provides the related standards and guidelines from which the target attainment data were derived.

Table 8.5-C Gaseous Contaminants of Concern (CoC) used in High School Application
Source: Stanley and Lamping (2007).

Occupants		Building Materials	
Acetone	Ethyl acetate	Acetone	Nonane
Acetaldeyde	Ethyl alcohol	Benzaldehyde	4-phenylcyclohexene
Acetic acid	Hydrogen sulfide	Benzene	Pinene
Allyl alcohol	Methane	n-butanol	Propanol
Amyl alcohol	Methyl alcohol	2-butonone	2-propanone
Ammonia	Methylene chloride	2-butoxyethanol	Siloxane
Benzene	Phenol	Decamethylcyclopentasiloxane	Tetrachloroethane
Butyric acid	Propane	n-decane	Texanol isomers
l-butanone	Tetrachloroethane	n-dodecane	Tolulene
Carbon dioxide	Tetrachloroethylene	Ethyl benzene	1,1,1-trichloroethane
Carbon monoxide	Toluene	2-ethyl-1-hexanol	Trimethyl benzene
Chloroform	1,1,1-trichloroethane	Formaldehyde	TVOCs
Diethyl ketone	Vinyl chloride monomer	Hexanal	Undecane
Dioxane	Xylene	Limonene	Xylene

Table 8.5-D Selected Standards and Guidelines Used to Determine CoC in High School Application
Source: Stanley and Lamping (2007).

Contaminant	Concentration	Time Duration	Description
Criteria Contaminant Examples			
Carbon monoxide	9 ppm (10.3 mg/m^3)	8 hours	National Ambient Air Quality Standards (NAAQS) (EPA 2008)
	50 ppm (57 mg/m^3)	8 hours	Permissible Exposure Limit Measured as a Time-Weighted Average (PEL-TWA) (OSHA 2009)
Lead	1.5 mg/m^3	Quarterly average	NAAQS
	50 mg/m^3	8 hours	PEL-TWA
Nitrogen dioxide	0.053 ppm (0.1 mg/m^3)	Annual mean	NAAQS
	5 ppm (9.4 mg/m^3)	Ceiling	Permissible Exposure Limit as an Acceptable Ceiling Concentration (PEL-C) (OSHA 2009)
Other Indoor Air Contaminant Examples			
Acetone	2.4 ppm (5.7 mg/m^3)	1 hour	Alberta Ambient Air Quality Objectives (Alberta Environment 2009)
	1000 ppm (2370 mg/m^3)	8 hours	PEL-TWA
Formaldehyde	0.04 ppm (0.05 mg/m^3)	8 hours	*Exposure Guidelines for Residential Indoor Air Quality* (Health Canada 1995)

Contaminant	Concentration	Time Duration	Description
	0.75 ppm (0.92 mg/m^3)	8 hours	PEL-TWA
Hydrogen sulfide	0.03 ppm (0.04 mg/m^3)	1 hour	California Ambient Air Quality Standards (ARB 2008)
	20 ppm (28 mg/m^3)	Ceiling	PEL-C

Documentation

The thorough documentation of the IAQP process is critical to ensure acceptance by local authorities. Documentation is also is critical to proper commissioning and training of operation and maintenance personnel. Each step of the process needs to be documented and provided to the the owner. The documentation ought to consist of not less than the following.

- The rationale for selecting the IAQP and the compliance method.
- The CoC used in the process.
- The sources and sources strengths of the CoC both outdoors and and indoors.
- The target concentration limits and their related sources of cognizant authority.
- An iteration and details about successful similar buildings along with the basis for concluding that the design approach was successful and that they are similar in design to the proposed usage.
- The evaluation details and with results if contaminant testing and occupant satisfaction evalution were employed to demonstrate compliance.

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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.

Appendix A

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.

Appendix A

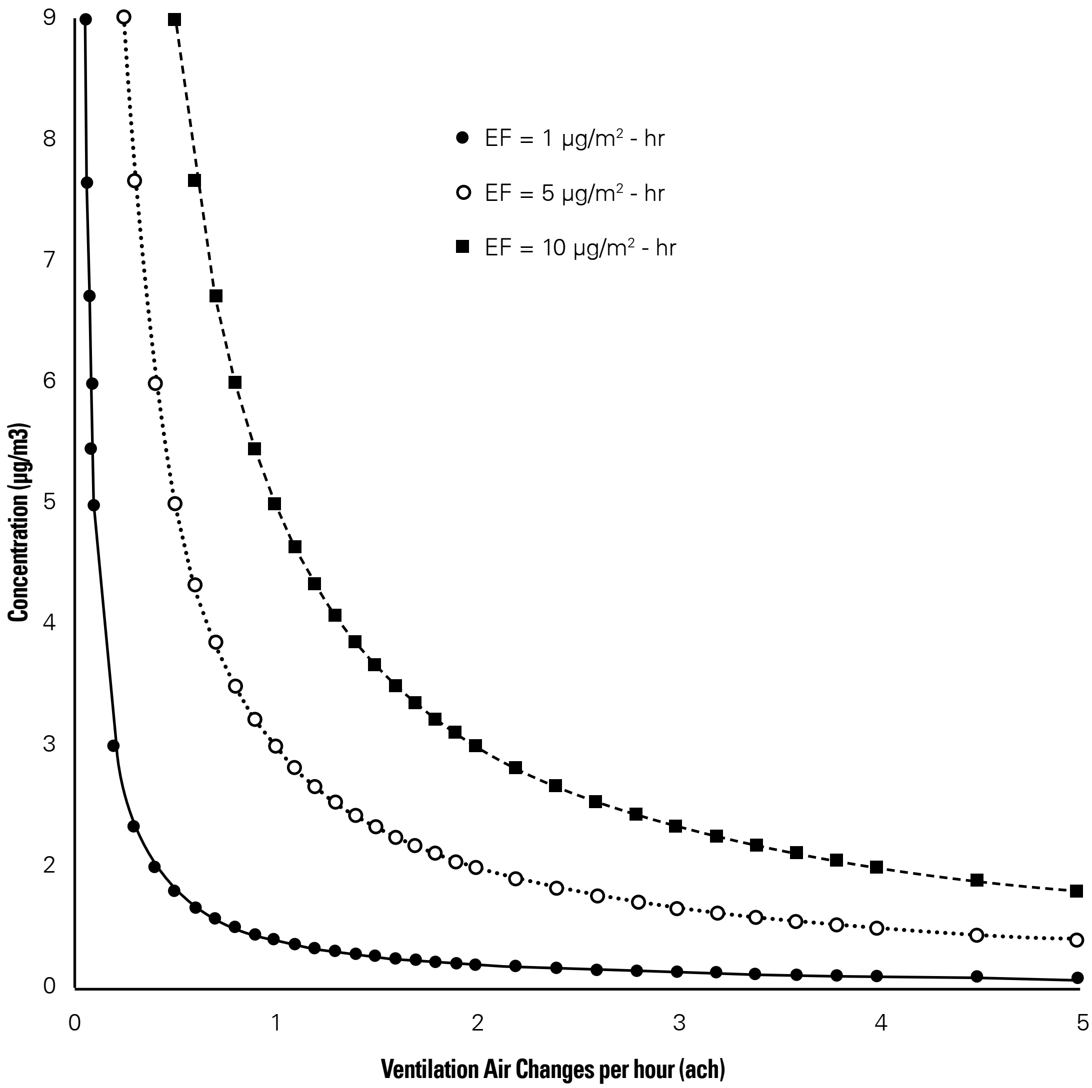

Figure A-1 Relationship of Source Strength, Ventilation, and Pollutant Concentration

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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Appendix B

Understanding Vapor Barriers

Vapor retarders may or may not be needed in a building assembly, depending on climate, the composition of the assembly, and the building's interior environment. The article "Understanding Vapor Barriers" by J.W. Lstiburek reprinted in this appendix (2004, *ASHRAE Journal* 46[8]:40–50), which formed the basis of code changes in the *International Energy Conservation Code* 2007 supplement (*IECC* 2007 Supplement, International Code Council, Washington, DC), is quite comprehensive and does the subject justice.

Understanding Vapor Barriers

By Joseph W. Lstiburek, Ph.D., P.Eng., Member ASHRAE

The function of a vapor barrier is to retard migration of water vapor. Where it is located in an assembly and its permeability is a function of climate, the characteristics of the materials that comprise the assembly and the interior conditions. Vapor barriers are not typically intended to retard migration of air. That is the function of air barriers.

Confusion on the issue of vapor barriers and air barriers is common. The confusion arises because air often holds a great deal of moisture in vapor form. When this air moves from location to location, due to an air pressure difference, the vapor moves with it. This is a type of migration of water vapor. In the strictest sense air barriers are also vapor barriers when they control the transport of moisture-laden air.

An excellent discussion about the differences between vapor barriers and air barriers can be found in Quirrouette.[1]

Vapor barriers are also a cold climate artifact that have diffused into other climates more from ignorance than need. The history of cold climate vapor barriers itself is a story based more on personalities than physics. Rose[2] regales readers of this history. It is frightening that construction practices can be so dramatically influenced by so little research and reassuring that the inherent robustness of most building assemblies has been able to tolerate such foolishness.

So What is The Problem?

Incorrect use of vapor barriers is leading to an increase in moisture-related problems. Vapor barriers were originally intended to prevent assemblies from getting wet. However, they often prevent assemblies from drying. Vapor barriers installed on the interior of assemblies prevent assemblies from drying inward. This can be a problem in any air-conditioned enclosure, in any below grade space, or when a vapor barrier is also on the exterior. Additionally, this can be a problem where brick is installed over building paper and vapor permeable sheathing.

What Do We Really Want to Do?

Two seemingly simple requirements for building enclosures bedevil engineers and architects almost endlessly:

- Keep water out, and
- Let water out if it gets in.

Water can come in several phases: liq-

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uid, solid, vapor and adsorbed. The liquid phase as rain and groundwater has driven everyone crazy for hundreds of years but can be readily understood — drain everything and remember the humble flashing.

The solid phase also drives everyone crazy when we have to shovel it or melt it, but at least most professionals understand the related building problems (ice damming, frost heave, freeze-thaw damage).

However, the vapor phase is in a class of craziness all by itself. We will conveniently ignore the adsorbed phase and leave it for someone else to deal with. Note that adsorbed water is different than absorbed water.[3]

The fundamental principle of control of water in the liquid form is to drain it out if it gets in — and let us make it perfectly clear — it will get in if you build where it rains or if you place your building in the ground where there is water in the ground. This is easy to understand, logical, with a long historical basis.

The fundamental principle of water control in the solid form is to not let it become solid. And, if it does, give it space. Or, if it is solid, do not let it become liquid. If it does become liquid, drain it away before it can become solid again. This is a little more difficult to understand, but logical and based on solid research. Examples of this principle include the use of air entrained concrete to control freeze-thaw damage and the use of attic venting to provide cold roof decks to control ice damming.

The fundamental principle of water control in the vapor form is to keep it out and to let it out if it gets in. Simple, right? No chance. It becomes complicated because sometimes the best strategies to keep water vapor out also trap water vapor in. This can be a real problem if the assemblies start out wet because of rain or the use of wet materials.

Photo credit: IBACOS

"Incorrect use of vapor barriers is leading to an increase in moisture-related problems."

It becomes even more complicated because of climate. In general, water vapor moves from the warm side of building assemblies to the cold side. This is simple to understand, except we have trouble deciding what side of a wall is the cold or warm side. Logically, this means we need different strategies for different climates. We also must take into account differences between summer and winter.

Finally, complications arise when materials can store water. This can be both good and bad. A cladding system such as a brick veneer can act as a reservoir after a rainstorm and significantly complicate wall design. Alternatively, wood framing or masonry can act as a hygric buffer absorbing water and lessening moisture shocks.

What is required is to define vapor control measures on a more regional climatic basis and to define the vapor control measures more precisely.

Part of the problem is that we struggle with names and terms. We have vapor retarders, vapor barriers, vapor permeable, vapor impermeable, etc. What do these terms mean? It depends on whom you ask and whether they are selling something, or arguing with a building official. In an attempt to clear up some of the confusion, the following definitions are proposed:

Vapor Retarder*: *The element that is designed and installed in an assembly to retard the movement of water by vapor diffusion.*

* taken somewhat from *2001 ASHRAE Handbook—Fundamentals*, Chapter 23.

The unit of measurement typically used in characterizing the water vapor permeance of materials is the "perm." It is further proposed here that there should be several classes of vapor retarders. (This is nothing new. It is an extension and modification of the Canadian General Standards Board approach that specifies Type I and Type II vapor retarders. The numbers here are a little different, however.).These classes are:

Class I	0.1 perm or less
Class II	1.0 perm or less and greater than 0.1 perm
Class III	10 perm or less and greater than 1.0 perm

Test procedure for vapor retarders: ASTM E-96 Test Method A (the desiccant method or dry cup method)

Finally, a vapor barrier is defined as:

Vapor Barrier: A Class I vapor retarder.

The current International Building Code (and its derivative codes) defines a vapor retarder as 1.0 perm or less (using the same test procedure). In other words, the current code definition of a vapor retarder is equivalent to the definition of a Class II vapor retarder proposed by the author.

Continuing in the spirit of finally defining terms that are tossed around in the enclosure business, it is also proposed that materials be separated into four general classes based on their permeance (again nothing new, this is an extension of the discussion in a previous *ASHRAE Journal* article[4]):

Appendix B

Vapor impermeable:	0.1 perm or less
Vapor semi-impermeable:	1.0 perm or less and greater than 0.1 perm
Vapor semi-permeable:	10 perms or less and greater than 1.0 perm
Vapor permeable:	greater than 10 perms

Recommendations for Building Enclosures

The following building assembly recommendations are climatically based (see sidebar, "Hygrothermal Regions") and are sensitive to cladding type (brick or stone veneer, stucco) and structure (concrete block, steel or wood frame, precast concrete).

The recommendations apply to residential, business, assembly, educational and mercantile occupancies. The recommendations do not apply to special use enclosures such as spas, pool buildings, museums, hospitals, data processing centers or other engineered enclosures such as factory, storage or utility enclosures.

The recommendations are based on the following principles:

• Avoiding use of vapor barriers where vapor retarders will provide satisfactory performance. Avoiding use of vapor retarders where vapor permeable materials will provide satisfactory performance. (thereby, encouraging drying mechanisms over wetting-prevention mechanisms).

• Avoiding the installation of vapor barriers on both sides of assemblies, i.e., "double vapor barriers," to facilitate assembly drying in at least one direction.

• Avoiding installation of vapor barriers such as polyethylene vapor barriers, foil faced batt insulation and reflective radiant

Hygrothermal Regions

Subarctic and Arctic

A subarctic and arctic climate is defined as a region with approximately 12,600 heating degree days (65°F basis) (7,000 heating degree days [18°C basis]) or greater.

Very Cold

A very cold climate is defined as a region with approximately 9,000 heating degree days or greater (65°F basis) (5,000 heating degree days [18°C basis]) or greater and less than 12,600 heating degree days (65°F basis) (7,000 heating degree days [18°C basis]).

Cold

A cold climate is defined as a region with approximately 5,400 heating degree days (65°F basis) (3,000 heating degree days [18°C basis]) or greater and less than approximately 9,000 heating degree days (65°F basis) (5,000 heating degree days [18°C basis]).

Mixed-Humid

A mixed-humid and warm-humid climate is defined as a region that receives more than 20 inches (50 cm) of annual precipitation with approximately 4,500 cooling degree days (50°F basis) (2,500 cooling degree days [10°C basis]) or greater and less than approximately 6,300 cooling degree days (50°F basis) (3,500 cooling degree days [10°C basis]) and less than approximately 5,400 heating degree days (65°F basis) (3,000 heating degree days [18°C basis]) and where the average monthly outdoor temperature drops below 45°F (7°C) during the winter months.

Marine

A marine climate is defined as a region where all of the following occur:

- A mean temperature of the coldest month between 27°F (–3°C) and 65°F (18°C);
- A mean temperature of the warmest month below 72°F (18°C);
- At least four months with mean temperatures over 50°F (10°C); and
- A dry season in the summer, the month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation.

Hot-Humid

A hot-humid climate is defined as a region that receives more than 20 in. (50 cm) of annual precipitation with approximately 6,300 cooling degree days (50°F basis) [3,500 cooling degree days (10°C basis)] or greater and where the monthly average outdoor temperature remains above 45°F (7°C) throughout the year.

This definition characterizes a region that is similar to the ASHRAE definition of hot-humid climates where one or both of the following occur:

- A 67°F (19.5°C) or higher wet-bulb temperature for 3,000 or more hours during the warmest six consecutive months of the year; or

- A 73°F (23°C) or higher wet-bulb temperature for 1,500 or more hours during the warmest six consecutive months of the year.

Hot-Dry, Warm-Dry and Mixed-Dry

A hot-dry climate is defined as region that receives less than 20 in. (50 cm) of annual precipitation with approximately 6,300 cooling degree days (50°F basis) [3,500 cooling degree days (10°C basis)] or greater and where the monthly average outdoor temperature remains above 45°F (7°C) throughout the year.

A warm-dry and mixed-dry climate is defined as a region that receives less than 20 in. (50 cm) of annual precipitation with approximately 4,500 cooling degree days (50°F basis) [2,500 cooling degree day (10°C basis)] or greater and less than approximately 6,300 cooling degree days (50°F basis) [3,500 cooling degree days (10°C basis)] and less than approximately 5,400 heating degree days (65°F basis) [3,000 heating degree days (18°C basis)] and where the average monthly outdoor temperature drops below 45°F (7°C) during the winter months.

barrier foil insulation on the interior of air-conditioned assemblies (a practice that has been linked with moldy buildings).[5]

• Avoiding installation of vinyl wall coverings on the inside of air-conditioned assemblies (a practice that has been linked with moldy buildings).[6]

• Enclosures are ventilated meeting ASHRAE Standards 62.1 or 62.2.

Each of the recommended building assemblies was evaluated using dynamic hygrothermal modeling. The moisture content of building materials that comprise the building assemblies all remained below the equilibrium moisture content the materials as specified in ASHRAE proposed Standard 160P, Design Criteria for Moisture Control in Buildings, under this evaluation approach. Interior air conditions and exterior air conditions as specified by 160P were used. WUFI was used as the modeling program.[7]

More significantly, each of the recommended building assemblies have been found by the author to provide satisfactory performance under the limitations noted. Satisfactory performance is defined as no moisture problems reported or observed during at least a 10-year period. The only exceptions relate to the assemblies containing low density spray applied foams. The author has only been familiar with their use in assemblies less than five years old.

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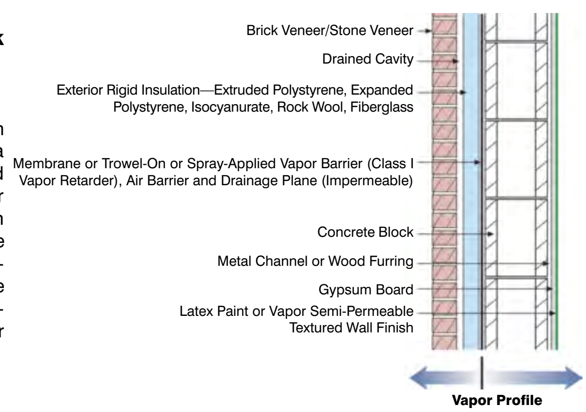
Assembly 1: Concrete Block With Exterior Insulation and Brick or Stone Veneer

Applicability: all hygrothermal regions.

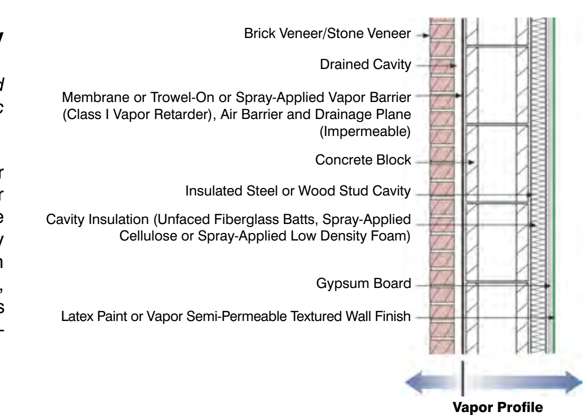
This is arguably the most durable wall assembly. It is constructed from non-water sensitive materials, and due to the block construction, has a large moisture storage (or hygric buffer) capacity. It can be constructed virtually anywhere. In cold climates condensation is limited on the interior side of the vapor barrier as a result of installing all of the thermal insulation on the exterior side of the vapor barrier (which is also the drainage plane and air barrier in this assembly). In hot climates any moisture that condenses on the exterior side of the vapor barrier will be drained to the exterior since the vapor barrier is also a drainage plane. This wall assembly will dry from the vapor barrier inwards and will dry from the vapor barrier outwards.



Assembly 2: Concrete Block With Interior Frame Wall Cavity Insulation and Brick or Stone Veneer

Applicability: Limited to mixed-humid, hot-humid, mixed-dry, hot-dry and marine regions; should not be used in cold, very cold, and subarctic/arctic regions.

This wall assembly has all of the thermal insulation installed to the interior of the vapor barrier, and therefore, should not be used in cold regions or colder. It is also a durable assembly due to the block construction and the associated moisture storage (hygric buffer) capacity. The wall assembly does contain water sensitive cavity insulation (except where spray foam is used) and it is important that this assembly can dry inwards—therefore, vapor semi-impermeable interior finishes such as vinyl wall coverings should be avoided. In this wall assembly the vapor barrier is also the drainage plane and air barrier.



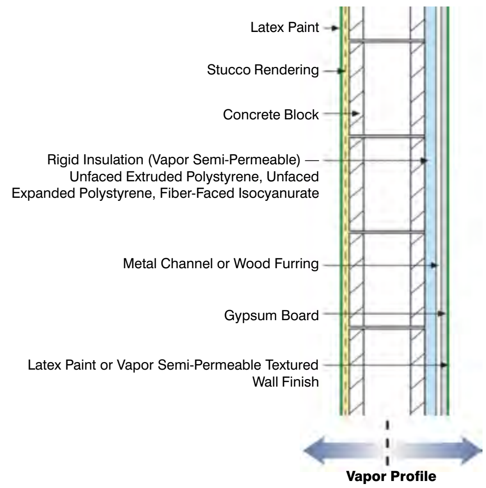
Appendix B

Assembly 3: Concrete Block With Interior Rigid Insulation and Stucco

*Applicability: all hygrothermal regions.**

This assembly has all of the thermal insulation installed on the interior of the concrete block construction but differs from *Assembly 2* since it does not have a vapor barrier on the exterior. The assembly also does not have a vapor barrier on the interior of the assembly. It has a large moisture storage (hygric buffer) capacity due to the block construction. The rigid insulation installed on the interior should be non-moisture sensitive and allow the wall to dry inwards, hence, the recommended use of vapor semi permeable foam sheathing. Note that the foam sheathing is not faced with aluminum foil or polypropylene skins. It is important that this assembly can dry inwards except in very cold and subarctic/arctic regions. Therefore, vapor semi-impermeable interior finishes such as vinyl wall coverings should be avoided in assemblies—except in very cold and subarctic/arctic regions. Vapor impermeable foam sheathings should be used in place of the vapor semi permeable foam sheathings in very cold and subarctic/arctic regions. The drainage plane in this assembly is the latex painted stucco rendering. A Class III vapor retarder is located on both the interior and exterior of the assembly (the latex paint on the stucco and on the interior gypsum board).

* In very cold and subarctic/arctic regions vapor impermeable foam sheathings are recommended.

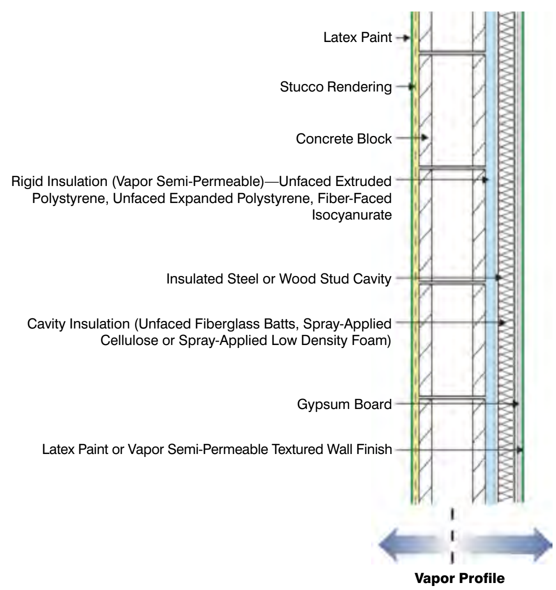


Assembly 4: Concrete Block With Interior Rigid Insulation/Frame Wall With Cavity Insulation and Stucco

*Applicability: all hygrothermal regions.**

This assembly is a variation of *Assembly 3*. It also has all of the thermal insulation installed on the interior of the concrete block construction but differs from *Assembly 3* due to the addition of a frame wall to the interior of the rigid insulation. This assembly also does not have a vapor barrier on the exterior. The assembly also does not have a vapor barrier on the interior of the assembly. It has a large moisture storage (hygric buffer) capacity due to the block construction. The rigid insulation installed on the interior should be non-moisture sensitive and allow the wall to dry inwards, hence, the recommended use of vapor semi permeable foam sheathing. Note that the foam sheathing is not faced with aluminum foil or polypropylene skins. It is important that this assembly can dry inwards even in very cold and subarctic/arctic regions. Therefore, vapor semi-impermeable interior finishes such as vinyl wall coverings should be avoided in assemblies. Vapor impermeable foam sheathings should be used in place of the vapor semi permeable foam sheathings in very cold and subarctic/arctic regions. The drainage plane in this assembly is the latex painted stucco rendering. A Class III vapor retarder is located on both the interior and exterior of the assembly (the latex paint on the stucco and on the interior gypsum board.

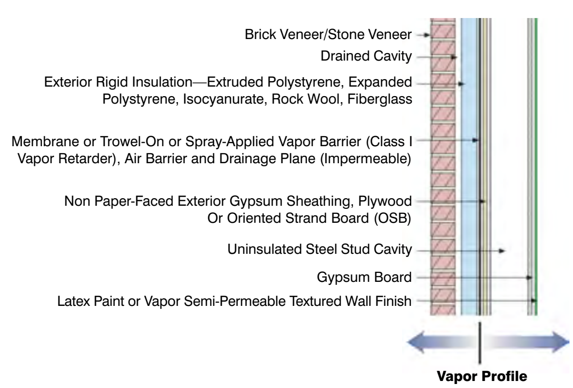
* In very cold and sub-arctic/arctic regions vapor impermeable foam sheathings are recommended—additionally the thickness of the foam sheathing should be determined by hygrothermal analysis so that the interior surface of the foam sheathing remains above the dew point temperature of the interior air (see sidebar, "Proposed Building Code Requirements for Vapor Retarders," see *Figures 2* and *3*).



Assembly 5: Frame Wall With Exterior Insulation and Brick or Stone Veneer

Applicability: all hygrothermal regions.

This wall is a variation of *Assembly 1* but without the moisture storage (or hygric buffer) capacity. This wall is also a durable wall assembly. It is constructed from non-water sensitive materials and has a high drying potential inwards due to the frame wall cavity not being insulated. It also can be constructed virtually anywhere. In cold climates condensation is limited on the interior side of the vapor barrier as a result of installing all of the thermal insulation on the exterior side of the vapor barrier (which is also the drainage plane and air barrier in this assembly). In hot climates any moisture that condenses on the exterior side of the vapor barrier will be drained to the exterior since the vapor barrier is also a drainage plane. This wall assembly will dry from the vapor barrier inwards and will dry from the vapor barrier outwards.

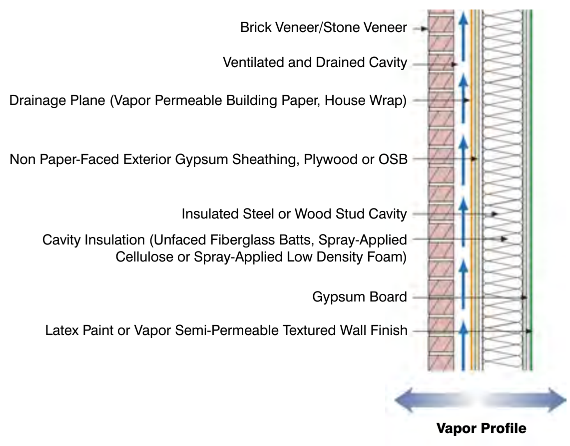


Appendix B

Assembly 6: Frame Wall With Cavity Insulation and Brick or Stone Veneer

Applicability: Limited to mixed-humid, hot-humid, mixed-dry, hot-dry and marine regions. It can be used with hygrothermal analysis in some areas in cold regions (Zone 5, but not Zone 6. See sidebar, "Proposed Building Code Requirements for Vapor Retarders"); should not be used in very cold and subarctic/arctic regions.

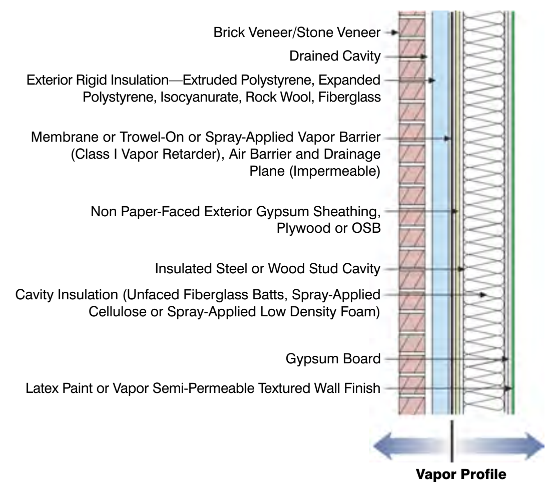
This wall is a flow-through assembly. It can dry to both the exterior and the interior. It has a Class III vapor retarder on the interior of the assembly (the latex paint on the gypsum board). It is critical in this wall assembly that the exterior brick veneer (a "reservoir" cladding) be uncoupled from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 2 in. (51 mm) wide (source: Brick Institute of America) and free from mortar droppings. It also must have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top to provide back ventilation of the brick veneer. The drainage plane in this assembly is the building paper or building wrap. The air barrier can be any of the following: the interior gypsum board, the exterior gypsum wallboard or the exterior building wrap.



Assembly 7: Frame Wall With Exterior Rigid Insulation With Cavity Insulation and Brick or Stone Veneer

Applicability: all hygrothermal regions except subarctic/arctic. In cold and very cold regions, the thickness of the foam sheathing should be determined by hygrothermal analysis so that the interior surface of the foam sheathing remains above the dew-point temperature of the interior air (see sidebar, "Proposed Building Code Requirements for Vapor Retarders," see Figures 2 *and* 3*).*

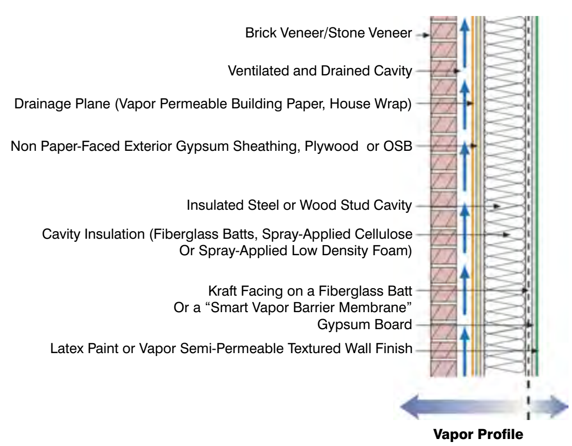
This wall is a variation of *Assembly 5*. In cold climates condensation is limited on the interior side of the vapor barrier as a result of installing some of the thermal insulation on the exterior side of the vapor barrier (which is also the drainage plane and air barrier in this assembly). In hot climates any moisture that condenses on the exterior side of the vapor barrier will be drained to the exterior since the vapor barrier is also a drainage plane. This wall assembly will dry from the vapor barrier inwards and will dry from the vapor barrier outwards. Since this wall assembly has a vapor barrier that is also a drainage plane it is not necessary to back vent the brick veneer reservoir cladding as in *Assembly 6*. Moisture driven inwards out of the brick veneer will condense on the vapor barrier/drainage plane and be drained outwards.



Assembly 8: Frame Wall With Cavity Insulation and Brick or Stone Veneer With Interior Vapor Retarder

Applicability: Limited to cold and very cold regions.

This wall is a variation of *Assembly 6* except it has a Class II vapor retarder on the interior limiting its inward drying potential—but not eliminating it. It still considered a flow-through assembly because it can dry to both the exterior and the interior. It is critical in this wall assembly, as in *Assembly 6,* that the exterior brick veneer (a "reservoir" cladding) be uncoupled from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 2 in. (51 mm) wide (source: Brick Institute of America) and free from mortar droppings. It also must have air inlets ("weep holes") at its base and air outlets ("weep holes") at its top to provide back ventilation of the brick veneer. The drainage plane in this assembly is the building paper or building wrap. The air barrier can be any of the following: the interior gypsum board, the exterior gypsum board or the exterior building wrap.

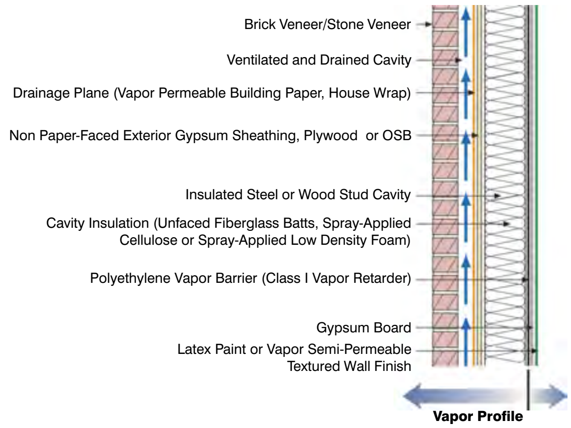


Appendix B

Assembly 9: Frame Wall With Cavity Insulation and Brick or Stone Veneer With Interior Vapor Barrier

Applicability: Limited to very cold, subarctic and arctic regions.

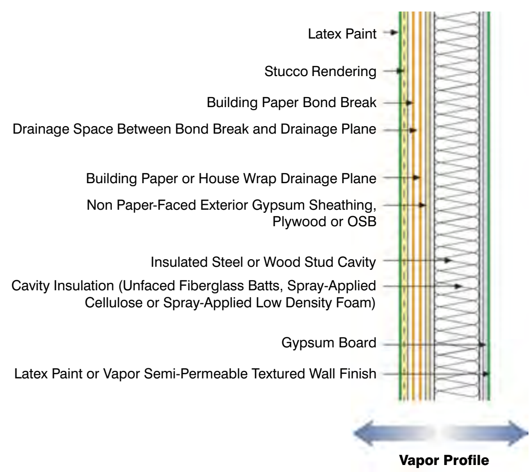
This wall is a further variation of *Assembly 6* but now it has a Class I vapor retarder on the interior (a "vapor barrier") completely eliminating any inward drying potential. It is considered the "classic" cold climate wall assembly. It is critical in this wall assembly, as in *Assemblies 6* and *8*, that the exterior brick veneer (a "reservoir" cladding) be uncoupled from the wall assembly with a ventilated and drained cavity. The cavity behind the brick veneer should be at least 2 in. (51 mm) wide (source: Brick Institute of America) and free from mortar droppings. It also must have air inlets at its base and air outlets at its top to provide back ventilation of the brick veneer. The drainage plane in this assembly is the building paper or building wrap. The air barrier can be any of the following: the interior polyethylene vapor barrier, the interior gypsum board, the exterior gypsum board or the exterior building wrap.



Assembly 10: Frame Wall With Cavity Insulation and Stucco

Applicability: Limited to mixed-humid, hot-humid, mixed-dry, hot-dry and marine regions. It can be used with hygrothermal analysis in some areas in cold regions (Zone 5, but not Zone 6; See sidebar, "Proposed Building Code Requirements for Vapor Retarders"); should not be used in very cold, and subarctic/arctic regions.

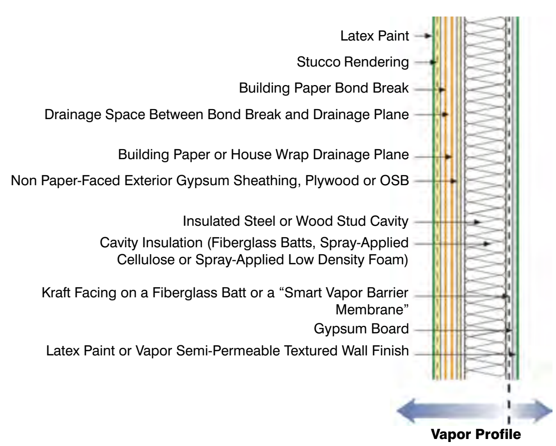
This wall is also a flow-through assembly similar to *Assembly 6*—but without the brick veneer. It has a stucco cladding. It can dry to both the exterior and the interior. It has a Class III vapor retarder on the interior of the assembly (the latex paint on the gypsum board). It is critical in this wall assembly that a drainage space be provided between the stucco rendering and the drainage plane. This can be accomplished by installing a bond break (a layer of tar paper) between the drainage plane and the stucco. A spacer mat can also be used to increase drainability. Alternatively, a textured or profiled drainage plane (building wrap) can be used. The drainage plane in this assembly is the building paper or building wrap. The air barrier can be any of the following: the interior gypsum board, the exterior stucco rendering, the exterior sheathing or the exterior building wrap.



Assembly 11: Frame Wall With Cavity Insulation and Stucco With Interior Vapor Retarder

Applicability: Limited to cold and very cold regions.

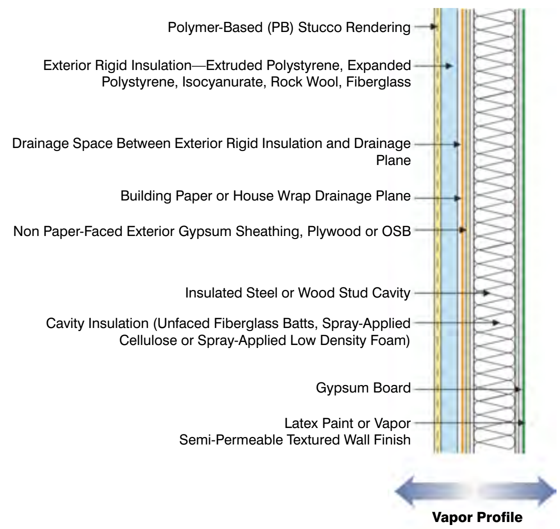
This wall is a variation of *Assemblies 6* and *10* except it has a Class II vapor retarder on the interior limiting its inward drying potential—but not eliminating it. It still considered a flow-through assembly. It can dry to both the exterior and the interior. It is critical in this wall assembly, as in *Assembly 10*, that a drainage space be provided between the stucco rendering and the drainage plane. This can be accomplished by installing a bond break (a layer of tar paper) between the drainage plane and the stucco. A spacer mat also can be used to increase drainability. Alternatively, a textured or profiled drainage plane (building wrap) can be used. The drainage plane in this assembly is the building paper or building wrap. The air barrier can be any of the following: the interior gypsum board, the exterior stucco rendering, the exterior sheathing or the exterior building wrap.



Assembly 12: Frame Wall With Exterior Rigid Insulation With Cavity Insulation and Stucco

Applicability: all hygrothermal regions except subarctic/arctic - in cold and very cold regions the thickness of the foam sheathing should be determined by hygrothermal analysis so that the interior surface of the foam sheathing remains above the dew point temperature of the interior air (see sidebar, "Proposed Building Code Requirements for Vapor Retarders," Section 4).

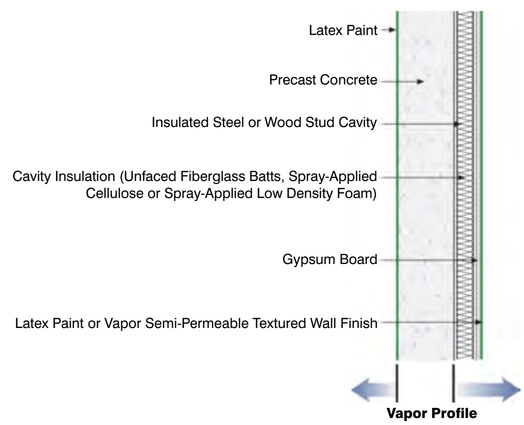
This is a water managed exterior insulation finish system (EIFS). Unlike "face-sealed" EIFS this wall has a drainage plane inboard of the exterior stucco skin that is drained to the exterior. It is also a flow-through assembly similar to *Assembly 6*. It can dry to both the exterior and the interior. It has a Class III vapor retarder on the interior of the assembly (the latex paint on the gypsum board). It is critical in this wall assembly that a drainage space be provided between the exterior rigid insulation and the drainage plane. This can be accomplished by installing a spacer mat or by providing drainage channels in the back of the rigid insulation. Alternatively, a textured or profiled drainage plane (building wrap) can be used. The drainage plane in this assembly is the building paper or building wrap. The air barrier can be any of the following: the interior gypsum board, the exterior stucco rendering, the exterior sheathing or the exterior building wrap.



Assembly 13: Precast Concrete With Interior Frame Wall Cavity Insulation

Applicability: Limited to mixed-humid, hot-humid, mixed-dry, hot-dry and marine regions; should not be used in cold, very cold, and subarctic/arctic regions.

The vapor barrier in this assembly is the precast concrete itself. Therefore, this wall assembly has all of the thermal insulation installed to the interior of the vapor barrier. Of particular concern is the fact that the thermal insulation is air permeable (except where spray foam is used). Therefore, this wall assembly should not be used in cold regions or colder. It has a small moisture storage (hygric buffer) capacity due to the precast concrete construction. The wall assembly does contain water sensitive cavity insulation (except where spray foam is used) and it is important that this assembly can dry inwards. Therefore, vapor semi-impermeable interior finishes such as vinyl wall coverings should be avoided. In this wall assembly the precast concrete is also the drainage plane and air barrier.

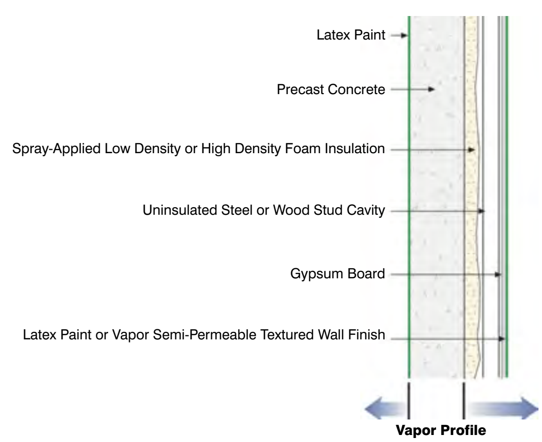


Assembly 14: Precast Concrete With Interior Spray Applied Foam Insulation

*Applicability: all hygrothermal regions.**

This assembly has all of the thermal insulation installed on the interior of the precast concrete. The assembly also does not have a vapor barrier on the interior of the assembly. It has a small moisture storage (hygric buffer) capacity due to the precast concrete construction. The spray foam insulation installed on the interior of the precast concrete is non-moisture sensitive and allows the wall to dry inwards. It is important that this assembly can dry inwards except in very cold and subarctic/arctic regions. Therefore, vapor semi-impermeable interior finishes such as vinyl wall coverings should be avoided in assemblies except in very cold and subarctic/arctic regions. High-density spray foam, due to its vapor semi-impermeable characteristics should be used in place of low-density foam in very cold and subarctic/arctic regions. The drainage plane in this assembly is the latex painted precast concrete. A Class III vapor retarder is located on both the interior and exterior of the assembly (the latex paint on the stucco and on the interior gypsum board).

* In very cold and subarctic/arctic regions, high-density spray foam (vapor semi-impermeable) is recommended.



Appendix B

Proposed Building Code Requirements For Vapor Retarders

The proposed building code requirements are based on a combination of field experience and laboratory testing. The requirements were also evaluated using dynamic hygrothermal modeling. The modeling program used was WUFI.[1] Under the modeling evaluation, the moisture content of building materials that comprise the building assemblies evaluated all remained below the equilibrium moisture content of the materials as specified in ASHRAE proposed Standard 160P, Design Criteria for Moisture Control in Buildings. Interior air conditions and exterior air conditions as specified by 160P were used. Enclosures are ventilated to meet ASHRAE Standards 62.1 or 62.2.

The climate zones referenced are the U.S. Department of Energy climate zones as proposed for adoption in the 2006 International Residential Code (IRC) and International Energy Conservation Code (IECC). Their development is the subject of two ASHRAE papers.[2,3] An accompanying map defines the climate zones.

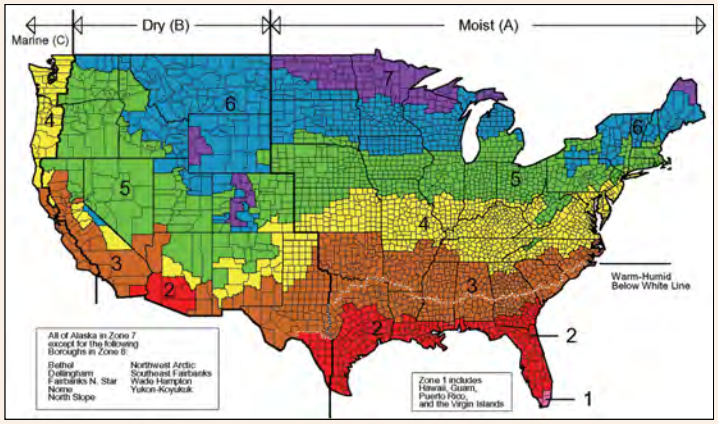


Figure 1: Department of Energy's proposed climate zone map.

Note that vapor retarders are defined and classed using ASTM E-96 Test Method A (the desiccant method or dry cup method) consistent with the current code language. However, exterior sheathing/cladding assemblies are defined and classed using Test Method B (the "wet cup" method) to take advantage of the ability of some sheathings to "breathe" as they are exposed to high relative humidities.

1. Zones 1, 2, and 3 do not require any class of vapor retarder on the interior surface of insulation in insulated assemblies (this recommendation has already been accepted by the code committee at the code hearings in Nashville, September 2003 and Kansas City, May 2004).

2. Zone 4 (not marine) requires a Class III (or lower) vapor retarder on the interior surface of insulation in insulated wall and floor assemblies.

3. Zone 4 (marine) requires a Class III (or lower) vapor retarder on the interior surface of insulation in insulated wall and floor assemblies where the permeance of the exterior sheathing/cladding assembly is greater than 1.0 perm as tested by Test Method B (the "wet cup" method of ASTM E-96).

4. Zone 4 (marine) requires a Class II (or lower) vapor retarder on the interior surface of insulation in insulated wall and floor assemblies where the permeance of the exterior sheathing/cladding assembly is less than or equal to 1.0 perm and greater than 0.1 perm as tested by Test Method B (the "wet cup" method) of ASTM E-96).

5. Zone 4 (marine) requires a Class III (or lower) vapor retarder on the interior surface of insulation in insulated wall and floor assemblies where the permeance of the exterior sheathing is 0.1 perm or less as tested by Test Method B (the "wet cup" method) of ASTM E-96) and the interior surface of the exterior sheathing shall be maintained above the dew-point temperature of the interior air. Under this design approach assume steady-state heat transfer, interior air at a temperature of 70°F (21°C), at a relative humidity specified in *Table 1* and exterior air at a temperature that is equal to the average outdoor temperature for the location during the coldest three months of the year (e.g., December, January and February).

Zone 4 (marine)	40% RH at 70°F	Dew Point 45°F
Zone 5	30% RH at 70°F	Dew Point 37°F
Zone 6	25% RH at 70°F	Dew Point 32°F
Zone 7	10% RH at 70°F	Dew Point 28°F

Table 1: Design conditions for steady-state design procedure (wall and floor assemblies).

Zone 5	35% RH at 70°F	Dew Point 39°F
Zone 6	30% RH at 70°F	Dew Point 37°F
Zone 7	25% RH at 70°F	Dew Point 32°F

Table 2: Design conditions for steady-state design procedure (roof and attic assemblies).

6. Zone 5 requires a Class III (or lower) vapor retarder on the interior surface of insulation in insulated wall and floor assemblies where the permeance of the exterior sheathing is greater than 1.0 perm as tested by Test Method B (the "wet cup" method) of ASTM E-96.

7. Zones 6 and 7 require a Class II (or lower) vapor retarder on the interior surface of insulation in insulated wall and floor assemblies where the permeance of the exterior sheathing is greater than 1.0 perm as tested by Test Method B (the "wet cup" method) of ASTM E-96.

8. Zones 5, 6 and 7 require a Class II (or lower) vapor retarder on the interior surface of insulation in insulated wall and floor as-

Appendix B

Zone	Wall Assembly Exterior Sheathing >1.0 Perm	≤1.0 Perm>0.1 Perm	Wall Assembly ≤0.1 Perm
1	Not Required	Not Required	Not Required
2	Not Required	Not Required	Not Required
3	Not Required	Not Required	Not Required
4 (Not Marine)	Class III	Class III	Class III
4 (Marine)	Class III	Class II	Class III*
5	Class III	Class II	Class II*
6	Class II	Class II	Class II*
7	Class II	Class II	Class II*

* Additionally, the interior surface of the exterior sheathing shall be maintained above the dew-point temperature of the interior air (see *Table 1*).

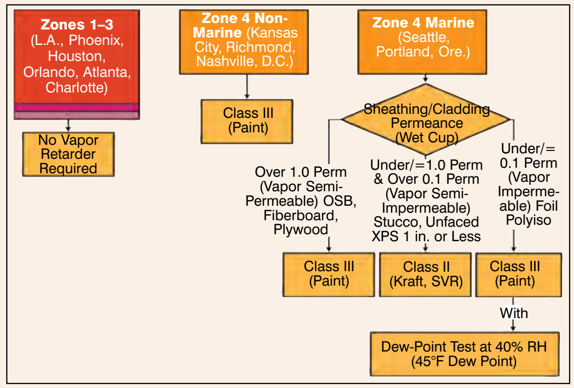


Table 3 (left): Summary of recommendations for vapor retarders on the interior of wall assemblies. Figure 2 (right): Vapor barrier flow chart, Zones 1–4.

semblies where the permeance of the exterior sheathing/cladding assembly is less than or equal to 1.0 perm and greater than 0.1 perm as tested by Test Method B (the "wet cup" method) of ASTM E-96.

9. Zones 5, 6 and 7 require a Class II (or lower) vapor retarder on the interior surface of insulation in insulated wall and floor assemblies, where the permeance of the exterior sheathing is 0.1 perm or less as tested by Test Method B (the "wet cup" method) of ASTM E-96 and the interior surface of the exterior sheathing shall be maintained above the dew-point temperature of the interior air. Under this design approach, assume steady-state heat transfer, interior air at a temperature of 70°F (21°C), at a relative humidity specified in *Table 1,* and exterior air at a temperature that is equal to the average outdoor temperature for the location during the coldest three months of the year (e.g., December, January and February).

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Appendix B

10. Zone 5 requires a Class III (or lower) vapor retarder on the interior surface of insulation in ventilated insulated roof or attic assemblies.

11. Zone 5 require a Class III (or lower) vapor retarder on the interior surface of insulation in unvented insulated roof or attic assemblies and the condensing surface shall be maintained above the dew-point temperature of the interior air. The condensing surface is defined as either the interior surface of the structural roof deck or the interior surface of an air-impermeable insulation applied in direct contact to the underside/interior of the structural roof deck. "Air-impermeable" is quantitatively defined by ASTM E 283. Under this design approach assume steady-state heat transfer, interior air at a temperature of 70°F (21°C), at a relative humidity specified in *Table 2* and exterior air at a temperature that is equal to the average outdoor temperature for the location during the coldest three months of the year (e.g., December, January and February).

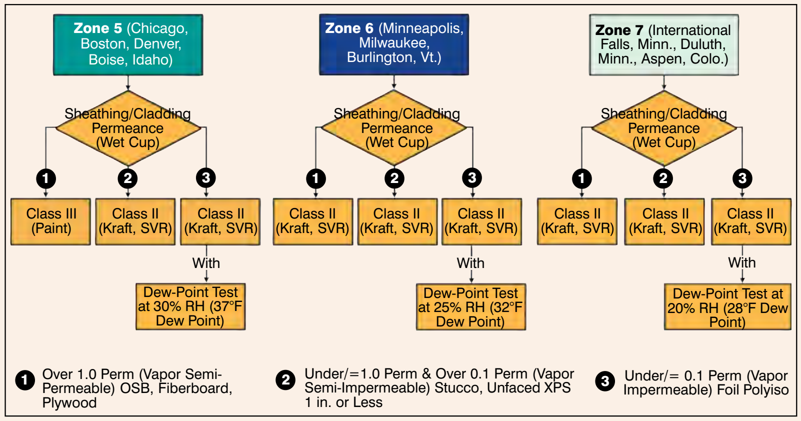


***Figure 3:** Vapor barrier flow chart, Zones 5–7.*

12. Zones 6 and 7 require a Class II (or lower) vapor retarder on the interior surface of insulation in unvented insulated roof or attic assemblies and the condensing surface shall be maintained above the dew-point temperature of the interior air. The condensing surface is defined as either the interior surface of the structural roof deck or the interior surface of an air-impermeable insulation applied in direct contact to the underside/interior of the structural roof deck. "Air-impermeable" is quantitatively defined by ASTM E 283. Under this design approach assume steady-state heat transfer, interior air at a temperature of 70°F (21°C), at a relative humidity specified in *Table 2* and exterior air at a temperature that is equal to the average outdoor temperature for the location during the coldest three months of the year (e.g., December, January and February).

13. Zones 6 and 7 require a Class II (or lower) vapor retarder on the interior surface of insulation in ventilated insulated roof or attic assemblies.

14. Zones 5, 6 and 7 require a Class III (or lower) vapor retarder on the interior surface of insulation in internally insulated below grade masonry and concrete walls. Frame walls (i.e. "stem walls") that are constructed on the top of concrete or masonry foundation walls are not considered below grade walls.

15. Exceptions to the above requirements shall be allowed when assemblies are evaluated by dynamic hygrothermal modeling. The moisture content of building materials that comprise the building assembly shall remain below the equilibrium moisture content the materials as specified in 160P under this evaluation approach. Interior air conditions and exterior air conditions as specified by 160P shall be used.

What This Means From a Practical Perspective

Polyethylene is a Class I vapor retarder. A kraft-faced fiberglass batt is a Class II vapor retarder. Latex painted gypsum board (one coat of latex paint) is a Class III vapor retarder.

Plywood sheathing and oriented strand board (OSB) have perm values of greater than 1 perm when using the wet cup test (similarly for exterior gypsum sheathing or fiberboard sheathing).

Extruded polystyrene of 1 in. (25 mm) thick or thicker has a perm value of 1.0 perm or less. Film faced extruded polystyrenes of 0.5 in. (13 mm) thickness that have perforated facings have perm values of greater than 1 perm. Non-perforated foil and polypropylene faced rigid insulations have perm values of less than 0.1 perms.

Three-coat hard-coat stucco installed over two layers of Type D asphalt saturated kraft paper and OSB has a combined perm value of less than 1.0 under a wet cup test. Therefore the sheathing/cladding assembly is less than or equal to 1.0 as tested by Test Method B of ASTM E-96.

Foil-faced isocyanurate 0.5 thick (R 3.5) installed over a 2x4 frame wall meets Requirement 9 in Chicago. Therefore, a kraft-faced batt (Class II vapor retarder) is required on the interior of this assembly.

Foil-faced isocyanurate 1 in. (25 mm) thick (R 6) installed over a 2x6 frame wall (R 19) meets Requirement 9 in Minneapolis. Therefore, a kraft-faced batt (Class II vapor retarder) is required on the interior of this assembly.

In Chicago where plywood or OSB exterior sheathing is used, an unfaced fiberglass batt can be installed within the wall cavity and gypsum board painted with latex paint (Class III vapor retarder) is required on the interior of this assembly. If this assembly is moved to Minneapolis, a Class II vapor retarder is required on the interior (a kraft paper faced fiberglass batt).

References

1. Kunzel, H.M. 1999. WUFI: PC Program for Calculating the Coupled Heat and Moisture Transfer in Building Components; Fraunhofer Institute for Building Physics, Holzkirchen, Germany.

2. Briggs, R.S., R.G. Lucas, and T. Taylor. 2003. "Climate classification for building energy codes and standards: part 1 – development process." *ASHRAE Transactions.*

3. Briggs, R.S., R.G. Lucas, and T. Taylor. 2003. "Climate classification for building energy codes and standards: part 2 – zone definitions, maps and comparisons." *ASHRAE Transactions.*

Appendix C

Dehumidification in Virginia

The example provided in this appendix comes from *62.1 Users Manual* (2007, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta) and speaks to the issue of humidity control in a southern climate and how to design a single-zone system that controls humidity and complies with *ANSI/ASHRAE Standard 62.1, Ventilation for Acceptable Indoor Air Quality* (2007, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta).

Example 5-F—Dehumidification in Virginia

Q

A 1000 ft^2 day care center in Richmond, VA is designed for ten people and is to be mechanically ventilated, cooled, and dehumidified using a constant volume rooftop unit controlled by a thermostat. The indoor design conditions are 70°F at 60% RH, and 1% outdoor design conditions are to be used. What are the design parameters for this single zone system to meet ASHRAE *Standard 62.1-2007*? What equipment selection parameters arise from these design conditions?

A

The required outdoor air ventilation is 10 people * 10 cfm/person + 0.18 cfm/ ft^2 * 1,000 ft^2 = 280 cfm, assuming that zone air distribution effectiveness is 1.0 (see § 6).

Calculate the coil cooling loads at the design dry-bulb and coincident wet-bulb conditions, which are 92°F dry-bulb/75°F wet-bulb. Assuming a 55°F supply air temperature at design, loads are shown in the table that follows. Space-relative humidity rises to about 63% at the dry-bulb design condition. While not required by the Standard, the cooling system will normally be designed to meet the sensible and latent loads at these conditions.

Recalculate the space and ventilation cooling loads and resulting space-relative humidity atthe design dewpoint condition (referred to in the 2005 ASHRAE Handbook-Fundamentals, Chapter 28 and the companion CD, as the "design dehumidification" condition) in accordance with § 5.10.1-in Richmond, 75ûF dewpoint / 82ûF dry-bulb (rounded to the nearest degree). In this case, the design uses the 1% design condition (outdoor conditions exceed this number only 1% of the time in a year) but the standard also permits the use of the 0.4% (stricter) and 2% (less strict) conditions. We analyze this space as though it had simple dry-bulb-modulating control, such as a chilled-water valve controlled by a room thermostat.* The resulting loads and space-relative humidity are shown in the table and psychrometric chart that follow. This example makes the simplifying assumption that return air conditions are the same as room air conditions. These conditions are indicated as "RA" on the psychrometric charts. Note that at the test conditions in § 5.10.1 the resulting room humidity is 75%, which does not meet the 65% limit.

To meet the required humidity limit, one of the following part-load strategies may be employed:

- Dynamically reduce airflow using variable air volume or more simply, a two-speed fan to meet part-load conditions (be sure to follow the part-load ventilation requirements of § 5.4).
- Employ reheat and control of cooling and reheat coils from humidity measurement. Be sure to consider energy consumption and possible sources of recovered heat, such as hot gas.
- Employ bypass of return air (not mixed air) around the cooling coil to meet part-load conditions.
- Employ a dedicated outdoor air system with dehumidification capability.

Had the building been located in a drier climate (with a lower design dewpoint), the 65% design limit may have been met at the test condition and no additional consideration would be needed.

**A modulating chilled water coil "unloads" on a coil curve and delivers air at a higher dewpoint (dp) and higher dry-bulb (db) temperature at part load. A cycling DX coil delivers air at very low dp, low db when "on" and at higher dp and higher db when "off" (how high depends on cycle rate). Some coil simulation analyses by equipment manufacturers indicate that a cycling DX coil, on average, follows the same coil curve as the modulating coil. This means that with either coil, the average leaving air dewpoint is about the same. Each coil delivers supply air at about the same db and dp, so a basic constant volume system without reheat or bypass, for instance, has about the same success in controlling space relative humidity indirectly, whether it uses a DX coil or a chilled water coil. The DX coil removes a lot of moisture when on, and re-evaporates some moisture when off, while the modulating coil removes a little moisture all the time.*

Appendix C

*Richmond, VA,
1000 square foot daycare room,
Indoor design conditions: 70°F, 60% rh (*Standard 62.1-2004* requires a minimum of 65% rh)
Ten people, 280 cfm outdoor air calculated per § 6

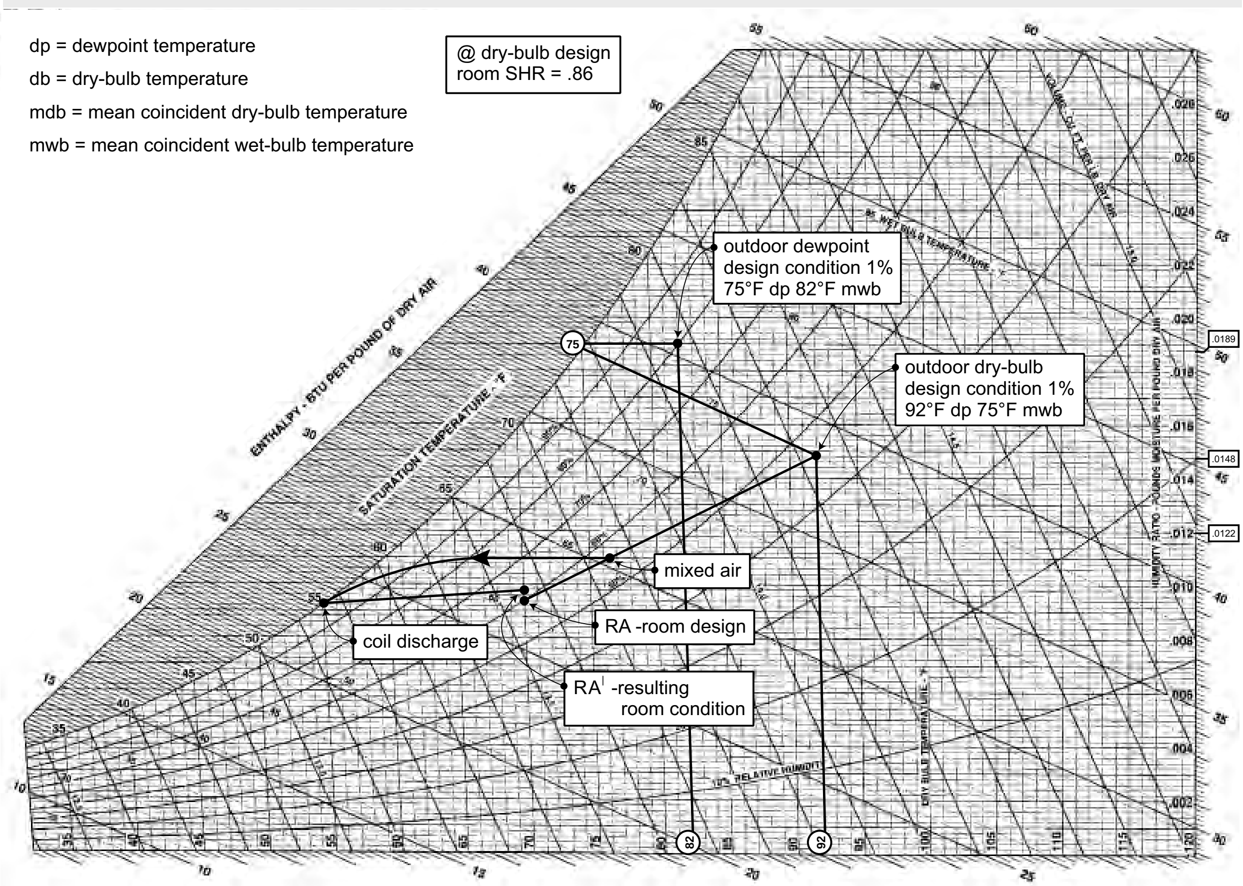
I. Loads as often calculated for peak air-conditioning load
Space loads in Btu/h at 1% peak dry-bulb design, 92°F db, 75°F mwb
Assumed supply air temperature: 55°F
Supply airflow: 960 cfm
Mixed air temperature: 76.4°F

	SENSIBLE	LATENT	TOTAL	SHR
Lighting	7000		7000	
People	2500	2500	5000	
Walls	2000		2000	
Roof	2000		2000	
Solar	2000		2000	
Space Total	15,500	2500	18,000	0.86
Ventilation	6780	5290	12,070	
TOTAL	22,280	7790	30,070	0.74

II. Loads calculated for peak outdoor dewpoint design conditions as required by § 5.10.1.1
Space loads at 1% peak dewpoint design, 75 dp, 82 mdb
Effective supply air temperature calculated: 59.8°F
Supply airflow: 960 cfm
Mixed air temperature: 73.5°F

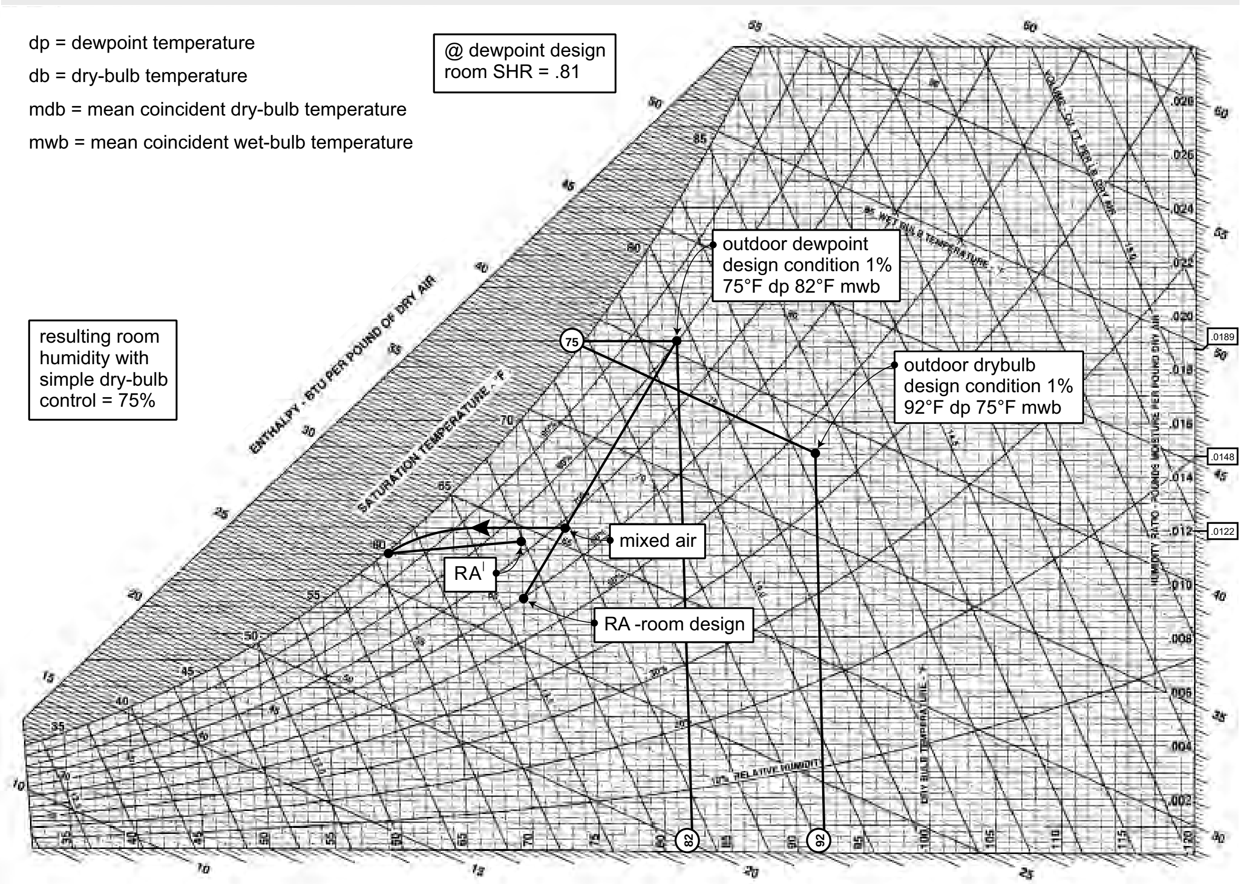
	SENSIBLE	LATENT	TOTAL	SHR
Lighting	7000	0	7000	
People	2500	2500	5000	
Walls	1090	0	1090	reduced due to outdoor dry-bulb of 82 F#
Roof	0	0	0	zero due to cloudiness, rain, and lower outdoor dry-bulb#
Solar	0	0	0	zero as required by Section 5.10.1.
Space Total	10,590	2500	13,090	0.81*
Ventilation	3700	10,840	14,540	adjusted for outdoor test condition—higher humidity & lower dry-bulb
TOTAL	14,290	†13,340	27,630	0.52‡

* *Room SHR is lower*
† *Coil latent is nearly double and sensible is about 2/3*
‡ *Coil SHR*
\# *The exact reduction is not dictated by the standard and will depend on the load calculation method used.*



PSYCHROMETRIC PROCESS AND RESULTING ROOM CONDITIONS AT DRY-BULB DESIGN

Appendix C



PSYCHROMETRIC PROCESS AND RESULTING ROOM CONDITIONS AT DEWPOINT DESIGN

Appendix D

Separation of Exhaust Outlets and Outdoor Air Intakes

The information in this appendix provides guidelines that allow the designer to calculate distances from various sources. This information is reproduced from Informative Appendix F of *ANSI/ASHRAE Standard 62.1-2007, Ventilation for Acceptable Indoor Air Quality* (2007, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., Atlanta).

Appendix D

(This appendix is not part of this standard. It is merely informative and does not contain requirements necessary for conformance to the standard. It has not been processed according to the ANSI requirements for a standard and may contain material that has not been subject to public review or a consensus process. Unresolved objectors on informative material are not offered the right to appeal at ASHRAE or ANSI.)

INFORMATIVE APPENDIX F SEPARATION OF EXHAUST OUTLETS AND OUTDOOR AIR INTAKES

F1. GENERAL

Exhaust air and vent outlets as defined in Table 5-1 shall be located no closer to outdoor air intakes, and operable windows, skylights, and doors, both those on the subject property and those on adjacent properties, than the minimum separation distance *L* specified in this section. The distance *L* is defined as the shortest "stretched string" distance measured from the closest point of the outlet opening to the closest point of the outdoor air intake opening or operable window, skylight, or door opening, along a trajectory as if a string were stretched between them.

F2. APPLICATION

Exhaust outlets and outdoor air intakes or other openings shall be separated in accordance with the following.

Exception: Laboratory fume hood exhaust air outlets shall be in compliance with NFPA 45-1991 and ANSI/AIHA Z9.5-1992.

F2.1 Outdoor Air Intakes. Minimum separation distance between exhaust air/vent outlets as defined in Table 5-1 and outdoor air intakes to mechanical ventilation systems or operable windows, skylights, and doors that are required as part of natural ventilation systems shall be equal to distance *L* determined in accordance with Section F3.

Exception: Separation distances do not apply when exhaust and outdoor air intake systems do not operate simultaneously.

F2.2 Other Building Openings. Minimum separation distance between building exhaust air/vent outlets as defined in Table 5-1 and operable openings to occupiable spaces shall be half of the distance *L* determined in accordance with Section F3. Minimum separation distance between high odor intensity or noxious or dangerous exhaust air/vent outlets and operable openings to occupiable spaces shall be equal to the distance *L* determined in accordance with Section F3.

F2.3 Additional Limitations for Noxious or Dangerous Air. Minimum separation distance between exhausts located less than 65 ft (20 m) vertically below outdoor air intakes or operable windows and doors shall be equal to a horizontal separation only as determined in accordance with Section F3; no credit may be taken for any vertical separation.

F2.4 Equipment Wells. Exhaust air outlets that terminate in an equipment well that also encloses an outdoor air intake shall meet the separation requirements of this section and, in addition, shall either

a. terminate at or above the highest enclosing wall and discharge air upward at a velocity exceeding 1000 fpm (5 m/s) or
b. terminate 3 ft (1 m) above the highest enclosing wall (with no minimum velocity).

Exception: Low contaminant or intensity air.

For the purpose of this section, an equipment well is an area (typically on the roof) enclosed on three or four sides by walls that are less than 75% free area, and the lesser of the length and width of the enclosure is less than three times the average height of the walls. The free area of the wall is the ratio of area of the openings through the wall, such as openings between louver blades and undercuts, divided by the gross area (length times height) of the wall.

F2.5 Property Lines. Minimum separation distance between exhaust air/vent outlets and property lines shall be half of the distance *L* determined in accordance with Section F3. For significant contaminant or odor intensity exhaust air, where the property line abuts a street or other public way, no minimum separation is required if exhaust termination is 10 ft (3 m) above grade.

F3. DETERMINING DISTANCE *L*

Separation distance *L* shall be determined using any of the following approaches:

a. Use the values of *L* in Table F-1.
b. Calculate *L* in accordance with Equation F-1 (a or b).
c. Determine *L* using any calculation or test procedure approved by the authority having jurisdiction that shows that the proposed design will result in equivalent or greater dilution factors than those specified in Table F-2.

$$L = 0.09 \cdot \sqrt{Q} \cdot (\sqrt{DF} - U/400) \text{ in feet (I-P)} \qquad \text{(F-1a)}$$

$$L = 0.04 \cdot \sqrt{Q} \cdot (\sqrt{DF} - U/2) \text{ in meters (SI)} \qquad \text{(F-1b)}$$

where

Q = exhaust air volume, cfm (L/s). For gravity vents, such as plumbing vents, use an exhaust rate of 150 cfm (75 L/s). For flue vents from fuel-burning appliances, assume a value of 250 cfm per million Btu/h (0.43 L/s per Kw) of combustion input (or obtain actual rates from the combustion appliance manufacturer.

DF = dilution factor, which is the ratio of outside air to entrained exhaust air in the outside air intake. The minimum dilution factor shall be determined as a function of exhaust air class in Table F-2.

For exhaust air composed of more than one class of air, the dilution factor shall be determined by averaging the dilution factors by the volume fraction of each class:

$$DF = \frac{\sum(DF_i \cdot Q_i)}{\sum Q_i}$$

where

DF_i = dilution factor from Table F-2 for class *i* air and Q_i is the volumetric flow rate of class *i* air in the exhaust airstream.

U = exhaust air discharge velocity, fpm (m/s). As shown in Figure F.1, *U* shall have a positive value when the exhaust is directed away from the outside air intake at an angle that is greater than 45° from the direction of a line drawn from the closest exhaust point the edge of the intake; *U* shall have a negative value when the exhaust is directed toward the intake bounded by lines drawn from the closest exhaust point the edge of the intake; and *U* shall be set to zero for other exhaust air directions regardless of actual velocity. *U* shall be set to 0 in Equation F-1 for vents from gravity (atmospheric) fuel-fired appliances, plumbing vents, and other nonpowered exhausts, or if the exhaust discharge is covered by a cap or other device that dissipates the exhaust airstream. For hot gas exhausts such as combustion products, an effective additional 500 fpm (2.5 m/s) upward velocity shall be added to the actual discharge velocity if the exhaust stream is aimed directly upward and unimpeded by devices such as flue caps or louvers.

TABLE F-1 Minimum Separation Distance, *L*, in ft (m)

Significant Contaminant or Odor Intensity	Noxious or Dangerous Particles
15 (5)	30 (10)

TABLE F-2 Minimum Dilution Factors

Exhaust Air Class	Dilution Factor, *DF*
Significant contaminant or odor intensity	15
Noxious or dangerous particles	50*

*Does not apply to fume hood exhaust. See Section F2.

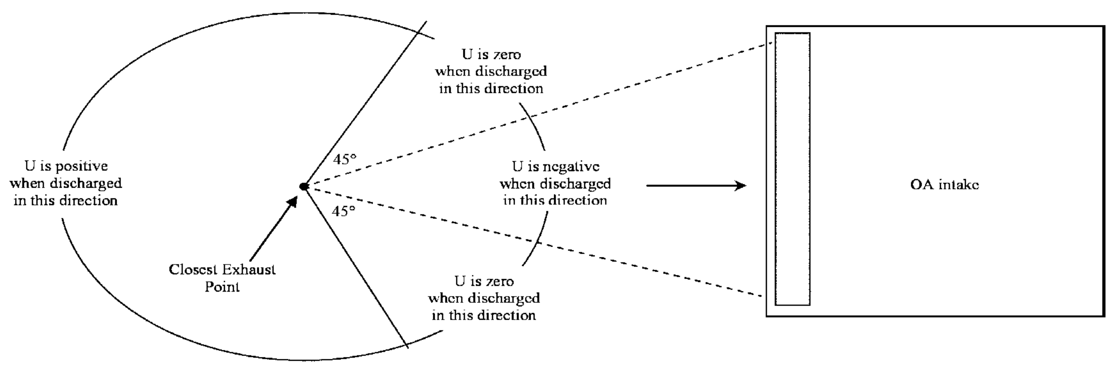


Figure F.1 Exhaust air discharge velocity (U).

Appendix E

Additional Information on Radon Control

Additional Information on Action Levels and Exposure Limits

The Occupational Safety and Health Administration (OSHA) maximum permissible level for radon in workplaces does apply to environmental radon in buildings (OSHA 1989, 1990, 1992, 2002) and has the force of law. However, like other occupational limits designed for adult male workers in the industrial workplace, the maximum permissible limit is much higher than is generally recommended for residential, commercial, or institutional buildings. The OSHA level for adult workers is 100 pCi/L (3750 Bq/m^3) for any 40 hours in a consecutive 7-day period or 30 pCi/L (1125 Bq/m^3) averaged over a work year (29 CFR 1910.1096 (c)(1) [GPO 2007] and Table 1 of Appendix B to 10 CFR Part 20 [GPO 2009]). The OSHA level for workers under 18 is 3 pCi/L (113 Bq/m^3). In general OSHA recommends that exposures to any contaminant be "as low as reasonably achievable" (frequently abbreviated to "ALARA"). OSHA interpretations note the U.S. Environmental Protection Agency (EPA) guideline of 4 pCi/L (150 Bq/m^3) and further note that radon levels less than 4 pCi/L (150 Bq/m^3) also pose a risk and in many cases can be reduced.

The International Commission on Radiological Protection recommends that national authorities set action levels for workplaces in the range of ~13.5 to 40.5 pCi/L (500 to 1500 Bq/m^3) (ICRP 1990). A number of European Union (EU) countries have set enforced action levels for both new and existing workplaces of ~10.8 pCi/L (400 Bq/m^3) and one (Sweden) has set an enforced action level for new workplaces of ~5.4 pCi/L (200 Bq/m^3). Several EU countries have set advisory action levels at ~5.4 pCi/L (200 Bq/m^3) for new workplaces (Akerblom 1999).

Several factors may cause a given radon concentration in schools or workplaces to have a different impact than would that same concentration in a residence. On a lifetime average basis, people in the U.S. spend only 18% of their time in all indoor places other than residences (Klepeis et al. 2001), so a workplace concentration of the same magnitude as a home concentration will result in only about one-fourth the cumulative exposure, all other things being equal. On the other hand, the risk per unit exposure is estimated to be somewhat higher for working-age people (roughly 20 to late 50s) than for younger or older people (EPA 2003). Finally, the equilibrium factor (a measure of the extent of equilibrium between radon and its short-lived decay products, which account for most of the radiation dose to the lung) and the fraction of radon progeny that are not attached to aerosols (and which therefore contribute a higher dose than attached progeny) may be different depending on aerosol generation rates, air circulation rates, filtration levels, or other factors. Evidence suggests that workplaces with high concentrations of aerosols (from production processes such as wood joinery or baking or from environmental tobacco smoke) have higher equilibrium factors but lower unattached fractions (Reichelt et al. 2000; Streil 2000; Yu et al. 1998). The higher equilibrium factors would tend to increase the effective dose for a given radon concentration, while the lower unattached fractions would tend to decrease it. The U.S. Congress Office of Technology Assessment (OTA) used EPA's (1993) school survey data estimate that exposure of schoolchildren to radon in schools was responsible for about 64 additional deaths/year and that "[o]nly in what appear to be exceptional circumstances do in-school exposures make significant contributions to lifelong radon exposures" (OTA 1995, p. 22).

Additional Information on Design of Load-Bearing Elements to Facilitate Active Soil Depressurization (ASD)

Figures E-1 through E-3 illustrate three types of foundation designs that reduce barriers to sub-slab airflow, reducing the number of suction pits, vent pipes, and vent fans required. Figure E-1 shows post-and-beam construction with the load carried by the outside walls and posts. The interior walls are non-load bearing and do not extend below the slab, so the entire sub-slab is interconnected. As a result, only one suction pit and suction fan are required. Figure E-2 shows the use of thickened slab footings below interior weight-bearing walls with aggregate run continuously below the footings. Here, too, the entire sub-slab is interconnected and only one suction pit and suction fan are required. Figure E-3 shows interior weight-bearing walls extending below the aggregate layer to conventional spread footings, but these are interrupted at the corridor. This interruption again makes the entire sub-slab interconnected so that only one suction pit and suction fan are required.

Appendix E

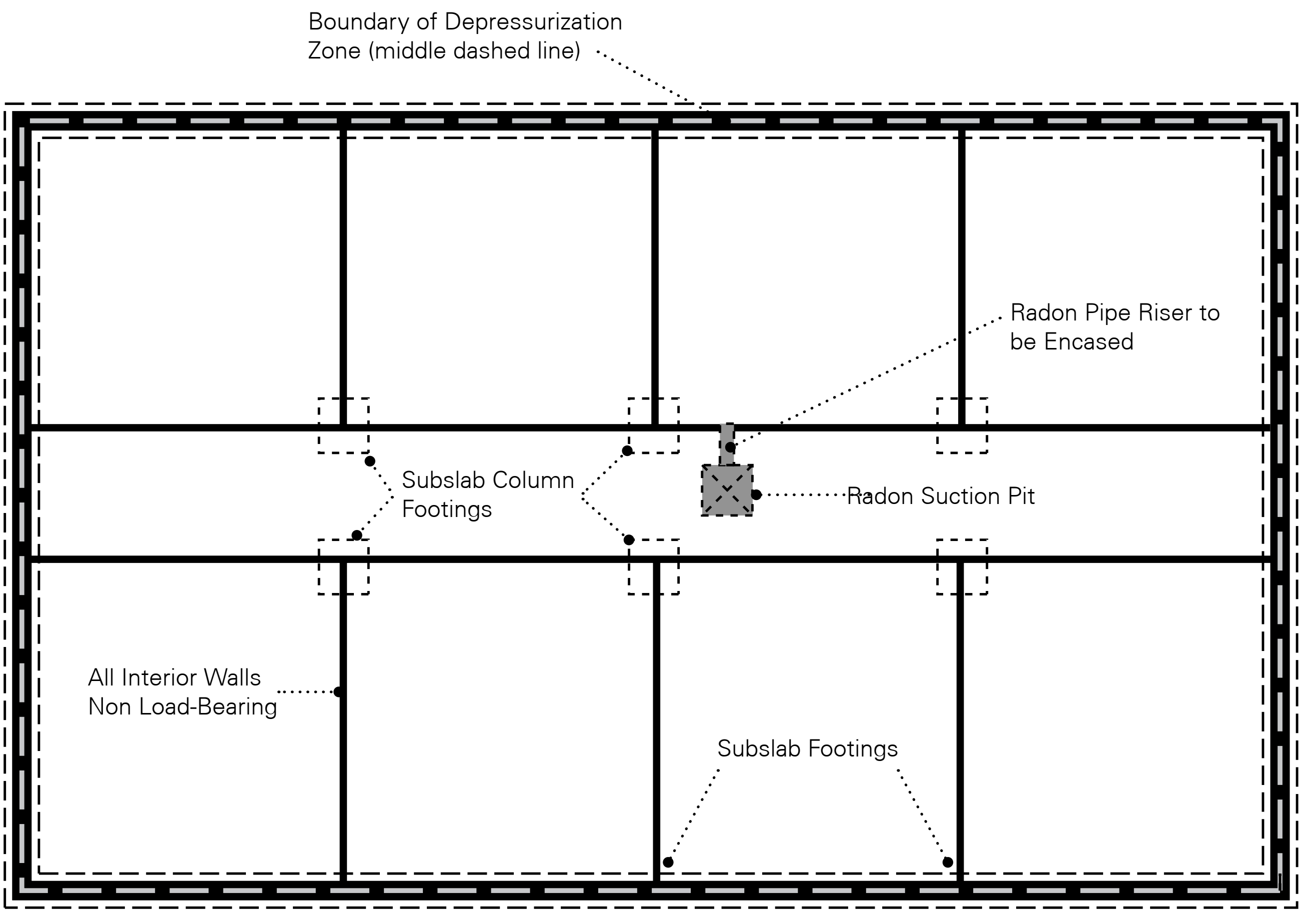


Figure E-1 Use of Post-and-Beam Construction with No Interior Weight-Bearing Walls to Minimize Sub-Slab Barriers to Airflow (Plan View)
Adapted from EPA (1994).

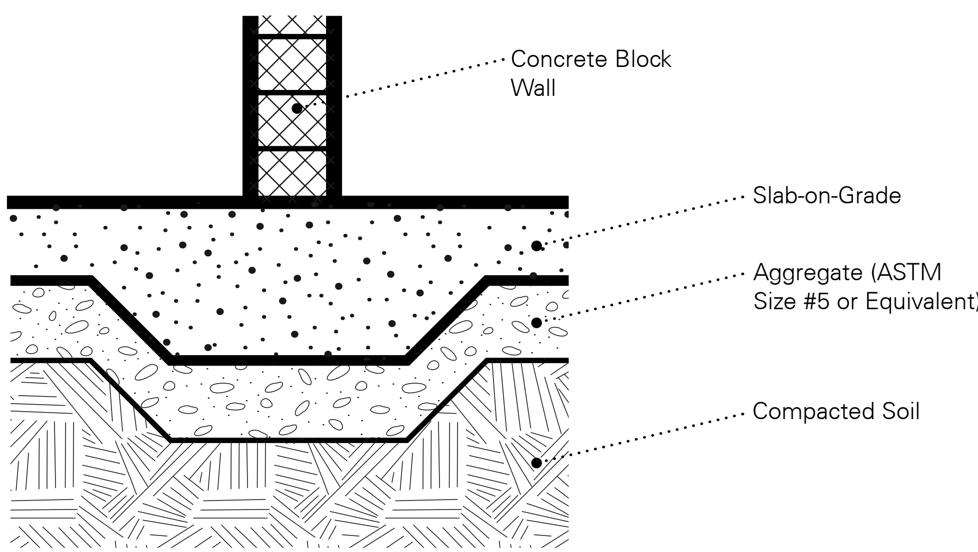


Figure E-2 Use of Thickened Slab Footings with the Aggregate Layer Extending Below Them to Minimize Sub-Slab Barriers to Airflow (Elevation View)
Adapted from EPA (1994).

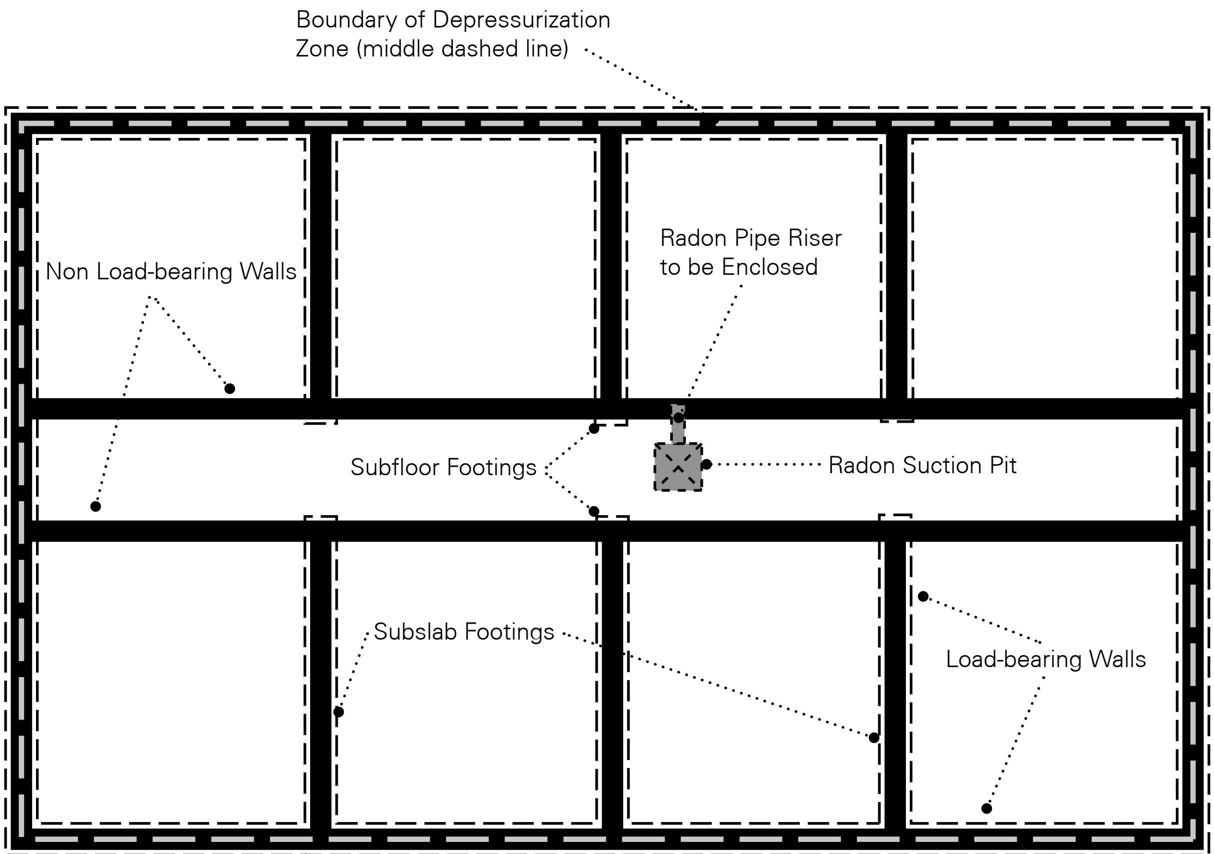


Figure E-3 Interruption of Interior Weight-Bearing Walls at the Corridor to Minimize Sub-Slab Barriers to Airflow
Adapted from EPA (1994).

Additional Information on Design of Suction Pits

Figures E-4 through E-6 show two designs for suction pits for large buildings (Figures E-4 and E-5) and one design for smaller buildings (Figure E-6). The 3 × 3 × 1 ft (~0.8 × 0.8 × 3 m) vertical-sided suction pit shown in Figure E-4 provides 7 ft^2 (~0.65 m^2) of void-to-aggregate interface. The 4 ft × 4 ft × 8 in. (~1.2 × 1.2 × 0.2 m) suction pit in Figure E-5 provides the same void-to-aggregate interface in a design with sloped sides. Figure E-6 shows a suction pit with a 48 in. (1.2 m) circumference suitable for smaller buildings. Based on EPA (1994) tests, an 8 in. (200 mm) deep pit like this with a 6 in. (150 mm) vent pipe will exhaust at least 20,000 ft^2 (1900 m^2) and a 6 in. (150 mm) deep pit with a 4 in. (100 mm) vent pipe and fan will exhaust about 10,000 ft^2 (~ 900 m^2) as long as the vent pipe run is less than about 20 ft (6.1 m) and all other recommendations are followed.

Sub-Membrane Depressurization of Crawlspaces

The most effective radon control technique for crawlspaces is sub-membrane depressurization (SMD) (EPA 1988; Pyle and Leovic 1991) (Figure E-7).[1]

The following design criteria are recommended by EPA (1994) for schools and other commercial buildings:

[1] The crawlspace itself can be depressurized, but it is difficult to effectively isolate it from the occupied space above.

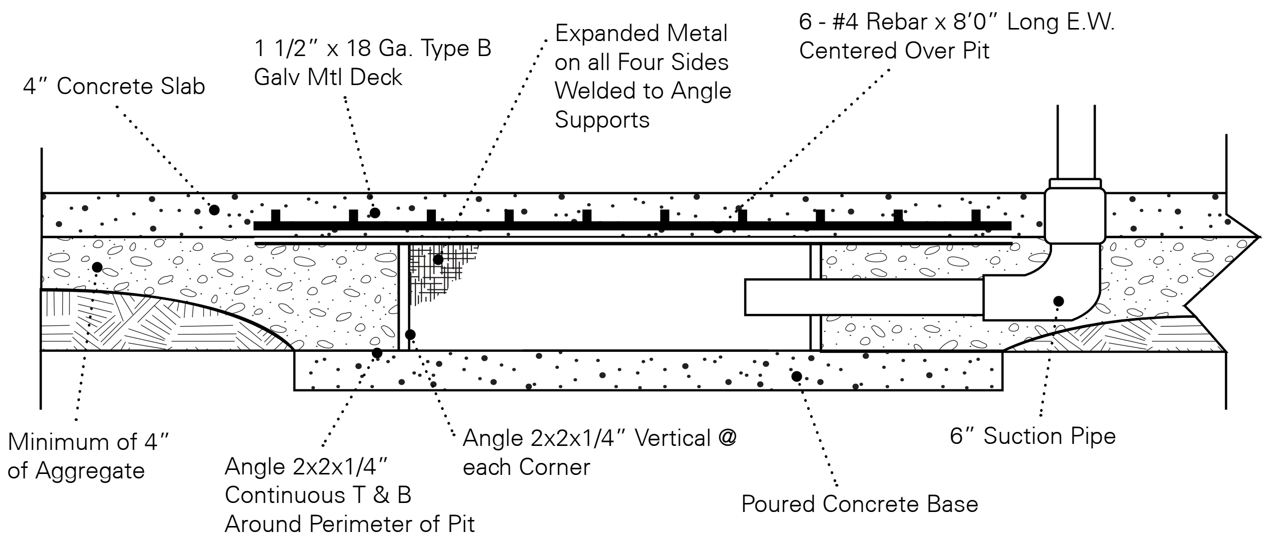


Figure E-4 Suction Pit Design for Large Buildings
Adapted from EPA (1994).

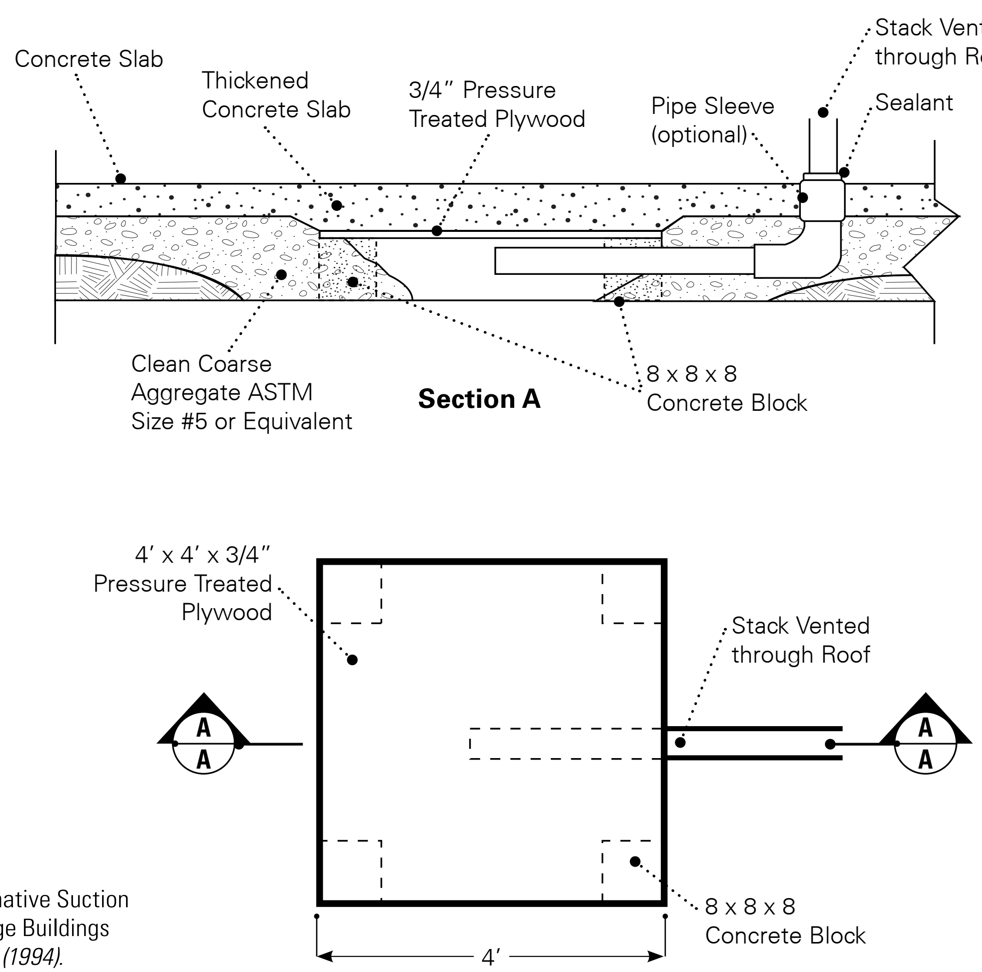


Figure E-5 Alternative Suction Pit Design for Large Buildings
Adapted from EPA (1994).

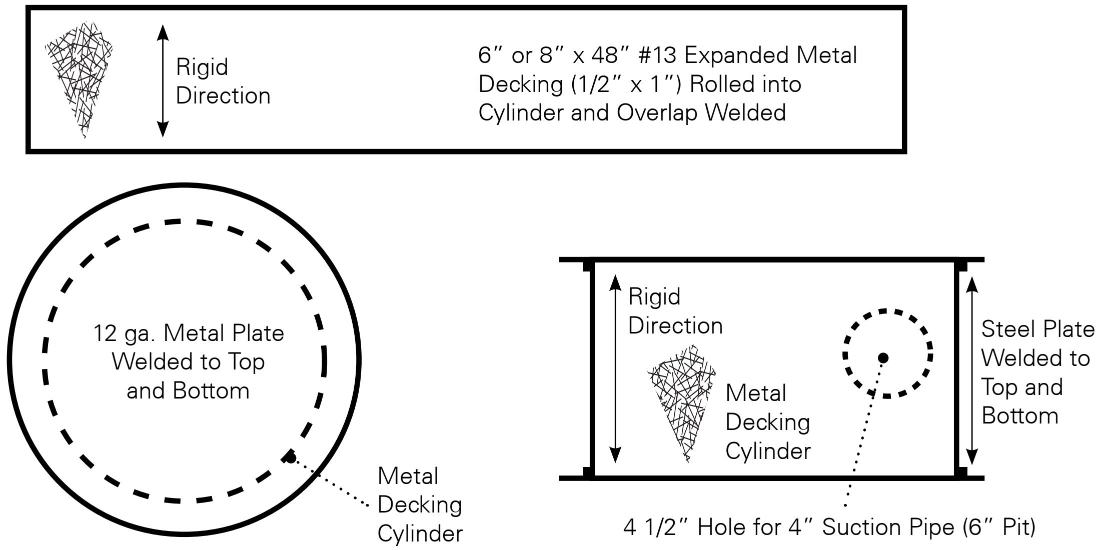


Figure E-6 Suction Pit Design Suitable for Small Buildings
Adapted from EPA (1994).

- If soil in crawlspace is not adequately permeable, provide a layer of permeable material or a perforated pipe network above the crawlspace floor.
- Remove large rocks, broken concrete masonry units (CMUs), and other obstructions.
- Provide 6 mil (~ 0.15 mm) or thicker polyethylene sheeting as a vapor retarder and as the upper surface of a "plenum" above the crawlspace floor. Overlap adjacent sheets at least 1 ft (~ 0.3 mm). Seal seams in the area near the suction point using a sealant recommended by the manufacturer. This will increase the area of the zone that can be effectively depressurized. Where sheeting goes around support piers, seal sheeting to piers.
- Provide suction pit, vent pipe, and suction fan as for ASD.

ITRC (2007) further recommends that if the crawlspace will be accessed periodically by maintenance staff or tradespeople, provide pads or other protective materials over the membrane to reduce the potential for damage. ASTM (2007) recommends for residences that crawlspaces have a ground cover consisting of a poured concrete slab, a thin concrete slab, or a sealed 6 mil (~ 0.15 mm) or thicker polyethylene membrane (or 3 mil [~ 0.08 mm] or thicker cross-laminated polyethylene membrane) to seal the top of the gas-permeable layer. The type of ground cover is determined by the intended use of the crawlspace.[2] Whichever type is used, the ASTM guidance requires that it be sealed at seams, at pipe and other penetrations, and at the crawlspace perimeter.[3]

[2] A regular poured concrete slab (≥ 3.5 in. [890 mm]) is to be used to support heavy equipment, frequent maintenance traffic, active storage, etc.; a thin slab (≥ 2 in. [510 mm]) is to be used to keep out small animals, when the space is intended for storage of light objects, when maintenance traffic is expected, or when a sealed polyethylene membrane will not ensure a durable sealed ground cover for the life of the building.

[3] For a polyethylene ground cover, ASTM (2007) requires that seams have a minimum 12 in. (305 mm) overlap and be sealed and that edges extend at least 12 in. (305 mm) up the foundation walls and be sealed to the walls. All openings for posts, pipes, and other penetrations must also be sealed. When traffic or storage is possible, the ground cover is to be protected by barriers that route traffic around it or durable walkways over it. Polyethylene membranes are also required to have a conspicuously posted label advising periodic inspections. The ASTM guidelines also require a vapor retarder under the ground-cover membrane. See ASTM (2007) for further requirements.

Appendix E

Additional Information on Radon Measurements

EPA (1994) recommends that radon measurements be made in newly constructed schools with ASD systems at least 24 hours after the ASD fan is turned on to verify that radon levels are below 4 pCi/L (150 Bq/m^3).

EPA also recommends that radon measurements be made in new schools in areas with high potential for radon (Zone 1 and other radon-prone areas that have been identified in Zones 2 and 3) if an ASD system was only roughed in to determine whether suction fans need to be added to activate the system (EPA 2009a).

Finally, EPA recommends that every existing school be tested for radon (EPA 2009b).

Since radon levels can vary greatly from one room to another, EPA recommends that measurements be made in all frequently occupied ground-contact rooms[4] (EPA 1993). This includes frequently occupied rooms

- on slabs-on-grade,
- in basements,
- directly above enclosed crawlspaces, and
- directly above basement spaces that are not frequently occupied.

Radon tests may be short term (2 to 90 days) or long term (more than 90 days). Measurements need to be taken during the colder months and with windows and doors closed except for normal entry and exit. Tests of 2 to 5 days need to be taken on weekdays with the HVAC systems operating normally and need to start after at least 12 hours of closed conditions, e.g., after a weekend. Short-term tests should not be carried out during abnormal weather. Testing shouldn't be conducted during structural changes, renovations, or replacement of the HVAC system (EPA 2003).

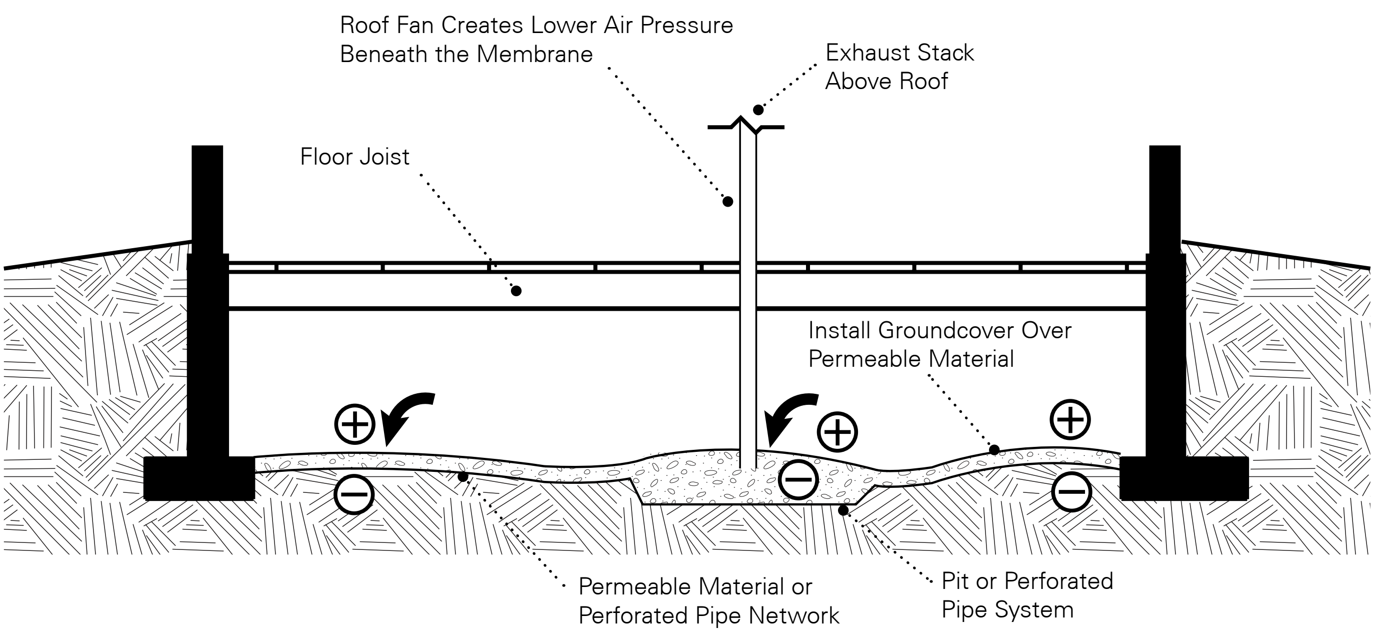


Figure E-7 Schematic of Sub-Membrane Depressurization in a Crawlspace
Adapted from EPA (1994).

[4] Rooms on upper floors can also have elevated radon levels, but they are unlikely to exceed those in the ground-contact rooms. Mitigation measures that reduce radon levels in ground-contact rooms will also reduce radon levels in rooms on upper floors.

Appendix E

If a school elects to use short-term tests for initial measurements, EPA (1993) recommends that these measurements be made in all frequently occupied ground-contact rooms simultaneously. Simultaneous follow-up tests are to be conducted in every room with an initial short-term test result of 4 pCi/L (150 Bq/m^3) or greater. EPA recommends that the follow-up tests be short-term measurements if results are needed quickly, for example, if the initial measurements are on the order of 10 pCi/L (375 Bq/m^3) or higher. Long-term follow-up tests, preferably over an entire school year, are appropriate if radon levels are in the range of 4 to 10 pCi/L (150 to 375 Bq/m^3), although short-term tests may also be used.

EPA (1993) provides additional guidance on placing the detectors in a room, on who may conduct the testing, and on quality assurance (QA) procedures. It is recommended that school districts contact their state radon office before testing, since some states may have their own requirements (EPA 2009b).

If the initial and follow-up tests are both of the short-term type, EPA (1993) recommends that action be taken to reduce radon levels if the average of the two measurements is 4 pCi/L (150 Bq/m^3) or more. If a long-term test is conducted, EPA recommends that action be taken if the long-term average is 4 pCi/L (150 Bq/m^3) or more.

Beyond the first round of testing (initial plus follow-up), EPA (1993, p. 9) recommends retesting as follows:

- "If no mitigation is required after initial testing (e.g., all rooms were found to have levels below 4 pCi/L) (150 Bq/m^3), retest all frequently occupied rooms in contact with the ground sometime in the future. As a building ages and settles, radon entry may increase due to cracks in the foundation or other structural changes."
- "If radon mitigation measures have been implemented in a school, retest these systems as a periodic check on any implemented radon reduction measures."
- "If major renovations to the structure of a school building or major alterations to a school's HVAC system are planned, retest the school before initiating the renovation. If elevated radon is present, radon-resistant techniques can be included as part of the renovation."
- "Retest after major renovations to the structure of a school building or after major alterations to a school's HVAC system. These renovations and alterations may increase radon levels within a school building."

Appendix E

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Appendix F

Additional Information on Material Emissions

Contaminant Irritancy, Odor, and Health Impact

Table F-1 lists resources that can be consulted for detailed information regarding the toxicological, irritant, and odor characteristics of individual contaminants.

Target Compounds

Tables F-2, F-3, and F-4 provide detailed lists of individual volatile organic compounds (VOCs) developed by various groups and agencies to be used in the characterization of emissions from building materials and products.

Material Specifications

Table F-5 lists 32 individual VOCs and their maximum allowable concentrations as specified by the State of California for office furniture emissions (DGS 2008).

Indoor Chemistry

Tables F-6, F-7, and F-8 list secondary reaction products arising from indoor chemistry interactions associated with building materials and the indoor chemistry parameters influencing different types of building materials.

Table F-1 Sources of Information on Odor/Irritancy/Toxicity of Indoor Contaminants

Agency/Author	Report/Publication	Available Information
Jensen and Wolkoff (1996)	VOCBASE	Odor thresholds, mucous membrane irritation thresholds, and physio-chemical parameters of VOCs
California Office of Environmental Health Hazard Assessment (OEHHA)	Toxic Air Contaminants (TAC) list (www.oehha.ca.gov/air/toxic_contaminants/tactable.html)	244 substances that have either been identified by the Air Resources Board (ARB) as toxic air contaminants (TACs) in California or are known or suspected to be emitted in California and have potential adverse health effects; TAC list includes all substances on the EPA list of hazardous air pollutants (EPA 2008) plus additional compounds
OEHHA	Proposition 65 list (www.oehha.ca.gov/prop65.html)	Over 600 chemicals known to the State of California to cause cancer or reproductive toxicity
OEHHA	Chronic Reference Exposure Levels (CRELs) (www.oehha.ca.gov/air/allrels.html)	Currently lists 80 chemicals with *non-cancer* health effects
U.S. Department of Health and Human Services, National Institute of Environmental Health Sciences of the National Institutes of Health (NIEHS/NIH)	National Toxicology Program's Report on Carcinogens (RoC) (http://ntp.niehs.nih.gov/?objectid=72016262-BDB7-CEBA-FA60E922B18C2540)	RoC, published biennially, is an informational scientific and public health document first ordered by Congress in 1978 that identifies and discusses agents, substances, mixtures, or exposure circumstances that may pose a hazard to human health by virtue of their carcinogenicity; the eleventh edition contains 246 entries

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Agency/Author	Report/Publication	Available Information
U.S. Department of Health and Human Services, Agency for Toxic Substances and Disease Registry (ATSDR)	Minimal Risk Levels (MRLs) for Hazardous Substances (www.atsdr.cdc.gov/mrls/index.html)	Derived using the no observed adverse effect level/uncertainty factor (NOAEL/UF) for hazardous substances; MRLs are set below levels that, based on current information, might cause adverse health effects in the people most sensitive to such substance-induced effects
U.S. Environmental Protection Agency (EPA)	Integrated Risk Information System (IRIS) (www.epa.gov/iris/)	Reports on specific substances found in the environment and their potential to cause human health effects; initially developed by EPA staff in response to a growing demand for consistent information on substances for use in risk assessments, decision-making, and regulatory activities
EPA	List of Hazardous Air Pollutants (www.epa.gov/ttn/atw/orig189.html)	Clean Air Act-mandated list of 188 pollutants that cause or may cause cancer or other serious health effects, such as reproductive effects or birth defects or adverse environmental and ecological effects
World Health Organization (WHO)—International Agency for Research on Cancer (IARC)	IARC Monographs on the Evaluation of Carcinogenic Risks to Humans (www.iarc.fr/en/publications/list/monographs/index.php)	Individual "monograph" assessments of health risk of chemical agents; since 1971, more than 900 agents have been evaluated, of which approximately 400 have been identified as carcinogenic or potentially carcinogenic to humans
Roytech/ Clansky (1996)	*Suspect Chemicals Sourcebook*	Guide to industrial chemicals covered under major federal regulatory and advisory programs
Lewis (2004)	*Sax's Dangerous Properties of Industrial Chemicals*, 11th ed.	Covers ~ 26,000 substances; includes description of each material, including physical properties and chemical name synonyms plus toxicology data with references to reports of primary skin and eye irritation plus mutation, reproductive, carcinogenic, and acute toxic dose data
Gosselin et al. (1984)	*Clinical Toxicology of Commercial Products*, 5th ed.	Provides alphabetical list of chemical substances commonly found in commercial products used by consumers and a brief description of toxic effects

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Table F-2 NRC-IRC Target VOC List for Building Material Emissions (Won et al. 2005a, 2005b)

Compound Identification				Physical Properties			VOCBASE Thresholds, mg/m³		Reference Levels, mg/m³		
VOC #	Class	Name	CAS No.	Molecular Weight	Boiling Point, °C	Vapor Pressure,[1] mm Hg	Odor Detection	Mucous Membrane Irritation	ACGIH-TLV[2]	OSHA-PEL[3]	OEHHA-CREL[4]
1	Aldehydes	Acetaldehyde	75-07-0	44.1	20.5	835.90	0.339	206.78	45.10	360.00	0.009
2		Acrolein	107-02-8				0.407	0.12		0.25	0.000
3		Benzaldehyde	100-52-7	106.1	178.9	1.03	0.186	48.04			
4		Butanal	123-72-8	72.1	75.0	101.40	0.028	112.38			
5		Decanal	112-31-2	156.3	215.2	0.09	0.006				
6		Formaldehyde	50-00-0				1.070	0.15		0.92	0.003
7		Furfural	98-01-1	96.1	161.9	1.90	0.250	31.13	7.92	20.00	
8		Heptanal	111-71-7	114.2	153.0	3.10	0.023				
9		Hexanal	66-25-1	100.2	128.5	10.00	0.058	134.22			
10		Nonanal	124-19-6	142.2	195.2	0.32	0.014				
11		Octanal	124-13-0	128.2	174.2	1.02	0.007				
12		Pentanal	110-62-3	86.1	103.2	30.90	0.022	124.31	177.43		
13	Ketones	Methylethylketone	78-93-3	72.1	79.8	87.00	0.870	886.28	594.16	590.00	
14		Acetone	67-64-1	58.1	56.4	210.50	13.900	3098.35	1782.60	2400.00	
15		Acetophenone	98-86-2	120.2	202.2	0.34	1.820	15.02	49.50		
16		Cyclohexanone	108-94-1	98.1	155.9	3.83	0.083	92.80	101.09	200.00	
17		Methylisobutyl ketone	108-10-1	100.2	116.7	17.70	0.540	400.17	206.33	410.00	
18	Alcohols, Glycols, GlycoEthers	1,2 Ethanediol	107-21-1	62.1	197.5	0.08	63.000		127.86		0.400
19		1,2 Propanediol	4254-15-3	76.1	187.8	0.11					
20		1-Butanol	71-36-3	74.1	117.8	6.12	0.090	356.70	152.69	300.00	
21		1-Methoxy-2-propanol	107-98-2	90.1	119.2	12.5*	0.012		371.29		7.000
22		1-Propanol	71-23-8	60.1	97.4	18.17	6.030	773.40	495.19	500.00	
23		2-Butoxyethanol	111-76-2	118.2	171.5	0.75	0.005	417.39	121.72	240.00	
24		2-Butoxyethoxyethanol	112-34-5	162.2	231.2	0.02	0.009				
25		2-Ethoxyethanol	110-80-5	90.1	135.2	4.64	4.570		18.57	740.00	0.070
26		2-Ethyl-1-hexanol	104-76-7	130.2	184.8	0.11	0.500	7.16			
27		2-Methoxyethanol	109-86-4	76.1	124.6	7.89	3.550		15.68	80.00	0.060
28		2-Methyl-2-propanol	75-65-0	74.1	82.6	36.80	71.000		305.38	300.00	
29		2-Propanol	67-63-0	60.1	82.4	40.30	1.180	706.59	990.38	980.00	7.000
30		Ethanol	64-17-5	46.1	78.4	52.73	0.280	1113.70	1898.03	1900.00	
31		Phenol	108-95-2	94.1	182.0	0.45	0.427	19.53	19.39	19.00	0.200
32	Esters	Acetic acid, 1-methylethyl ester	108-21-4	102.1	88.7	54.62	10.200	544.32	1051.96	950.00	
33		Acetic acid, 2-ethoxyethyl ester	111-15-9	132.2	156.5	2.04	1.000	118.98	27.22	540.00	0.300
34		Acetic acid, butyl ester	123-86-4	116.2	126.2	10.24	0.047	106.03	717.86	710.00	
35		Acetic acid, ethyl ester	141-78-6	88.1	77.2	84.64	2.410	65.72	1451.98	1400.00	
36		2,2,4-Trimethyl-1,3-pentanediol diisobutyrate	6846-50-0	286.4							
37	Halo Carbons	Benzene, 1,2-dichloro	95-50-1	147	180.6	1.19	0.447	33.26	151.41	300.00	
38		Benzene, 1,4-dichloro	106-46-7	147	174.2	1.54	0.295		60.20	450.00	0.800
39		Methylene chloride	75-09-2	84.9	39.9	399.30	3.420		174.96	87.00	0.400
40		Trichloroethylene	79-01-6	131.4	87.1	67.12	8.000		270.66	540.00	0.600

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Compound Identification				Physical Properties			VOCBASE Thresholds, mg/m³		Reference Levels, mg/m³		
VOC #	Class	Name	CAS No.	Molecular Weight	Boiling Point, °C	Vapor Pressure,[1] mm Hg	Odor Detection	Mucous Membrane Irritation	ACGIH-TLV[2]	OSHA-PEL[3]	OEHHA-CREL[4]
41	Aliphatic Hyddrocarbons	2-Methyl pentane	107-83-5	86.2	60.4	194.40	0.289		1775.23		
42		3-Methyl pentane	96-14-0	86.2	63.4	174.60					
43		Decane	124-18-5	142.3	174.3	1.25	4.370				
44		Dodecane	112-40-3	170.3	216.5	0.12	14.500				
45		Heptane	142-82-5	100.2	98.6	41.18	40.700	2179.35	1651.35	2100.00	
46		Hexadecane	544-76-3	226.4	287.0	0.00					
47		Hexane	110-54-3	86.2	68.9	139.90	79.400		177.52	1800.00	7.000
48		Nonane	111-84-2	128.3	151.0	3.93	6.760		1056.84		
49		Octane	111-65-9	114.2	125.8	12.55	27.500		1411.89	2350.00	
50		Pentadecane	629-62-9	212.4	270.8	0.00					
51		Tetradecane	629-59-4	198.4	253.7	0.01					
52		Tridecane	629-50-5	184.4	235.6	0.05	16.600				
53		Undecane	1120-21-4	156.3	196.1	0.35	7.760				
54	Aromatic Hydrocarbons	1,2,4,5-Tetramethylbenzene	95-93-2	134.2	197.0	0.48	0.148				
55		2-Ethyl toluene	611-14-3	120.2	165.3	2.30					
56		3-Ethyltoluene	620-14-4	120.2	161.5	2.67					
57		4-Ethyltoluene	622-96-8	120.2	162.2	2.63					
58		4-Phenylcyclohexene	31017-40-0	158.3		0.038*					
59		Benzene	71-43-2	78.1	80.2	86.55	32.500		32.00	32.00	0.060
60		Benzene, 1,2,3-trimethyl-	526-73-8	120.2	176.3	1.48					
61		Benzene, 1,2,4-trimethyl-	95-63-6	120.2	169.5	1.99	0.776		123.80		
62		Benzene, 1,2-dimethyl-	95-47-6	106.2	144.6	5.89	3.800	194.74	434.50	435.00	0.700
63		Benzene, 1,3,5-trimethyl-	108-67-8	120.2	164.9	2.18	1.150		123.00		
64		Benzene, 1,3-dimethyl-	108-38-3	106.2	139.3	7.52	1.410		434.50	435.00	0.700
65		Benzene, 1,4-dimethyl-	106-42-3	106.2	138.5	7.92	2.140	176.03	434.50	435.00	0.700
66		Benzene, isopropyl	98-82-8	120.2	152.6	4.01	0.120	340.12	247.60	245.00	
67		Benzene, propyl-	103-65-8	120.2	159.4	3.02					
68		Ethylbenzene	100-41-4	106.2	136.4	8.58		320.00	311.00	435.00	2.000
69		Naphtalene	91-20-3	134.2	177.3	1.28	0.079		55.30	55.00	0.009
70		Isopropyltoluene	99-87-6	128.2	218.1	0.23	0.012				
71		Styrene	100-42-5	104.2	145.3	5.41	0.160	51.09	214.55	430.00	0.900
72		Toluene	108-88-3	92.1	110.8	25.60	0.644	487.29	189.81	750.00	0.300
73	Cyclo Alkanes	Cyclohexane	110-82-7	84.2	80.9	89.90	315.000		1040.22	1050.00	
74		Cyclohexane, butyl-	1678-93-9	140.3	181.1	1.15					
75		Cyclohexane, ethyl-	1678-91-7	112.2	132.0	11.48					
76		Cyclohexane, propyl-	1678-92-8	126.2	156.9	3.71					
77		Decahydronaphthalene	493-02-7	138.3	187.5	1.06					

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Compound Identification				Physical Properties			VOCBASE Thresholds, mg/m³		Reference Levels, mg/m³		
VOC #	Class	Name	CAS No.	Molecular Weight	Boiling Point, °C	Vapor Pressure,[1] mm Hg	Odor Detection	Mucous Membrane Irritation	ACGIH-TLV[2]	OSHA-PEL[3]	OEHHA-CREL[4]
78	Terpenes	alpha-Pinene	80-56-8	136.2	156.3	4.23	3.890				
79		alpha-Terpinene	99-86-5	136.2	177.4	1.32	2.330				
80		beta-Pinene	127-91-3	136.2	166.2	2.58					
81		gamma-Terpinene	99-85-4	136.2	183.2	0.95	1.500				
82		3-Carene	13466-78-9	136.2	170.2	3.72*					
83		Camphene	79-92-5	136.2	160.7	3.69					
84		Limonene	5989-27-5	136.2	176.7	1.74	2.450				
85	Other	2-Pentylfuran	3777-69-3	138.2	58.2						
86		2-Pyrrolidinone, 1-methyl-	872-50-4	99.1	202.2	0.29					
87		Acetic acid	64-19-7	60.1	118.1	14.03	0.043	23.14	24.74	25.00	
88		Hexanoic acid	142-62-1	116.2	205.9	0.044*	0.060				
89		n-Butyl ether	142-96-1	130.2	140.4	5.31	0.030				
90		Pentanoic Acid	109-52-4	102.1	185.7	0.21	0.020				

[1] Vapor Pressures measured at 23°C, except values with asterisks were measured at 25°C.
[2] American Conference of Governmental Industrial Hygienists Threshold Limit Value
[3] Occupational Safety and Health Administration Permissible Exposure Limit
[4] Office of Environmental Health Hazard Assessment (OEHHA) Chronic Reference Exposure Level

Table F-3 California Department of Health Services List of Target Chemicals (Alevantis 2003)

	Compound Name	CAS No.	OEHHA CREL,[1] g/m³	Prop. 65 Listed?	TAC (ARB) Listed?	Odor Threshold	
						ppb	g/m³
1	Acetic acid	64-19-7				140	360
2	Acetone (2-propanone)[4]	67-64-1				>1000	
3	Acetophenone	98-86-2			x	360	1800
4	Acetaldehyde[4]	75-07-0	9	x	x		
5	Acrolein (2-propenal)[4]	101-02-8	0.06		x	170	410
6	Benzaldehyde[4]	100-52-7				42	190
7	Benzene	71-43-2	60	x	x	>1 ppm	
8	Butanoic acid	107-92-6				3.9	14
9	n-Butanol	71-43-2				490	1500
10	2-Butoxy ethanol[8] (ethylene glycol monobutyl ether)	111-76-2			x	340	1700
11	2-(-2-butoxyethoxy)-ethanol (diethylene glycol monobutyl ether)	112-34-5			x		
12	Butoxy-2-propanol	5131-66-8					
13	Butylcyclohexane	1678-93-9					
14	n-Butyl ethanoate (butyl acetate)	123-86-4				190	930
15	n-Butyl ether	142-96-1				47	250
16	n-Butyl propanoate	590-01-2					
17	Butyraldehyde[4]	123-72-8					
18	Butyrolactone	96-48-0					

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	Compound Name	CAS No.	OEHHA CREL,[1] g/m^3	Prop. 65 Listed?	TAC (ARB) Listed?	Odor Threshold ppb	Odor Threshold g/m^3
19	Caprolactam[6,9]	105-60-2			x		
20	3-Carene	13466-78-9					
21	Chlorodecane	1002-69-3				52	390
22	Chlorododecane	112-52-7					
23	Chloroform (trichloromethane)	67-66-3	300	x	x	>1 ppm	
24	Cumene (isopropylbenzene)	98-82-8			x	24	120
25	Cyclododecane	294-62-2					
26	Cyclohexanone[4,6]	108-94-1				710	2900
27	Decanal[4]	112-31-2				0.9	5.9
28	Decanol	112-30-1				18	120
29	n-decane (decane)	124-18-5				740	4400
30	1-Decene	872-05-9					
31	Dicyclopentadiene	77-73-6					
32	Diethyl Propanedioate (diethyl malonate)	105-53-3					
33	1,3-Diisopropyl benzene	99-62-7					
34	1,4-Diisopropyl benzene	100-18-5					
35	2,2-Dimethyl-1,3-propanediol	126-30-7					
36	N,N-Dimethylformamide	68-12-2	80		x		
37	1,4-Dioxane	123-91-1	3000		x		
38	Dipropylene glycol	106-62-7					
39	Dodecanal	112-54-9					
40	Dodecane	112-40-3					
41	2-Ethoxy ethanol	110-80-5	70	x	x	>1 ppm	
42	2-Ethoxy ethyl acetate	111-15-9	300	x	x	180	1000
43	Ethyl benzene	100-41-4	2000		x	2.9	13
44	2-Ethyl hexanoic acid	149-57-5					
45	2-Ethyl-1-hexanol (2-Ethylhexan-1-ol)	104-76-7				250	1300
46	2-Ethylhexyl acetate	103-09-3				320	2300
47	1-Ethyl-2-methylbenzene	611-14-3					
48	1-Ethyl-3-methylbenzene	620-14-4					
49	1-Ethyl-4-methylbenzene	622-96-8					
50	Ethylene glycol (1,2-ethanediol)	107-21-1	400		x		
51	Formaldehyde (methanal)[4,7]	50-00-0	33[4]	x	x	870	1100
52	2-Furancarboxaldehyde (furfural)	98-01-1				780	3200
53	Heptanal[4]	111-71-7				4.8	23
54	n-Heptane	142-82-5					
55	Heptanoic acid	111-14-8				28	150
56	Hexanal[4]	66-25-1				14	58
57	n-Hexane	110-54-3	7000		x		
58	Hexanoic acid	142-62-1				13	60
59	2-Hydroxybenzaldehyde (salicylaldehyde)	90-02-8				7.4	38
60	Indene	95-13-6				8.7	43
61	Isopropyl alcohol (2-propanol)	67-63-0	7000		x	>1 ppm	
62	Isovaleraldehyde (3-methylbutanal)[4]	590-86-3				2.2	8.1
63	δ-Limonene (limonene)	138-86-3				440	2500
64	Linalyl propanoate	144-39-8					

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	Compound Name	CAS No.	OEHHA CREL,[1] g/m³	Prop. 65 Listed?	TAC (ARB) Listed?	Odor Threshold ppb	Odor Threshold g/m³
65	Longifolene	475-20-7					
66	2-Methoxy ethanol	109-86-4	60	x	x	1100	3500
67	1-(2-methoxy-1-methylethoxy)-2-propanol (dipropylene glycol monomethyl ether)	20324-32-7					
68	1-(2-Methoxypropoxy)-2-propanol	13429-07-7					
69	Methyl cyclohexane	108-87-2					
70	Methyl isobutyl ketone (MIBK)	108-10-1			x		
71	2-Methyl-2,4-pentanediol	107-41-5					
72	2-Methyl propanoic acid (isobutyric acid)	79-31-2				19	72
73	2-Methyl-2-propenoic acid, methyl ester (methyl methacrylate)[10]	80-62-6			x	350	1500
74	1-Methyl-2-pyrrolidinone[6] (N-methylpyrrolidinone)	872-50-4		x			
75	Methylene chloride (dichloromethane)	75-09-2	400	x	x		
76	Naphthalene	91-20-3	9		x	15	79
77	Nonanal[4]	124-19-6				2.2	13
78	n-Nonane (nonane)	111-84-2				>1 ppm	
79	Nonanoic acid	112-05-0				1.9	13
80	2-Nonenal	18829-56-6					
81	2-Norbornene	498-66-8				74	370
82	Octanal[4]	124-13-0				1.3	7.2
83	Octane	111-65-9				>1 ppm	
84	Octanoic acid	95-47-6				4	24
85	2-Octenal (trans-2-octenal)	2548-87-0				2	11
86	2,2′-Oxybis-ethanol (diethylene glycol)	111-46-6					
87	Pentadecane	629-62-9					
88	Pentanal (valeraldehyde)[4]	110-62-3				6	22
89	Pentanoic acid	109-52-4				4.8	20
90	Phenol	108-95-2	200		x	110	430
91	β-Pinene	127-91-3				690	3900
92	4-Phenylcyclohexene (4-PC)	4994-16-5				0.5 [2]	2.5
93	Propionaldehyde[4,6]	123-38-6			x		
94	Propylene glycol	57-55-6					
95	2-pyrrolidinone	616-45-5					
96	Styrene (vinylbenzene)	100-42-5	900		x	140	630
97	α-Terpineol	98-55-5				37	240
98	Tetrachloroethene (tetrachloroethylene, perchloroethylene)	127-18-4	35	x	x	> 1 ppm	
99	Tetradecane	629-59-4				> 1 ppm	
100	Toluene	108-88-3	300		x	> 1 ppm	
101	trans-2-Decenal	3913-71-1				0.36	2.3
102	trans-Ethyl cinnamate	103-36-6					
103	trans-2-methyl-3-heptene	692-92-6					
104	trans-3-Octene	1449-01-8					
105	1,1,1-Trichloroethane[6] (methylchloroform)	71-55-6	1000		x	> 1 ppm	
106	Trichloroethylene	79-01-6	600	x	x		
107	Tridecane	629-59-4					
108	Triethylene glycol monomethyl ether	112-35-6					
109	Triethylphosphate	78-40-0					

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	Compound Name	CAS No.	OEHHA CREL,[1] g/m³	Prop. 65 Listed?	TAC (ARB) Listed?	Odor Threshold	
						ppb	g/m³
110	1,2,3-Trimethylbenzene	526-73-8					
111	1,2,4-Trimethylbenzene (psuedocumene)	95-63-6				155	770
112	1,3,5-Trimethyl Benzene	108-67-8				230	1100
113	2,2,4-Trimethyl-1,3-pentanediol monoisobutyrate (texanol monoisobutyrate)	25265-77-4					
114	2,2,4-Trimethyl-1,3-pentanediol	144-19-4					
115	Trimethyl silanol	1066-40-6					
116	Undecane (n-undecane)	1120-21-4				1200	7800
117	Vinyl acetate	108-05-4	200		x	600	2200
118	5-Vinyl-2-norbornene	3048-64-4					
119	o-Xylene (1.2-dimethylbenzene)	95-47-5	700		x	850	3800
120	m-Xylene (1,3-dimethylbenzene)	108-38-3	700		x	320	1400
121	p-Xylene (1,4-dimethylbenzene)	106-42-3	700		x	490	2100

[1] Office of Environmental Health Hazard Assessment (OEHHA) Chronic Reference Exposure Level (OEHHA 2008)
[2] Proposition 65, the Safe Drinking Water and Toxic Enforcement Act of 1986 (OEHHA 2007b)
[3] Toxic Air Contaminants (OEHHA 2007a)
[4] Aldehyde-DNPH analysis.
[5] From Van Ert et al. (1987).
[6] Chemical on Proposition 65 or TAC lists without a CREL.
[7] Based on the current 1-hour Acute Reference Exposure Level (REL) of 76 ppb (94 μg/m³), an exposure level of 27 ppb (33 μg/m³) can be extrapolated based on an 8-hour exposure period (OEHHA 1999). The current CREL of 3 μg/m³ was not used.
[8] CREL is 20μg/m³ from the TAC list (OEHHA 2007a).
[9] Interim State of California concentration limit is 100 μg/m³.
[10] CREL is 980μg/m³ from the TAC list (OEHHA 2007a).

Table F-4 European Commission 63-Compound List (EC 1997)
(Used by DGS [2008] and BIFMA [2007])

Chemical Class	Compound	CAS No.	Boiling Point (°C)
Aromatic Hydrocarbons	Benzene	71-43-2	80.1
	Toluene	108-88-3	111
	Ethylbenzene	100-41-4	136.2
	m/p-Xylene	108-38-3/106-42-3	139.1/138.3
	o-Xylene	95-47-6	144
	n-propylbenzene	103-65-1	159
	1,2,4-Trimethylbenzene	95-63-6	169.4
	1,3,5-Trimethylbenzene	108-67-8	165
	2-Ethyltoluene	611-14-3	165.2
	Styrene	100-42-5	145.2
	Naphthalene	91-20-3	218
	4-Phenylcyclohexene	31017-40-0	251-3

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Chemical Class	Compound	CAS No.	Boiling Point (°C)
Aliphatic Hydrocarbons ($n\text{-}C_6$ to $n\text{-}C_{16}$)	n-Hexane	110-54-3	69
	n-Heptane	142-82-5	98.4
	n-Octane	111-65-9	125.7
	n-Nonane	111-84-2	150.8
	n-Decane	124-18-5	174.1
	n-Undecane	1120-21-4	196
	n-Dodecane	112-40-3	216.3
	n-Tridecane	629-50-5	235.4
	n-Tetradecan	64036-86-3	253.7
	n-Pentadecane	629-62-9	270.6
	n-Hexadecane	544-76-3	287
	2-Methylpentane	107-83-5	60.3
	3-Methylpentane	96-14-0	63.3
	1-Octene	111-66-0	121.3
	1-Decene	872-05-9	170.5
Cyclo-Alkanes	Methylcyclohexane	108-87-2	101
	Methylcyclopentane	96-37-7	71.8
	Cyclohexane	100-82-7	81
Terpenes	3-Carene	13466-78-9	167
	alpha-Pinene	80-56-8	156
	beta-Pinene	181172-67-3	164
	Limonene	138-86-3	170
Alcohols	2-Propanol	67-63-0	82.4
	1-Butanol	71-36-3	118
	2-Ethyl-1-hexanol	104-76-7	182
Glycols / Glycol Ethers	1–Methoxy-2-propanol	107-98-2	118
	2-Ethoxyethanol	110-80-5	118135
	2-Butoxyethanol	111-76-2	231171
	2-Methoxyethanol	109-86-4	124-25
	2-Butoxyethoxyethanol	112-34-5	231
Aldehydes	Butanal	123-72-8	76
	Pentanal	110-62-3	103
	Hexanal	66-25-1	129
	Nonanal	124-19-6	190-2
	Benzaldehyde	100-52-7	179
Ketones	Methylethylketone	78-93-3	780
	Methylisobutylketone	108-10-1	116.8
	Cyclohexanone	108-94-1	155.6
	Acetophenone	98-86-2	202
Halocarbons	Trichloroethene	79-01-6	87
	Tetrachloroethethene	127-18-4	121
	1,1,1–Trichloroethane	71-55-6	74.1
	1,4-Dichlorobenzene	106-46-7	173
Acids	Hexanoic acid	142-62-1	202-3

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Chemical Class	Compound	CAS No.	Boiling Point (°C)
Esters	Ethylacetate	141-78-6	77
	Butylacetate	123-86-4	126.5
	Isopropylacetate	108-21-4	85
	2-Ethoxyethylacetate	111-15-9	156.4
	TXIB(Texanolisobutyrate)	6846-50-0	
Other	2-Pentylfuran	3777-69-3	>120 (2-tert-butylfuran)
	THF(Tetrahydrofuran)	109-99-9	67

Table F-5 State of California Maximum Allowable VOC Concentration Limits (DGS 2008)

Compound Name	CAS No.	Molecular Weight	Maximum Allowable Concentration, μg/m^3
Ethylbenzene	100-41-4	106.2	1000
Styrene	100-42-5	104.2	450
p-Xylene	106-42-3	106.2	350
1,4-Dichlorobenzene	106-46-7	147	400
Epichlorohydrin	106-89-8	92.52	1.5
Ethylene glycol	107-21-1	62.1	200
1-Methoxy-2-propanol (propylene glycol monomethyl ether)	107-98-2	90.12	3500
Vinyl acetate	108-05-4	86.1	100
m-Xylene	108-38-3	106.2	350
Toluene	108-88-3	92.1	150
Chlorobenzene	108-90-7	112.56	500
Phenol	108-95-2	94.1	100
2-Methoxyethanol	109-86-4	76.1	30
Ethylene glycol monomethyl ether acetate	110-49-6	118.13	45
n-Hexane	110-54-3	86.2	3500
2-Ethoxyethanol	110-80-5	90.1	35
2-Ethoxyethyl acetate	111-15-9	132.2	150
1,4-Dioxane	123-91-1	88.1	1500
Tetrachloroethylene	127-18-4	165.8	17.5
Formaldehyde	50-00-0	30.1	16.5
Isopropanol	67-63-0	60.1	3500
Chloroform	67-66-3	119.4	150
N,N-Dimethyl formamide	68-12-2	73.09	40
Benzene	71-43-2	78.1	30
1,1,1-Trichloroethane	71-55-6	133.4	500
Acetaldehyde	75-07-0	44.1	9
Methylene chloride	75-09-2	84.9	200
Carbon disulfide	75-15-0	76.14	400
Trichloroethylene	79-01-6	131.4	300
1-Methyl-2-Pyrrolidinone	872-50-4	99.13	160
Naphthalene	91-20-3	128.2	4.5
o-Xylene	95-47-6	106.2	350

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Table F-6 Examples of Secondary VOC Emissions from Building Products and Equipment (Wolkoff 1999)

Building Product	Secondary VOCs	Condition*	Literature
Carpet—wool based	Aldehydes, formaldehyde, aldehydes, acids, benzothiazol	Ozone, heat	Knudsen et al. (1999); Wolkoff (1998); Brzezinskiet et al. (1996); Weschler et al. (1992); Sollinger et al. (1993)
Carpet cushion	Acetic acid	Water, nitrogen	Schaeffer et al. (1996)
Cork	Acetic acid, furfural	Heat	Horn et al. (1998)
Duct lines	$C_{6,8\text{-}10}$ aldehydes, fatty acids	Ozone	Morrison et al. (1998)
Furniture coating	Aldehydes, acrylates, isocya-nates, styrene, terpenes		Salthammer et al. (1999b)
Linoleum	Aldehydes, unsaturated aldehydes	Water	Jensen et al. (1996); Wolkoff et al. (1995)
Alkyd paint—"natural" paint	C_3 and $C_{5\text{-}6}$ aldehydes, fatty acids, terpenes		Rothweiler et al. (1993); Ullrich et al. (1992); Volland and Zölter (1996); Zellweger et al. (1997)
Office equipment/humans	Formaldehyde, aldehydes	Ozone	Leovic et al. (1996); Wolkoff et al. (1992)
Paint—acrylic, latex	Aldehydes, formaldehyde, acet-aldehyde, formic acid	Ozone	Chang and Guo (1998); Knudsen et al. (1999); Young (1992); Reiss et al. (1995a, 1995b)
Primer—water based	Hexanal		Zellwegar et al. (1997)
Polyvinyl chloride (PVC)	2-exthylhexanol	Water	Knudsen et al. (1999); Wolkoff (1998); Van der Wal et al. (1997)
Thermal insulation	Aldehydes	Moisture	Van der Wal et al. (1989)

*Clean air is used, if not otherwise stated.

Table F-7 Possible Reaction Products in Indoor Air with Potential Emission Sources and Reactants (Uhde and Salthammer 2007)

Reactants	Products	Possible Sources
x-Pinene	Pinene oxide, pinonaldehyde	Wood, wood-based products
Limonene	Limonene oxide, carvone, formaldehyde	Wood, coating systems
Oleic acid	Heptanal,octanal, nonanal, decanal, 2-decanal	Linoleum, eco-lacquers, nitrocellulose
Linolenic acid	2-Pentenal, 2-hexenal, 3-hexenal, 2-hep-tenal, 2.4-heptedienal, 1-penten-3-one	Lacquers, alkyd resins
Linoleic acid	Hexanal, heptanal, 2-haptenal, octanal, 2-octenal, 2-nonenal,2-decenal, 2,4-nonadienal, 2,4-decadienal	
Hemicelluloses	Furfural, acetic acid	Cork
5-Methyl-N-Phenyl-2-Pyrrolidone (PHMP)	Benzaldehyde, acetone, benzil	Ultraviolet-cured coatings
1-hydroxycyclohexyl phenyl ketone (HCPK)	Benzaldehyde, cyclohexanone, benzil	Ultraviolet -cured coatings
2-Ethyl-hexyl acetate	Acetic acid, 2-ethyl-a-hexanol	Solvent
Zn-2-ethylhexanoate	2-Ethyl-a-hexanoic acid	Stabilizers
n-Butylacrylate	n-Butanol	Acylate coatings
Di(2-ethylhexyl)-phthalate (DEHP)	2-Ethyl-q-hexanol	Plasticiser
Di-n-butyl-phthalate (DBP)	n-Butanol	Plasticiser
Di-iso-butyl-phthalate (DIBP)	2-Butanol	Plasticiser
Tris (2-chloroisopropyl) phosphate (TCPP)	1-Chloro-2-propanol, 2-chloro-1-propanol	Flame retardant
Tris(2,3-dichloropropyl) phosphate(TDCPP)	1,2-Dichloropropane, 1,2-dichloropropanol	Flame retardant
Tris (2-chloroethyl) phosphite (TCEP)	2-Chloro-ethanol	Flame retardant
Tert-Butyl peroxypivalate (TBPP)	1-Bromo-2-propanol, 2-bromo-1-propanol	Flame retardant
Tris(2,4di-t-butylphenyl)phosphite (TDBPP)	2,3-Dibromo-1-propanol	Flame retardant
Styrene + cis-1,3-butadiene	4-Phenylcyclohexene (4-PC)	Styrene-butadiene rubber
Cis-1,3-butadiene + trans-1,3-butadiene	4-Vinyl-cyclohexene (4-VCH)	Styrene-butadiene rubber

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Reactants	Products	Possible Sources
2-Chloro-1,3-butadiene	1-Chloro-4-(1-chlorovinyl)-cyclohexene 1-Chloro-5-(1-chlorovinyl)-cyclohexene	Rubber
Zn-diethyldithiocarbamate	Carbon disulfide, diethylamine	Vulcanization accelerator
Azodicarbonamide	Semicarbazide	Foaming agent
Adipinic acid + 1,4-butanediol	1,6-Dioxa-cyclododecane-7,12-dione	Adhesive
Dimethylaminoethanol + formic acid	Dimethylformamide	"Green" paint
1-Tryptophane	o-Aminoacetophenone	Casein products
2,3,4,6-Tetrachlorophenol	2,3,4,6-Tetrachloroanisole	Application of pentachlorphenol (PCP)
T4MDD	MIBK, 3,5-dimethyl-1-hexyne-3-ol	Water-based paint
AIBN	Tetramethyl succinonitrile	Flexible polyurethane foam

Table F-8 Test Chamber Studies on Primary and Secondary Emissions from Building Materials (Uhde and Salthammer 2007)

Building Product	Parameters	Reference
Carpet	Ozone	Weschler et al. (1992)
Carpet		Sollinger et al. (1993, 1994)
Linoleum		Jensen et al. (1995a, 1995b)
Latex paint	Ozone	Reiss et al. (1995b)
Wallcovering, latex paint, carpet, plaster, plywood		Moriske et al. (1998)
Polyvinyl chloride (PVC), parquet, carpet, sealant, paint	Air velocity, humidity, temperature, air	Wolkoff (1998)
Cork products		Horn et al. (1998)
PVC, parquet, carpet, sealant, paint	Air velocity	Knudsen et al. (1999)
Wood-based furniture coatings		Salthammer et al. (1999b)
Carpet, PVC flooring, sealant, floor varnish, wall paint	Temperature, humidity	Fang et al. (1999)
PVC, adhesive	Complete floor structures	Sjöberg (2000)
Particle board, medium density fiberboard		Baumann et al. (1999, 2000)
Ultraviolet-cured lacquer	Light	Salthammer et al. (2002)
Wood	Heat Treatment	Manninen et al. (2002)
Carpet	Ozone	Morrison and Nasaroff (2002)
Polyurethane		Salthammer et al. (2003)
Plasterboard, paint, carpet, linoleum, pinewood, melamine	Ozone	Knudsen et al. (2003)
Wood-based products, laminate, cork, adhesive, lacquer	Complete floor structures	Salthammer et al. (2004)
Adhesives, PVC, linoleum, rubber, polyolefine	Complete floor structures	Wilke et al. (2004)
Ultraviolet coating	Light	Salthammer et al. (2002)

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Appendix G

Single-Path Multiple-Zone System Design

The article "Standard 62-2001 Addendum 62n: Single-Path Multiple-Zone System Design" by D. Stanke reproduced in this appendix (2005, *ASHRAE Journal* 47[1]:28–35) provides an example of how to calculate E_z and V_{ot} for a single-path multiple-zone recirculating system with variable-air-volume (VAV). This article assumes the worst-case VAV box conditions. Experienced designers may be able to make more accurate predictions of the behaviors of the systems that they design. With either extensive field experience or a realistic simulation of the system's dynamic behavior, the outdoor air requirements may approach those of a constant-volume system. Lacking such information, the method shown in the article provides a conservative design approach.

Standard 62-2001 Addendum 62*n*

Single-Path Multiple-Zone System Design

By Dennis Stanke, Member ASHRAE

ANSI/ASHRAE Standard 62-2001, *Ventilation for Acceptable Indoor Air Quality,*[1] as modified by Addendum 62*n*,[2] prescribes new minimum breathing-zone ventilation rates and new calculation procedures to find intake airflow for different ventilation systems. Previous articles[3,4] discussed the design of "simple" ventilation systems (single-zone, 100% outdoor-air, and changeover-bypass VAV) in compliance with Addendum 62*n* requirements. Here, we examine the design of a more complex set of ventilation systems, namely single-path, multiple-zone recirculating systems.

Although the Ventilation Rate Procedure in Standard 62 has required specific calculations (Equation 6-1) for multiple-zone systems since 1989, the calculation procedure was sketchy at best; consequently, it was widely misunderstood and largely ignored by designers. Addendum 62*n* includes a detailed calculation procedure for multiple-zone system design. Use of this procedure is expected to increase consistency among designers and reduce the tendency to design multiple-zone systems—especially VAV systems—that provide inadequate ventilation for some fully occupied zones. Addendum 62*n* also includes operational control options that can be used to modulate ventilation capacity as ventilation load and/or efficiency varies, but these options are left to a future article. The following discussion covers only design calculations.

Many HVAC systems are configured as "single-supply" or single-path, multiple-zone, recirculating ventilation systems. For instance, constant-volume systems with terminal reheat, traditional constant-volume multizone systems, single-duct VAV systems, and single-fan dual-duct VAV systems all provide ventilation from a single source or path. (A single-fan, dual-duct system supplies air to each space using two different ducts, but the air in each duct contains the same fraction of outdoor air, because one fan—a single source—delivers the same air mixture to each duct.) Other systems have multiple ventilation paths, including dual-fan, dual-duct VAV systems and VAV systems with fan-powered or induction terminal units. Single-duct VAV systems with series fan-powered boxes are always dual-path ventilation systems, but those with parallel fan-powered boxes are single-path with the local fan off and dual-path with it on. Although any of these HVAC systems may be used in vari-

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ous building types, we narrow our discussion to a single-duct VAV system, with throttling VAV boxes for interior zones and reheat VAV boxes in perimeter zones, applied in an example office building.

Demonstrating Compliance by Example

Our example system (*Figure 1*) includes a central air handler, with a modulating outdoor-air damper that may be controlled as an economizer; a variable-volume supply fan to deliver primary air; cooling-only, throttling VAV boxes in the interior zones; throttling VAV boxes with electric reheat in the perimeter zones; a central return fan; and a central relief damper for building pressure control. Although we won't discuss system control details here, it's important that we share the same mental "picture" of the VAV system we're designing:

• Intake airflow is sensed and maintained by adjusting the intake damper position. (Often, the return- and outdoor-air dampers are linked such that closing the outdoor-air damper opens the return-air damper proportionately. Alternately, these dampers can be controlled separately to reduce fan energy while maintaining proper intake airflow, but this has no impact on ventilation requirements at design conditions.)

• Primary air temperature is sensed and maintained by sequentially adjusting the heating-coil control valve, economizer dampers, and cooling-coil control valve.

• Duct pressure is sensed and maintained at setpoint by adjusting the primary fan capacity (via fan speed, for instance, or inlet guide vane position).

• Zone temperature is sensed and maintained at the cooling setpoint by adjusting the setpoint for VAV-box primary airflow.

• VAV-box airflow is sensed and maintained at setpoint by adjusting the position of the VAV-box damper.

• For zones that need reheat, zone temperature is sensed and maintained at the heating setpoint by adjusting reheat capacity (electric reheat or a hot water valve) and, thereby, discharge air temperature.

• Return air plenum pressure (at the central air handler) is sensed and maintained by adjusting return fan capacity.

• Building pressure is sensed and maintained between set limits by adjusting the relief (central exhaust) damper position.

Since multiple-zone systems provide the same primary air mixture to all zones, the fraction of outdoor air in the primary airstream must be sufficient to deliver the outdoor airflow needed by the "critical" zone—the zone needing the greatest fraction of outdoor air in its primary airstream. In the past, many designers simply added the zone outdoor airflow requirements and set the intake airflow to match this sum, which resulted in a very low outdoor-air fraction and many underventilated zones.

Some designers went to the other extreme, finding the highest fraction of outdoor air needed by any zone in the system and setting the intake airflow to provide this fraction at all times. This approach considers only first-pass outdoor air, giving no credit for unused recirculated outdoor air, and results in a very high outdoor-air fraction and overventilation in all zones.

Proper design in compliance with Addendum 62*n* calculation procedures strikes a balance between these extremes, appropriately accounting for both critical-zone needs and unused, recirculated outdoor air.

Let's look at an example office building (*Figure 2*). We assumed that thermal comfort can be achieved using only eight VAV thermostats, with each thermostat controlling one or more VAV boxes. We considered each of these "comfort zones" (or "HVAC zones" per ASHRAE Standard 90.1-2001) as a separate "ventilation zone."

According to Addendum 62*n*, a ventilation zone is "one occupied space or several occupied spaces with similar occupancy category, occupant density, zone air-distribution effectiveness, and zone primary airflow per unit area."

Most (but not all) HVAC zones qualify as ventilation zones. The area and population for each zone in this example were selected to help illustrate the calculations rather than to reflect typical zone sizes or population densities.

To comply with Addendum 62*n*, our design calculations begin by finding the ventilation needs at the zone level and conclude by determining the required intake airflow at the system level.

Zone Ventilation Calculations

Following the procedure under "zone calculations" in Section 6.2.1, we found zone outdoor airflow (V_{oz}) for each zone (*Figure 3*):

1. Referring to Addendum 62*n*, Table 6.1 (not shown), look up the prescribed minimum *people outdoor-air rate* (R_p) and the prescribed minimum building *area outdoor-air rate* (R_a). In our example office building, each zone needs 5 cfm/person and 0.06 cfm/ft². Using these values, along with the design *zone population* (P_z) and *zone floor area* (A_z), find the minimum *breathing-zone outdoor airflow* by solving Equation 6-1 ($V_{bz} = R_p \times P_z + R_a \times A_z$). Either peak or average expected occupancy may be

used to establish P_z; we used peak population in all zones. (An earlier article[3] covered population-averaging calculations in detail. See www.ashrae.org for the most current version.)

For our example, the west offices need V_{bz} = 5 × 20 + 0.06 × 2,000 = 100 + 120 = 220 cfm for proper ventilation in the breathing zone.

2. Look up *zone air-distribution effectiveness* (E_z), based on the air-distribution configuration and the default values presented in Addendum 62*n*, Table 6.2 (not shown). All of our example zones use overhead diffusers and ceiling returns, and they all receive 55°F primary air, so E_z = 1.0 when cooling. If the thermostat calls for heat in any of the perimeter zones, primary air is reheated and discharged at 95°F; so, E_z = 0.8 when heating.

3. Find the minimum *zone outdoor airflow* by solving Equation 6-2 ($V_{oz} = V_{bz} / E_z$) for both cooling and heating operation. For example, the west offices need V_{oz} = 220/1.0 = 220 cfm at the diffusers when cooling, and V_{oz} = 220/0.8 = 275 cfm when heating.

System Ventilation Calculations

As in Standard 62-1989, -1999, and -2001, Addendum 62*n* recognizes that multiple-zone recirculating systems must overventilate some zones to properly ventilate all zones. It also recognizes that "unused" outdoor air recirculated from overventilated zones reduces the required intake airflow, but that unused outdoor air that leaves the building (by exhaust or exfiltration) increases the required intake airflow. Proper accounting results in a ventilation credit for recirculated outdoor air and a ventilation debit for exhausted outdoor air.

Addendum 62*n* makes this accounting straightforward by requiring a specific calculation procedure to determine the minimum *outdoor-air intake flow* based on the *system ventilation efficiency* inherent in every multiple-zone recirculating system.

Earlier versions of the standard required use of the "multiple-space" equation, $Y = X/(1 + X - Z)$, to find the fraction of intake air needed. This approach resulted in about the same intake airflow as Addendum 62*n* for single-path systems; but without a clear procedural explanation, the equation was widely misunderstood and largely ignored by designers.

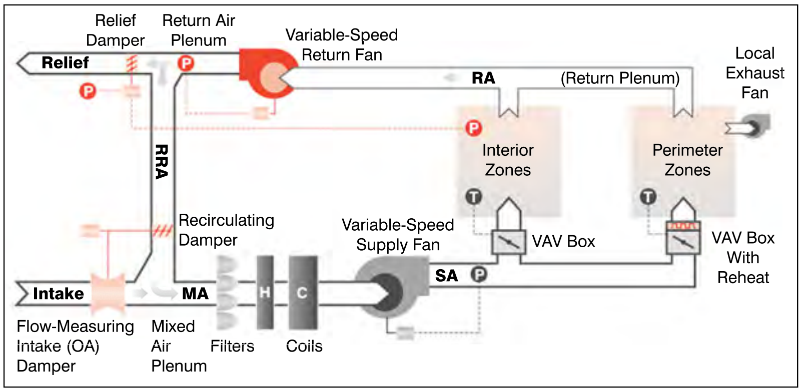

Figure 1: Variable air volume reheat system.

Designs based on the 62*n* procedure result in proper ventilation for the critical zone at worst-case design conditions while allowing credit for "good" outdoor air that recirculates from all other overventilated zones.

From the zone calculations that we completed earlier, we know how much outdoor airflow must reach the diffusers in each zone. Now, let's figure out the minimum required intake airflow for the system at design conditions.

Before we start, we should recognize something that Addendum 62*n* implies but doesn't explain: *The "worst-case" or highest required intake airflow may or may not occur at the design cooling condition* (when system primary airflow is highest). In some cases, it may actually occur at the design heating condition (when zone primary airflow values are very low). With

Averaging Zone Population for Ventilation System Design

In earlier versions of the standard, only "intermittent occupancy" zones (at peak population for three hours or less) could be designed for ventilation at the average population (but not less than one-half of the peak population). Now, any zone may be designed for average population. According to the "short-term conditions" section of Addendum 62*n*, the system must be designed to deliver the required outdoor airflow to each occupied breathing zone.

However, if occupancy or intake airflow varies, the ventilation system design may be based on average conditions over a specific time period rather than on peak conditions. The averaging time *T* for a given zone is determined according to Equation 6-9 ($T = 3\,v/V_{oz}$) using zone volume and the breathing-zone outdoor airflow that would be needed at peak population. *T* equals three zone time constants, the time it takes for contaminant concentration to achieve a nearly steady-state value in response to a step change in contaminant source. When applied to population, this averaging approach replaces the population-averaging option for "intermittent occupancy" spaces, found in previous versions of the standard,

Averaging time may be applied to make design adjustments when changing conditions in the zone can be predicted. For instance, if zone population fluctuations are predictable, then the design breathing-zone outdoor airflow may be calculated based on the highest average population over any *T*-minute period.

this in mind, we'll need to check the required intake airflow at both design cooling *and* design heating because it's ultimately the worst-case outdoor-air intake flow that will establish the required capacities for the heating and cooling coils.

For our example, we tried to use "reasonable" values for *zone primary airflow* (V_{pz}) at design cooling load. We arbitrarily set all minimum primary airflow settings (V_{pz}-min) to 25% of design cooling airflow. We assumed that each reheat box enters reheat mode after its primary airflow decreases to the minimum setting and the zone temperature drops below the heating setpoint. Reheat operation continues until the zone temperature exceeds the heating setpoint.

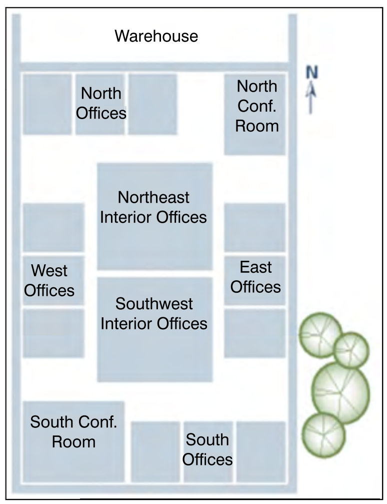

Figure 2: Multiple-zone office building.

Case 1: Ventilation Calculations for "Default" Cooling Design

Building on our earlier zone-level calculations (*Figure 3*), we followed the step-by-step, "multiple-zone recirculating systems" procedure to find the minimum, system-level, *outdoor-air intake flow* (V_{ot}) at the design cooling condition (*Figure 4*):

4. For each zone, find the *zone primary outdoor-air fraction* by solving Equation 6-5 ($Z_p = V_{oz}/V_{pz}$) using the *zone outdoor airflow* (V_{oz}) values for cooling from Step 3 and the minimum primary airflow setting. As an example, at minimum primary airflow, the south offices need $Z_p = 210/475 = 0.44$ when delivering cool air.

5. Addendum 62*n* allows the designer to use a either default value for *system ventilation efficiency* (E_v) using Table 6.3 (not shown) or a calculated value (found using equations in Appendix G). In this case, we used Table 6.3 and the highest *zone primary outdoor-air fraction* among the zones served ("max Z_p" = 0.50 for the north offices) to look up the corresponding default *system ventilation efficiency* (E_v). From that value, we can interpolate to find $E_v = 0.65$.

6. Find *occupant diversity* according to Equation 6-7 ($D = P_s/\Sigma P_z$) by using the expected peak *system population* (P_s) and the sum of design zone populations. For our example, we expect a maximum system population of 164 people, so $D = 164/224 = 0.73$.

7. Find the *uncorrected outdoor-air intake flow* for the system by solving Equation 6-6 $\left(V_{ou} = D \times \Sigma(R_p \times P_z) + \Sigma(R_a \times A_z)\right)$. Without correcting for zone ventilation effectiveness and system ventilation efficiency, we find that the system needs V_{ou} = 2,800 cfm of outdoor air at the breathing zones.

8. Finally, find *outdoor-air intake flow* for the system by solving Equation 6-8 ($V_{ot} = V_{ou}/E_v$). In our example, $V_{ot} = 2{,}800/0.65 = 4{,}310$ cfm at the design cooling condition.

But, is this really the worst-case (highest volume) intake airflow? What happens at design heating conditions?

Case 2: Ventilation Calculations for "Default" Heating Design

Let's find the minimum system-level *outdoor-air intake flow* (V_{ot}) for the design heating condition. The procedure is the same one that was just described for default cooling design in Case 1. It builds on the zone-level calculations that were completed earlier (*Figure 3*), but in this case, we assume that each space receives minimum primary airflow at the design outdoor heating condition (*Figure 5*).*

4. For each zone, find the *zone primary outdoor-air fraction* by solving Equation 6-5 ($Z_p = V_{oz}/V_{pz}$) with the *zone outdoor*

* Some readers might deem this to be a radical assumption because interior zones typically need more than minimum cooling airflow, even on the coldest day. But, it's an assumption that is likely to require a high intake airflow, which is useful for this demonstration.

Design Cooling Condition

For single-path VAV systems, the worst-case condition for ventilation (that is, the lowest system ventilation efficiency and the highest required intake airflow) in the cooling mode usually occurs when the VAV primary airflow for the system is at its highest value. Since almost all VAV systems exhibit load diversity (all zones don't require peak cooling airflow simultaneously), the critical zone can be assumed to be delivering minimum primary airflow with the central fan at cooling-design or "block" primary airflow. In some cases, worst-case ventilation in the cooling mode may actually occur at a central fan airflow that's slightly lower than block airflow. If a system doesn't have much load diversity (all interior zones, for example)—and if the critical zone requires a lot of primary airflow—then the central fan may or may not be at block airflow when the critical zone is at minimum primary airflow.

How can you find out the system primary airflow at the worst-case ventilation condition? Simply assume that primary airflow at the fan is the sum of all noncritical-zone peak airflow values plus the minimum primary airflow for the critical zone. At this condition, the difference between X_s and Z_p will be greatest, so system ventilation efficiency will be at its lowest value and outdoor-air intake flow will be at its highest values—the worst-case condition. (Operationally, this worst-case condition may not actually occur, since it assumes that the critical zone requires minimum primary airflow even when fully occupied; this might be the case for some perimeter zones, for example, during cold weather.)

						Cooling			Heating	
Procedural Step						**1**	**2**	**3**	**2**	**3**
Variable		R_p	P_z	R_a	A_z	V_{bz}	E_z*	V_{oz}	E_z**	V_{oz}
Ventilation Zone	**Box Type**	cfm/p	p	cfm/ft²	ft²	cfm		cfm		cfm
South Offices	Reheat	5	18	0.06	2,000	210	1.0	210	0.8	260
West Offices	Reheat	5	20	0.06	2,000	220	1.0	220	0.8	275
South Conference Room	Reheat	5	30	0.06	3,000	330	1.0	330	0.8	410
East Offices	Reheat	5	20	0.06	2,000	220	1.0	220	0.8	275
Southwest Interior Offices	VAV	5	50	0.06	10,000	850	1.0	850	1.0	850
Northeast Interior Offices	VAV	5	50	0.06	10,000	850	1.0	850	1.0	850
North Offices	VAV	5	16	0.06	2,000	200	1.0	200	1.0	200
North Conference Room	VAV	5	20	0.06	2,000	220	1.0	220	1.0	220

* For zones with a throttling VAV box, discharge air is usually cool whenever the zone is occupied (morning warmup usually occurs before occupancy).
** For zones with terminal reheat, discharge air temperature can be either cool or warm when the zone is occupied, so E_z drops from 1.0 when cooling to 0.8 when heating.

Figure 3: Zone ventilation calculations.

airflow (V_{oz}) values for heating from Step 3 and the minimum primary airflow setting. At minimum primary airflow, the south office needs $Z_p = 260/475 = 0.55$ when delivering warm air.

5. Using Table 6.3 (not shown) and the highest *zone primary outdoor-air fraction* among the zones served ("max Z_p" = 0.55 for the south, west, and east offices) to look up the corresponding default *system ventilation efficiency* (E_v), we find that $E_v = 0.60$.

6. Find *occupant diversity* according to Equation 6-7 ($D = P_s/\Sigma P_z$), as shown previously. In our example, $D = 164/224 = 0.73$.

7. Find the *uncorrected outdoor-air intake flow* for the system from Equation 6-6 $\left(V_{ou} = D \times \Sigma(R_p \times P_z) + \Sigma(R_a \times A_z)\right)$. Once again, without correcting for zone air-distribution effectiveness and system ventilation efficiency, our system needs $V_{ou} = 2{,}800$ cfm of outdoor air.

8. Finally, find *outdoor-air intake flow* for the system by solving Equation 6-8 ($V_{ot} = V_{ou}/E_v$). In our example, $V_{ot} = 2{,}800/0.60 = 4{,}670$ cfm at design heating conditions.

The system is less efficient at this heating condition than it was at the design cooling condition (*system ventilation efficiency* of 0.60 in heating vs. 0.65 in cooling). So, using the "default" approach (Table 6.3), worst-case/highest *outdoor-air intake flow* occurs at the design heating condition (V_{ot} = 4,670 cfm), assuming that all zones receive minimum primary airflow.

Multiple-Zone Systems

In multiple-zone recirculating systems, such as constant-volume reheat systems and all varieties of VAV systems, one air handler supplies a mixture of outdoor air and recirculated return air to two or more ventilation zones. The required outdoor-air intake flow only can be determined by properly accounting for system ventilation efficiency. Why?

These ventilation systems include an unavoidable "built-in" inefficiency. This inefficiency exists because the intake airflow must be sufficient to ventilate the *critical zone*—the zone that requires the highest fraction of outdoor air in its primary airstream. Since a multiple-zone system delivers the same primary air mixture to each ventilation zone, proper minimum ventilation in the critical zone overventilates all other zones. As a result, some outdoor air leaves the building via the relief, exhaust, and exfiltration airstreams without performing useful dilution.

This inefficiency isn't necessarily "bad;" it simply must be recognized and accounted for in system ventilation calculations.

Case 3: Ventilation Calculations for "Calculated" Cooling Design

As mentioned previously, Addendum 62*n* allows the designer to use either a default or calculated value for *system ventilation efficiency* (E_v). We used the default approach in Cases 1 and 2. Now, let's look at the calculated approach, which uses the equations found in Appendix G.

Again, we build on the zone-level calculations (*Figure 3*) to find the minimum system-level *outdoor-air intake flow* (V_{ot}) needed at the design cooling condition (*Figure 6*):

4. Find the *minimum discharge outdoor-air fraction* ($Z_d = V_{oz}/V_{dz}$) for each zone, using the *zone outdoor airflow* (V_{oz}) for cooling operation. Notice that this fraction differs from the *primary outdoor-air fraction* ($Z_p = V_{oz}/V_{pz}$) in the "default" approach. In this case, we're interested in the fraction of outdoor air in the airstream that discharges into the zone—not in the primary airstream from the air handler.†

5. Find *occupant diversity* according to Equation 6-7 ($D = P_s/\Sigma P_z$) using expected *peak system population* (P_s) and *design zone population*; as in the "default" approach (Case 1), $D = 164/224 = 0.73$.

6. Find the *uncorrected outdoor-air intake flow* for the system by solving Equation 6-6 $\left(V_{ou} = D \times \Sigma(R_p \times P_z) + \Sigma(R_a \times A_z)\right)$. Again, without correcting for zone air-distribution effectiveness and system ventilation efficiency, the system needs $V_{ou} = 2{,}800$ cfm of outdoor air.

7. Establish the *system primary airflow* ($V_{ps} = LDF \times \Sigma V_{pz}$-

† This nuance makes no difference for single-path systems ($V_{pz} = V_{dz}$), but becomes an important distinction for dual-path systems with local recirculation, as we'll see in future articles.

		From Figure 3		From Table 6.3		
Procedural Step				**4**	**5**	**6–8**
Ventilation Zone	**V_{pz} (Design) cfm**	**$V_{pz\text{-}min}$ cfm**	**$V_{oz\text{-}clg}$ cfm**	**$Z_{p\text{-}clg}$**	**E_v**	
South Offices	1,900	475	210	0.44	—	—
West Offices	2,000	500	220	0.44	—	—
South Conference Room	3,300	825	330	0.40	—	—
East Offices	2,000	500	220	0.44	—	—
Southwest Interior Offices	7,000	1,750	850	0.49	—	—
Northeast Interior Offices	7,000	1,750	850	0.49	—	—
North Offices	1,600	400	200	0.50*	0.65	—
North Conference Room	1,800	450	220	0.49	—	—
System…						
(Step 6) D						0.73
(Step 7) V_{ou}						2,800
(Step 8) V_{ot}						4,310

* For ventilation-critical zones with a throttling VAV box, discharge air is usually cool whenever the zone is occupied (morning warmup usually occurs before occupancy).

***Figure 4:** System ventilation calculations for default efficiency cooling design (Case 1).*

		From Figure 3		From Table 6.3		
Procedural Step				**4**	**5**	**6–8**
Ventilation Zone	**V_{pz} (Design) cfm**	**$V_{pz\text{-}min}$ cfm**	**$V_{oz\text{-}htg}$ cfm**	**$Z_{p\text{-}htg}$**	**E_v**	
South Offices	1,900	475	260	0.55*	0.60	—
West Offices	2,000	500	275	0.55*	—	—
South Conference Room	3,300	825	410	0.50	—	—
East Offices	2,000	500	275	0.55*	—	—
Southwest Interior Offices	7,000	1,750	850	0.49	—	—
Northeast Interior Offices	7,000	1,750	850	0.49	—	—
North Offices	1,600	400	200	0.50	—	—
North Conference Room	1,800	450	220	0.49	—	—
System…						
(Step 6) D						0.73
(Step 7) V_{ou}						2,800
(Step 8) V_{ot}						4,670

* For ventilation-critical zones with a throttling VAV box, discharge air is usually cool whenever the zone is occupied (morning warmup usually occurs before occupancy).

***Figure 5:** System ventilation calculations for default efficiency heating design (Case 2).*

peak). In VAV systems, primary airflow to each zone varies with load. Of course, system primary airflow also varies but it never can be more than the central fan can deliver. (The system is always least efficient when primary airflow is high and critical-zone[††] airflow is low because all noncritical zones are overventilated at this condition.) The central VAV fan usually is selected to deliver "block," not "sum-of-peak," airflow. In our example office, we assumed a system load diversity factor (*LDF*) of 0.70, so the central fan delivers $V_{ps} = 0.70 \times 26{,}600 = 18{,}600$ cfm at the design cooling load.

8. Find the *average outdoor-air fraction* ($X_s = V_{ou}/V_{ps}$) for the system. In our example, $X_s = 2{,}800/18{,}600 = 0.15$ at the design cooling condition.

9. For each zone, find *zone ventilation effectiveness* using Equation G-1 ($E_{vz} = 1 + X_s - Z_d$) for single-path systems.

10. Find *system ventilation efficiency* using Equation G-3 (E_v = minimum E_{vz}). In our example, $E_v = 0.65$ at the design cooling condition. As in the "default" approach (Case 1), the north offices are the ventilation-critical zone.

11. Finally, find *outdoor-air intake flow* for the system by solving Equation 6-8 ($V_{ot} = V_{ou}/E_v$). In our example, $V_{ot} = 2800/0.65 = 4310$ cfm at the design cooling condition.

This is identical to the intake requirement we found using the "default" approach. Why? The "default" approach is based on an assumed *average outdoor-air fraction* (X_s) of 0.15. By coincidence, that value matches this example's average outdoor-air fraction at design cooling. In most cases, however, these numbers will differ.

[††] We refer to the zone that requires the highest fraction of outdoor air in its discharge (primary plus recirculated) airstream as the "ventilation critical zone."

Now that we know the minimum intake at the design cooling condition, let's use the "calculated" approach to find the minimum intake for the design heating condition. The highest of these two intake values is the worst-case intake airflow.

Case 4: System Ventilation Calculations for Calculated Heating Design

As in the "default" approach for heating design (Case 2), assume that all spaces receive minimum primary airflow at the design heating condition. Building on the zone-level calculations (*Figure 3*), we'll follow the same steps that we used in Case 3 to calculate efficiency and intake airflow for cooling design (*Figure 7*).

4. For each zone, find the *minimum discharge outdoor-air fraction* ($Z_d = V_{oz}/V_{dz}$), using the appropriate V_{oz} value for heating operation. For example, the south offices need $Z_d = 260/475 = 0.55$ when heating.

5. Find *occupant diversity* according to Equation 6-7 ($D = P_s/\Sigma P_z$), $D = 164/224 = 0.73$.

6. Find the *uncorrected outdoor-air intake flow* for the system by solving Equation 6-6 $\left(V_{ou} = D \times \Sigma(R_p \times P_z) + \Sigma(R_a \times A_z)\right)$; as before, $V_{ou} = 2{,}800$ cfm.

7. Establish the *system primary airflow* (V_{ps}). For design heating calculations, we assume that all zones receive minimum primary airflow at worst case, so $V_{ps} = 6{,}650$ cfm in our example.

8. Find the *average outdoor-air fraction* ($X_s = V_{ou}/V_{ps}$) for the system. In our example, $X_s = 2{,}800/6{,}650 = 0.42$ at the design heating condition.

9. For each zone, find *zone ventilation effectiveness* using Equation G-1 ($E_{vz} = 1 + X_s - Z_d$).

Procedural Step	From Figure 3			4	5–8	9	10–11
Ventilation Zone	V_{pz} (Design) cfm	$V_{pz\text{-}min}$ cfm	$V_{oz\text{-}clg}$ cfm	$Z_{d\text{-}clg}$		$E_{vz\ clg}$	
South Offices	1,900	475	210	0.44	—	0.71	—
West Offices	2,000	500	220	0.44	—	0.71	—
South Conference Room	3,300	825	330	0.40	—	0.75	—
East Offices	2,000	500	220	0.44	—	0.71	—
Southwest Interior Offices	7,000	1,750	850	0.49	—	0.66	—
Northeast Interior Offices	7,000	1,750	850	0.49	—	0.66	—
North Offices	1,600	400	200	0.50	—	0.65*	—
North Conference Room	1,800	450	220	0.49	—	0.66	—
System…							
(Step 5) D					0.73		
(Step 6) V_{ou} ²					2,800		
(Step 7) V_{ps}					18,600		
(Step 8) X_s					0.15		
(Step 10) E_v							0.65
(Step 11) V_{ot}							4,310

* For ventilation-critical zones with a throttling VAV box, discharge air is usually cool whenever the zone is occupied (morning warmup usually occurs before occupancy).

Figure 6: System ventilation calculations for calculated efficiency cooling design (Case 3).

Procedural Step	From Figure 3			4	5–8	9	10–11
Ventilation Zone	V_{pz} (Design) cfm	$V_{pz\text{-}min}$ cfm	$V_{oz\text{-}htg}$ cfm	$Z_{d\text{-}htg}$		$E_{vz\ htg}$	
South Offices	1,900	475	260	0.55	—	0.87*	—
West Offices	2,000	500	275	0.55	—	0.87*	—
South Conference Room	3,300	825	410	0.50	—	0.92	—
East Offices	2,000	500	275	0.55	—	0.87*	—
Southwest Interior Offices	7,000	1,750	850	0.49	—	0.94	—
Northeast Interior Offices	7,000	1,750	850	0.49	—	0.94	—
North Offices	1,600	400	200	0.50	—	0.92	—
North Conference Room	1,800	450	220	0.49	—	0.93	—
System…							
(Step 5) D					0.73		
(Step 6) V_{ou} ²					2,800		
(Step 7) V_{ps}					6,650		
(Step 8) X_s					0.42		
(Step 10) E_v							0.87
(Step 11) V_{ot}							3,220

* For ventilation-critical zones with a throttling VAV box, discharge air is usually cool whenever the zone is occupied (morning warmup usually occurs before occupancy).

Figure 7: System ventilation for calculated efficiency heating design (Case 4).

10. Find *system ventilation efficiency* using Equation G-3 (E_v = minimum E_{vz}). In our example, E_v = 0.87 at the design heating condition. As before, the south, west, and east offices are equally "critical" for design heating calculations. Notice, too, that the ventilation system is much more efficient at this condition. When the *average outdoor-air fraction* (X_s) approaches the *critical zone's outdoor-air fraction* (Z_d), less unused air is exhausted; consequently, system ventilation efficiency rises.

11. Finally, find *outdoor-air intake flow* for the system by solving Equation 6-8 ($V_{ot} = V_{ou}/E_v$). In our example, V_{ot} = 2,800/0.87 = 3,230 cfm at the design heating condition.

The system is more efficient at the design heating condition than it was at the design cooling condition (*system ventilation efficiency* of 0.87 in heating vs. 0.65 in cooling). So, using the "calculated" approach (Appendix G), worst-case/highest *outdoor-air intake flow* occurs at the design cooling condition (V_{ot} = 4,310 cfm).

Reviewing our previous calculations, if we simply use the default table to find system ventilation efficiency (Cases 1 and 2), our example design needs *outdoor-air intake flow* of 4,670 cfm, which occurred at the design heating condition. If we use the more complicated but more accurate calculations in Appendix G (Cases 3 and 4), our example design needs *outdoor-air intake flow* of 4,360 cfm, which occurred at the design cooling condition. Since either approach is allowed, the designer can comply using either of these intake airflow values.

Assuming that our system controls can maintain the minimum required intake airflow, we can now size both the cooling coil and the heating coil for worst-case outdoor-air intake flow.

What About Part-Load Operation?

To comply with Addendum 62*n*, we need to find the highest minimum *outdoor-air intake flow* (V_{ot}), which we've called "worst-case" intake airflow. We could apply optional adjustments (averaging) for "short-term conditions" in our worst-case calculations, but we chose not to do so in the preceding discussion. In some cases, averaging adjustments can lower the worst-case intake value. In others, averaging can be used to assure proper ventilation when either supply-fan capacity or outdoor-air intake flow varies.

Adjustments for short-term conditions can help the designer find the appropriate worst-case minimum intake flow. Having found this value, the system can be designed to maintain this intake airflow during all occupied hours. In VAV systems, where both primary airflow and mixing-box pressure change in response to zone demands for cooling, this usually requires some means for sensing intake airflow and modulating the outdoor-air damper to maintain the minimum airflow setting.

But, do we really need to treat the worst-case outdoor airflow at all operating conditions, without regard to current ventilation needs? No.

Equations and Variables from Addendum 62*n*

[6-1] $V_{bz} = R_p P_z + R_a A_z$

[6-2] $V_{oz} = V_{bz}/E_z$

[6-3] $V_{ot} = V_{oz}$ single-zone systems

[6-4] $V_{ot} = \Sigma V_{oz}$ 100% outdoor-air systems

[6-5] $Z_p = V_{oz}/V_{pz}$

[6-6] $V_{ou} = D\Sigma_{allzones} R_p P_z + \Sigma_{allzones} R_a A_z$
$= D\Sigma_{allzones} V_{bzp} + \Sigma_{allzones} V_{bza}$

[6-7] $D = P_s/\Sigma_{allzones} P_z$

[6-8] $V_{ot} = V_{ou}/E_v$ multiple-zone recirculating systems

[6-9a] $T = 3v/V_{bz}$ IP version

[6-9b] $T = 50v/V_{bz}$ SI version

where

$\boldsymbol{A_z}$ is zone floor area, the net occupiable floor area of the zone, ft² (m²)

$\boldsymbol{D}$ is occupant diversity, the ratio of system population to the sum of zone populations

$\boldsymbol{E_v}$ is ventilation efficiency of the system

$\boldsymbol{E_z}$ is air-distribution effectiveness within the zone

$\boldsymbol{P_s}$ is system population, the maximum simultaneous number of occupants in the area served by the ventilation system

$\boldsymbol{P_z}$ is zone population, the largest expected number of people to occupy the ventilation zone during typical usage (See caveats in Addendum 62n–Section 6.2.1.1)

$\boldsymbol{R_a}$ is area outdoor air rate, the required airflow per unit area of the ventilation zone determined from Addendum 62n–Table 6.1, cfm/ft² (L/s·m²)

$\boldsymbol{R_p}$ is people outdoor air rate, the required airflow per person determined from Addendum 62n–Table 6.1, in cfm/person (L/s·person)

$\boldsymbol{T}$ is averaging time period, minutes

$\boldsymbol{v}$ is ventilation-zone volume, ft³ (m³)

$\boldsymbol{V_{bz}}$ is breathing-zone outdoor airflow, the outdoor airflow required in the breathing zone of the occupiable space(s) of the ventilation zone, cfm (L/s)

$\boldsymbol{V_{ot}}$ is outdoor air intake flow, adjusted for occupant diversity and corrected for ventilation efficiency, cfm (L/s)

$\boldsymbol{V_{ou}}$ is the uncorrected outdoor air intake flow, cfm (L/s)

$\boldsymbol{V_{oz}}$ is zone outdoor airflow, the outdoor airflow that must be provided to the zone by the supply-air-distribution system at design conditions, cfm (L/s)

$\boldsymbol{V_{pz}}$ is zone primary airflow, the primary airflow that the air handler delivers to the ventilation zone; includes both outdoor air and recirculated return air

$\boldsymbol{Z_p}$ is zone primary outdoor air fraction, the fraction of outdoor air in the primary airflow delivered to the ventilation zone … for VAV systems, Z_p for design purposes is based on the minimum expected primary airflow, V_{pzm}.

In multiple-zone recirculating systems, system ventilation efficiency almost always increases as primary fan airflow decreases—provided, of course, that design efficiency is properly calculated at the worst-case condition (that is, with low primary airflow to the critical zone).

Although we must design the system with sufficient capacity for worst-case intake airflow, we could operate it at many conditions with less-than-worst-case intake and still comply with Addendum 62*n*. To do so, our design could incorporate one of the optional "dynamic reset" approaches presented in Addendum 62*n*, using a control approach that resets intake airflow to match current requirements at part-cooling load.

In a future article, we'll examine part-load operation and optional dynamic reset in detail. For now, we simply note we always must design for worst-case intake flow (as discussed earlier), regardless of any "dynamic reset" control options we may choose to implement. In other words, dynamic reset does not alter the worst-case outdoor-air intake flow needed to comply with the standard.

Summary

Historically, Standard 62 required both zone- and system-level calculations for the design of single-path, multiple-zone ventilation systems (like throttling VAV systems). Unfortunately, the calculation procedures were unclear and frequently misinterpreted or ignored by designers. As a result, many multiple-zone systems were improperly ventilated.

Addendum 62*n* clarifies the multiple-zone system calculations to reduce both underventilation and unnecessary over-ventilation. It allows a simple "default" approach, as well as a more accurate "calculated" approach for determining system ventilation efficiency.

As shown here, either calculation procedure can be readily applied to single-path VAV systems at the design conditions for both cooling and heating, to provide a compliant determination of worst-case minimum outdoor-air intake flow.

References

1. ANSI/ASHRAE Standard 62-2001, *Ventilation for Acceptable Indoor Air Quality.*

2. ANSI/ASHRAE Addendum *n* to ANSI/ASHRAE Standard 62-2001.

3. Stanke, D. 2004. "Addendum 62*n*: single-zone and dedicated-OA systems." ASHRAE Journal 46(10): 12–21.

4. Stanke, D. 2004. "Standard 62-2001 Addendum 62*n*: ventilation for change-over-bypass VAV systems." ASHRAE Journal 46(11):22–32.

Appendix H

Carbon Dioxide Generation Rates

The information in this appendix contains additional discussion on CO_2 generation rates as a function of occupant size and activity and can provide additional insight on the use of CO_2 sensors in DCV systems. This information is reproduced from a paper titled "Evaluating Building IAQ and Ventilation with Indoor Carbon Dioxide" by A. Persily (1997, *ASHRAE Transactions* 103[2]:193–204).

Carbon Dioxide Generation Rates

Both the relationship between indoor carbon dioxide concentrations and indoor air quality and the relationship between carbon dioxide and ventilation are based on the rate at which people generate carbon dioxide. People generate carbon dioxide, and consume oxygen, at a rate that depends primarily on their level of physical activity and their size. The relationship between activity level, size and the rates of carbon dioxide generation and oxygen consumption is discussed in *ASHRAE Fundamentals* (ASHRAE 1993) and is summarized below.

The rate of oxygen consumption, V_{O_2}, in L/s, of a person is given by the following equation:

$$V_{O_2} = \frac{0.00276 A_D M}{(0.23RQ + 0.77)} \qquad \text{(1a)}$$

A_D is the DuBois surface area in m², which is described below. When using inch-pound (I-P) units, A_D is in ft² and V_{O_2} is in cfm, and Equation Ia takes the form

$$V_{O_2} = \frac{0.000543 A_D M}{(0.23RQ + 0.77)} \qquad \text{(1b)}$$

where *RQ* is the respiratory quotient, i.e., the relative volumetric rates of carbon dioxide produced to oxygen consumed. *M* is the level of physical activity, or the metabolic rate per unit of surface area, in mets (1 met = 58.2 W/m² = 18.5 Btu/h·ft²). A_D, the DuBois surface area in m², can be estimated by the following equation:

$$A_D = 0.203 H^{0.725} W^{0.425} \qquad \text{(2a)}$$

where *H* is the body height in m and *W* is the body mass in kg. When using inch-pound units, A_D is in ft², *H* is in ft, *W* is in lb, and Equation 2a takes the form

$$A_D = 0.660 H^{0.725} W^{0.425} \qquad \text{(2b)}$$

For an adult of average size, A_D equals about 1.8 m² (19 ft²). Additional information on body surface area is available in the EPA's *Exposure Factors Handbook* (EPA 1989). The value of *RQ* depends on diet, the level of physical activity, and the physical condition of the person and is equal to 0.83 for an adult of average size engaged in light or sedentary activities. *RQ* increases to a value of about 1 for heavy physical activity (about 5 met). Given the expected range of *RQ*, it has only a secondary effect on carbon dioxide generation rates.

The carbon dioxide generation rate of an individual is therefore equal to V_{O_2} multiplied by *RQ*. Figure 1 shows oxygen consumption and carbon dioxide generation rates as a function of physical activity for an

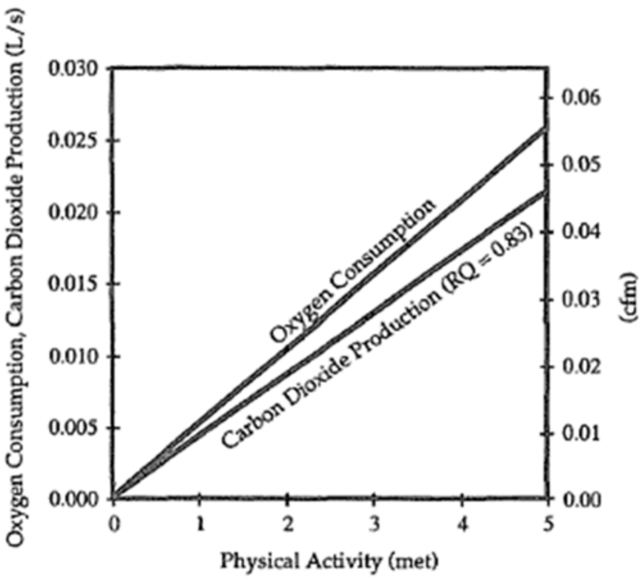

Figure 1 Carbon dioxide generation and oxygen consumption as a function of physical activity.

Table 1 Typical Met Levels for Various Activities

Activity	Met
Seated, quiet	1.0
Reading and writing, seated	1.0
Typing	1.1
Filing, seated	1.2
Filing, standing	1.4
Walking at 0.9 m/s (2 mph)	2.0
House cleaning	2.0-3.4
Exercise	3.0-4.0

average-sized adult with a surface area of 1.8 m^2 (19 ft^2) and $RQ = 0.83$.

Based on Equation 1, the carbon dioxide generation rate corresponding to an average-sized adult engaged in office work (1.2 met) is about 0.0052 L/s (0.011 cfm). However, the generation rate depends strongly on activity level and can cover a range from less than 0.0050 L/s (0.011 cfm) at 1 met to as high as 0.010 L/s (0.021 cfm) at about 2 met for the occupants of an office building. The carbon dioxide generation rate for a child with $A_D = 1$ m^2 (11 ft^2) and a physical activity level of 1.2 met is equal to 0.0029 L/s (0.0061 cfm). When making calculations that use the carbon dioxide generation rate in a building, one must consider the level of physical activity and the size of the building occupants. Chapter 8 of *ASHRAE Fundamentals*, "Physiological Principles and Thermal Comfort" (ASHRAE 1993), contains typical met levels for a variety of activities. Some of these values are reproduced in Table 1.

Oxygen depletion is sometimes cited as a cause of indoor air quality complaints in buildings. Based on the oxygen consumption rates determined with Equation 1, it can be shown that oxygen depletion due to low ventilation rates is not typically an issue of concern. Given an activity level corresponding to office work, about 1.2 met, the oxygen consumption rate of an individual equals 0.006 L/s (0.013 cfm). At an outdoor air ventilation rate of 7.5 L/s (16 cfm) per person, the steady-state indoor oxygen concentration is reduced from its typical outdoor level of 21% to 20.9%. At 2.5 L/s (5.3 cfm) and 0.5 L/s (1 cfm) per person, the indoor oxygen concentration is reduced to 20.8% and 19.8%, respectively. Health effects do not generally occur until oxygen levels decrease to less than 19.5% (NIOSH 1987), which corresponds to an outdoor air ventilation rate of only 0.4 L/s (0.8 cfm) per person.

Written by experts in the field of indoor air quality (IAQ), the *Indoor Air Quality Guide* is the most comprehensive and practical resource ever developed on design and construction for enhanced IAQ. For architects, engineers, and building owners who want commercial and institutional buildings with high-quality indoor environments, this Guide provides the strategies needed to achieve good IAQ using proven technologies and without significantly increasing costs.

Most building designs provide minimally acceptable indoor environments through compliance with requirements in building codes and standards. Enhancing IAQ can improve occupant health, comfort, and productivity while increasing building value and reducing risk for owners. As the industry moves toward high-performance green buildings, building professionals must become more knowledgeable about principles and methods for achieving enhanced IAQ.

This Guide bridges this gap by focusing on the major IAQ issues: moisture management, ventilation, filtration and air cleaning, and source control. Equally important, it highlights how design and construction teams can work together to ensure that good IAQ strategies are incorporated from initial design through project completion.

Part I of the Guide provides summary guidance and is ideal for a general understanding of the importance of these major IAQ issues. Part II provides the detailed guidance essential for practitioners to design for and achieve good IAQ. Throughout Parts I and II are numerous case studies, illustrations, and photographs.

The Part I summary guidance is included in the printed book, and both Part I and Part II are included on the CD in pdf format. The CD not only provides the information in a searchable and printable form but also includes interactive hyperlinks from the summary information in Part I to the relevant detailed information in Part II, making the guide both comprehensive and easy to use.

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