RP-1663

Residential INDOOR AIR QUALITY Guide

Best Practices for Home Design, Construction, Operation, and Maintenance

Expert Guidance on Indoor Air Quality in Single-Family and Multifamily Housing for

- Designers
- Builders
- Property Managers
- Homeowners, Buyers, and Renters

Residential Indoor Air Quality Guide

Best Practices for Home Design, Construction, Operation, and Maintenance

This is an ASHRAE Guide developed under ASHRAE's Research Project procedures and is not a consensus document. This document is an application manual that provides voluntary recommendations for consideration in achieving improved indoor air quality.

This publication was supported by ASHRAE Research Project 1663 under the auspices of the ASHRAE Environmental Health Committee.

Development of this Guide was funded by ASHRAE, with donations in kind from the authors and support from the U.S. Environmental Protection Agency (EPA) Office of Radiation and Indoor Air, Indoor Environments Division.

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www.ashrae.org/publicationupdates

RP-1663

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Atlanta

ISBN 978-1-947192-02-7 (paperback)
ISBN 978-1-947192-03-4 (PDF)

1791 Tullie Circle, NE
Atlanta, GA 30329
www.ashrae.org

Printed in the United States of America.

Cover Design by: Laura Haass
Cover Design Concept by: Walter Grondzik
Page Design and Layout by: Adela Groth
Illustrations by: Sharon Alitema, Adela Groth, Nathan Leigh, Alexa Thornton, and Ayush Vaidya
Cover Image Credits: front cover top (right and left) used under license from Shutterstock.com; front cover bottom from 2017 Race to Zero Competition, Attached Housing Category, Jamie Craine, Shelby Harris, Shan Wang; back cover from 2017 Race to Zero Competition, Urban Single Family Category, Jordan Duke, Joshua Markiewicz, Tyler Bracht
Objective icons used under Creative Commons license (Rob Armes, StoneHub, Alfa Design, Alex Sheyn, Ravindra Kalkani, Ermankutlu, Oliver Kittler, Olga, Justin Blake, Markus, Maxim Kulikov, Numero Uno, Arthur Shlain, Anton Gajdosik, Supalerk Laipawat, Vectors Market, Mello, Sarah Parkinson, Adrien Coquet, Saeful Muslim, Alex Vaughn)
Illustrations Coordinated by: Walter Grondzik
Technical Editors: Deborah Berlyne and Hannah Bachman

Library of Congress information

LCCN: 2018019568

ASHRAE Special Publications Staff
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Publisher W. Stephen Comstock

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Preface

Dwellings come in a variety of sizes, shapes, and configurations and are expected to provide shelter and comfort, fulfill a variety of functional requirements, meet applicable codes and standards, and fit into the local environment and community. People spend most of their time indoors, and much of that is at home. At the same time, occupants continue to perform more and more activities, such as work and exercise, in their homes.

Indoor air quality (IAQ) is typically addressed through compliance with building codes, which in turn are based on industry consensus standards, such as ANSI/ASHRAE Standard 62.2 (ASHRAE 2016b). Such codes and standards provide minimum requirements that do not fully address all the IAQ issues that contribute to human health and comfort in the dwelling.

Although builders and the general public might recognize the importance of IAQ, they often do not appreciate the impact of routine decisions on IAQ. In addition, they might assume that achieving good IAQ is very costly and requires novel or even risky technical solutions. In other cases, they might seek a “silver bullet” device, test, or one-time activity to improve their dwelling’s IAQ, sometimes at significant cost, with limited success. The manufacturers and sellers of products for cleaning the air might make questionable claims based on little or no evidence, and their products might therefore not achieve the desired result.

Information is available on how to achieve good IAQ without requiring excessive expenses or practices that are beyond the capabilities of residents, builders, and construction and maintenance tradespeople. This guide was written by some of the most experienced individuals in residential IAQ and presents best practices for design, construction, maintenance, and operation of dwellings to maximize IAQ that have proven to be successful. It provides information and tools that residents, home designers, and builders can use to integrate IAQ into dwellings while addressing budget constraints and other functional requirements.

The IAQ field is too broad to cover everything in one book, so the authors and ASHRAE’s Project Monitoring Subcommittee selected those topics that they believe could have the biggest impact. In many cases, the guide provides only a brief summary of an issue and refers readers to other sources for more details. In other cases, when other good references on a subject are not readily available, the authors cover a topic in greater detail. IAQ knowledge is incomplete and growing constantly, and this document presents the best available information in the authors’ judgement to allow informed decision making.

The guide addresses residential dwelling units covered by ASHRAE Standard 62.2 (ASHRAE 2016b) and was written for the following audiences:

- Homeowners and renters who might choose a dwelling and/or its custom features or work with designers to build a dwelling from scratch and who can choose materials, products, and activities that improve or at least do not reduce IAQ

- Architects, home designers, and builders who can apply the recommended practices during design, construction, and renovation

- Developers of multifamily building (e.g., duplex, rowhouse, or low- or high-rise apartment or condominium) projects and other decision makers who direct the work of the above professionals

- Home energy raters and commissioning authorities who determine whether design elements, construction observation, functional testing, and the finished dwelling meet IAQ-related goals and requirements

- Organizations with sustainable building rating programs and/or that conduct training for these programs

- Indoor environmental professionals who seek a broader understanding of residential building practice in order to better serve their clients' concerns about their home IAQ

- Multifamily building managers and operators who need to understand the IAQ implications of existing heating, ventilation, and cooling (HVAC) systems (the components in a dwelling that that heat, cool, ventilate, and/or dehumidify it) and operations and maintenance practices

Message to Developers and Builders

Some have questioned the movement to make dwellings tighter and the resulting need to provide whole-dwelling ventilation, usually using mechanical means. This guide does not revisit this subject because such features are now required by consensus standards and construction codes.

IAQ is one of many issues that building owners and developers must address to meet their needs and those of the dwelling occupants. Although occupants do sometimes complain about poor IAQ, IAQ is not always their top concern. So why should developers and builders worry about IAQ when they have so much else to think about?

- Better IAQ leads to more satisfied residents, better referrals, and fewer complaints. The general public often has incomplete knowledge about IAQ. Buyers and renters depend on professionals to deliver high-quality dwelling units and sound advice.

- IAQ problems that get out of hand can be quite costly by distracting developers and builders from other business goals, requiring expensive building or mechanical system repairs, incurring legal costs, and resulting in bad publicity. Although extreme IAQ problems are rare, they do occur, and the consequences can be dramatic. Less severe problems are more common and can affect occupancy and/or rent levels. They can also lead to expenses for more minor legal disputes or repairs.

- Many of the measures that are used to achieve good IAQ also contribute to durability of the building.

Educating occupants is also important. If they understand the importance of not smoking or burning candles indoors, using the kitchen range hood if they have one, and closing windows when outdoor air quality is poor, they are more likely to make positive IAQ-related choices.

This guide presents a wealth of practical information on how to design and construct dwellings that have good IAQ without large financial investments or use of untested technologies. Although the guide is full of information on design and construction approaches to control moisture, reduce contaminant entry, and provide effective ventilation, probably the

most important message for the owner and developer is to incorporate IAQ at the start of the development and design processes. Doing so will make efforts to provide good IAQ at a low or even no added cost easier and more effective.

By the time a dwelling's basic layout (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.

Message to Homeowners, Renters and Other Residents

Opportunities to achieve better indoor air quality at all the stages of occupancy occur in the following situations:

- When choosing features of the dwelling design or construction
- When choosing a dwelling to acquire or rent
- When renovating, retrofitting, or painting a dwelling
- When purchasing appliances, equipment, and furnishings
- When choosing activities to perform inside the dwelling
- When purchasing and using cleaning, pest control, maintenance, and personal care products
- During daily activities, such as bathing and cooking

Homes built to current codes and standards or that are retrofitted for energy purposes are much tighter (have lower air and energy leakage) than in the past. Yet they require outdoor air to dilute contaminants produced by people and their activities as well as by the building and its fixtures and furnishings. Because these new homes cannot depend on natural leakage, they have mechanical ventilation systems for this purpose. These systems need to be operated as designed, and operation of local exhaust (kitchen and bath) fans is particularly important in tight homes.

It is essential to avoid smoking indoors, limit the burning of candles and incense, and use the kitchen range hood. Windows need to be closed when outdoor air quality is poor, and consideration should be given to opening them when outdoor air quality and temperature are good.

This guide presents a wealth of other practical information on how to live in a home to achieve good IAQ without large financial investments or use of untested technologies. Probably the most important message for the home occupant is to incorporate thinking about

IAQ into all the other activities that make the home comfortable. There is no “silver bullet” device, test, or one-time activity to improve a dwelling’s IAQ, despite claims of manufacturers and sellers of products and services. However, a variety of small actions will improve IAQ at a low or even no added cost.

Special IAQ Considerations for Low-Income Housing

Builders, owners, and designers need to be aware of special IAQ concerns related to low-income housing and to take steps to reduce the risks associated with them.

Socioeconomic disparities related to indoor exposure to particulate matter (discussed in Strategy 7.2) are large (Adamkeiwicz et al. 2010). Many building and occupancy characteristics associated with greater particulate matter exposure are more pronounced in lower-income housing. These features include greater building age, peeling paint, heavy street traffic nearby, factories and industrial buildings nearby, uncomfortable temperatures, small floor area, high occupant density, and visible cracks in the building enclosure (roofs, ceilings, above-grade and below-grade walls, windows, and floors that separate the indoors from outdoors).

Indoor smoking adds significantly to indoor particulate matter in units in which smoking occurs and in adjacent multifamily units, including those occupied by nonsmokers. The risk of poor IAQ can disproportionately affect housing and multifamily dwellings occupied by elderly and low-income populations. A best practice is therefore to ban or at least discourage smoking in multifamily dwellings (HUD 2018).

Furthermore, residents of these buildings often have limited choice in where they live and less empowerment to demand repairs, and they might be affected by the decisions of other people who live in the same unit. In addition, occupants with limited financial resources or access to transportation need to be able to buy replacement filters locally and inexpensively because ordering products online might be expensive and difficult to accomplish without a credit card (Singer 2016). If management does not change filters, it should make it easy for residents to obtain them.

There are actions everyone can take to improve the air quality in homes, whether one’s responsibility is to design, build, buy, rent, operate, clean or simply occupy a dwelling.

Keeping homes clean, dry, and ventilated is often not complicated, but it takes continued effort. This includes exercising care with products brought into the home, avoiding moisture problems and correcting them promptly if they appear, providing ventilation with outside air, and good air filtration.

The authors hope that you, the reader, find this Guide informative, helpful, and interesting and that it helps lead to health and vitality through homes that have clean and comfortable air to breathe.

Acknowledgments

The *Indoor Air Quality Guide* provides a long-needed resource for homeowners and the residential building community. The authors, Terry Brennan, Amy Musser, Armin Rudd, and Lawrence Schoen; graphic designers Walter Grondzik, Sharon Alitema, Adela Groth, Nathan Leigh, Alexa Thornton, Ayush Vaidya; student intern Lauren Shen; and Project Monitoring Subcommittee Jianshun Zhang, Steve Emmerich, Paul Francisco, and Kevin Kennedy worked extremely hard to pull together practical, technically sound information covering the full range of dwelling-related indoor air quality (IAQ) issues that are important to a wide audience. The authors brought to this project many years of experience in design, construction, commissioning (a quality-control process), forensic IAQ investigation, research, and facilities management.

Deborah Berlyne, Ph.D., joined the project as technical editor and helped make the guide much clearer and more coherent, with editorial assistance from Hannah Bachman. The authors sought input from other experts, too numerous to mention, to capture the latest and best thinking on their topics, and they appreciate those contributions. The authors extend their personal thanks and appreciation to this group for the extraordinary effort they poured into this guide and the passion they displayed about providing quality indoor environments.

This project would not have been possible without funding from ASHRAE and its membership for Research Project 1663 and the in-kind support provided by Camroden Associates, Inc., Vandemusser Design, PLLC, Schoen Engineering Inc., and AB Systems, LLC. The U.S. Environmental Protection Agency, Office of Radiation and Indoor Air, Indoor Environments Division also provided support for this effort. Mike Vaughn, Steve Comstock, Cindy Michaels, and other ASHRAE staff members developed the solicitation, executed the agreement with Schoen Engineering Inc., and assisted with publication while fully supporting the effort from beginning to end.

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May 2018

Abbreviations and Acronyms

ACCA	=	Air Conditioning Contractors of America
ACH50	=	air changes per hour at 50 Pascals
AHAM	=	American Home Appliance Manufacturers
AHU	=	Air Handling Unit
ANSI	=	American National Standards Institute
ASTM	=	ASTM International (formerly the American Society for Testing and Materials)
BPI	=	Building Performance Institute
Bq/m^3	=	Becquerels per cubic meter
CADR	=	clean air delivery rate
CFA	=	conditioned floor area
CFM	=	cubic feet per minute
DALY	=	disability-adjusted life year
EPA	=	U.S. Environmental Protection Agency
ERV	=	energy recovery ventilator
HEPA	=	high-efficiency particulate air
HRV	=	heat recovery ventilator
HVAC	=	heating, ventilating, and air conditioning
IAQ	=	indoor air quality
ICC	=	International Code Council
IMC	=	International Mechanical Code
in. w.g.	=	inches, water gauge
IP	=	inch-pound
IRC	=	International Residential Code
LEED	=	Leadership in Energy and Environmental Design
MERV	=	Minimum Efficiency Reporting Value
NFPA	=	National Fire Protection Association
NIST	=	National Institute of Standards and Technology
OSB	=	oriented strand board
Pa	=	Pascals
pCi/L	=	picocuries per liter
PM	=	particulate matter
PM2.5	=	particulate matter with a diameter of 2.5 μm or less
RESNET	=	Residential Energy Services Network
RH	=	relative humidity
SI	=	International System of Units
SVOC	=	semivolatile organic compound
TVOC	=	total volatile organic compound
UFP	=	ultrafine particles
VOC	=	volatile organic compound

Definitions

Air pressure: Force delivered by air molecules bumping into a surface. Air moves from areas of low to areas of high pressure, which drives the movement of contaminants.

Air sealing: Sealing of gaps, cracks, and holes in a surface or building enclosure against the flow of air in the dwelling walls, ducts, or air-handling units. See definition of “air-handling unit.”

Air-handling system: Assembly of components, including the air-handling unit and attached ductwork, that deliver conditioned air to a dwelling. See definition of “air-handling unit.”

Air-handling unit (AHU): Equipment containing a fan or blower that draws air in; passes it through components that heat, cool, and/or dehumidify it; and blows it out.

Backdraft: Potentially dangerous condition that occurs when negative pressure causes combustion products to be drawn back from a natural draft venting system into the occupied portions of a dwelling. See definitions of “air pressure” and “natural draft venting system.”

Bathroom: Any room containing a bathtub, shower, spa, or similar source of moisture.

Building enclosure (or building envelope): Roofs, ceilings, above-grade and below-grade walls, windows, and floors that separate the indoors from outdoors.

Chase (e.g., duct or plumbing chase): Vertical shaft among floors of a multistory building that accommodate ducts, wires, or plumbing.

Combustion appliance: One that burns fuel (e.g., natural gas, propane, or kerosene) to heat a dwelling or produce hot water.

Commissioning: Quality control process of determining whether heating, ventilation, and air conditioning systems are designed, installed, functionally tested, and capable of being operated and maintained according to the owner’s requirements; can also be applied to building enclosures. See definition of “building enclosure.”

Compartmentalization: Sealing of each dwelling unit in a multifamily building so that they are separated from each other, utility chases, and common areas. See definitions of “multifamily buildings” and “chase.”

Conditioned air: Air that has been treated to control its temperature, relative humidity, and/or purity. See definition of “relative humidity.”

Conditioned space: Parts of the dwelling that are intentionally heated and/or cooled to achieve occupant comfort.

Cubic feet per minute (CFM): Measure of airflow rate by volume. The comparable unit in the International System (SI) is the liter per second (l/s). 10 CFM is approximately equivalent to 5 l/s.

Dwelling unit: A single unit providing complete, independent living facilities for one or more persons, including permanent provisions for living, sleeping, eating, cooking, and sanitation.

Energy recovery ventilator (ERV): Device that transfers both sensible and latent heat between the incoming air that ventilates a dwelling and the outgoing exhaust air so that when it is cold and dry outside, the incoming air is warmed and humidified, and when it is hot and humid outside, the incoming air is cooled and dehumidified. See definitions of “heat recovery ventilator,” “latent heat,” and “sensible heat.”

Definitions

Exfiltration: Uncontrolled outward leakage of air through cracks and interstices in any building element and around windows and doors.

Exhaust air (or exhaust): Air removed from a dwelling using a fan. See definition of "exhaust-only system" under "ventilation system."

Grade (e.g., above-grade or below-grade): Level of the ground surface outside a dwelling.

Heat recovery ventilator (HRV): Device that transfers sensible heat between the incoming air that ventilates a dwelling and the outgoing exhaust air so that the incoming air is warmed in winter or cooled in summer, with no transfer of latent heat. See definitions of "energy recovery ventilator," "latent heat," and "sensible heat."

Heating, ventilation, and air conditioning (HVAC) systems: All components in a dwelling that heat, cool, ventilate, and/or dehumidify it.

Infiltration: Uncontrolled inward leakage of air through cracks and interstices in any building element and around windows and doors.

Intake: Location where air is pulled into a fan or duct system. For example, the outdoor air intake for a dwelling is the outdoor location where air is pulled into its ventilation system.

Latent heat: Heat added to or removed from air that causes humidity to be added to or removed from the air but does not change the air temperature.

Local exhaust system (or local exhaust): System that removes indoor air in a location where levels of indoor air contaminants or moisture are expected to be high, such as a kitchen hood used to remove cooking contaminants or a bathroom fan that removes odors and moisture.

Mechanical ventilation: Active process of ventilating a dwelling unit using powered equipment, such as motor-driven fan and blowers.

Minimum efficiency reporting value (MERV): Scaled rating of the effectiveness of air filters in removing particulate matter (PM):

- *Low-efficiency filters (MERV 6 and under):* Low filtration efficiency, can remove some coarse particles, but has little impact on fine particles.
- *Medium-efficiency filters (MERV 8-12):* Widely available and can remove fine particles from the air without significant cost, energy use, or system considerations.
- *Higher-efficiency filters (MERV 13 and up):* Increasingly able to remove fine particles and ultrafine particles.

See definition of "particulate matter."

Minisplit: Small, low-capacity heat pump or air conditioner, often in or close to the living space it serves. The indoor units are often ductless and serve a single room, but some can accommodate a small amount of ductwork and serve a few closely grouped rooms.

Multifamily buildings (or dwellings): Residential buildings containing units built one on top of another and those built side-by-side which do not have a ground-to-roof wall and/or have common facilities (i.e., attic, basement, heating plant, plumbing, etc.) Includes duplexes, some rowhouses, and low- and high-rise apartments and condominiums.

Definitions

Natural draft venting system: Venting system that relies on a draft produced by the difference in the density of gases inside a chimney or vent and the density of air outside the chimney or vent to convey combustion products outside.

Oriented strand board (OSB): Engineered wood product formed by the addition of adhesives and compression of layers of wood strands or flakes in specific orientations; widely used as a sheathing material in residential construction.

Particulate matter (PM): Mixture of solid particles (typically organic and inorganic particles, including dust, pollen, soot, and smoke) and liquid droplets suspended in air; often subgrouped by size because different-sized particles have different health effects and filtration requirements. For example, PM2.5 refers to all PM with a diameter of 2.5 μm and smaller.

Permeance (or vapor permeance, measured in perms): Rate of water vapor that passes through a given area of solid building material driven by a difference in water vapor pressure rather than air pressure. The lower the permeance (or “perm rating”) of a material, the less water vapor can pass through it. See definition of “air pressure.”

Plenum: Cavity in a building that is part of an air-handling system. See definition of “air-handling system.”

Point source: Source of pollution that can be attributed to a specific physical location.

Relative humidity (RH): Amount of water vapor in air expressed as a percentage of the maximum possible amount of water vapor that could be present at a given temperature.

Remodeling: Process of making changes to the construction of a dwelling and/or building systems.

Retrofit: Modification of existing equipment, systems, or buildings to improve performance, update operations, and/or improve energy performance.

Return (or air return or return grille): Location from which air is drawn into an air-handling system.

Semivolatile organic compounds (SVOCs): Subgroup of volatile organic compounds that evaporate at higher temperatures than other volatile organic compounds. See definition of “volatile organic compounds.”

Sensible heat: Heat added to or removed from air that raises or lowers the air temperature without causing condensation or evaporation.

Stack effect: Movement of air driven by buoyancy and resulting from temperature differences.

Supply air: Conditioned air delivered to the dwelling by its air-handling system. See definition of “air-handling system.”

Thermal comfort: Thermal conditions deemed acceptable by an occupant or group of occupants.

Thermal conditioning: Process of heating, cooling, and/or dehumidifying a dwelling to achieve human comfort and durability of the dwelling.

Thermal enclosure: Enclosure that is insulated and air sealed to reduce the flow of heat between the inside and outside.

Definitions

Toilet room: Any room containing a toilet.

Total volatile organic compounds (TVOCs): Total concentration of volatile organic compounds in an air sample; a measurement that groups together a wide range of chemical compounds into a single measurement, rather than singling out individual compounds. See definition of "volatile organic compounds."

Ventilation system: Assembly of fan or fans, ductwork, controls, passive building features and other components that work together to introduce outdoor air into a dwelling to dilute indoor contaminants. In this document, the terms ventilation system, whole-dwelling ventilation system and dwelling-unit ventilation are used interchangeably.

- *Balanced ventilation system:* System that mechanically supplies outdoor air and exhausts indoor air such that the total supply and exhaust quantities are approximately equal to each other.

- *Exhaust-only ventilation system:* System that exhausts air from the home without mechanical (fan-driven) outdoor air intake. Exhaust is done by one or more fans, which usually also serve as bathroom or kitchen fans. A small negative air pressure causes an equal amount of outdoor air to leak into the dwelling through the enclosure. See definitions of "air pressure" and "building enclosure."

- *Supply-only ventilation system:* System that supplies outdoor air to the home whether or not the home's exhaust fans are operating. A small positive air pressure causes an equal amount of indoor air to leak to the outside through the enclosure. See definitions of "air pressure" and "building enclosure."

- *Natural ventilation system:* System that ventilates as a result of only natural forces, such as wind pressure or differences in air density.

Ventilation: Process of supplying outdoor air to or removing indoor air from a dwelling by natural or mechanical means to dilute indoor contaminants. Such air might or might not have been conditioned.

Volatile organic compounds (VOCs): Organic chemicals that can evaporate at normal indoor temperature and air pressure. See definition of "air pressure."

Weatherization: Process of retrofitting an existing dwelling to make it more energy efficient. See definition of "retrofit."

Zoning: Control strategy that allows different parts of the dwelling to be conditioned using separate thermostats. One purpose of zoning is to maintain thermal comfort in locations that have different rates of heat gain or loss (e.g., because they are on different floors). See definition of "thermal comfort."

IAQ is one of many factors that make a dwelling healthy, comfortable, and functional. When IAQ is good, it is nearly invisible; when IAQ is poor, it can have a negative effect on the health of children and adults. With good IAQ, builders retain an unblemished reputation and rental housing occupancy rates remain strong.

The High Cost of Poor IAQ

Poor IAQ in a new dwelling or professionally managed multifamily housing can require the developers, designers, and managers to devote considerable resources to addressing resident complaints, making major repairs, engaging in expensive legal actions, and, in extreme cases, relocating residents.

The costs of poor IAQ can include legal fees and damages. IAQ has direct effects on health, comfort, and the ability to do normal activities. Well-established, serious health impacts of poor IAQ include circulatory and lung disease from exposure to secondhand smoke, Legionnaires' disease from legionella bacteria in the air, lung cancer from radon exposure, and death from acute carbon monoxide poisoning (from, for example, a backdrafting combustion appliance). More widespread health effects include increased rates of allergy and asthma from exposure to indoor pollutants (particularly those associated with dampness and biological growth), colds and other infectious diseases from microbes transmitted through the air, and cardiovascular risks related to particulate matter exposure. These more widespread effects have the potential to affect large numbers of people and are associated with significant costs in the form of health care expenses, sick leave, and lost productivity at work and school.

Despite these significant effects, many dwelling design and construction decisions are made without an understanding of the potentially serious consequences of poor IAQ or consideration of the well-established body of knowledge on how to avoid IAQ problems. Although controlling indoor contaminants, providing adequate ventilation, and achieving thermal comfort (thermal conditions deemed acceptable by an occupant or group of occupants) has been part of the construction and use of dwellings for centuries, awareness of and concerns about IAQ have increased in recent decades, as severe IAQ problems have received media coverage. But in most cases, IAQ is still not a high priority for dwelling design or management compared with function, cost, living space, aesthetics, location, and accessibility.

Given the very real benefits of good IAQ and the potentially serious consequences of poor IAQ, residents, builders, designers, contractors, and building managers can all benefit from an increased focus on achieving good IAQ in dwellings. This guide can enhance all parties' ability to design, construct, and operate buildings with good IAQ using proven strategies without significant expense.

What is Good IAQ?

This guide is intended to help move beyond current practice to provide good IAQ in dwellings. A dwelling with good IAQ provides air in occupied rooms that contains no known or expected contaminants at concentrations likely to be harmful, does not create conditions likely to be associated with health or comfort complaints, and results in satisfaction of most occupants. Good IAQ requires consideration of both indoor air pollution levels and thermal environmental parameters. However, the limits of existing knowledge about the health and comfort effects of specific contaminants and contaminant mixtures, addition of unstudied chemicals to manufactured products, and variations in human susceptibility make it impossible to develop a single IAQ metric that can provide a summary measure of IAQ in dwellings.

Therefore, in this guide, good IAQ results from:

- Diligent compliance with both the letter and intent of building codes and ASHRAE Standard 62.2 (ASHRAE 2016b)
- Technically sound and well-executed efforts to meet or exceed these minimum requirements
- Application of IAQ-sensitive practices in design and construction
- Efforts by the occupants to avoid generating contaminants indoors, and efforts by building operators, managers and occupants to utilize systems designed to remove these contaminants when they occur.

Adherence to today's minimum standards (i.e., building codes and ASHRAE Standard 62.2) is essential to achieve acceptable IAQ, yet current practice does not always result in a dwelling that meets these standards. Furthermore, codes and standards do not cover operation and maintenance practices well or help residents, builders, and designers achieve better-than-acceptable IAQ. These factors are the primary motivations for the development of this guide.

Importance of Considering IAQ in the Design and Construction Process

Although ample information and experience is available on achieving good IAQ in newly built dwellings, good IAQ is not automatic because it requires a level of awareness and commitment, including an effort to make IAQ part of the design from the very beginning, that is not typical of most dwelling building and renovation projects. The three primary reasons to include IAQ considerations in the earliest stages of project planning are to avoid problems when IAQ is treated as an afterthought, to allow consideration of alternative design concepts that require decisions early in the design process, and because it is more cost effective to do this early in the design process

Incorporating IAQ at the very beginning of the conceptual design process—on par with function, aesthetics, and energy use—enables the design team to consider high-performance design concepts that can support good IAQ, energy efficiency, and other important design goals, and make informed decisions that will affect the project throughout the construction

and occupancy phases. The issues owners and residents need to consider and decisions they must make include their expectations for IAQ, contaminant sources in or near the dwelling, activities expected to occur in the dwelling and contaminants that might be associated with them, and resident characteristics (e.g., age range, health status, and how they heat, cool, and ventilate the dwelling). If these considerations are not addressed until after the building layout has been determined and the ventilation system is designed, it will be difficult to meet the needs of the dwelling and its occupants.

Examples of decisions made in the early phases of design that can promote good IAQ include:

- Mechanical systems that provide outdoor air ventilation independently of heating and cooling
- High-efficiency air cleaning strategies
- Selection of low-emitting materials based on sound technical consideration of options
- Opportunities for natural ventilation

Decisions made in the early phases that can lead to poor IAQ include the following:

- Site selection, building orientation, and surface grading that can lead to moisture problems
- Poor location of outdoor air intakes (locations where air is pulled into a fan or duct system) that introduces unwanted contaminants into the building
- Inadequate space for mechanical equipment, limiting the types of systems that can be selected, making it more difficult to filter and distribute air
- Limited access for inspection and maintenance, which can result in IAQ problems going undiscovered and unaddressed
- Use of materials that can lead to high levels of volatile organic compound emissions

Making a commitment to good IAQ at the beginning of a project and maintaining that focus throughout the design and construction will result in a dwelling that more successfully achieves its design goals and the desired level of performance throughout its lifespan.

Sometimes, even if intentions to achieve a high-quality dwelling with good IAQ are high, things can go wrong. Here are a few problems that can be avoided by addressing their root causes.

Lack of Quality Control

Although a good design is critical to good IAQ, neglecting to install and test the HVAC system and building enclosure so that they operate as designed often compromises IAQ. Therefore, a key factor in achieving good IAQ is a serious commitment to the comprehensive commissioning (quality control process of determining whether heating, ventilation, and air conditioning systems are designed, installed, functionally tested, and capable of being operated and maintained according to the owner's requirements; can also be applied to building enclosures) of HVAC and ventilation systems and assemblies that are critical to good IAQ. This commitment must start in the design phase and continue well into occupancy.

Moisture in the Enclosure

Many notable cases of IAQ problems have been associated with excessive levels of moisture. These problems can be very difficult to fix without major renovation efforts and costs. Moisture problems arise for a variety of reasons, including leaks where a roof meets a wall and in roofs and windows, designs that respond inappropriately to ambient moisture (e.g., low-permeability wall coverings in hot and humid climates), and poor air pressure control. These problems are largely avoidable but require an understanding of building moisture movement and attention to detail in enclosure design and construction and in mechanical ventilation system (system that actively ventilates a dwelling unit using powered equipment, such as motor-driven fan and blowers) selection, installation, and operation.

Poor Outdoor Air Quality

The traditional way to promote IAQ is through outdoor air ventilation, which can dilute indoor contaminants but is only effective when 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 make IAQ worse. Outdoor air quality is poor when outdoor contaminant levels and local contaminant sources (e.g., motor vehicle exhaust from nearby roads and contaminants generated by activities in adjacent buildings) are high. Whether to increase outdoor air ventilation rates above minimum requirements depends upon the potential effects of outdoor air quality.

ASHRAE Standard 62.2 (ASHRAE 2016b) does not require an assessment of outdoor air quality in a dwelling's vicinity. Given the key role of outdoor air ventilation in IAQ control, this guide covers outdoor air quality and air-cleaning alternatives.

Moisture and Dirt in Ventilation Systems

Dirt accumulation in ventilation systems combined with poor water management can lead to biological growth in the airstream and serious IAQ problems. These conditions generally result from inadequate particle filtration, poor filter maintenance, pooling of cooling coil condensate, or other moisture sources. ASHRAE Standard 62.2 (ASHRAE 2016b) has some requirements related to dirt and moisture management in ventilation systems. This guide addresses the topic in Strategy 4.1.

Indoor Contaminant Sources

Normal building materials and furnishings release many contaminants, especially when these materials are new, as do materials and substances brought into the dwelling once it is occupied. Unusual, unexpected, or atypically high contaminant emissions from indoor sources are associated with many IAQ problems, and this guide addresses material selection, cleaning, and other indoor sources.

IAQ problems can also result from improper equipment operation, inadequate exhaust ventilation (removal of air from a dwelling using a fan), and use of inappropriate materials for activities in the dwelling. This guide contains information on how to decrease the likelihood of such problems.

Inadequate Ventilation Rates

Although building codes and standards have addressed outdoor air ventilation for decades, many dwellings are poorly ventilated, which increases the likelihood of poor IAQ. The many potential causes of inadequate ventilation include lack of compliance with applicable codes and standards, installation or maintenance problems that prevent delivery of the target ventilation rate, or incorrect use of the installed systems by occupants. Also, even when system-level outdoor air intake rates are adequate, poor air distribution can under-ventilate some portions of the dwelling. ASHRAE Standard 62.2 (ASHRAE 2016b) covers the determination of target ventilation rates, and this guide offers additional advice to help address these issues.

Ineffective Filtration and Air Cleaning

Filtration and air cleaning are effective ways to control many indoor air pollutants, particularly those associated with poor outdoor air quality. Air filtration or air cleaning, therefore, is an important adjunct to outdoor air ventilation. This guide provides information on filtration and air-cleaning alternatives that, when properly implemented and maintained, can both improve IAQ and reduce energy use.

What is Covered in This Guide

This guide addresses the design and construction of dwelling units, including single-family homes and horizontally- (duplexes, triplexes, and row houses) and vertically-attached multifamily housing, and it is not restricted by building sizes or HVAC system type. These dwelling unit distinctions are covered by ASHRAE Standard 62.2 and are the focus of most of the recommendations in this guide.

What is Not Covered in This Guide

This guide does not cover spaces in residential buildings that are outside the dwelling unit, such as mailrooms, lobbies, corridors, exercise rooms, natatoriums, offices, or storage and equipment rooms. For guidance on these other types of spaces, see the Indoor Air Quality Guide (ASHRAE 2009) and ASHRAE Standard 62.1 (ASHRAE 2016b). Furthermore, this guide does not address multiple chemical sensitivity, although improved IAQ will benefit people with this condition.

Many of the recommendations of this guide can make dwellings more resilient in extraordinary incidents, either natural (e.g., earthquakes, fires, and floods) or intentional (e.g., terrorist attacks). This is not the primary focus of this guide and it certainly does not guarantee safety or good IAQ in these circumstances. Information planning for such events in building designs is available from several sources, including the Federal Emergency Management Agency and the National Fire Protection Association.

The housing and shelters for homeless people are often substandard in many ways, including IAQ, even in developed nations like the United States. This guide does not cover the challenges society faces in dealing with this major problem that affects public health, shortens lifespans, reduces productivity, and increases health care costs.

This guide does not cover ventilation for smoking and recommends against smoking indoors or any location outdoors where smoke could enter a dwelling. Any level of secondhand smoke (also known as environmental tobacco smoke) is incompatible with good IAQ based on the health risks and the inability of engineering controls to adequately control those risks.

This guide does not provide a metric, or method for quantifying, what good IAQ is, because there are no comprehensive consensus methods to measure or evaluate IAQ in any indoor environment. Health data are limited, at best, on dwelling features that enhance health and well-being across large populations, except for environmental tobacco smoke exposure. The authors long for a day when such tools exist and dwellings can have automatic protective features similar to those for preventing vehicle collisions and protecting drivers and passengers in modern automobiles.

This Guide focuses on IAQ and not the broader category of Indoor Environmental Quality (IEQ), except in limited cases. IEQ is generally understood to include not just air contaminants, but temperature comfort (which is covered in Strategy 8.3), acoustic comfort, and visual comfort (lighting and glare). Many also include ergonomics, daylight and views, and aesthetics.

The information in this guide addresses the IAQ problems that have been occurring in dwellings for several decades based on the authors' experience in investigating, resolving, and preventing these problems. Based on the known causes of the IAQ problems discussed in this introduction, this guide is organized into eight sections that address each of eight objectives for improving IAQ:

- Objective 1 – Acquire, Design, Construct, and Operate to Achieve Good IAQ
- Objective 2 – Manage Moisture
- Objective 3 – Limit Entry of Outdoor Contaminants
- Objective 4 – Control Contaminants Related to Mechanical Systems
- Objective 5 – Limit Contaminants from Indoor Sources
- Objective 6 – Minimize Exposure to Unavoidable Contaminants
- Objective 7 – Use Ventilation and Filtration to Reduce Contaminant Concentrations
- Objective 8 – Energy, Comfort, and Interactions

Each section offers details on several strategies to help achieve each objective.

What to Expect in Each Section of this Guide

Objectives and strategies. The overview section at the beginning of each objective explains why the objective is important for good IAQ. Each overview is followed by descriptions of the strategies that can be used to achieve that objective and provides a visual depiction of these strategies.

Sidebars. Sidebars are interspersed throughout the guide to define terms, address specific topics, or offer examples.

Bibliography. All sources cited in this guide are listed in the bibliography.

Appendix. Case studies describing different ventilation system and filtration options are included in Appendix A. They provide insights into system selection and integration, advantages and disadvantages of each, and guidance for practical implementation.

Objective 1

ACQUIRE, DESIGN, CONSTRUCT, AND OPERATE A DWELLING TO ACHIEVE GOOD IAQ

Many important choices made at the beginning—when a dwelling is designed, built, renovated, bought, or rented—influence the potential to reliably achieve good IAQ. Residents and those who operate and maintain the dwelling subsequently make other critical choices that also influence IAQ. Without good quality control during construction, even the most sophisticated design and IAQ technologies might not deliver the desired results. The quality control processes described in this objective can help even simple designs avoid IAQ problems and provide a good indoor environment.

This section describes how these choices affect IAQ and how to make decisions that are most likely to have a positive effect. The Objective 1 strategies are as follows:

Strategy 1.1 Build, Buy, or Rent a Dwelling with Good IAQ identifies important issues to consider when selecting, building, or renovating a dwelling. Many IAQ problems occur when building elements are designed by different people working in isolation from one another. This strategy therefore includes approaches to integrate design across disciplines while minimizing the cost of achieving good IAQ and other performance goals.

Strategy 1.2 Select Heating, Ventilation, and Air Conditioning (HVAC) Systems to Manage the Energy Effects of Ventilation explains how the type of HVAC system selected can constrain options for achieving good IAQ by limiting ventilation (process of supplying outdoor air to or removing indoor air from a dwelling by natural or mechanical means to dilute indoor contaminants), filtration, and space humidity control capability. HVAC system choice can also have a major impact on the energy consumed by ventilation.

Strategy 1.3 Schedule and Manage Construction and Renovations 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, humidity, or water during construction can threaten occupant health in dwellings undergoing renovation and long-term IAQ in new dwellings.

Strategy 1.4 Observe, Verify, and Test Dwelling Construction provides guidance on quality control for IAQ, including establishment of IAQ requirements and construction observation, verification, and testing. This strategy also covers the need for a full commissioning process for multifamily buildings.

Strategy 1.5 Effectively Operate and Maintain the Dwelling to Maximize IAQ explains the responsibilities of residents and, if applicable, professional property managers to operate and maintain the dwelling so as to maximize IAQ. This strategy also covers actions for homeowners to take or avoid for preventing IAQ degradation.

Objective 1

ACQUIRE, DESIGN, CONSTRUCT, AND OPERATE A DWELLING TO ACHIEVE GOOD IAQ

Other important strategies for acquiring, designing, constructing, and operating a dwelling to achieve good IAQ are discussed in the following sections:

- Strategy 2.2 – Control Indoor Humidity
- Strategy 3.6 – Control Entry of Contaminants from Unoccupied Spaces
- Strategy 4.1 – Control Moisture and Dirt in AHUs
- Strategy 6.2 – Provide Local Capture and Exhaust for Point Sources of Contaminants
- Strategy 7.1 – Implement Appropriate Outdoor Air Ventilation Strategies and Quantities
- Strategy 7.2 – Provide Particle Filtration and Air Cleaning

The example below shows how the strategies in Objective 1 work together and with strategies elsewhere in this guide as part of a process for creating good IAQ.

An exhaust hood over the kitchen range and oven can remove particles and gases released during cooking (Strategy 6.2). The performance of a range hood depends on its height above the cooking surface, depth, and width as well as its provision of sufficient exhaust air to capture the plume of contaminants from the stove. The hood design (Strategy 1.1) must address all these factors. Changes can be made to the HVAC system design to accommodate an unusually large flow hood (Strategy 1.2). The contractor must install the hood far enough from the stovetop and not make any small mistakes that reduce airflow (Strategies 1.3 and 1.4). Common mistakes are forgetting to remove the tape that holds the backdraft damper closed during shipping or using a screw to secure the duct to the damper fitting that is too long and prevents the damper from opening. At the completion of the construction, the flow rate of the hood should be tested to demonstrate that it is working properly (Strategy 1.4). Of course, the cook must turn the exhaust hood fan on to reap the benefit of the care taken to plan and install the hood (Strategy 1.5).

Strategy 1.1 Build, Buy, or Rent a Dwelling with Good IAQ

1.1

Introduction

Anyone renting, buying, or building a dwelling should select one that has met the requirements of one of the label programs that includes IAQ requirements. Examples of these programs are the Environmental Protection Agency's (EPA's) ENERGY STAR and Indoor airPLUS, Leadership in Energy and Environmental Design (LEED) for Homes of the U.S. Green Building Council, and National Green Building Standard of the International Code Council and ASHRAE. None of the programs addresses all IAQ features, but they are a good place to start. Your local builder may have options meeting a state or local green building code or program.

To promote good IAQ when renting or buying a dwelling:

- Choose a dwelling that has an EPA ENERGY STAR Indoor airPLUS label or a Standard 62.2 compliant ventilation system.
- Have the home inspected; include indoor environmental problems (e.g., biological growth and moisture problems, indoor pests, odors, bath and kitchen exhaust fans, and nearby sources of air pollution) in the inspection list.

To promote good IAQ when building a new dwelling:

- Ask the builder or architect for the EPA ENERGY STAR Indoor airPLUS label.
- Determine whether the building enclosure and HVAC recommendations in this guide have been implemented.

Buying or Renting an Existing Dwelling

Those buying or renting an existing dwelling should look for the following signs of existing problems:

- Moisture:
  - Identify biological growth, stains, peeling paint, or musty odors indoors, including locations such as the ceiling in the level below the roof, window sills, and cabinets under sinks in the kitchen and bathrooms (any room containing a bathtub, shower, spa, or similar source of moisture).
  - Examine the outside for puddles or low spots near foundations as well as damaged flashing, siding, gutters, or roofing. Make sure that grading slopes away from the dwelling to allow water to move away from the foundation and that gutters direct water to a sloping grade (level of ground surface outside) away from the dwelling.
  - Check for signs of moisture or past moisture intrusion in basements and crawlspaces, such as rusty metal (e.g., hangers or heads of flooring nails) in crawlspaces.
- Pests:
  - Check for signs of rodents, cockroaches, or bats in cabinets, stoves, closets, attics, basements, and crawlspaces.
- Odors:
  - In a multifamily building, check the common corridors for odors (a potential sign of an air quality problem) because they are likely to enter the living spaces.
- Ventilation equipment:
  - Make sure that the kitchen and bath exhausts are present and operational, quiet enough to use, and vented to the outdoors. If they are not vented properly, determine whether they could be vented to the outdoors.

    - Check whether the dwelling has a whole-dwelling mechanical ventilation system (assembly of fan or fans, ductwork, controls, and other components that work together to introduce outdoor air into a dwelling to dilute indoor contaminants). It might be integrated into the central HVAC system or be a standalone system. If the dwelling does not have a whole-dwelling mechanical ventilation system, determine whether installing such as system is feasible and practical.

- Entryways:
    - Make sure that the entryway has room for a good track-off mat and for residents to remove boots and change into indoor shoes. In a multifamily building this should already be in use.

- Outdoor air pollution:
    - Check whether the dwelling is next to a busy highway or industry with noticeable emissions.

Special Considerations for Buyers of an Existing Dwelling

Common practice standards for home inspectors (e.g., those of the International Association of Certified Home Inspectors and the American Society of Home Inspectors) exclude IAQ and combustion equipment (which burns fuel, such as natural gas, propane, or kerosene to heat a dwelling or produce hot water). It might be necessary to search widely to find a home inspector with specific expertise in indoor air issues, though most have experience evaluating the installation of key building components that affect IAQ (such as insulation or ductwork) and performing tests such as those outlined in Strategy 1.4. Home inspectors with additional credentials, such as Home Energy Rating System (HERS) raters or those with a Building Performance Institute (BPI) credential, often have more specialized skills. The home inspection should include a radon test.

Special Considerations for Renters

Finding rental properties with no-smoking policies has become much easier. If the building has a professional property manager, that individual should answer these questions:

- Have you implemented other IAQ policies in your operation and maintenance programs?

- Was the building designed and constructed to provide good IAQ as part of a high-performance or labeling program?

- What ventilation systems have been installed?

- How is the indoor air filtered?

In addition to the programs listed at the beginning of this section, ENERGY STAR Multifamily High Rise Program guidelines can be applied to taller buildings (ENERGY STAR 2017b).

Table 1.1-A Sample IAQ Checklist for Renting an Apartment

Table 1.1-A provides a sample checklist that renters might use to select an apartment with good IAQ. Renters assign points to indicate the extent to which the apartment has each feature so that they can compare the scores of several apartments. They can assign partial points for partial implementation of a feature or when they are not sure whether the apartment has the feature.

IAQ Features	Max Points	Points Achieved
No unusual odors or known pollution outside and no highway next to the building	2	
No standing water outside	2	
Track-off mats at main entryway	2	
Nonsmoking building	3	
Radon test result below 2.7 pCi/L (100 Bq/m3) (important for apartments on ground, first, second, and third floors)	3	
Designed and constructed to Indoor airPLUS, ENERGY STAR, National Green Building, or LEED for Homes standards	3	
Free of lead and asbestos or these have been encapsulated according to the landlord	3	
No unusual odors in apartment or corridors, including from neighbors' cooking	3	
Mats at the main building entrance and room for mats and a place to leave shoes by unit entrance	1	
Exhaust system covering top of range with a draft that can be felt	2	
Range hood vented to outside and not back into the kitchen	3	
Exhaust fan in each full bathroom strong enough to hold toilet paper against the surface of the inlet	3	
No water stains, peeling paint, or moldy smell, including under sinks	3	
No signs of pests in kitchen cabinets, closets, or other concealed places, and landlord uses integrated pest management and has sealed pest entry points	3	
Windows that can be opened easily	2	
Outside ventilation air ducted directly into apartment	2	
No garage under the living space	2	
HVAC filter with 2 in. (50 mm) thick slot accessible (assign 1 point if the slot is 1 in. (25 mm) thick) or landlord uses a filter with a Minimum Efficiency Reporting Value (MERV) of 13 or higher (assign 1 point if the MERV is at least 8)	2	
Solid cleanable surfaces throughout (assign fewer points for extensive carpets, fabrics, and upholstery), and carpets meet the Carpet and Rug Institute's Green Label Plus or similar standards	3	
Thermostat in the apartment that responds to adjustment	3	
Kitchen and bathroom cabinets, if new, have a seal indicating certification by the Kitchen Cabinet Manufacturers Association Environmental Stewardship Program	1	
Labels on plywood, medium-density fiberboard, oriented strand board, and particle board, if new, indicating compliance with California Air Resources Board requirements or that they meet a low-emissions standard	2	
Total score:	53	

Table 1.1-A Sample IAQ Checklist for Renting an Apartment

Special Considerations for those Purchasing a New Dwelling

IAQ features need to be fully integrated into the design of the building enclosure, HVAC equipment, layout of the building and landscape, and selection of materials.

A person buying or designing a new dwelling should work with a builder, architect, or engineer to implement the strategies in this guide. Many of them can be completed even if the purchaser is buying a unit in a multifamily building.

It is a good idea to sign a contract with a verifier with one of the label programs mentioned at the beginning of this strategy. A third party should test the dwelling and verify that it meets the program's specifications. Most builders do not have the specialized equipment needed for this testing and verification, and a project can always benefit from an additional set of eyes. Ideally, this verifier should be involved throughout the construction process. Consideration should be given to adding IAQ features in this guide that are missing from the selected program.

The design of a custom dwelling needs to take into consideration the needs of the new owners. For example, if one of the occupants has asthma or allergies, care can be taken to avoid known asthma triggers and allergens and to control moisture during construction and in the operation and maintenance of the dwelling. If an occupant is sensitive to odors or chemical emissions, building materials, finishes, and furnishings with lower emissions can be used. The National Institute of Standards and Technology (NIST) has a specification that can provide guidance (NIST 2015). To address particular needs, a team member (e.g., architect, contractor, or consultant) should have experience and training in designing and/or installing enhanced IAQ features for buildings.

One of the best ways to achieve a house design that addresses IAQ protection is to ask an independent party to review the design. Residential construction design is rarely reviewed by an IAQ consultant. However, some performance programs—such as ENERGY STAR, Indoor airPLUS (which requires ENERGY STAR labeling), and LEED for Homes—include design reviews, typically by a Home Energy Rating System (HERS) rater. Similarly, Passive House Institute US (PHIUS) certification requires verification by PHIUS+ Raters and Verifiers.

By the time occupants move into a new dwelling, developers, architects, engineers, building contractors, and code officials have been involved in designing and building the dwelling. The contractor might have employed subcontractors to excavate, build, and waterproof the foundation; frame and sheath the house; install the roofing and siding, air seal (sealing of gaps, cracks, and holes in a surface or building enclosure against the flow of air in the dwelling walls, ducts, or air-handling unit), insulate, install plumbing and HVAC equipment, install cabinets in the kitchen and bathrooms, hang gypsum board; hang doors; lay the flooring; and paint and varnish the interior finishes. One should never assume that these individuals will have communicated with each other about indoor air quality.

Strategy 1.1 Build, Buy, or Rent a Dwelling with Good IAQ

1.1

Integrated design brings several professionals with different areas of expertise together early on so that specific features are included and coordinated among team members and that desired outcomes are achieved. The most important IAQ features that need to be integrated into the design are as follows:

- A building enclosure designed to:
  - Be airtight and well insulated
  - Prevent condensation, rain leaks, and below-grade water leaks
  - Prevent pipe freezing and plumbing leaks

- HVAC systems that:
  - Are located inside the thermal enclosure (enclosure that is insulated and air sealed to reduce the flow of heat between the inside and outside)
  - Implement a whole-house mechanical ventilation strategy that meets the guidelines in Strategy 7.1
  - Keep the indoor temperature in the desired comfort range
  - Keep indoor humidity levels below 65% relative humidity (RH; amount of water vapor in air expressed as a percentage of the maximum possible amount of water vapor that could be present at that temperature) during the cooling season by sizing cooling equipment correctly, or by providing supplemental dehumidification where needed
  - Implement a whole-house filtering strategy that meets the guidelines in Strategy 7.2

- Fan-powered local exhaust systems (systems that remove indoor air in a location where level of indoor air contaminants or moisture are expected to be high, such as a kitchen hood that is used to remove cooking contaminants or a bathroom fan that removes odors and moisture) that truly exhaust to the outside.

For guidance on selecting the HVAC system, see Strategy 1.2 below.

After Move-In

Some IAQ improvements are easy to add, regardless of whether the person has bought or rented a new or existing dwelling. For example, the occupant can install a portable air cleaner or a basement dehumidifier and take it with them if they move. See Strategy 1.5 for other ways the occupant can maximize the IAQ in the dwelling.

Strategy 1.2 Select Heating, Ventilation, and Air Conditioning (HVAC) Systems to Manage the Energy Effects of Ventilation

1.2

Introduction

Selection of the heating system, air conditioning system, or both for a dwelling is usually driven by cost, available fuels, and the local climate. The choice sets in motion a cascade of decisions that affect IAQ, creating opportunities and challenges for meeting IAQ goals. This section is for designers and builders, although it can also provide guidance to potential buyers and occupants.

Although people often talk about the HVAC system, dwellings sometimes have multiple systems that perform these functions, and some dwellings do not have a system that provides one of these functions.

The function of heating and cooling systems in dwellings is to maintain conditions that are thermally comfortable for the occupants. Dehumidification is an important additional function of cooling systems. Ventilation systems enhance IAQ by introducing outdoor air to dilute and remove contaminants, and they might or might not be integrated into the heating and cooling system.

Key criteria to consider when designing an HVAC system:

- Thermal comfort
- Humidity
- Noise
- Cost
- Maintenance
- Integration with filtration and ventilation air
- Impact on building pressure relationships
- Transfer of contaminants from unconditioned spaces through ductwork

In addition to making sure that an HVAC system has basic features — heating, cooling, dehumidification and ventilation with outdoor air — those choosing an HVAC system should consider several secondary features, including the system's energy efficiency, potential for affordable installation and operation, ease of maintenance, and contribution to good IAQ. Although IAQ is important for human comfort, it goes beyond what the occupants perceive because they are unlikely to be aware of many very harmful indoor air pollutants, such as carbon monoxide, nitrogen dioxide, and radon.

There is no "one size fits all" approach to selecting HVAC systems to support good IAQ. Each system that might be chosen influences the options available to the designer to address IAQ. Designers who consider IAQ when choosing an HVAC system can exploit the benefits of each system while taking steps to prevent problems. Regardless of the system chosen, designers need to include methods to dilute contaminants using outdoor air (Strategy 7.1) and filter air (Strategy 7.2). They also need to be aware of how the HVAC system's design might influence building pressurization and durability. The case studies in Appendix A show several system combinations that achieve these goals using different combinations of methods.

Air-Handling System and Conditioned Air

Air-handling system: Assembly of components, including the air-handling unit and attached ductwork, that deliver to a dwelling conditioned air.

Conditioned air: Air that has been treated to control its temperature, relative humidity, and/or purity.

Central Air-Handling Systems

Perhaps the most consequential choice for the dwelling's design is whether to use a central air-handling system. Central air-handling systems have a centralized fan that delivers heated or cooled air to the conditioned spaces of the dwelling through a system of ducts. Possible methods of heating or cooling the air for these systems include forced-air furnaces, heat pumps, air conditioners, and ground-source

heat pumps. Central air handling systems are common because they are often economical, have less equipment to maintain than more distributed systems, and offer the most options to integrate heating and cooling into a single system.

A central air-handling system provides several opportunities for integration with systems that support IAQ. Outdoor ventilation air (Strategy 7.1) and filters (Strategy 7.2) can be integrated into the air-handling system. This type of system provides more options for designers, who can sometimes simplify the system in ways that reduce installation, maintenance, and replacement costs. Also, the mixing of indoor air when these systems are used can prevent contaminant “hot spots” from reducing IAQ in certain rooms.

However, integrating a filter or outdoor air ventilation strategy into the central air-handling system is not always the best choice. The impact of system runtime must be considered. Allowing the system to turn on only when heating and cooling are needed (as is typical in most dwellings) reduces the effectiveness of the filter and the quantity of ventilation air in mild weather. Because filtration and ventilation are needed in all weather conditions, a controller must be added to achieve minimum run time of the air-handler (AHU; equipment with a fan or blower that draws air in one side, passes it through components that heat, cool, and/or alter its humidity, and blows it out the other side) when demand for heating and cooling is insufficient to support these functions. In addition, the AHU fan is typically large and consumes more energy than the smaller fans typically used for standalone outside air ventilation or filtration. The designer should consider ways to reduce this energy impact (such as those presented in Strategies 7.1, 7.2, and 8.1) while maintaining good IAQ.

The duct system provides a pathway through which several problems can arise. If leaky ducts are outside the conditioned space, they can introduce contaminants from attics, garages, or crawlspaces (Strategy 3.6). They can also alter the pressure balance in the dwelling, creating combustion safety problems (Strategy 6.1), reducing energy efficiency, or increasing contaminant transfer from adjacent spaces (Strategy 6.3). Locating the ducts inside the enclosure of the dwelling, testing the ducts for leakage, and sealing them if necessary can prevent or at least reduce these problems. Because the AHU is an important part of the duct system, it should be inside the thermal enclosure and included in airtightness testing and air sealing.

When air conditioning is added to existing dwellings with ducts that previously carried hot air only, complete insulation and a vapor retarder are particularly important (Strategy 4.2). In climate zones 1, 2, 3, and 4 (Figure 1.2-A), the addition of air conditioning usually requires replacing the ducts because larger airflow volumes are typically needed.

Nonducted HVAC Systems

A wide variety of system options are available for thermal conditioning (process of heating, cooling, and/or dehumidifying a dwelling to achieve human comfort and durability) without a central ducted system, including: radiant floor heating, baseboard or radiator heating, ductless minisplits (small, low-capacity heat pump or air conditioner, often in or close to the living space; shown in Figures 1.2-B and 1.2-C), and self-contained through-the-wall air conditioners and heat pumps. These systems are common in small dwellings, apartments, and larger dwellings that lack air conditioning.

Figure 1.2-A 2017 North American Climate Zones

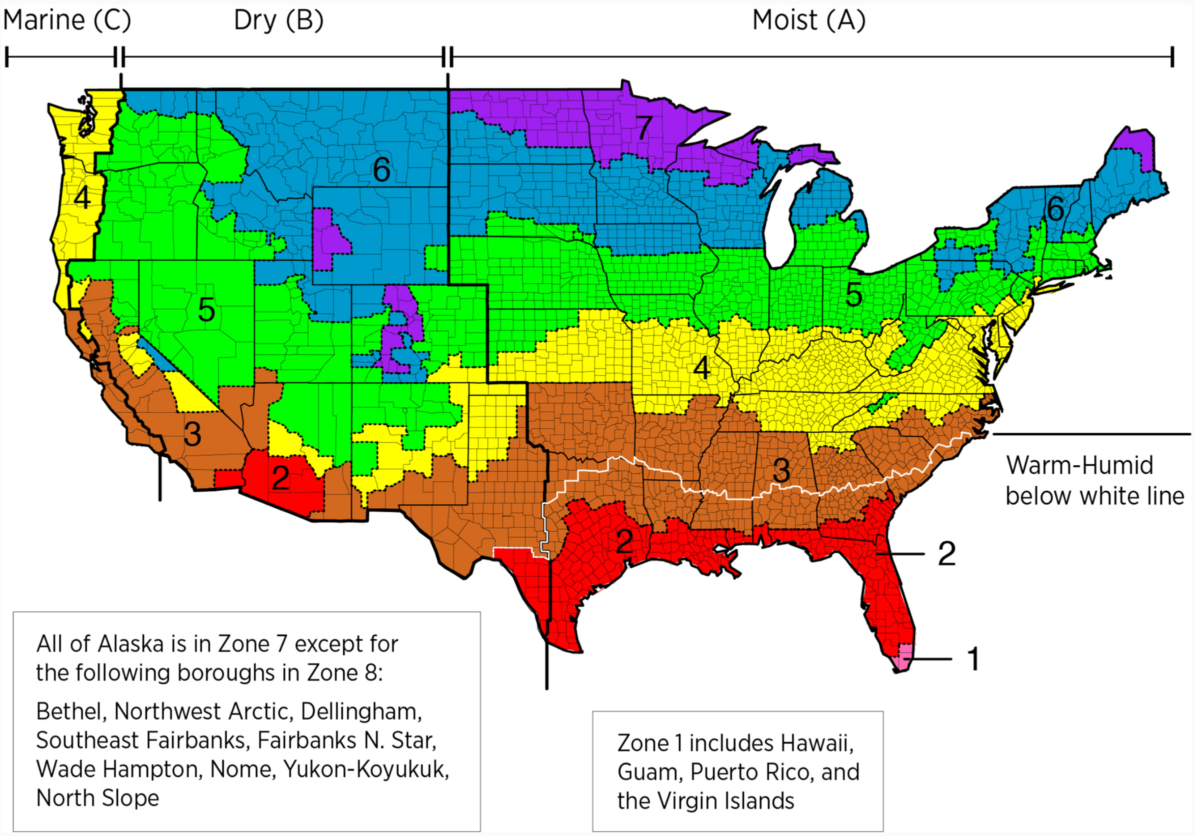


Figure 1.2-A 2017 North American Climate Zones
Map courtesy ASHRAE (2017e).

When a nonducted system is used, no central duct system is available to filter or deliver outside ventilation air, and the indoor air cannot be easily mixed. These issues do not mean that the dwelling cannot have very good systems to achieve good IAQ, but the available options are limited. The case studies in Appendix A include some options for ventilation and filtration that do not require a ducted HVAC system.

Filtration options (Strategy 7.2) for nonducted systems are limited. Standalone filter units take

up space, each sleeping room needs its own unit and they generate sound, although many people become accustomed to the background noise of a standalone filter unit while sleeping. Dedicated-purpose ducted filter units are another option. However, their fans typically have only enough power to serve a few rooms that are close to one another and the filter unit. The duct design for these dedicated systems should be strategic and provide filtered air to heavily occupied areas.


Figure 1.2-B Ceiling-Mounted Ductless Minisplit

If the dwelling has no central duct system, fewer options are available for delivering outdoor ventilation air (Strategy 7.1). Exhaust-only ventilation strategies to exhaust air from the dwelling without mechanical, or fan-driven, supply air are easy to use because they do not require central ductwork, but this might not be the best choice for every dwelling. Supply-only ventilation strategies (which supply outdoor air to the home without mechanical, or fan-driven, exhaust methods) can cause conditioning problems in many climates since the outside air is usually not conditioned before being delivered to the occupied space.

If the outdoor air is likely to be very cold, hot, or humid, comfort and other problems can develop. A balanced (supply and exhaust) approach that mechanically supplies outdoor air and exhausts indoor air using a standalone device, such as an energy recovery ventilator (ERV; device that transfers both sensible heat and latent heat between the incoming air that ventilates a dwelling and the outgoing exhaust air) or heat recovery ventilator (HRV; device that transfers sensible heat


Figure 1.2-C Wall-Mounted Ductless Minisplit

Zoning for Temperature Control

Maintaining a comfortable indoor temperature is an aspect of indoor environmental quality and can affect occupants' perceptions of the indoor air (Strategy 7.3). One strategy for maintaining occupants' desired temperature conditions is zoning (a control strategy that allows different parts of the dwelling to be conditioned using separate thermostats).

With a central forced-air system, zoning is accomplished by using separate supply ducts to serve different parts of the dwelling that have different thermal loads. Dampers (Figure 1.2-D) are placed in each of these ducts and are controlled (Figure 1.2-E) to provide airflow to the rooms served by the duct when a thermostat in that zone calls for heating or cooling. This allows the occupants to have separate thermostats in different parts of the dwelling that can direct heating or cooling to that part of the dwelling only.

Zone dampers can create noise directly from their air-control vanes and indirectly by forcing more air through a single zone. Quiet dampers should be chosen, and each zone should be designed to handle the required minimum airflow of the central HVAC system. When a large system has to provide conditioning to only one small zone, too much air can be pushed through ductwork, resulting in noise. This problem can be reduced by using dual-stage systems, which can operate at two speeds: a higher full-capacity airflow or a lower airflow (typically about 70% of maximum) when only one zone needs heating or cooling. Multistage or variable-capacity equipment can use much lower airflows, reducing the noise even more. When using zones, the designer must choose equipment or use the manufacturer's guidelines to prevent forcing too much air through a single zone.

Figure 1.2-D Zone Damper Actuator

An alternative to using zoning controls in a dwelling with central forced air is to use separate HVAC systems for each zone. This approach requires more equipment and probably more maintenance. However, if one system fails, the other system(s) can partially heat and cool the dwelling until repairs are made. This strategy can make integration of ventilation air with the AHU more complex, because designers need to choose whether to install multiple ventilation systems or use a single system to handle all of the dwelling's ventilation. If they choose a single system, the air will not be distributed as thoroughly throughout the dwelling, and the likelihood of contaminant "hot spots" rises.

A less expensive option to allow some occupant control over the distribution of heating and cooling among rooms is for the HVAC installer to provide dampers at all supply ducts in a dwelling, allowing manual adjustments to the heating and cooling delivered to each room. Supply registers with adjustable openings also allow some occupant control. Window treatments in rooms with many windows also give homeowners some flexibility to adjust the amount of solar heat entering a room.

Non-ducted systems are often easier to integrate with zoning controls. Radiant heating systems, for example, often have a separate thermostat to control the heat in each room. Minisplits typically have indoor units that serve each major room in a dwelling (e.g., living areas and bedrooms). Because the filtration and outdoor air systems are separate from these systems, the zoning does not directly affect these strategies.

Figure 1.2-E Zone Controller

Figure 1.2-F HVAC Zones to Enhance Thermal Comfort

Rooms and areas with heating and cooling patterns that are different (e.g., because a room has a large glass area or overhead roof) from those of other areas benefit from having their own zone and thermostat. A best practice is to place different floors in separate zones. Subsets of rooms with different orientations or uses might also function best as separate zones. For example, a master suite, particularly if most of its windows face in a different direction from other rooms on the same floor, might form a zone. Because of limitations in the ability to adjust the airflow of central AHU fans, implementing very small zones or large numbers of zones is neither easy nor inexpensive (Figure 1.2-F).

Figure 1.2-F HVAC Zones to Enhance Thermal Comfort

Humidity Control

Designers of dwellings in humid climates need to consider dehumidification because high indoor humidity can have a negative effect on thermal comfort and can contribute to problems with biological growth (Strategy 2.2). In many dwellings, simply operating a properly sized air conditioner or heat pump to cool the dwelling is enough to adequately control humidity because dehumidification is a natural byproduct of cooling humid air.

The dehumidification byproduct of cooling does not allow feedback control based on indoor humidity levels. As a result, when the indoor humidity level rises, the system does not necessarily respond by performing more dehumidification unless the dwelling also happens to need cooling. Proper sizing techniques using Air Conditioning Contractors of America (ACCA) manuals J and S (ACCA 2016a, 2014) can improve dehumidification, but some dwellings need more dehumidification than the cooling system can provide. These dwellings need a dehumidifier. Strategies 2.2, 3.6, and 7.1 discuss the types of dwellings that typically need dehumidifiers and ways to integrate them into the dwelling's design. Standalone dehumidifiers can be used for below-grade areas, such as sealed crawlspaces (Strategy 3.6) and basements; ducted dehumidifiers can be integrated with a dwelling's AHU; and dehumidifier-ventilators (Case Study 7) can dehumidify ventilation air.

Additional dehumidification is often necessary for dwellings in humid climates (e.g., Zones 1, 2, 3 in the Moist region and Zones 4 and 5 in the Marine region in Figure 1.2-A). Very energy-efficient dwellings and below-grade spaces, which are both likely to use less air conditioning, are more likely to need dehumidifiers. Dehumidifiers can use a substantial amount of energy, and not every dwelling needs one. However, when additional dehumidification is necessary, the dehumidification is worth the cost.

Not all excess humidity problems are best solved with a dehumidifier. For existing dwellings or when humidity is excessive in the winter, the first strategy is to identify the source of the humidity and try to reduce or manage it (Strategies 2.2 and 6.2). For example, condensation problems during winter can result from defects in the building enclosure (Strategy 2.1), such as a highly conductive window frame or a defect in insulation. In these situations, eliminating the cold surface prevents the condensation (Strategy 2.1). Wintertime condensation problems can also be caused by excessive indoor generated moisture, which can be addressed in many cases using bathroom or kitchen exhaust fans (Strategy 6.2).

Dwellings in climates that can have very cold outdoor temperatures can also experience very dry conditions that require a humidifier for occupant comfort. However, humidification can threaten IAQ when the system malfunctions, is operated at a higher humidity setting than appropriate, or is allowed to develop biological growth (Strategy 2.2).

Sound Control

Sound is an aspect of comfort that must be considered for any HVAC system. Equipment, particularly fans, should be selected and located so that the sound is acceptable to occupants. Zones should be designed carefully to avoid forcing too much air through a smaller zone when only one zone requires heating or cooling. The use of multistage or variable-speed systems can be helpful.

Noise problems with central AHUs can be reduced by locating equipment in rooms with sound insulation in the walls and not adjacent to sleeping rooms. Room air cleaners, minisplits, and exhaust fans are designed to be located in occupied spaces. However, they generate some sound that could annoy sensitive individuals. When possible, units with low sound ratings should be selected and sometimes exhaust fans can be located outside the room they serve.

HVAC System Selection for Multifamily Buildings

System selection has additional repercussions in multifamily buildings. Designers of these buildings must consider how HVAC systems will be maintained and who will be responsible for maintenance. Centralized HVAC systems shared by many dwelling units are easier for a building manager to maintain and control, because access to each unit is not needed. However, the building owner, homeowner's association, or other operator must perform this maintenance properly over the long term.

Separate systems in each dwelling unit offer more flexibility and can be easily changed or maintained by occupants to meet their needs. These systems also prevent cross-contamination between dwelling units and the need to balance airflow between the units. However, someone (e.g., the occupant or building manager) needs to have the access, education, ability, and budget to maintain the system.

Strategy 1.3 Schedule and Manage Construction and Renovations to Facilitate Good IAQ

1.3

Introduction

This section applies to dwellings and multifamily buildings that are being designed and constructed or are undergoing major renovations. Well-managed construction and renovation scheduling and protective actions can avoid many IAQ-related problems.

Important steps for scheduling and managing construction and renovations to facilitate good IAQ are to:

- Schedule construction activities so that materials that need to be protected from rain, dust, and dirt are not delivered until they can be safely stored or installed in protected areas.
- Control dust during construction using techniques that reduce dust emissions and protect finished portions of the dwelling from dust produced in areas under construction.
- Offer HVAC equipment maintenance and service contracts to occupants.

Construction and Renovation Scheduling

A construction or renovation schedule helps to see that required preparation is completed before new work starts. Some steps to include in the schedule that can have major ramifications for IAQ are as follows:

- Install foundation damp proofing, foundation drainage, and/or exterior foundation insulation before the excavators backfill the foundation.
- Complete and inspect all wiring, plumbing, piping, and blocking installation in exterior walls (and the attic floor if the attic is outside the enclosure) before insulation is installed.*
- Allow adequate time for damp-applied building products, such as wet blown cellulose, to dry before enclosing them with drywall.
- Follow the manufacturer's instructions and schedules for building products that need to cure, such as spray foam insulation.
- Leave enough time in the schedule for porous materials (e.g., concrete, masonry, lumber, and wood-based products) to dry before covering them with structural or finish materials.
- Check the moisture content of wood to make sure that it is dry. Meters are available at home improvement stores.
- Leave time in the construction schedule for flush out, especially for multifamily buildings. This can be done more informally for single-family dwellings, where operable windows and exhaust fans can be used to ventilate the building prior to occupancy.

*Subsequent removal of insulation to perform this work often results in enclosure defects and thermal bypasses that create problems later.

Strategy 1.3 Schedule and Manage Construction and Renovations to Facilitate Good IAQ

Job Site Material Storage

Deliveries of required materials and equipment should be scheduled so that these items are onsite when they are needed, which will reduce the likelihood that someone will need to buy materials at the last minute without following the specifications. However, if products arrive too early, keeping them dry and preventing them from being damaged could be difficult (see Figure 1.3-A for an image of water-damaged building materials), especially for materials that are easily damaged by water. In addition to timely delivery, ways to prevent water damage include placing materials on pallets and wrapping them in plastic sheeting before installation (Figure 1.3-B). When possible, products should be delivered after the dwelling is weathertight and the indoor humidity can be kept low enough to prevent condensation. If materials are delivered with water damage or excessive moisture content, the delivery should be refused.

Figure 1.3-A Job Site Material Storage that Exposes the Materials to Water

Figure 1.3-B Job Site Material Storage that Protects the Materials from Water

Contaminant Prevention

Several construction activities produce dust and fine airborne particles. For example, sawing, sanding, grinding, soldering, welding, using heat guns, and using unvented combustion heaters all create particles that can cause problems in the short term for the workers and in the long term for the occupants. Some strategies to avoid excessive particle exposure during and after construction are as follows:

- Use processes and equipment that do not produce particles (e.g., wet sanding rather than dry sanding and using electric or vented combustion heaters).

- Use tools with integral dust collection features (e.g., sanders and grinders with collection shrouds and attached high-efficiency filtered vacuum cleaners).

- Physically isolate the work areas, including by covering all open ductwork as well as air-handling equipment and associated grilles, diffusers, and registers in the work area.

- Arrange for activities that create dust to occur offsite, outdoors, or when containment and dust control measures are in place.

Precautions against contamination should be taken when necessary. In climates with extreme weather, damage from water and other contaminants should be prevented during construction. Dwellings in hot and humid climates might need operational air conditioning systems and/or dehumidification equipment before construction is complete to dry out building materials. However, overcooling the building interior can cause condensation and moisture problems. If faster dehumidification is desired, a temporary dehumidifier is a better option than overcooling the dwelling. Dwellings with sealed crawlspaces might need a temporary dehumidifier installed during construction to prevent humidity problems before the permanent dehumidification strategy can be employed.

The specified products should be used for all steps in the construction process. Many materials that are related to IAQ are purchased by multiple parties at multiple times, and extra care is required to make sure that they are all buying the appropriate materials. For example, it is easy to overlook the need to purchase low–volatile organic compound (VOC) paints, primers, adhesives, grout, and wood trim products during a quick trip to the store.

Efficient Turnover to the Owner or Occupant

When turning over a new dwelling or system to the owner or occupant, home builders and companies that replace HVAC systems should always offer the option of a service contract and provide complete documentation for all systems, information on proper ventilation settings, and instructions for operating all thermostats and controllers and for changing filters. The dwelling design and HVAC systems chosen should make maintenance as easy as possible for the owner or occupant. For example, filters that must be replaced and coils that need periodic cleaning should be easy to access, and controls should have labels that are easy to understand. Sensors that indicate a need for maintenance (e.g., when a filter needs to be changed) will increase the likelihood that this maintenance will be performed. Instructing occupants to use easily available products (such as filters) also makes it more likely that the maintenance will be done properly and on schedule.

Strategy 1.4 Observe, Verify, and Test Dwelling Construction

Introduction

This strategy applies to new construction and major renovations. For the strategies and practices in this document for improved IAQ to be useful, they must be incorporated into the design; the builder must effectively implement them; and the owner or occupant must perform the maintenance needed to keep the IAQ features working properly. Failure to complete any of these steps will reduce the effectiveness of the features designed to prevent IAQ problems. This strategy focuses on the builder's implementation of these features during construction.

To promote construction practices that achieve good IAQ:

- Incorporate good IAQ features in the design (Strategy 1.1).
- Arrange for a third party to review plans and conduct inspections so that IAQ features are included in the design and are effectively installed.
- Test HVAC equipment to be certain that it works properly.
- Participate in a label program, such as ENERGY STAR and Indoor airPLUS, which require third-party plan reviews, inspections, and testing.

Observation and Verification of IAQ Feature Installation

Design professionals (architects, engineers, and designers) and contractors assess the quality of installation and construction of IAQ features by directly observing work in progress and verifying completed work. Observation of work in progress can be necessary to fully verify correct installation. For example, window installation requires multiple carpentry, sealing, and flashing steps to achieve air and water resistance, and the results of several of these steps are no longer visible once the process is complete.

Problems with work in progress must be identified early, and any necessary changes to installation processes must be implemented immediately. Design professionals can assist with this identification and determine how to verify the quality of the completed installation. For example, a design professional can visit the site and inspect the installation of rain-control systems during construction.

However, because design professionals are not on the jobsite full time, the primary responsibility for supervising, observing, and documenting work remains with the general contractor. Both direct supervision by the general contractor and verification of completed work by the design professional help see that critical details are effectively completed. This also allows mistakes or omissions in the design to be caught, discussed, and addressed before they become problems. Careful documentation by the contractor helps others judge whether the work was effectively completed.

A popular and important method for the homebuyer or occupant to achieve correct installation of IAQ features consists of observation, verification, and testing by a third party. Several organizations (e.g., Residential Energy Services Network [RESNET], BPI, and U.S. Green Building Council) provide certification programs for inspecting, verifying, and testing IAQ features as part of quality assurance programs. Most trained third-party home inspectors or "raters" have experience evaluating the installation of key building components (such as insulation or ductwork) and performing the tests outlined in the following section. Their work is often packaged as part of an above-code new home rating program, such as ENERGY STAR (EPA 2017f) with Indoor airPLUS (EPA 2015c), to implement a package of verification and testing measures that will substantially reduce the risk of IAQ problems.

Strategy 1.4 Observe, Verify, and Test Dwelling Construction

1.4

There is tremendous value in having a third-party rater or inspector visit the site to provide an additional set of eyes to check important details. This individual can document the installation quality by filling in checklists, writing a narrative, and augmenting observations with photographs, infrared scans, or illustrations. An “above-code” program is a labeling program with requirements that exceed those of the building code. The use of an above-code rating program (e.g., ENERGY STAR New Homes, Indoor airPLUS, or LEED for Homes) is helpful to make sure that this individual’s scope of work includes the most important testing and verification steps. Most such programs are intended to achieve greater energy efficiency or verify use of green construction measures.

Observation & Verification Example: Figure 1.4-A Kickout Flashing

Figure 1.4-A Kickout Flashing

An example of how observation and verification might involve all of these parties working together is the installation of kickout flashing (Figure 1.4-A). A kickout flashing is used to prevent rainwater from leaking into the wall cavity where a section of roof meets the bottom of an exterior wall. The design professional includes these features in the design, but the contractor is responsible for making sure that the siding and roofing contractor are aware of their importance and that the flashing is integrated properly into the siding, roofing, and gutters. An installation mistake can cause a leak or even channel rain into the walls or roof. The design professional must visually verify during a site visit that the flashing was installed and appears to be functioning correctly. The home energy rater might also check the flashing later and might catch a problem that occurred later in construction (e.g., if a careless worker installing cable television wire punctured the flashing, allowing water to enter).

Testing

Many dwelling features that are relevant to IAQ can be assessed with observation and documentation alone. However, some features also need to be tested to determine whether they function correctly. Recommended tests for dwellings that have the applicable systems are described below. Additional detail can be found in ASHRAE Guideline 24 (ASHRAE 2015a).

Combustion safety. This testing determines whether flue gases from combustion appliances have unacceptable spillage, which can lead to carbon monoxide poisoning or excessive humidity. These tests are most applicable to existing dwellings that have atmospherically vented gas appliances (not recommended in this guide for new dwellings) and are discussed in more detail in Strategy 6.1.

Figure 1.4-B Blower Door Test Setup

Dwelling unit airtightness ("blower door test"). The ACH50 test characterizes the dwelling's relative airtightness at a pressure much higher than in normal weather conditions to minimize the effects of weather on the day of the test. This allows test results from different dwellings to be compared to one another.

A calibrated, variable-speed fan is placed in an exterior doorway, and it pressurizes or depressurizes the dwelling to a standard pressure (usually 50 Pa) to determine the airtightness of the building enclosure (Figure 1.4-B). The airflow required to achieve this pressure is measured in CFM or $l/min/m^2$. This result is often normalized by the dwelling's volume (air changes per hour at 50 Pa, referred to as ACH50) or surface area (referred to as $CFM50/ft^2$ or $l/min/m^2$ at 50 Pa) and compared to a benchmark, such as in the building code or the requirements of an above-code program. Smoke bottles or infrared scanners can be used in combination with blower door tests to find air leaks, and leaks can often be felt manually. The leakier the building is, the more airflow is necessary to achieve the target pressure difference.

Knowing that a building will be tested when construction is complete and that the building must pass a blower door test encourages contractors to pay attention to air sealing. This is important because by the time the test can be conducted, many air leakage sites (e.g., those hidden behind finished walls and installed cabinets, and under attic insulation) are inaccessible.

For new buildings the recommended maximum allowable air leakage tested using a blower door varies by building type and climate. Climate Zones are shown in Figure 1.2-A. Dwellings should at least meet the airtightness standards of the 2015 International Energy Conservation Code (ICC 2015a) and 2018 International Residential Code (ICC 2018b); in jurisdictions that have adopted these Codes, this is a legal requirement. Tests are in accordance with American National Standards Institute (ANSI)/RESNET)/International Code Congress (ICC) Standard 380-2016 (RESNET 2016):

- For Climate Zones 1–2: 5 ACH50
- For Climate Zone 3: 5 ACH50 for multifamily dwellings covered by IECC and 3 ACH50 for all others
- For Climate Zones 4–8: 3 ACH50

New methods and materials have made it easier to air seal new buildings to tighter levels than those required by the ICC codes. Best practice airtightness is less than 3 ACH50. Some of the high-performance programs require buildings to be even tighter. For example, PHIUS requires

Figure 1.4-C Typical Airtightness Values

Figure 1.4-C shows various levels of dwelling airtightness measured in ACH50. The numbers in the figure are air changes at the test condition when forced by a fan and are much higher than those in normal weather conditions.

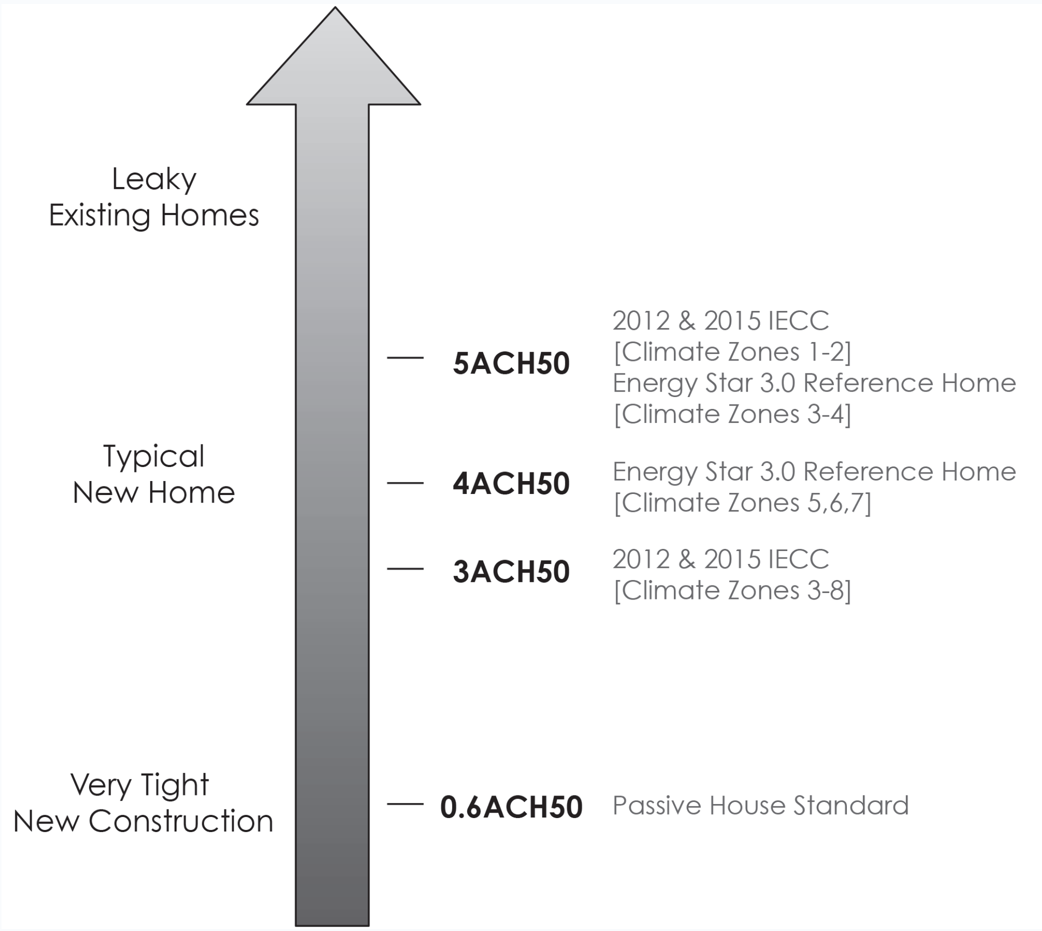


Figure 1.4-C Typical Airtightness Values

the building to be sealed to 0.6 ACH50 or less (PHIUS 2015) and the R-2000 Canadian standard requires air sealing to 1.5 ACH50 (NRC 2012).

There are different ways to calculate the airtightness of a dwelling based on a blower door test. Blower door tests do not predict the infiltration rate under real world conditions, and the infiltration rate varies with outdoor conditions. Nevertheless, if a blower door test is performed, it can be used to reduce the amount of mechanical ventilation air that ASHRAE requires (Strategy 7.1; ASHRAE 2016a).

Dwelling units in multifamily buildings should also meet the ENERGY STAR Multifamily High Rise Program's compartmentalization (sealing dwelling units from each other and from common areas)

airtightness target of 0.30 CFM50/ft^2 (91.4 L/s/m^2 at 50 Pa) based on enclosure area (ENERGY STAR 2015).

Multifamily buildings with at least four stories should meet ASHRAE Standard 189.1 (ASHRAE 2017f) with an airtightness target of 0.25 CFM75/ft^2 (76.2L/s-m^2 at 75 Pa) based on enclosure area when tested in accordance with the Air Barrier Association of America Standard Method for Building Enclosure Airtightness Compliance Testing or equivalent (ABAA 2016, DOD 2014).

It is typically much easier to air seal dwellings when they are being built than to seal them after they are completed and filled with people and their belongings. This guide recommends deferring air sealing of existing dwellings until a decision is made to undergo major renovations and additions or improvements are undertaken to improve comfort, reduce fuel cost and to solve IAQ problems. For example, air sealing might help solve condensation problems in both cold climates and hot, humid climates, keep pests out, and isolate garages from the living space. See Strategies 3.5 and 3.6.

In such cases, this guide recommends:

When a renovation includes removing the exterior siding and roofing, or interior wall and ceiling cavities are gutted, meet new dwelling airtightness standards.

For new additions, meet the new dwelling airtightness recommendations. Additions can sometimes be tested independently of the existing house.

For occupied houses measure the airtightness before air sealing efforts begin and after they have been completed. Aim to reduce air leakage by 30%. The US Department of Energy has resources that describe methods for finding and sealing air leaks in existing houses (Energy.gov 2018).

Duct system airtightness. To test the airtightness of the duct system, a small fan is connected to each duct system in the dwelling, and all supply and return vents are sealed. The duct system is pressurized or depressurized to a standard pressure (usually 0.1 in. w.g. [25 Pa]) to determine its airtightness. The result is then typically normalized to the floor area served by the duct system and reported in CFM25/ft^2 (L/min/m^2 at 25 Pa). If the duct system is tested while a door or window is open, the test measures the total duct leakage, including all duct leakage inside and outside the building enclosure.

A second type of duct test, in which the duct system and the house are simultaneously pressurized to the same pressure, should also be performed. The duct leakage measured using this test represents only the leakage outside the building enclosure, also known as the *duct leakage to outdoors*. The duct leakage to outdoors is the most important measure of energy efficiency and the interaction between the duct system and unconditioned crawlspaces, garages, attics, and other spaces whose air might be undesirable. Total duct leakage can also affect IAQ, because large leaks in the system can influence the pressure balance of the house, causing combustion safety problems or increasing infiltration (uncontrolled inward leakage of air through cracks and interstices in any building element and around windows and doors; discussed in more detail in Strategy 6.3).

The results of a duct airtightness test can vary significantly depending on when the test is performed. Most building codes or above-code programs specify when the test can be performed. These programs might have different airtightness requirements for tests performed at different phases of construction. Typically, ducts are tested during one of the following three phases:

- *Before AHU installation*: Sections of duct are tested immediately after installation and before the AHU is installed. This testing can be useful to find leaks before they are covered up by drywall, but it does not identify leakage related to the AHU or gaps between the duct boots (ends of sections of duct that penetrate the drywall or subfloor and to which the grille is attached) and the drywall or flooring. Because these gaps are significant sources of leakage in duct systems, this guide recommends using this method of testing only as a preliminary check and performing another test later in the construction phase.

- *Rough-in testing*: Testing of the complete duct system is performed with the AHU installed but before the finished flooring or drywall is installed. Testing at this stage includes leakage related to the AHU, but it still leaves out leakage related to gaps between the duct boots and drywall or flooring and incidental leakage from subsequent damage to ducts.

- *Final testing*: The duct system is tested when construction is complete, finished flooring and drywall have been installed, and the supply and return grilles have been installed. This method provides the best evaluation of the final system airtightness, but some sources of duct leakage might be inaccessible at this phase.

Various codes and above-code programs set maximum allowable duct system leakage rates by building type. For new ductwork and AHUs in low-rise houses and multifamily dwellings, this guide recommends meeting either the requirements of the 2015 IECC (ICC 2015a) or those of the ENERGY STAR New Homes program. Tests should be performed in accordance with ANSI/RESNET/ICC Standard 380-2016 (RESNET 2016):

- 2015 IECC (ICC 2015a):
  - *Total duct leakage before installation of AHU:* less than 3 CFM25 per 100 ft^2 (85 L/min per 9.29 m^2) of conditioned floor area (CFA) or
  - *Total duct leakage including the AHU at rough-in or final:* less than 4 CFM25 per 100 ft^2 (113 L/min per 9.29 m^2) of CFA

- ENERGY STAR New Homes program, version 3 (EPA 2017f):
  - *Total duct leakage measured at rough-in:* Less than 4 CFM25 per 100 ft^2 (113 L/min per 9.29 m^2) of CFA (with an alternate upper limit of 40 CFM25 [1,132 L/min] for small dwellings), with an AHU and all ducts, building cavities used as ducts, and duct boots installed. In addition, all duct boots must be sealed to the finished surface and verified by the rater upon completion of construction.

  or
  - *Total duct leakage measured at completion of construction:* Less than 8 CFM25 per 100 ft^2 (227 L/min per 9.29 m^2) of CFA (80 CFM [2,265 L/min] upper limit allowed for small dwellings), with the AHU and all ducts, building cavities used as ducts, duct boots, and register grilles on top of the finished surface (e.g., drywall or floor) installed

  and
  - *Duct leakage to outdoors:* Less than 4 CFM25 per 100 ft^2 (113 L/min per 9.29 m^2) of CFA (40 CFM25 [1,132 L/min] upper limit allowed for small dwellings)

Strategy 1.4 Observe, Verify, and Test Dwelling Construction

1.4

New ductwork systems in multifamily dwellings with at least four stories must meet the airtightness standards required by ENERGY STAR Multifamily High Rise Program's testing and verification protocols (ENERGY STAR 2015):

- *Total duct leakage measured at rough-in:* Less than 4 CFM25 per 100 ft^2 (113 L/min per 9.29 m^2) of CFA with all ducts installed

- *Total duct leakage measured at completion of construction:* Less than 8 CFM25 per 100 ft^2 (227 L/min per 9.29 m^2) of CFA

Supply air duct and register balancing. Best practice air handling system design results in air flow to each supply air grille that is reasonably close to the room by room needs for comfort and air quality. Many systems have levers at the supply air grille, and some have them in the duct leading to the grille, that can be used to adjust airflow to compensate for variations in duct installation and the way that occupants use rooms. For many systems, adjustment of room by room air flow by occupants is sufficient. If this does not achieve comfort, airflow to each supply can be measured and adjusted by the HVAC installer or a HERS rater. This process is called "air balancing" and many systems will benefit from it.

Controls and airflows for local exhaust. Although a simple go/no-go test can be done by finding out whether the exhaust grille holds toilet paper against its surface when it is operating, local exhaust should be measured using a flow hood to demonstrate that it delivers at least the rate prescribed in Strategy 6.2. If the exhaust grille won't even hold toilet paper against its surface, it is certainly not working. If special controls have been installed (e.g., timers, humidity controls, or occupancy sensors), whether they work as intended should be verified. Verify not just that enough exhaust air leaves the room but that it is exhausted all the way to outside the dwelling.

Whole-dwelling ventilation. Airflows at inlets and outlets should be measured using a flow hood, airflow resistance device, flow grid, or bag inflation method to verify that they meet the targets in Strategy 7.1. Care should be taken to use devices only for the applications for which they are intended; for example, many airflow resistance devices are designed only to measure exhaust air. Proper operation of controls should also be verified.

Closed door pressure. With the AHU fan on and interior doors closed, the pressure should be measured between the bedrooms and the hallway or main living space. The ENERGY STAR New Homes program (EPA 2017f) recommends that this pressure differential be less than 3 Pa.

Refrigerant charge testing. An HVAC technician who is licensed to work with refrigerants must perform this test (ACCA 2018b). However, the home energy rater or general contractor should ask for a copy of the results to verify that the test was conducted (RESNET 2016).

Indoor contaminants. Sampling for indoor air contaminants should only be done in certain situations. For example, if a public health maximum allowable standard or action level has been established for a contaminant, the sample methods and interpretation are defined by the applicable public health agency. This is most commonly done for radon (Strategy 3.3), a contaminant for which the EPA has established indoor guideline thresholds. The EPA has also established standards for lead in dust, soil, and paint.

Indoor contaminants should only be measured if the result can be interpreted and used to make decisions about the design, construction, or operation of the dwelling and HVAC systems.

Multifamily buildings. Multifamily buildings have some additional considerations. For those that will be professionally managed or have multiple units on more than one floor, a commissioning process of both the mechanical systems (ASHRAE 2013b) and the building enclosure is advisable (ASHRAE 2017f; ENERGY STAR 2015; ASHRAE 2017b).

Multifamily blower door tests should be conducted to verify that each dwelling unit is sealed from the outdoors, neighboring units, and common spaces (e.g., corridors). Each unit should meet the ASHRAE 62.2 and ENERGY STAR Multifamily High Rise Program's compartmentalization (sealing of each dwelling unit in a multifamily building so that they are separated from each other, utility chases, and common areas) airtightness target of 0.30 CFM50/ft^2 (91.4 L/min/m^2) enclosure (ASHRAE 2016b; ENERGY STAR 2015).

Strategy 1.5 Effectively Operate and Maintain the Dwelling to Maximize IAQ

1.5

Introduction

Operation and maintenance (O&M) can have as great an effect on IAQ as design and construction. The other objectives and strategies in this guide include detailed steps to achieve a healthy indoor environment; this strategy focuses on maintaining one.

Effective dwelling operation and maintenance to maximize IAQ requires the following actions:

- Do not smoke in or near your dwelling or anyone else's.
- Keep the dwelling dry. Promptly correct moisture problems, including roof or wall leaks, damp basements or crawlspaces, or visible biological growth.
- Keep the dwelling clean and pest free while minimizing the use of cleaning chemicals and pesticides.
- Maintain the HVAC system and keep the outdoor air whole-dwelling ventilation running.
- Run the kitchen exhaust fan during cooking, run the bathroom exhaust fan during showering, and make sure that these fans release the exhaust air to the outside.

Some Important O&M Actions

The most important actions occupants can take to maintain the dwelling and its systems are described in this section.

Dwellings need to be ventilated, so occupants should turn the mechanical ventilation system on if their dwelling has one. They should also check the written instructions from the installer and avoid readjusting the ventilation, including timed or cycled systems, unless they know what they are doing. If the ventilation seems to be too high or too low, occupants should ask a professional to recalculate the ventilation rate and make sure that the system has the capacity to condition any added outside air. For more information, see Strategy 7.1.

If a dwelling has signs of moisture, condensation, or biological growth, occupants should address the issue as quickly as possible. These problems are often easy and inexpensive to fix if they are addressed right away, but they can become expensive if they are ignored. Objective 2 and Strategy 4.2 provide additional guidance on addressing various moisture problems.

Additional actions to maintain the dwelling and its systems include the following:

- See the "HVAC System Maintenance" section below for more details on maintaining the HVAC system.

- Operate range exhaust fans and bath exhaust fans regularly (Strategy 6.2). Bath exhaust fans should continue to run for 15-20 minutes after each shower ends. Verify not just that enough exhaust air leaves the room but that it is exhausted all the way to outside the dwelling.

- Control pests without polluting the dwelling (Strategy 3.5).

- Clean the dwelling regularly (including vacuum cleaning) without adding cleaning-related contaminants (Strategy 5.3).

- Do not allow anyone to smoke indoors, especially where others are exposed to secondhand smoke. A large body of evidence has shown the harm this can cause (DHHS 2006). The relatively new practice of "vaping" with electronic nicotine delivery systems

has been studied less extensively, but it should not be done indoors because secondhand e-cigarette aerosol has been found to contain at least ten chemicals that are known to cause cancer, birth defects, or other reproductive harm (Chapman 2018).

- Instead of using air fresheners, occupants should find and address odor sources. Fresheners have many ingredients, and manufacturers do not disclose most of them. So-called natural or organic ones, including "essential oils" are unregulated and unmonitored and are not necessarily better (Steinemann 2016).

- The traditional practice of airing out bedding each morning might help to reduce the risk of dust mites and other moisture-related allergy and asthma triggers. Occupants who wake up with symptoms should change their bedding more frequently.

The National Center for Healthy Housing has published a brief yet comprehensive guide to seasonal maintenance activities in dwellings (NCHH 2009).

Asthma and Allergies

In dwellings in which occupants have allergies to outdoor sources, such as pollen, the windows should be closed during the season in which occupants are affected, filtration systems should be run, and the level of filtration should be increased (Strategy 7.2). Asthma, Allergy and Immunology experts provide additional recommendations, including about carpets, pets, and weekly washing of bedding in hot water (AAAAI 2017, Portnoy 2013). Caution should be used in implementing the academy's recommendation to use hot water (130°F or 54°C) for laundry because of the scalding risk. A guide on the shared roles of landlords and tenants is available from the National Center for Healthy Housing (NCHH 2017).

HVAC System Maintenance

Most occupants of single-family dwellings should consider buying an HVAC maintenance contract from a qualified company because this provides peace of mind that maintenance will be done properly, service calls will receive high priority, and a reliable relationship is in place when it is time to upgrade or replace a system. An airtight and properly functioning HVAC system reliably heats and cools the dwelling year after year, and often requires only preventive maintenance.

For those that can tolerate receiving lower priority for repair requests, doing without a contract is reasonable, but only if they also have the skill, willingness, and discipline to perform some of the regular tasks described in this strategy. In addition, they need to call a professional at the first sign of trouble that goes beyond their abilities.

Different levels of contracts are available. Some include only preventive maintenance tasks and no repairs, whereas others include some repair costs, perhaps for parts but not labor. So-called "full maintenance" contracts include almost all parts and labor costs but might be only be in effect for a limited time. Of course, the more that a contract covers, the highest the cost, but the risk of unexpected expenses will be lower. Occupants should read the contract and use referrals and the discussion below to evaluate both the company and the contract. Some referral services

receive income from service providers, which could affect their objectivity. In some areas of the country, nonprofit consumer organizations, such as Consumer's Checkbook, provide unbiased noncommercial evaluations of service providers.

The Air Conditioning Contractors of America (ACCA) has published an exhaustive list of the types of maintenance required for each type of HVAC equipment (ACCA 2013). This list can form the basis of a high-end maintenance contract; however, less extensive programs can also be effective. Although the ACCA does not recommend specific maintenance frequencies, it does state that annual or semiannual checks are likely to be important. Some tasks might be required less frequently.

Consumer Reports recommends that occupants perform the following once a year (Consumer Reports 2017):

- Clean and flush the coils.
- Check and clean the drain pan and its pipe.
- Vacuum clean the blower compartments.
- Change all filters (this guide recommends doing so three to four times per year).

Additional recommendations are to:

- Clear leaves and debris from the outside condensing unit.
- Check and clean the outside air intake (if the dwelling has one).

The following is a brief description of selected HVAC maintenance activities to help occupants understand what technicians should do. For the few occupants who want to try some of these activities, some do-it-yourself websites and videos might be helpful.

Clean and flush the coils. Air conditioning systems have two types of coils: the evaporator coil inside the dwelling (at the furnace or AHU), and the condenser coil in the outside unit. Both coils need cleaning to keep the building comfortable for occupants while preserving energy efficiency and should be cleaned whenever dirt has built up. Do-it-yourself home centers sell cleaning fluids for this purpose, and users should follow the instructions on the product. Some of these products are not suitable for use on indoor coils.

Another reason to clean the evaporator coil is to reduce the opportunity for biological growth. The evaporator coil in most climates becomes wet (Strategy 4.1), and the first defense against biological growth is to keep it clean. Cleaning once per year is generally recommended, but less frequent cleaning might be appropriate with improved filtration, particularly in dry climates.

The condenser coil needs cleaning because it has no filters and is exposed to outside materials, such as leaves and dust. Once-yearly cleaning is generally recommended, but more frequent cleaning might be needed, such as when leaves or other plant matter are prevalent. Leaves and debris should be cleared from the outside condensing unit, not because the debris will enter

the dwelling, but to keep temperatures inside the dwelling comfortable and to maximize efficiency. The coil and the area around it should be washed with care so that the water stream does not bend the coil fins.

Check and clean the condensate pan and its drain. The condensate pan collects the water that the cold coil removes from the air. Because the pan is often wet and can collect dirt, biological growth may occur. The condensate pan should be accessible so that dirt and sludge can be cleaned. Minor corrosion is acceptable as long as it does not lead to leakage. If water droplets on the coil are blown off by fast moving air, this should be corrected (see Strategies 4.1 and 4.3). The drainpipe might need to be cleaned out with a utility wet/dry vacuum cleaner (see sidebar).

Change all filters. This guide recommends changing the filters, including in energy recovery and heat recovery units, three to four times per year. The filters should be replaced with ones that are at least as good and consider using better ones (see Strategy 7.2).

Vacuum clean the blower compartments. The blower power must be turned off before this is done! After the blower is opened up the panels are removed, the inside is vacuum cleaned and the blower condition checked.

Check and clean the outside air intake (if the dwelling has one). See Strategy 3.2.

Check the refrigerant charge on the air conditioning system and tune the gas furnace. This generally requires a licensed technician; however, see the text box Signs of Acceptable HVAC System Performance. The ACCA guide recommends using temperature performance as an indicator of the proper charge. Unusual noise and vibration can indicate improper mechanical function.

When a problem does arise, checking the charge requires measuring pressures inside the system using specialized equipment (a manifold gauge set). The U.S. Clean Air Act requires this to be done by a certified technician. If a leak is found, Clean Air Act rules require repairs of leaks of more than 15% per year (EPA 2017p).

Checking combustion on a gas furnace can require specialized instruments, but many of the tasks in the ACCA guide for licensed technicians consist of simple observations (ACCA 2013). For example, the ACCA recommends observing the physical condition of the equipment, burner, heat exchanger

How to Unclog a Condensate Pan Drainpipe

Drainpipes from condensate drain pans are almost guaranteed to clog but are easy to unclog. Like plumbing drains, condensate drains have P traps, which seal the pipe so that air does not blow out. When water containing organic matter from the air sits in the drain, the traps become clogged with biological growth. A condensate drain can be unclogged by sucking air from the drain outlet using a utility wet/dry vacuum cleaner without needing to open the cabinet of the AHU or furnace. It is possible to buy or make a fitting to make a tight seal. For those who are not squeamish, this can be done using one's hand to form a nice, tight seal around the vacuum cleaner's hose and sucking air from the end of the pipe.

Signs of Acceptable HVAC System Performance

An HVAC system's performance in maintaining comfort is a good indication that the refrigerant charge, combustion, and other functions are acceptable. Many HVAC systems do not need a recharge or combustion check for years, and modern systems often have multiple automatic safety checks in the combustion system and its controls. Some of the simple tasks of preventive maintenance, such as cleaning and changing filters, do not require a license and can be done by handy occupants.

and its operation through a heating cycle, heat output, burner view port for igniter glow, and blue flame. Occupants who wish to make these observations without consulting a technician should check the requirements in the owner's manual. Occupants can also make sure that the flue pipe is clear outside the dwelling.

Professionally Managed Multifamily Buildings

Professional managers of multifamily buildings have responsibilities similar to those of operators of commercial or institutional HVAC systems, as described in Strategy 1.5 (ASHRAE 2009) and Standard 170 (ASHRAE 2017c).

Some systems have never worked properly from day one because of design or installation problems, or stopped functioning well due to age, incomplete maintenance, or changes to the building or its systems that were not well-thought out. Solutions to these conditions are retro-commissioning, for buildings that have never been commissioned; and re-commissioning, for buildings that were once commissioned. Both are versions of the commissioning process used for existing buildings (Strategy 1.4).

Involuntary exposure to secondhand smoke can be reduced, but not eliminated, by modifying existing, occupied multiunit buildings (Bohac et al. 2011). Multifamily buildings should prohibit indoor smoking, which is the only way to effectively control contaminant transfer to other units, especially in public housing units (Arku et al. 2015). Multifamily buildings that are four or more stories above grade are covered by ASHRAE Standard 189.1 (ASHRAE 2017f), which does not allow smoking inside or within 25 ft (7.5 m) of entrances and requires signage stating this policy at each entrance. An increasing number of jurisdictions are adopting this standard or the related Green Construction Code (ICC 2015b).

Emerging Technology: Low-Cost IAQ Monitors

Occupants are more aware of IAQ in their dwellings and what they can do to improve it. Inexpensive devices are proliferating with claims that they can measure indoor pollutants, such as VOCs, fine particulate matter (with a diameter of 2.5 µm or less [$PM_{2.5}$]), and carbon dioxide. The accuracy of the devices is untested, and reliable instruments cost many times more than these devices. Also, these devices can give occupants a false sense of security. For example, a device might indicate that the overall VOC level is low but not that the level of a specific compound, such as formaldehyde, is of concern. Furthermore, some of the information these devices provide, such as that the carbon dioxide level is low, means little if anything for IAQ in dwellings due to their low occupant density. Dwellings need to be ventilated for both occupancy and building materials, and reliance of carbon dioxide data (commonly used as an indicator of occupancy in commercial buildings), might lead to under-ventilation. Finally, most of these devices provide no information about potential moisture problems. For a discussion of inexpensive types of real-time monitoring that can help occupants to identify serious moisture problems, see Strategy 2.2.

Accurate information about outdoor air is available elsewhere (EPA 2017d). Occupants who want to make their own measurements using one of these inexpensive monitors indoors or outdoors should be aware of the limitations of inexpensive sensors beyond those discussed above (EPA 2017a).

These inexpensive devices do have some potential benefits, however. For example, they might increase awareness of high-polluting activities. Their results could also be used to guide activities that occupants should or should not do in the dwelling. For example, the particle reading might increase dramatically during cooking, which could motivate occupants to use the range fan when cooking. However, users need to understand that the values reported by these devices are not necessarily accurate and take the manufacturer's recommendations about what is a good or bad level with a grain of salt.

Objective 2

MANAGE MOISTURE

The strategies in Objective 2 address ways to control moisture and avoid mold and other effects of excessive moisture:

Strategy 2.1 Avoid Water Penetration and Moisture Problems in the Enclosure discusses strategies to control water drainage and seepage in roofs, above-grade walls, and foundation walls and floors as well as condensation in the exterior enclosure (including management of air leakage, surface temperature, drying potential, and vapor diffusion).

Strategy 2.2 Control Indoor Humidity describes approaches to maintain indoor humidity levels that reduce the potential for moisture problems

Strategy 2.3 Select Suitable Materials, Equipment, and Assemblies for Unavoidably Wet Areas covers selection of materials to avoid moisture problems in rooms that are likely to become wet during normal use (e.g., bathrooms, kitchens, and entryways)

Strategy 2.4 Manage Effects of Landscaping and Indoor Plants describes ways to control moisture and contaminants from outdoor landscaping and indoor plants.

Other important strategies related to moisture control are discussed in the following sections:

- Strategy 3.6 – Control Entry of Contaminants from Unoccupied Spaces
- Strategy 6.2 – Provide Local Capture and Exhaust for Point Sources of Contaminants

Objective 2

MANAGE MOISTURE

Striking the right balance between the extremes of no action on moisture in dwellings and avoiding overconcern is important. The popular press uses the term "toxic mold" to generate attention, but there are good reasons to remain calm when a dwelling has too much moisture. If an occupant finds biological growth in the dwelling in the middle of the night, he or she can wait until the next morning to contact someone to mitigate the cause. However, the resident should not wait to call someone until the problem gets worse.

The Three States of Matter

Remember your high-school physics? All matter has three different physical forms at different temperatures: solid, liquid, and gas. For water, these three forms are known as ice, water, and water vapor.

Wetting or moisture problems can result in:

- Colonization of materials by mold (e.g., cladosporium, aspergillus, and penicillium, which are found indoors in urban, suburban, and rural locations throughout the United States), wood-decaying fungi, algae, bacteria, or moss

- Corrosion of metals because of chemical reactions with water

- Transport of water-soluble compounds that appear as stains, or a white deposit that has a salty color and texture or causes the surface of the brick or stone to flake off (the technical terms are efflorescence, and subflorescence)

- Warping of wood or wood-based materials

- Delamination of coatings and composite materials (e.g., peeling paints, varnishes, stucco, plywood, oriented strand board [OSB; engineered wood product formed by the addition of adhesives and compressing layers of wood strands or flakes in specific orientations], laminated cabinets and shelves, adhered flooring, wallpaper, and roofing)

Clean rainwater does not carry much contamination. If materials become wet from a rain leak and the wet materials are quickly dried, no contamination will need to be cleaned up. However, if those materials remain wet for several days, they will become more contaminated. Mold and bacteria will colonize the materials, and the biological contamination will need to be removed.

In some flood conditions, river water becomes contaminated by sewage, fuel oil, or industrial pollution that has been swept up by the flood water (CDC 2017). Contaminated water in buildings is usually the result of poorly managed rainwater, plumbing leaks, condensation, or a rising water table. The amount of damage and which cleaning, decontamination, and restoration efforts are needed depend on the nature of the contaminated water, the moisture sensitivity of the wet materials, and how long the materials have been wet.

Some moisture is released inside dwellings from human sweat and such activities as cooking and bathing. When the weather is humid, ventilation air and the building enclosure introduce some outside air humidity into the dwelling. Moisture inside dwellings should not be allowed to build up

to unacceptable levels. In some locations, such as basements, controlling the indoor humidity level is a practical means to avoid moisture problems.

Indoor and outdoor plants can also be sources of moisture in a dwelling. Practices to prevent or reduce plant-related moisture include smart placement of outdoor landscaping and avoidance of overwatering or excessive amounts of houseplants. Plants have aesthetic, shade, and food value, but they do not improve IAQ, despite claims to the contrary that are common on the Internet.

Air is another moisture source in dwellings. Air is a mixture that always contains some water vapor. As moist air is cooled to a low enough temperature, it becomes saturated (100% RH) and some of the water vapor condenses (becomes liquid). The temperature at which this happens is called the dew point, and condensation occurs on surfaces that are cooler than the dew point of the surrounding air. This dew can be seen, for example, on the outside of a cold drinking glass on a warm humid day. Two strategies to prevent condensation are limiting high indoor humidity, which is discussed in strategy 2.2, and eliminating cold surfaces, which is discussed in Strategies 2.1 and 4.2

Moisture is not a contaminant but, rather, a nutrient that contaminants use to proliferate. Some humidity is necessary in a dwelling's air and building materials. But if moisture is present in a dwelling in a form and quantity that allows fungal, microbial, and other biological growth to flourish, it becomes a problem. It is therefore important to manage moisture to keep these populations in check.

Strategy 2.1 Avoid Water Penetration and Moisture Problems in the Enclosure

2.1

Introduction

Rain, snowmelt, surface water that pools near or against foundations, and below-grade water are outdoor sources of water that can cause moisture problems if the water enters the building. Most below-grade water leaks result from poorly managed rainwater rather than a rising water table.

Steps to prevent water and moisture from penetrating the enclosure are as follows:

- Protect the dwelling from rain, snow melt, surface and below-grade water.
- Use water-resistant membrane under roofing and siding materials to stop the water.
- Use flashing to drain the water back out.
- Use materials in the roof, ceilings, exterior walls, foundation walls, floors, and windows to prevent condensation on and water within the materials.

Weatherproofing Features of the Building Enclosure

Siding and roofing are the first lines of defense against rain, snow, sleet, and snowmelt. Most of the rain that hits them is drained away from the house. Siding is made from materials that can tolerate moisture. These horizontal or vertical boards can be made of wood, wood composites, fiber cement, vinyl, aluminum, brick, stone, or decorative concrete masonry units.

Under the siding and roofing, a water-resistant barrier keeps water that leaks through from reaching the sheathing, framing, insulation, and interior finishes. This membrane sheds water, does not let water wick through, and has drains at the bottom. The most common water barriers include asphalt-impregnated (tar) paper and synthetic house wraps that can be fastened; peel-and-stick membranes that can be fastened; and coatings that can be sprayed, brushed, or troweled onto plywood or OSB sheathing.

On sloped roofs, a backup water-resistant barrier protects the roof sheathing, rafters, and insulation from water that flows past the shingles or metal roof panels. Common examples of water-resistant barriers for roof systems, known as underlayment, are asphalt-impregnated paper, synthetic underlayment, and self-adhering water and ice protection membranes.

Windows and doors are manufactured assemblies. The glass, frames, and weather stripping form their own rain and air barriers. Many windows have internal drainage features to collect rain seepage and drain it away at the sills. Windows are flashed into the water-resistant barrier and siding so that water drains away from the walls.

Skylights are similar to windows in that they are flashed to the roofing and underlayment. Because they are on a sloped rather than vertical surface, skylights and associated flashing must withstand far more water than windows in walls.

The building enclosure separates the indoors from the outdoors using layers that provide the following:

- *Moisture barrier under the roof and siding:* The “raincoat and boots” that keeps water outside
- *Air barrier:* The “windbreaker” that keeps wind-driven outdoor air, which might contain moisture or particulate matter, out of the dwelling
- *Insulation:* The “sweater or jacket” that maintains indoor thermal conditions
- *Water vapor management*: The “breathability of clothing layers” requiring the permeability of each part of the building enclosure to be selected based on the climate to manage airborne water vapor within the enclosure and prevent condensation or allow it to dry quickly and appropriately

Foundations are made of materials, such as concrete or concrete masonry units, that can tolerate moisture without damage. Water-resistant membranes applied to the exteriors of foundations keep below-grade water from wicking through them. A vapor barrier placed under concrete slab floors prevents water from moving upward through the floor.

Rainwater Control, Air Barrier, and Insulation Systems

Figure 2.1-A illustrates the rainwater-control features of a single-story house with an insulated basement. A semitransparent, heavy blue line traces the rain-control layers from the roof peak to the eaves, wall and windows, foundation walls, and back to the center of the basement floor slab.

Rain control features. The rain-control features of the dwelling in Figure 2.1-A are as follows, starting from the peak of the roof:

- The roof shingles cover a ridge vent so that the attic is vented to the outdoors, but rain is kept out of the attic by the shingles, which form an "umbrella" on the top, and by baffles to help keep out wind-driven rain.

- The shingles and underlayment keep the roof sheathing, rafters, and insulation dry in the main field of the roof.

- At the bottom of the roof, a drip edge causes water to collect and drip, preventing water from wicking back into the roof sheathing or facia board.

- Soffit vents and baffles allow air into the vented attic.

- The wall is protected from rain by the siding and the weather-resistant barrier.

- A head flashing at the top of the window diverts water running down the front or back of the siding out of the wall to a drip edge at the top of the window. The flashing is lapped from above by the weather-resistant barrier.

- The window has its own rain protection and drainage built in at the factory.

- At the bottom of the wall, the weather-resistant barrier forms a drip edge behind the siding.

- Damp proofing or waterproofing on the foundation prevents water from wicking through the concrete block into the basement.

- Surface water drains away from the house on the sloped landscape or is drained to the footing drains by a below-grade drainage mat on the exterior of the damp-proofing layer.

- The top footing at the bottom of the foundation wall is coated with damp proofing to prevent water from wicking up into the foundation wall.

- A layer of coarse gravel covered by extruded styrene insulation prevents water from wicking up through the basement floor slab.

Air barrier. In addition to the rain-control layers in the roof, walls, and foundation, the enclosure needs an air barrier that extends around the entire building. The air barrier blocks the flow of air through the enclosure, just as a windbreaker does. This is important for energy efficiency, and it reduces the entry of outdoor particulate matter and moisture. Most of the water vapor that moves through the building enclosure travels with moving air, so this layer is an important part of moisture management.

The air barrier in Figure 2.1-A goes from the center of the ceiling to the center of the basement floor:

- The gypsum board taped at the seams and sealed at penetrations forms the ceiling air barrier.

- The gypsum board is sealed to the wall OSB sheathing with a layer of spray polyurethane foam.

- The wall OSB sheathing, sealed at the joints and penetrations with special air barrier tape, forms the wall air barrier.

- The wall air barrier wraps into the window opening, where it is connected to the window with sealant.

- At the bottom of the wall, the sheathing is sealed to the foundation coating with specialized tape.

- The foundation coating carries the air barrier to the footing, where the concrete block carries it to the vapor barrier under the floor slab.

Insulation. The primary function of the insulation layer is to maintain thermal conditions inside the enclosure, but it also has a role in moisture management. Well-insulated enclosures are less likely to have cold surfaces that can develop condensation.

The insulation in Figure 2.1-A starts from the center of the ceiling and wraps around the wall to the foundation as follows:

- Cellulose insulation above the ceiling gypsum board extends to the exterior wall, where a layer of spray polyurethane foam connects the cellulose to the wooden top plate of the wall, wall OSB sheathing, and layer of foam board insulation on the wall.

- The foam board insulation on the wall and fiberglass insulation between the wall studs carry the wall insulation to the floor.

- Windows in the wall are connected to the wall insulation with sealant and backer rod or canned polyurethane foam sealant.

Figure 2.1-A Materials that Control Rain and Condensation

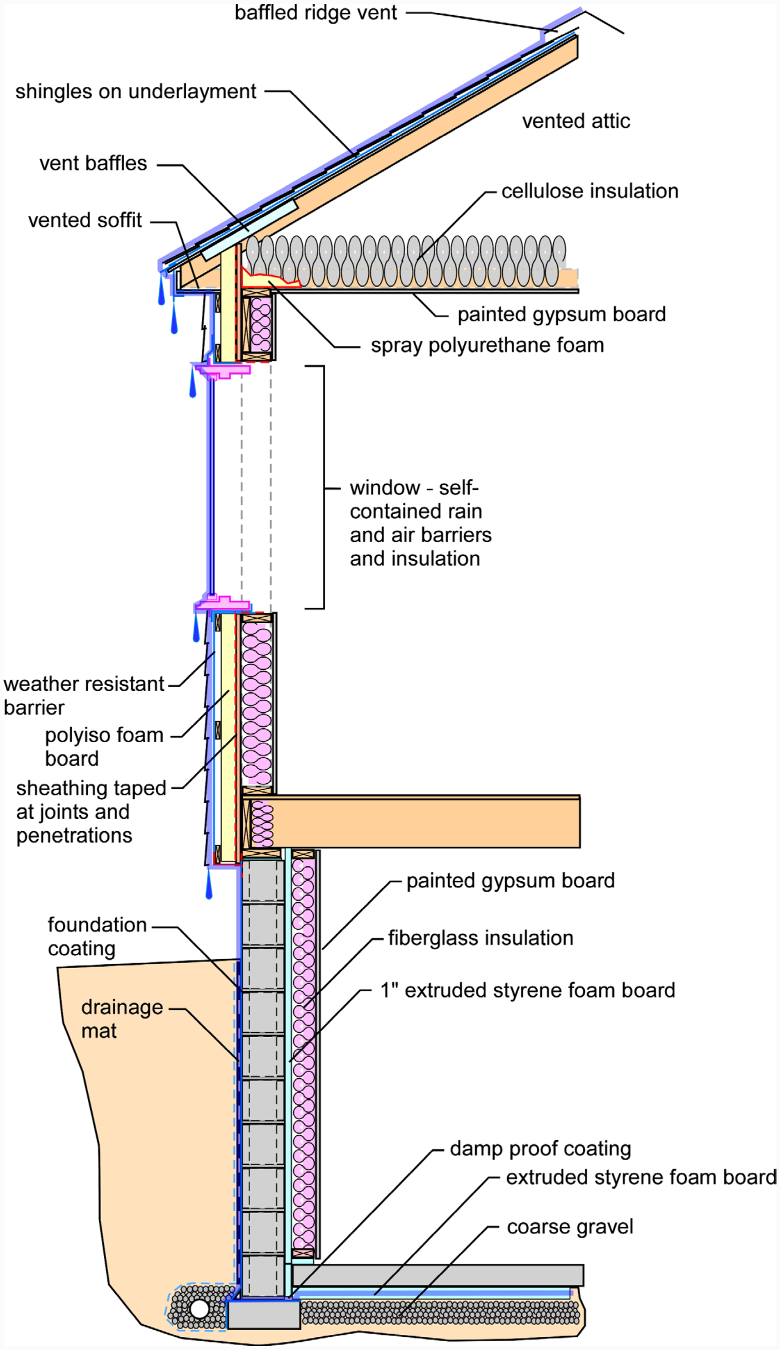


Figure 2.1-A House Section Showing Materials that Control Rain and Condensation

- The wall foam board is connected to an interior basement wall through the wall sheathing, the rim joist, and some interior fiberglass insulation.

- The basement wall is covered with an inch of continuous foam board insulation separating the foundation from an interior stud wall that has fiberglass insulation. The wall is finished with painted gypsum board. A half-inch layer of styrene foam board separates the bottom plate of the wall from the concrete floor.

- In cold climates, foam board insulation (not shown) can be placed under the basement slab floor.

Preventing Condensation and Water in Building Materials

The combination of materials selected for a wall, roof, or floor jointly prevent condensation on or within the enclosure. Water may also not be visible yet present in the pores of building materials, such as gypsum board. This water promotes biological growth (ASHRAE 2009). Indoor and outdoor air contain water molecules in vapor form. The humidity level is high when the air contains many water vapor molecules. Water vapor can become a moisture problem in the enclosure when it undergoes condensation on a cool surface. Condensation occurs on hidden surfaces within the enclosure when water vapor moving through the enclosure meets surfaces with temperatures that are lower than the dew point temperature of the air.

Water vapor migrates through the enclosure in two ways. The simplest (and most common) way is by being carried by air leaking through the enclosure from inside to outside or from outside to inside. The second way is by diffusion through vapor-permeable materials, or solid materials that are porous enough to let water vapor molecules move through them even though no air is moving through them, just as an exercise shirt can be designed to “wick” sweat away and dry quickly. Other building materials are vapor-impermeable, allowing very few water vapor molecules to pass through them—these materials perform a similar function to a raincoat made of plastic that does not breathe (is vapor impermeable). When this coat is worn, water vapor (sweat) can build up inside until the inner layer of the raincoat becomes damp.

Materials in the enclosure are cooled by heat loss to outdoor air during cold weather and by heat loss to the indoors when air conditioning is used in warm weather. Basement and crawlspace foundations are cooled by the surrounding earth year-round.

Water that migrates inward through the enclosure from warm humid outdoor air can form condensation when it contacts any cool surface. Water migrating outward through the enclosure from warm, humid, indoor air can condense on or within materials cooled by the cold outdoor air. The air on the warm side of the building assembly is almost always more humid, so designers can expect humidity to move from the warm side to the cool side of the enclosure.

Problems within walls, roofs, basements, or crawlspaces arise when enough water accumulates within or on the surface of a cool material to support corrosion or biological growth. Water in the enclosure can also allow carpenter ants or termites to establish colonies.

Because water vapor is primarily transported into building enclosures through air leakage, a continuous air barrier layer is important for limiting the development of condensation within the enclosure. Many air barrier materials also act as a backup water-resistant barrier, and some can also serve as insulation.

To address vapor permeance (the amount of water vapor that can pass through a solid building material driven by a difference in water vapor pressure) in building materials, the International Code Council has identified three vapor retarder classes based on the material's permeability to water vapor. In the United States, vapor permeance is measured in perms; materials with low perm ratings allow less water vapor to pass through. Vapor retarder class is defined using the desiccant method of ASTM E 96 as follows (ASTM 2016):

- Class I: Sheet polyethylene or nonperforated aluminum foil with a perm rating of 0.1 or less
- Class II: Kraft-faced fiberglass batts or paint with a perm rating of 0.1 to 1.0
- Class III: Latex or enamel paint with a perm rating of 1.0 to 10.0

Insulation, air barriers, and other enclosure materials must be layered in such a way as to limit condensation within vapor-permeable materials in the heating or cooling season. Many combinations of walls, roofs, and floor assemblies can manage the condensation of water vapor, but the approach must be tailored specifically to the climate. In climates where both heating and air conditioning are needed throughout the year, managing water vapor can be complicated because the building assembly needs to function in both conditions. Many resources provide in-depth information on vapor retarders and building assemblies (see, for example, Bliss 2006, Lstiburek 2009). Some methods are designed to keep water vapor out of the materials that make up the building enclosure entirely, whereas others allow condensation to occur sometimes, but they allow it to dry to the inside or outside quickly.

The three broad categories of techniques are as follows, and examples are included:

1. *Impermeable assemblies*: Most of the temperature variation within the wall, roof, or floor assembly occurs within materials that have a very low perm rating.
    - Example: Low-vapor permeance foam could be used as thermal insulation and serve as the air barrier system for a wall assembly through insulation of a wall, floor, or ceiling with closed-cell spray polyurethane foam. This type of assembly can prevent condensation from humidity in indoor or outdoor air.

2. Mixed permeance assemblies: A low-permeance layer of insulation is used on one side of the assembly (usually the outside) to manage condensation in one condition (usually cold outdoor weather), coupled with a higher-permeance layer of insulation (usually on the inside).
    - Example: A wall design uses low-permeance rigid foam board insulation on the outside and a high-permeance fiberglass or cellulose insulation between the studs (as shown in Figure 2.1-A). The guidance in the IECC (IECC 2015a) should be followed to determine the fraction of R-value (a measure of an insulation material's resistance to heat flow) required for the low-permeance foam insulation. If the R-value is not high enough, condensation can occur in the permeable layer. Low-permeance materials

should not be placed on both sides of a layer of porous, high-permeance insulation (e.g., fiberglass, mineral wool, cellulose, or open-cell spray polyurethane foam).

3. High-permeability assemblies: These assemblies must be carefully designed to shed water and function as continuous air barriers, even though they are made of vapor-permeable materials.
   - Example: The ceiling in Figure 2.1-A has a vented attic space between the insulated, airtight ceiling and the roof. The roof sheds water to prevent it from entering the enclosure. The sealed drywall has high vapor permeance, but it forms an air barrier. The cellulose insulation also has high vapor permeance, but it serves as insulation. In both summer and winter, some water vapor can condense within the cellulose insulation, but it can quickly dry to the outside or inside.

Preventing condensation is one of the most difficult aspects of building enclosure design. Many homeowners, contractors, and even design professionals can become confused or overwhelmed by this task for many reasons, including those listed below:

- What works well in one climate might lead to problems in another.
- No one “right answer” exists; multiple solutions can work well in a particular climate.
- Some materials perform multiple functions. For example, rigid foam board can serve as an air barrier, water-resistant layer, and insulation.
- Many dwellings use both heating and cooling at different times throughout the year. The moisture dynamics during heating and cooling are very different, but the building enclosure needs to function well in all conditions.
- The success of any enclosure system depends on attention to detail and workmanship.

Adding Moisture-Control Features to Existing Dwellings

In 2015, approximately 1.15 million new housing units were built in the United States, but the country has over 135 million existing dwelling units (FRED 2018; U.S. Census Bureau 2018). Most existing dwellings do not have all of the moisture-control features described above. Adding these features can be difficult and expensive. For example, if the builder has not used a water-resistant barrier under the siding, it is unlikely that one will be installed until the siding must be replaced or rain leaks must be repaired.

However, homeowner’s insurance might cover the costs of some repairs, particularly those resulting from sudden and accidental damage. Remodeling the dwelling (making changes to its construction and/or building systems), replacing the roof, installing new siding, or gutting and replacing the interior of the house provide a chance to implement some of the moisture control-methods for new houses listed above.

Steps to add moisture-control features in existing dwellings are as follows:

- Identify moisture problems that are damaging building materials, mechanical systems, or belongings.
- Identify methods to address the moisture source, repair damage, and clean biological growth if present (EPA 2013c).
- Estimate the cost of repairs and determine how to work safely around the occupants.
- Do the repairs that are feasible based on the amount of money available and occupants' tolerance for disruptions.

Resources

This guide is not an exhaustive resource on building enclosure design. Instead, the principles discussed here can be kept in mind and the resources listed below consulted to select an enclosure design with the required features for a given climate. These sources provide well-thought-through details that are appropriate in North American climates on integrating condensation control, air barrier systems, and insulation to avoid condensation and moisture in new and existing construction.

For low-rise residential new construction:

- Bliss, S. 2006. Best Practices Guide to Residential Construction, Materials, Finishes, and Details. Hoboken, NJ: John Wiley & Sons.
- Lstiburek, J. 2004. Builder's Guide to Hot-Dry & Mixed-Dry Climates. Westford, Massachusetts: Building Science Corporation.
- Lstiburek, J. 2005. Builder's Guide to Hot-Humid Climates. Westford, Massachusetts: Building Science Corporation.
- Lstiburek, J. 2005. Builder's Guide to Mixed-Humid Climates. Westford, Massachusetts: Building Science Corporation.
- Lstiburek, J. 2006. Builder's Guide to Cold Climates. Westford, Massachusetts: Building Science Corporation.
- Lstiburek, J. 2009. Builder's Guide to Cold Climates. Westford, Massachusetts: Building Science Corporation.
- Lstiburek, J. 2009. Building Science Digest 012: Moisture Control for New Residential Buildings. Westford, Massachusetts: Building Science Corporation.
- EPA. 2017. Environmental Protection Agency. Indoor airPlus Technical Specification . https://www.epa.gov/indoorairplus/indoor-airplus-technical-guidance
- Energy Star. 2015. Water Management System Builder Requirements: ENERGY STAR Certified Homes, Version 3 / 3.1 (Rev. 08). https://www.energystar.gov/ia/partners/bldrs_lenders_raters/downloads/water_mgmt_sys_bldr_req.pdf?271c-2061

- Building codes, including the following:
- ICC. 2015. International Code Council. International Building Code. https://codes.iccsafe.org/public/document/toc/542
- ICC. 2018. International Code Council. International Residential Code https://www.iccsafe.org/codes-tech-support/codes/2018-i-codes/irc
- ICC. 2018. International Code Council. International Energy Conservation Code. https://www.iccsafe.org/codes-tech-support/codes/2018-i-codes/iecc

For new residential buildings with four stories or more and for commercial and institutional buildings:

- EPA. 2017. Environmental Protection Agency. Moisture control guidance in the design, construction and maintenance of commercial and institutional buildings. https://www.epa.gov/indoor-air-quality-iaq/moisture-control-guidance-building-design-construction-and-maintenance-0
- Straube, J. 2013. High Performance Building Enclosures. Westford, MA: Building Science Press.

For existing dwellings:

- EPA. 2014. Environmental Protection Agency. Healthy indoor environment protocols for home energy upgrades. https://www.epa.gov/sites/production/files/2014-12/documents/epa_retrofit_protocols.pdf
- Department of Energy. 2013. Standard work specifications for single-family home energy upgrades. https://sws.nrel.gov/sites/default/files/sws_singlefamily_0.pdf

Strategy 2.2 Control Indoor Humidity

Introduction

Indoor humidity control is important for maximizing health and comfort because high humidity and condensation levels can degrade materials and support biological contamination, including mold. High humidity levels also support dust mite populations, which are allergens. At the same time, low humidity levels can be detrimental to health because they can dry out mucous membranes and promote disease transmission (ASHRAE 2017d). Physicians sometimes suggest use of a humidifier when an occupant has asthma or other respiratory conditions. Humidity levels also affect perceptions of IAQ (see strategy 8.4).

All indoor and outdoor air contains water vapor. Indoor humidity control means keeping the relative humidity (RH) in a range that is not so low that it causes discomfort and other problems for the occupants without being high enough to allow condensation or biological growth.

Visible and Invisible Condensation

Condensation can form on hidden surfaces even when the RH level in the middle of the room is below 100%. Furthermore, the RH level near walls can be higher than that in the middle of the room, which can lead to the presence of water that is not visible in the pores of building materials, such as gypsum board. This water promotes biological growth (ASHRAE 2009).

Even the surface of an insulated air conditioning duct can be cool enough to develop condensation or moisture problems. Condensation can also form on cold water supply pipes carrying water at approximately the local ground temperature (see Strategy 4.2).

For these reasons, experts often recommend a maximum of 65% RH when a dwelling is being cooled, a level that is required in nonresidential building standards (ASHRAE 2016a). In cold weather, wall and window surfaces become colder and indoor humidity must be even lower to prevent moisture problems (see discussion below).

High Humidity Levels

An early, if not the first line of defense against high humidity is to make sure that the bathroom and kitchen exhaust fans are working correctly and are used by the occupants (Strategy 6.2).

Contributors to the risk of high humidity include:

- Hot and humid climates, especially when the ventilation system does not adequately dehumidify outdoor air (Strategy 7.1) or when there are long periods of no conditioning (such as vacation homes that are shut down seasonally)

Do the following to control indoor humidity:

- Select multistage, variable speed, or modulating cooling systems with controls that have dehumidification capability.
- When the central cooling system cannot keep humidity at 65% or lower, add a dehumidifier.
- Promptly correct moisture problems, including roof or wall leaks, damp basements or crawlspaces, and visible biological growth.
- In the heating season, do not overhumidify the dwelling (see table 2.2-B for recommended levels).

- Rooms or areas where moisture flows through the enclosure, such as basement floors and walls (see Strategies 2.1 and 3.6 for ways to prevent outside moisture from seeping into the dwelling)

- Rooms or areas with large indoor moisture sources (such as indoor pools or heavily used kitchens and bathrooms), particularly if exhaust fans are not functioning optimally or the occupants do not use them

- Oversized cooling systems with excessive airflow, particularly with single-stage cooling (a compressor that is either on full blast or is shut off)

- Areas where large volumes of humid outdoor air enter the dwelling, such as near doors

- Dwellings with energy-efficient lighting and appliances that emit less dry heat, causing the air conditioning system to run less often

- Dwellings in humid climates with below-grade spaces

- Areas where moisture-producing activities (e.g., some hobbies, indoor laundry drying, and firewood drying) are performed and where unvented heaters, which also emit other contaminants (Strategy 6.1), are used

Dehumidification Limitations of Air Conditioning

Air conditioning systems remove moisture from the air as a byproduct of their operation. Dwellings in humid climates are usually air conditioned, which helps reduce indoor humidity and is often enough to prevent moisture-related problems. However, air-conditioning systems do not always provide enough dehumidification to eliminate humidity problems in dwellings.

Air-conditioning systems are designed to meet dwellings' needs for cooling at nearly peak conditions (when it is very hot and sunny outside). However, most of the time, dwellings need less cooling, and air-conditioning systems need a way to adjust to this "part-load" condition. Three broad categories of systems adapt in various ways:

- *Single stage systems*: Can only operate at full capacity or turn off. When operating under part-load conditions, they cycle on and off as needed to achieve the thermostat setting. These systems are common because they are the least expensive.

- *Dual-stage systems*: Can operate at full capacity, at lower capacity (usually about 70% of maximum), or turn off. They can therefore operate longer at lower capacity to meet part-load conditions. When a load is very low, however, they still cycle off periodically.

- *Multistage and variable-capacity systems*: Can operate at more than two distinct capacities or can modulate their capacity based on the dwelling's current need for cooling. They can thus operate continuously or nearly continuously in a wide variety of peak and part-load conditions. Because the equipment and controls are more complex, these systems are more expensive than the other types.

Air conditioners dehumidify the air because when it passes through the system and is cooled, it reaches its dew point, and moisture condenses out and is drained away. When systems cycle off in part-load conditions, they do not always provide enough dehumidification to keep indoor humidity within an acceptable range. Even when they successfully dehumidify the dwelling during each run cycle, moisture reevaporates from the cooling coil during the off cycle, raising indoor humidity levels.

Oversized systems exacerbate this problem because they have more part-load operation and longer off-cycle times. Single-stage systems are the most problematic because they have the longest “off” periods. Multistage or variable-capacity equipment can operate at a lower capacity when less cooling is needed, allowing the system to run longer and perform better dehumidification.

For new construction or system replacement, “right sizing” air-conditioning systems is an important way to maximize the system’s dehumidification. ASHRAE methods (ASHRAE 2017a) or ACCA Manual J load calculations (Rutkowski 2016) can be used to determine the cooling load (how much air conditioning a system needs to provide). ASHRAE’s residential guidance (ASHRAE 2015b) and ACCA Manual S (Rutkowski 2014) can be used to select “right-sized” equipment that matches the cooling load well and has longer run times. However, even a right-sized system operates only when the need for cooling demands it. When the humidity (latent) load is high and the dry heat (sensible) load is low, these systems do not provide dehumidification.

Air-conditioning system manufacturers have started to incorporate humidity control capability into their residential products, but choices of these products are limited. Some central HVAC systems are designed to maintain humidity by reducing fan speed and airflow, allowing the system to provide more dehumidification when it is running. However, this technology is not helpful when the system is not running (Rudd 2013). If the room has reached the temperature set on the thermostat, the unit does not turn on. If a humidistat (a humidity sensor that causes the system to operate) forces the unit to turn on, it might overcool the room.

The amount of dehumidification that even an enhanced air-conditioning system can provide is limited. Furthermore, dwellings without air conditioning can require some form of supplemental dehumidification, especially if humidity levels are often high. In these cases, a dehumidifier is needed.

Standalone Dehumidifiers

Standalone dehumidifiers use a compressor and refrigerant, much like air conditioners. These dehumidifiers are often the easiest and least expensive way to dehumidify a dwelling, especially an existing one. When choosing a stand-alone dehumidifier and deciding where to place it, keep the following factors in mind:

- The dehumidifier generates noise in the room where it is located. If someone stands 3 ft (1 m) from the unit, a quieter unit might be as loud as a loud conversation and a noisier unit could be as noisy as street traffic.

- If the unit can be located near the main return intake for the central HVAC system, the dehumidified air can be delivered into the system and distributed throughout the dwelling.

- The dehumidifier's capacity needs to be appropriate for the size of the dwelling and the amount of moisture that needs to be removed.

- How the condensed water from the air will be disposed of must be considered. Piping this water to a floor drain, sink, or sump pump avoids the need to manually empty a tank, which might need to be done every day or more frequently.

- If a dehumidifier is older than 5 years, purchasing a new ENERGY STAR-rated one should be considered because it can save energy and operating costs. Consumer Reports (2016a) periodically reviews stand-alone dehumidifiers.

- A dehumidifier should have a filter to protect the air coils from clogging.

- The manufacturer's instructions indicate how to avoid icing for a dehumidifier used in a basement, crawlspace, or other cool location.

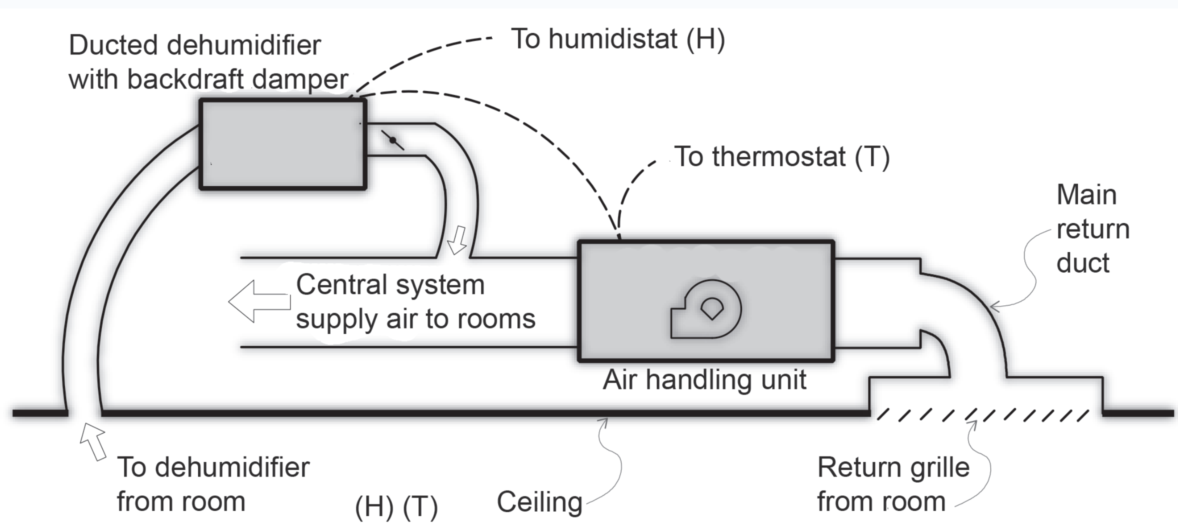
- The benefit of a low humidity setting must be balanced against the energy cost and the risk that the coil will freeze.

Figure 2.2-A Side-Stream Dehumidifier

As with stand-alone dehumidifiers, a central air side stream dehumidifier should have the following features:

- ENERGY STAR rating
- Ability to drain or pump condensate away automatically
- A filter that prevents the coil from becoming clogged

The side-stream dehumidifier needs a humidity sensor and the ability to automatically turn the dehumidification system on and off in response to humidity levels in the dwelling. The setting should be adjusted to maintain 60-65% RH inside the living space.



Central HVAC System Side Stream Dehumidifiers

At the time of this writing, the most commonly available option for integrating dehumidification into the central HVAC system is a ducted “side stream” dehumidifier, as shown in Figure 2.2-A. This unit dehumidifies a stream of air from the dwelling and then mixes it back into the main air supply using its own small compressor.

Figure 2.2-B Central Stand-Alone Dehumidifier as a Return Air Plenum

If the central HVAC system is in its own closet and room air is “pulled” into that closet, a stand-alone dehumidifier in the HVAC closet can produce a similar effect to a ducted side-stream dehumidifier (Figure 2.2-B). In this case, the closet acts as a plenum for return air, which can be directly dehumidified.

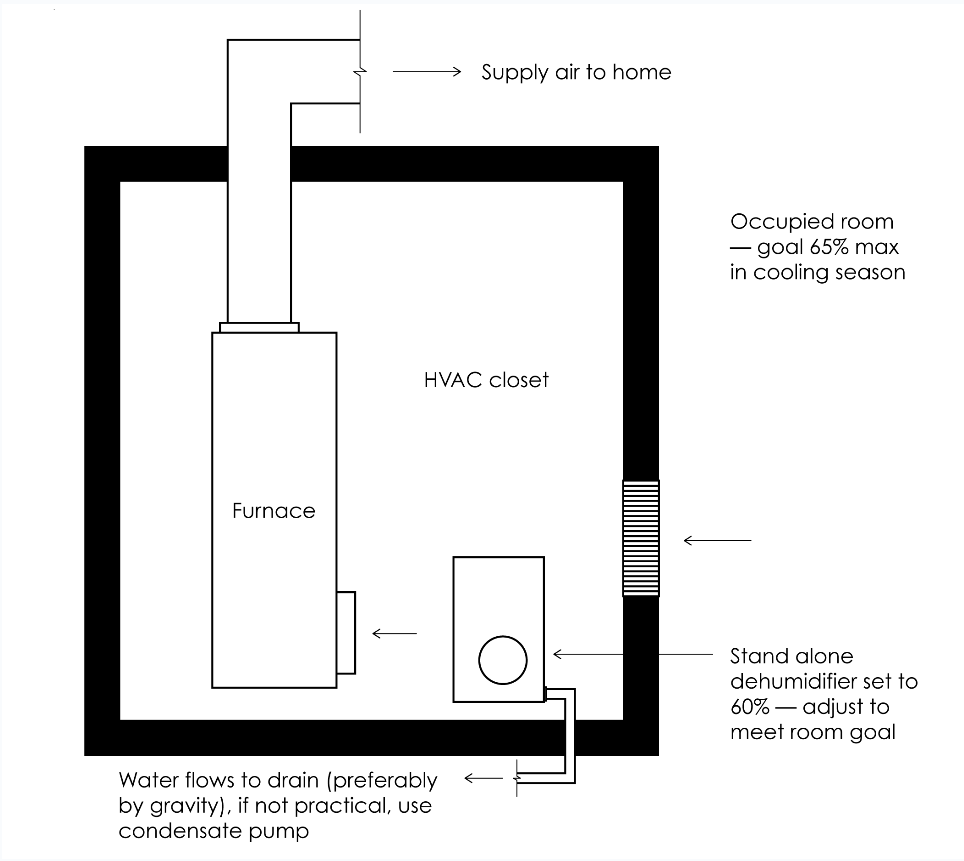


Figure 2.2-B Central Stand-Alone Dehumidifier in HVAC Closet as a Return Air Plenum

Waste Heat (Hot Gas) Reheating

When an air conditioner runs, it draws heat out of the room and sends refrigerant gas containing that heat (so-called "hot gas") to the outdoor unit. With a ground source heat pump (sometimes marketed as a "geo-exchange" or incorrectly labeled as "geothermal"), the heat is rejected to the surrounding earth. This heat is waste heat in the sense that it is usually an unwanted byproduct. However, several manufacturers make systems that use this waste heat to control humidity ("hot gas reheating"). Currently, only so-called ductless split systems and ground source heat pumps offer this feature.

The advantages and disadvantages of the available dehumidification methods are shown in Table 2.2-A. All these systems benefit from measurements of humidity and feedback to control them.

Table 2.2-A Dehumidification strategy

Standalone	Central System Side Stream	Enhanced air conditioning (right sized, dual or variable capacity), reduced fan speed or airflow	Hot Gas Reheat
Simple and easy to purchase from multiple sources	Available from multiple manufacturers	Wide product availability, but more expensive	Currently, only ductless split systems and ground source (so-called "geothermal") heat pumps are sold with this strategy
No installation required except for a drainpipe, which increases convenience	Can be installed in an existing HVAC system	Primarily applies to new systems	Best if purchased with a central HVAC system
Low-risk purchase because product is returnable	Requires high-quality installation	Part of central HVAC system; does not require field assembly	Part of central HVAC system; does not require field assembly
Produces noise in room where it is used	Quieter	Quietest	Quietest
Pipe must drain or be emptied manually	Unit, pipes, and ducts out of sight	Unit, pipes, and ducts out of sight	Unit, pipes, and ducts out of sight
Can be used in homes without central air conditioning	Requires a central air-conditioning system	Requires air-conditioning	Requires a central air-conditioning system
Can be used when the central air conditioner is off	Best if used when the central air conditioner is on	Air conditioning system must be on	Central air conditioning system must be on
Dehumidifies air fully in one room; lesser effects migrate to other rooms	Distributes dehumidified air to entire dwelling	Distributes dehumidified air to entire dwelling	Distributes dehumidified air to entire dwelling
Good for localized humidity problem (e.g., in basement)	Might not address localized humidity problems	Might not address localized humidity problem	Might not address localized humidity problem

Table 2.2-A Dehumidification strategy

Spaces with Large Moisture Sources

Spaces with large moisture sources (e.g., showers, indoor swimming pools, and kitchens) sometimes require dedicated humidity control systems. In these areas, condensation is common. Therefore, surfaces in these spaces need to be inorganic, nonabsorbent, and cleanable (Strategy 2.3). Exhaust systems help keep moisture out of less moisture-tolerant parts of the dwelling by keeping spaces with high humidity at lower pressure than adjoining spaces (Strategy 6.2) and by removing moisture where it occurs.

Low Humidity and Humidifiers

Buildings in cold climates sometimes have extremely low humidity levels, which can cause drying of human airways and increase the spread of certain airborne infections (ASHRAE 2017d). Humidifiers can cause any of the problems described at the beginning of Objective 2, especially if they are set too high in cold weather or they are not cleaned and maintained well.

For this reason, ASHRAE Standard 62.1 (ASHRAE 2016a) no longer sets a minimum humidity level, and many designers prefer to err on the side of caution by not including a humidifier in the dwellings they design. However, this view is not universal. Humidifiers can have real benefits if they are properly installed, maintained, and operated (Schoen 2006).

It has been argued that short-term humidification can reduce symptoms of dryness (Mendell 1993). However, long-term humidification can substantially increase the risk of biological growth in the humidifier or elsewhere. When humidification is used, these other recommendations should be followed:

- Use the humidifier for as little time and in as small an area as possible. For example, if it is used to reduce a child's cold-related respiratory symptoms, this should be done only in the sleeping room and no longer than necessary.

- If the humidifier is part of a central HVAC system, it should be downstream from the heating coil, where RH is lowest and the moisture has the best opportunity to evaporate. As a result, the air will not carry water. A clear straight metal duct with a metal inside surface should be behind the humidifier, and the humidifier should have no obstructions, dampers, or changes in direction.

- Humidifiers that use reservoirs of standing water should not be used unless the water can be changed daily.

- The combination of high levels of indoor humidity and low outdoor temperatures increases the potential for condensation on building surfaces. Therefore, over-humidification must be avoided (see Table 2.2-B). If condensation is visible inside the windows, the humidifier needs to be turned down or off.

- The humidifier needs to be cleaned and maintained before the first use each season and monthly after that to avoid biological growth and other contamination.

Table 2.2-B Recommended Maximum Humidification Settings

Overnight Low Temperature	-20°F (-29°C)	-10°F (-23°C)	0°F (-18°C)	10°F (-12°C)	20°F (-7°C)	30°F (-1°C)
Humidifier Setting (Maximum RH)	10%	15%	20%	25%	30%	40%

Table 2.2-B Recommended Maximum Humidification Settings

Monitoring Humidity

Whether the goal is to remove humidity from indoor air or to increase humidity, humidity should be monitored with a wall sensor to identify high or low humidity problems early.

Humidity is difficult to measure accurately, especially when it is very low or high. Low-cost sensors are sufficiently accurate to measure mid-range humidity and identify trends and relative levels. Sensors to measure humidity usually cost more than those that measure temperature. They also require more maintenance and are more difficult to calibrate.

Inexpensive real-time monitors that can prevent serious problems are liquid moisture sensors in below-grade floors that are subject to flooding, secondary condensate pans (a second pan to collect condensate that is underneath the one inside the air conditioner, advisable especially for those suspended above the living space), and water heater overflow pans.

Special Humidification Needs

If valuable artwork, antiques, or health conditions (eczema, psoriasis) require higher levels of humidification, special steps are needed, such as providing heating near the windows and ensuring that the home has an airtight building enclosure with low moisture permeability (Strategy 2.1). It is critical to work with a professional who has experience in building enclosure design and humidity control in these cases.

Existing Homes

Weatherization (the process of retrofitting an existing dwelling to make it more energy efficient) of existing dwellings without providing mechanical ventilation can result in increases in indoor humidity in winter and slight increases in formaldehyde (Pigg et al. 2014). It is therefore strongly recommended to combine weatherization with whole-dwelling mechanical ventilation. Monitoring indoor humidity after a retrofit and being aware that changes may occur is advisable. Most homeowners and renters have little experience with operating and maintaining ventilation systems, so they should receive clear instructions that are easy to understand (Strategy 1.5).

Strategy 2.3 Select Suitable Materials, Equipment, and Assemblies for Unavoidably Wet Areas

2.3

Introduction

Baths, showers, and some other areas in dwellings that often or occasionally experience high humidity levels should be carefully designed. They need to be able to become wet briefly without damage and dry as quickly as possible without raising the humidity level in other areas of the dwelling.

Other spaces that can become wet unexpectedly or unintentionally, such as when a water heater or washing machine leaks, need to be designed to limit damage.

Common building materials that are easily damaged by moisture:

- Gypsum board (drywall)
- Medium density fiberboard
- OSB
- Carpet

The EPA's Indoor airPLUS and ENERGY STAR for New Homes programs have water management system requirements that include above-code best practices to promote durability in unavoidably wet areas (EPA 2015c; ENERGY STAR 2015).

Moisture-Resistant Building Materials

Entrances, kitchens, bathrooms, and utility rooms occasionally have wet floors that tend to require frequent cleaning because they become heavily soiled. The flooring in these rooms should have a moisture-resistant, hard surface that can be mopped and allowed to dry without damage. Concrete, tile, and vinyl flooring surfaces are all easily cleaned. Laminate or sealed wood flooring can tolerate a small amount of occasional moisture, such as in an infrequently used entrance that has a covered porch for shoe and raingear removal.

Spaces at risk of large spills or leaks (including basements, garages, sealed crawlspaces, and rooms that contain a water heater, ground source heat pump, or washing machine) need floor drains. Highly moisture-resistant flooring (such as tile or concrete) should be used and sloped toward the floor drain. At a minimum, drain pans should be placed under washing machines. In these types of spaces, materials that are easily damaged by moisture should not be used because they contain nutrients that easily attract biological growth, absorb water easily and dry slowly, or are easily damaged or deformed when wet. Some examples of inappropriate materials include paper-faced gypsum board, medium density fiberboard, OSB, and carpet (EPA 2013c).

Bathrooms

Bathrooms do not typically have floor drains, but they are particularly vulnerable to plumbing leaks, and a floor drain is a valuable durability upgrade. Bathrooms with floor drains should have a way to prevent the plumbing trap from becoming dry (e.g., by using a self-priming trap). Another way to accomplish this is to have a curbless shower with a sloped bathroom floor.

Bathrooms typically have high humidity levels when an occupant is taking a shower. See Strategy 6.2 for instructions on how to remove this moisture and prevent it from migrating throughout the house

The use of larger tiles on walls in bathrooms can reduce the amount of grout in the enclosure, making the surface easier to clean. However, smaller tiles should be used on floors to prevent cracking. Bliss (2006) provides very detailed specifications for successful tile installations in

bathrooms. His criteria include a stiff and well-supported subfloor, a backer material appropriate for the expected wetness of the tile surface, leveling, moisture barriers, and methods for preventing cracking at backer board seams. Grout should be sealed to repel moisture. Most sealants need to be reapplied annually to remain effective.

The ENERGY STAR New Homes program requires that walls with tile or caulked panel in showers be made of cement backer board or a water-resistant material (evaluated by the ICC Evaluation Service per Acceptance Criterion 115; ICC-ES 2016.) This program prohibits paper-faced drywall in this setting, unless it is behind a monolithic enclosure or protected by a waterproof membrane that has been evaluated by ICC-ES per Acceptance Criterion 115 and the drywall meets ASTM International mold-resistant standards D3273 or D6329 (EPA 2015g). Moisture-resistant drywall (e.g., “green board” shown in Figure 2.3-C or “purple board”) meets this standard and can be helpful in bathrooms, but it should not be considered waterproof or be used in wet areas without a waterproofing membrane.

Figure 2.3-A Continuous Drain Pan & Figure 2.3-B Sloped Shower Floor

Showers and baths should be designed and installed in ways that make cleaning easy and allow drying. Continuous fiberglass tub and shower enclosures with only a few seams offer an easy way to accomplish this. If seams cannot be avoided, antimicrobial caulk should be used. Glass doors instead of a shower curtain can also keep water inside the shower enclosure. For site-built tub and shower enclosures with tile, a continuous waterproof drain pan (also known as a “shower pan”) should be used underneath (see Figure 2.3-A) because a drain could become clogged and the bottom of the shower might need to hold a couple inches of water. Tile on shower floors should be slightly sloped to the floor drain, and grout should be sealed to repel moisture (see Figure 2.3-B).

Figure 2.3-A Continuous Drain Pan for a Shower

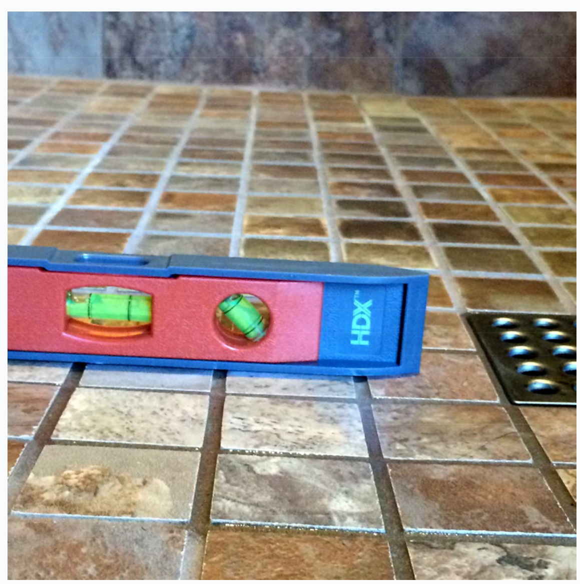


Figure 2.3-B Sloped Shower Floor

Figure 2.3-C Moisture-Resistant Drywall

Figure 2.3-C Moisture-Resistant Drywall

Hot Tubs, Pools, Spas, and Other Humid Spaces

When considering whether to add a wet space to a dwelling, the first question should always be, “Does this absolutely have to be inside my dwelling’s thermal boundary?” Keeping it simple is usually the best line of defense against moisture problems. Rather than designing systems to prevention migration of moisture from spas, pools, or saunas into other parts of the dwelling, accommodating these functions in a detached structure is often the safest and simplest strategy. Hobbies that generate a great deal of moisture, demand more than 60% RH, or require vastly different temperatures than the dwelling’s interior should also be accommodated outside whenever possible. Many of these activities can also generate substantial amounts of unwanted heat, which can reduce comfort and energy efficiency.

When these spaces must be attached to the dwelling, care should be taken to isolate them from the dwelling using an airtight enclosure that has been designed to support the expected

temperature and humidity profile. Enclosure techniques for hot, humid climates can be used (Lstiburek and Carmody 1996; Lstiburek 2005) by a designer who has experience with these types of spaces. If frequent high humidity is expected, all interior surfaces should be constructed of moisture-resistant materials, and exhaust fans should be used to maintain the space at negative pressure with respect to the remainder of the dwelling.

In most cases, if the enclosure of the space is airtight, a 50–100 CFM (24-47 l/s) continuous exhaust fan is enough to maintain negative pressure in the space. The pressure should be field verified, preferably by measuring at least 0.02 in. w.g. (5 Pa) or alternatively by checking that air flows into the moist room through cracks around the door. The space should not share a forced air conditioning system with the rest of the dwelling, and the mechanical systems should be designed by a professional experienced with these types of spaces. Such as professional will be aware of the many pitfalls inherent in these spaces, and he or she might recommend alternative locations for the space.

Multifamily Dwellings

Compared with those in single-family dwellings, wet spaces in multifamily dwellings often result in more problems. A swimming pool area definitely requires specialized design and construction (ASHRAE 2015c). Common entry areas in multifamily dwellings experience more traffic (Strategy 3.4). Multifamily living units are often more densely occupied, and wet areas (e.g., bathrooms) might be used more frequently, making the guidance in this strategy even more important. Such problems as water leaks might not be reported as quickly, might continue longer, and can damage more living units, so durable flooring and appropriate use of drain pans and floor drains are also critical.

Existing Dwellings

In existing dwellings, durability of wet areas should be considered when surfaces, materials, and equipment are replaced. Visibly water-damaged materials should be replaced with more durable ones, and any water problems that might have caused the damage should be fixed promptly.

Strategy 2.4 Manage Effects of Landscaping and Indoor Plants

Introduction

Plantings in or around dwellings can be both beneficial and problematic. Home occupants typically choose plants for their aesthetic, shade, and food value. But plants cannot improve IAQ, despite claims to the contrary that are readily found on the Internet.

Steps to maximize IAQ by managing landscaping and indoor plants are as follows:

- Plants, except in rare cases, cannot improve IAQ. The correct use of plants, in moderation, is to create a pleasing, aesthetic home environment.
- If a dwelling has more than 25 typical plants, the dwelling should have a supplemental dehumidifier.
- Do not overwater houseplants.
- Use fertilizers or insecticides only when needed and apply them outside.

Purported IAQ Benefits

Of course, outdoor plants are necessary for a healthy biosphere, but they have no established benefits for IAQ. Studies by the National Aeronautics and Space Administration in the 1970s suggested that many indoor potted plants could reduce VOC levels by insignificant amounts (Levin 1992), possibly because of the activity of root-zone soil microorganisms (Guieysse et al. 2008; Kim et al. 2008; Wood et al. 2006; Wang and Zhang 2011). Because this impact is minimal, using potted plants indoors is not a valid technique to control VOC concentrations.

Psychological Benefits of Potted Plants

A moderate number of well-maintained plants (Figure 2.4-A) is aesthetically pleasing and can offer modest psychological benefits (Bringslimark et al. 2007; Ceylan et al. 2008; Shibata and Suzuki 2002, 2004).

Figure 2.4-A Interior Plants—Pleasing, But They Do Not Mitigate IAQ

Overwatering

Wet carpets, fiberboard, or other biodegradable finishing materials that result from plant watering promote biological growth and any of the problems described at the beginning of Objective 2. If potted plants are overwatered, they can become a source of moisture (Strategy 2.1). Moist dwelling materials and the root zones of plants also promote various types of biological growth.

Humidity

Plants themselves and the soil in which they are planted emit water molecules into the air, a process which is called evapotranspiration. Inside buildings, an average-sized houseplant emits up to 0.22 lb (100 g) of water per day into the indoor air. For example, 10 plants contribute about as much

moisture to the inside of the dwelling as a single person. More than 25 plants in a dwelling could therefore raise indoor RH levels, which could be advantageous during the dry season, depending on the source of the water. However, this humidity increase can be disadvantageous in a warm, humid condition if it exceeds the cooling system's capacity to manage.

Potted Plant Contaminants

Mold can grow on moist mulch (e.g., bark and wood chips) and dead leaves in the pot. In addition, some potting materials, such as wicker baskets, are susceptible to water damage and mold growth (Kozak et al. 1980, 1985).

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 contains fungi, including pathogenic Aspergillus species, such as A. fumigatus. Simple activities, such as cultivating soil and watering, can increase indoor levels of biological growth, including unusual species that can cause symptoms or disease.

Fertilizers or insecticides used on houseplants can release airborne contaminants. If insecticides must be applied to houseplants, this should be done outside.

Greenhouses

Plants that require more than 65% RH are not compatible with a good IAQ (Strategy 2.2).

If large quantities of plants must be grown—whether for aesthetic, recreational, or medicinal purposes (e.g., cannabis)—it is best to keep them in an area that is separated from the living space and designed to handle the moisture (Strategy 2.3). Ideally, this area is not attached to the dwelling, to keep moisture and contaminants out of the living space. At a minimum, the air from this space should be kept out of the living space by maintaining it at a negative pressure (Strategy 6.3).

Some experts argue that buildings with attached greenhouses have higher levels of mold spores in the indoor air than in the outdoor air (Botzenhart et al. 1984). The sources of elevated indoor mold spores include fungi growing on green leaves (e.g., Cladosporium species), Aspergillus species (including A. fumigatus), and Penicillium species that grow on dead vegetation on the moist greenhouse floor.

Indoor Plants to Avoid

Figure 2.4-B shows ferns growing from carpeted flooring in a room previously damaged by a hurricane. The ferns are growing nicely even though the debris on the floor surface feels dry to the human hand, indicating that the moisture is adequate to support the growth of fungi and bacteria in the flooring substructure.

Outdoor Plants

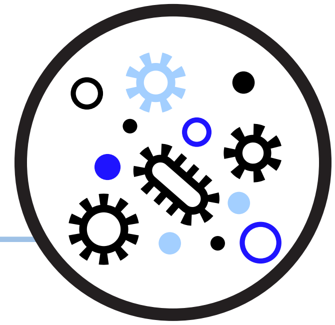
Outdoor plants provide shade for outdoor areas and the dwelling, resulting in aesthetically pleasing spaces for recreation and relaxation for residents. Rain gardens can manage runoff, thus protecting the dwelling and surrounding waterways.

However, 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 dwellings with conventional roofs that were heavily shaded by trees tended to have more allergies, possibly because of elevated biological growth levels resulting from debris on damp roofs and next to buildings.

To prevent excessive water near the foundation, and capillary entry of water through porous masonry into the building interior, avoid overwatering of planter boxes at grade level close to walls. If water sprinklers are used, they should be directional, with the spray pointed away from the dwelling.

Figure 2.4-B Plants Run Amok

Objective 3



LIMIT CONTAMINANT ENTRY INTO THE LIVING SPACE

Contaminants from sources outside the living space can have a major influence on IAQ. These contaminants include particles and gases in outdoor air, microbes or radon in the soil and groundwater, herbicides and pesticides applied around the dwelling, and allergens produced by pests. Contaminants can also come from unoccupied spaces, such as the attic, garage, crawlspace, and basement. The strategies in this objective are intended to limit entry of these contaminants into the dwelling.

The entry of outdoor air pollutants into a dwelling through ventilation and infiltration (unintended air leakage through the walls, floor, roof, or window and door systems) can have significant health effects. 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 United States, outdoor levels of these and other pollutants exceed standards set by the EPA. Even in areas where regional outdoor air quality is good, pollution might be high at certain sites because of local sources, such as nearby highways. This objective includes the following strategies:

Strategy 3.1 Determine Regional and Local Outdoor Air Quality describes assessments of outdoor air pollution levels and control measures to limit pollutant entry.

Strategy 3.2 Locate Outdoor Air Intakes to Minimize Introduction of Contaminants addresses the separation of air intakes from local and onsite sources, such as motor vehicles, exhaust air, landscaping, vegetation, and pests.

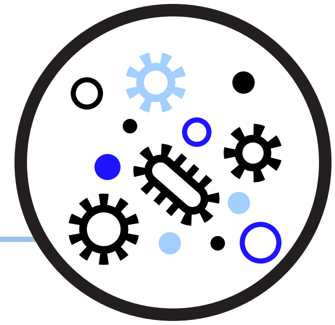
Strategy 3.3 Control Entry of Radon and Other Subsurface Contaminants describes mitigation techniques for radon, a natural radioactive soil gas that that is the second leading cause of lung cancer in the United States, and other contaminants in the soil.

Strategy 3.4 Use Doormats to Keep Out Contaminants describes strategies to reduce contaminants that people track in when entering the dwelling, such as pesticides, dirt, and water, that can foster biological growth.

Strategy 3.5 Use Design, Building, and Maintenance Strategies to Resist Pests describes techniques to limit infestation by pests, such as rodents, birds, insects, and others. These pests can be sources of infectious agents and allergens

Strategy 3.6 Control Entry of Contaminants from Unoccupied Spaces discusses ways to control contaminants that can enter the living space from crawlspaces, basements, attics, and garages.

Objective 3



LIMIT CONTAMINANT ENTRY INTO THE LIVING SPACE

Other important strategies for limiting entry of outdoor contaminants are discussed in the following sections:

- Strategy 1.1 – Build, Buy, or Rent a Dwelling with Good IAQ
- Strategy 1.3 – Select HVAC Systems to Improve IAQ and Manage the Impact of Ventilation
- Strategy 2.1 – Avoid Water Penetration and Moisture Problems in the Enclosure
- Strategy 2.4 – Manage Effects of Landscaping and Indoor Plants
- Strategy 6.3 – Maintain Proper Pressure Relationships Between Spaces
- Strategy 7.1 – Implement Appropriate Outdoor Air Ventilation Strategies and Quantities
- Strategy 7.2 – Provide Particle Filtration and Air Cleaning

Strategy 3.1 Determine Regional and Local Outdoor Air Quality

Introduction

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… [T]he engineer will find, at times, that odors originating outside buildings in industrial or 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).

Important outdoor air quality considerations are the following:

- Outdoor air is not always "fresh" and can contain contaminants.
- Home weatherization reduces the entry of outdoor pollutants.
- Good particle filtration in a central HVAC system or at the outdoor air entry point can control the most common outdoor pollutants.
- Filters with activated carbon can be difficult to find but can reduce the effect of ground-level ozone on IAQ.

More than 70 years after this statement was published, the outdoor atmosphere in many parts of the world still contains particles and gases that can adversely affect IAQ. In most areas of the United States, Canada, and Western Europe, outdoor air is relatively, but not completely, clean. People sometimes call outdoor air "fresh air," yet in some locations and during some periods, outdoor air has contaminants that render it neither clean nor fresh.

Such locations include urban areas or areas near industrial or agricultural sources of air pollution, which might have outdoor air with high enough concentrations of some contaminants to increase indoor concentrations, or that would dilute the indoor concentrations less than expected. For example, in areas with heavy automobile traffic, fine particulate matter (PM) generated by vehicles can pass easily into dwellings. This outdoor PM often accounts for 50% of the indoor PM levels.

Outdoor pollution consists of gases and particles—the latter are generally the predominant indoor contaminants of outdoor origin. In the United States, a primary resource for information on outdoor air pollution is in the EPA's Green Book (EPA 2017h). Two pollutants that affect health, ground-level ozone and particulate matter, are of interest because regulatory standards for these pollutants are often exceeded, and relatively simple actions can be taken to reduce exposure in a dwelling.

The EPA provides maps to illustrate so-called "nonattainment areas" where air does not meet the National Ambient Air Quality Standards (EPA 2017h). Furthermore, local sources of outdoor air pollution, such as nearby industry, highways, agriculture, or construction, can affect the dwelling. Pollen and other biological material of outdoor source can cause or aggravate allergies and other respiratory conditions.

Outdoor pollution enters dwellings either by ventilation with outdoor air (Strategy 7.1); by infiltration; or through open windows and doors. All of these methods of air exchange dilute contaminants of indoor origin while increasing indoor levels of contaminants that originate outdoors.

Strategy 3.1 Determine Regional and Local Outdoor Air Quality

The major codes and standards that require ventilation in residences do not currently require the contaminants in outdoor air to be addressed. The 2016 version of ASHRAE Standard 62.2 (ASHRAE 2016b) covers all dwelling units, but its forward says that it "does not address certain potential pollutant sources such as contamination from outdoor sources." The 2015 versions of the ICC (ICC 2015d), which covers low-rise dwellings and International Mechanical Code (ICC 2015c), which covers high-rise dwellings, also have no requirements for outdoor air contaminants. This Strategy makes best-practice recommendations that go beyond the Code requirements.

Particles

Particles come from many sources; those with the greatest known health impact typically come from combustion (WHO 2013). Major outdoor sources include vehicle engines, power plants, and wood burning. Particles adversely affect heart and lung health in everyone, not only those with asthma or other respiratory diseases. The risk of heart attack, stroke, and other circulatory diseases is greater than the risk of lung diseases (EPA 2017m and Strategy 7.2).

Small particles are measured in micrometers (μm). In most cases, the smaller the particle, the greater the health impact and the more difficult it is for filters to remove it.

Fine inhalable particles, which have diameters of 2.5 μm or less (see Figure 3.1-A), are referred to as "$PM_{2.5}$." Outdoor particulate matter in this size range is the primary concern with respect to human health, and $PM_{2.5}$ is usually the value reported by health and environmental authorities. Ultrafine particles (smaller than 0.1 μm) also have distinct health effects, but this category is not yet regulated as an outdoor pollutant (Strategy 7.2)

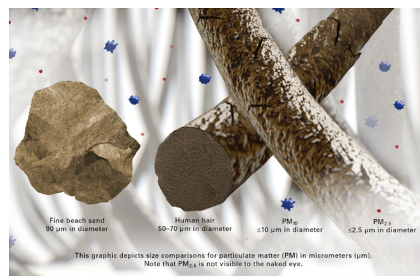


Figure 3.1-A Examples of Particles of Different Sizes
Graphic courtesy of EPA.

Even attainment regions can have localized "hot spots" for $PM_{2.5}$ pollution because of highways (WHO 2005) or wood smoke (New Hampshire Department of Environmental Services 2017). If a dwelling is in a nonattainment area or near a local source of outdoor contaminants, one or more of the strategies discussed below should be considered to control contaminants of outdoor origin.

Even the levels of contaminants permitted by regulations might not provide enough protection (Shi et al. 2015). Evidence is growing of health effects at levels far below these levels. Furthermore, regulated levels are not necessarily appropriate for people with certain health conditions.

Ozone

The ozone layer in our upper atmosphere is beneficial to human health because it protects us from ultraviolet radiation. However, ozone located at ground level where humans can inhale it is unhealthy and undesirable.

Ozone is an odorless pollutant formed in the atmosphere by a chemical reaction between VOCs and nitrogen oxides under sunlight. For this reason, several air quality regulations are designed

Figure 3.1-B Areas of Nonattainment for EPA Fine Particle Standard

$PM_{2.5}$ is a regulated pollutant in the United States, yet several regions do not meet current standards. See Figure 3.1-B for areas of non-attainment of the $PM_{2.5}$ standard in 2017.

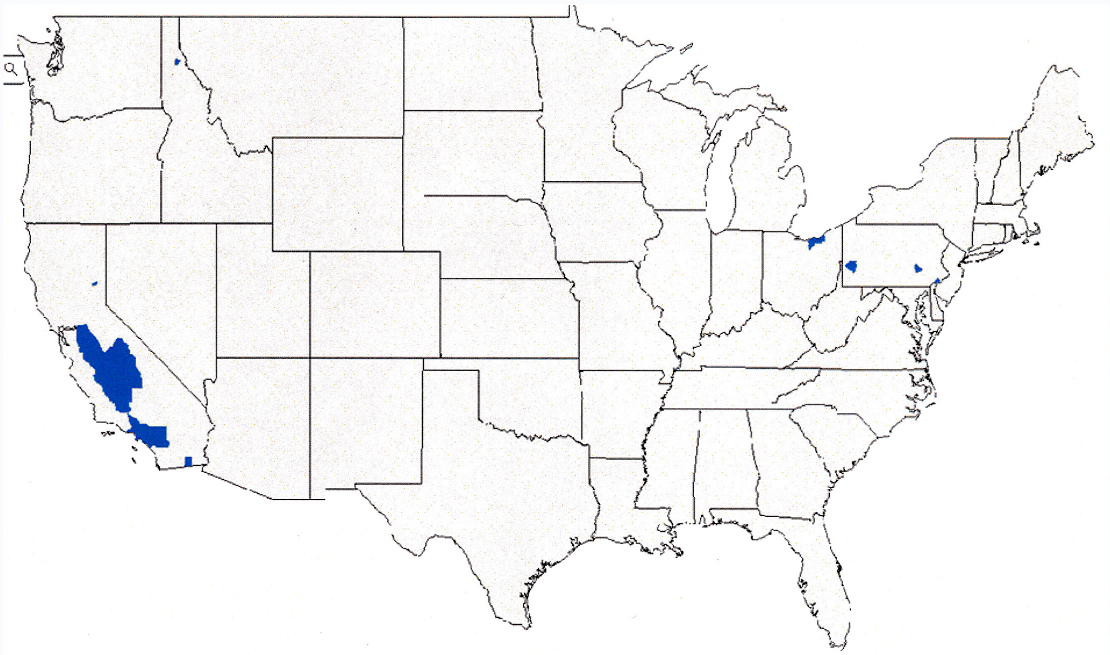


Figure 3.1-B Areas of Nonattainment for EPA Fine Particle Standard (as of 5/12/17)
Map courtesy of EPA.

to reduce emissions of VOCs and nitrogen oxides. Ozone pollution results in several adverse health effects, including lung irritation and respiratory illness. Ozone levels are lower indoors than outdoors, but ozone's chemical reactions with other indoor substances can raise the level of other contaminants. Ozone can also damage documents, books, furniture, and fabric. The EPA provides the air quality index for ozone (Table 3.1-A; EPA 2017d)

Ozone can also come from indoor sources, and all should be avoided. Some are intentional attempts to reduce odors, such as ozone generators, which should never be used (these devices and the dubious marketing claims associated with them are discussed in more detail in Strategy 7.2), and some are unintentional, such as printers and copiers (Strategy 5.2).

Other Pollutants

Airborne dust particles larger than 10 μm are no longer regulated as National Ambient Air Quality Standards pollutants but can be a problem in areas with agriculture, construction, high pollen, certain industries, or desert climates. Some states regulate visible emissions, including Delaware, Maryland, and Michigan (Delaware Department of Natural Resources and Environmental Control

Table 3.1-A Air Quality Guide for Ozone

Air Quality Index	Who Needs to be Concerned?	What Should I Do?
Good (0-50)	It's a great day to be active outside.	
Moderate (51-100)	Some people who may be unusually sensitive to ozone.	**Unusually sensitive people:** *Consider reducing* prolonged or heavy outdoor exertion. Watch for symptoms such as coughing or shortness of breath. These are signs to take it easier. **Everyone else:** It's a good day to be active outside.
Unhealthy for Sensitive Groups (101-150)	Sensitive groups include **people with lung disease such as asthma, older adults, children and teenagers, and people who are active outdoors.**	**Sensitive groups:** *Reduce* prolonged or heavy outdoor exertion. Take more breaks, do less intense activities. Watch for symptoms such as coughing or shortness of breath. Schedule outdoor activities in the morning when ozone is lower. **People with asthma** should follow their asthma action plans and keep quick- relief medicine handy.
Unhealthy (151-200)	**Everyone**	**Sensitive groups:** *Avoid* prolonged or heavy outdoor exertion. Schedule outdoor activities in the morning when ozone is lower. Consider moving activities indoors. **People with asthma**, keep quick-relief medicine handy. **Everyone else:** *Reduce* prolonged or heavy outdoor exertion. Take more breaks, do less intense activities. Schedule outdoor activities in the morning when ozone is lower.
Very Unhealthy (201-300)	**Everyone**	**Sensitive groups:** *Avoid all* physical activity outdoors. Move activities indoors or reschedule to a time when air quality is better. **People with asthma**, keep quick-relief medicine handy. **Everyone else:** *Avoid* prolonged or heavy outdoor exertion. Schedule outdoor activities in the morning when ozone is lower. Consider moving activities indoors.
Hazardous (301-500)	**Everyone**	**Everyone:** *Avoid all* physical activity outdoors.

Table 3.1-A Air Quality Guide for Ozone
Image courtesy Airnow (2015).

2013; Maryland Department of the Environment 2017; MDEQ 2016), where enforcement can be driven by citizen complaints. Because the particles are large, filters are effective at removing them. However, the particles can clog filters, so the filters need to be checked frequently. Soil often has high levels of biological growth, so activities, such as construction, that stir up earth might increase their levels. In most cases, this is a problem only for people with a compromised immune system.

Outdoor sources of VOCs include industrial emissions, traffic, wastewater lagoons, and some natural sources. Effective removal of VOCs requires large filtration systems and is usually not

practical for dwellings. More practical strategies include avoiding these locations and pointing air intakes away from the sources (Strategy 3.2).

Semivolatile compounds (SVOCs) are of increasing concern, and pesticides are one class of outdoor SVOC sources. Because SVOCs often become attached to particles, the steps to reduce particles can help reduce SVOC exposure. For more information about SVOCs, see Strategy 5.1.

Odors in the atmosphere are often (but not always) regulated in urban environments in response to citizen complaints. Odors can be removed from outdoor air with an air-cleaning technology that is tailored to the compounds that cause the odor. This approach is usually more practical at the source of the odor than at the dwelling.

Volatile, Semivolatile, and Total Volatile Organic Compounds

Volatile organic compounds (VOCs): VOCs are a group of organic chemicals that can evaporate at normal indoor temperature and air pressure (EPA 2015f). Liquid formaldehyde, for example, in wood products is volatile because it can turn into a vapor and enter the air at room temperature.

Semivolatile organic compounds (SVOCs): SVOCs are a subcategory of VOCs that evaporate at higher temperatures.

Total volatile organic compounds (TVOCs): TVOCs are the total concentrations of the individual VOCs in an air sample. A TVOC concentration is less informative than those of individual VOCs because the former does not distinguish among constituent VOCs.

Strategies for Controlling Contaminants of Outdoor Origin

Controlling contaminants of outdoor origin in dwellings can be beneficial, even though no codes or standards currently require this.

Airtightness. Tightening (air sealing) the dwelling, which is usually done to save energy, can also reduce exposure to outdoor particles. The penetration of outdoor particles in dwellings has been correlated with airtightness measured using blower door tests (Stephens and Siegel 2012).

Weatherization retrofits (sometimes known as home energy retrofits) that include air sealing can also offer a long-lasting, effective way to lower exposure to outdoor particulate matter in low-income housing. However, weatherization can also adversely affect health if ventilation is not adequate. A recent study showed that using ASHRAE ventilation standards improves IAQ and self-reported health (Francisco et al. 2017). Outcomes are also significantly better if the ASHRAE 2010 or later Standard is used instead of the old ASHRAE 1989 standard still commonly used by many weatherization and other housing programs. Such programs should comply with the newer ASHRAE standard to improve health and IAQ.

Particle filtration. Particle filtration is a practical and effective way to reduce the impact of outdoor particulate matter on the IAQ of any dwelling. Filtration of particles of outdoor origin requires highly effective filtration media at the ventilation air entry point, in the central HVAC system, or in the room (Strategy 7.2).

Ozone control. Ozone can be reduced in any dwelling by using filters containing activated carbon during the hot sunny season when ozone concentrations are higher, and they do not need to be used during the rest of the year. For more information, see Strategy 7.2.

Ventilation timing. A less common strategy is to shift outdoor air ventilation to times of day when outdoor pollutant concentrations are lower. A particle counter can be installed (Strategy 1.5) to control ventilation timing automatically (Strategy 7.1). If the control strategy causes the ventilation to stop for more than an hour, more overall ventilation air will likely be needed throughout the rest of the day. For this reason, consultation with a knowledgeable professional is recommended before implementing this type of strategy.

Strategy 3.2 Locate Outdoor Air Intakes to Minimize Introduction of Contaminants

3.2

Introduction

Outdoor air is used as part of a whole-dwelling unit ventilation system to improve indoor air quality by diluting indoor contaminants (Strategy 7.1). For HVAC systems with outdoor air intakes, care must be taken to draw this air from a clean location and to remove outdoor contaminants (Strategies 3.1 and 7.2) before introducing it into the dwelling.

Placement of the outdoor air intake can strongly affect indoor humidity (Strategy 2.2), indoor particle concentrations (Strategy 7.2), and, possibly, building pressure relationships (Strategy 6.3).

Install outdoor air intakes at least 2 ft (0.7 m) above the ground or rooftop and keep them away from:

- Garages and parking areas
- Combustion vents
- Exhaust outlets
- Neighboring buildings with emissions
- Busy roads
- Expected snow accumulation levels

Locating and Protecting the Outdoor Air Intake

The outdoor air intake should be in an unobstructed location, away from known pollutant sources (see Figure 3.2-A). Such sources include areas with parked vehicles; places where people smoke; busy streets; and bath, kitchen, and combustion air exhaust outlets.

Figure 3.2-A Recommended Locations for Outdoor Air Inlets

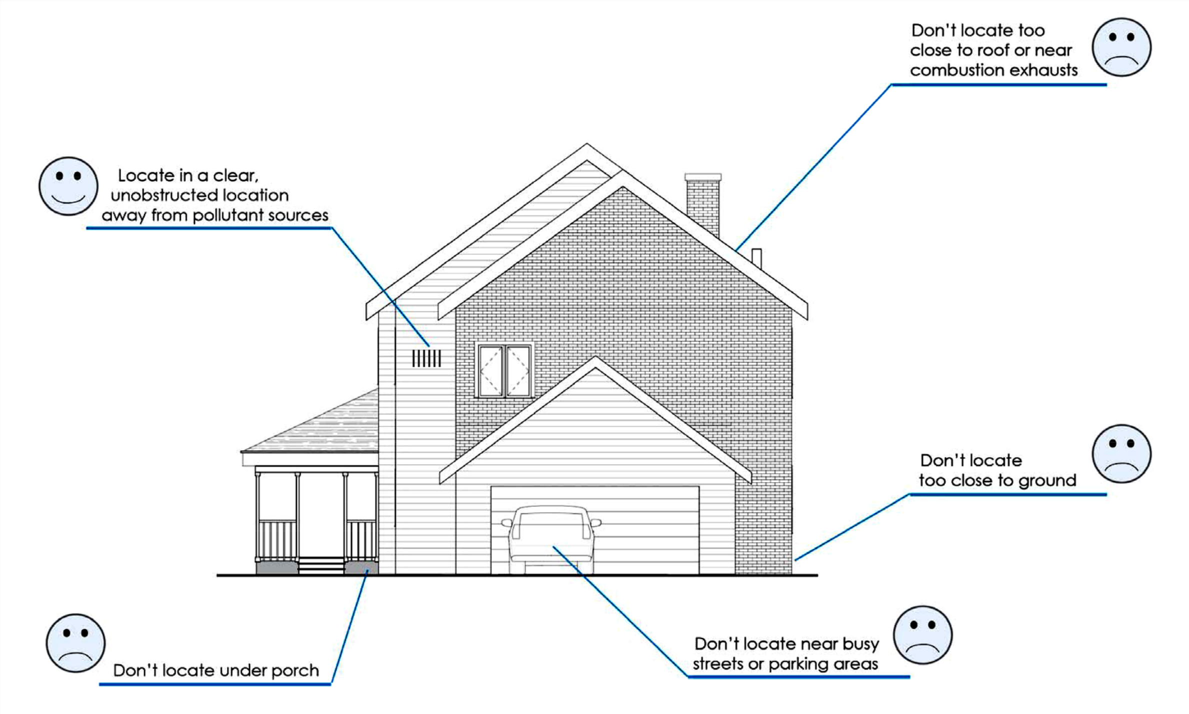


Figure 3.2-A Recommended Locations for Outdoor Air Inlets

Building codes usually require that vents related to fuel burning equipment be kept away from air intakes. ASHRAE Standard 62.2-2016 (ASHRAE 2016b) requires a distance of 10 ft (3 m) between air intakes and these known sources of contamination. However, this distance can be reduced to 3 ft (1 m) if the ventilation inlet is in the wall and the source of contamination exits through the roof or is a dryer exhaust outlet. The standard also allows balanced ventilation systems to have a combined manufactured inlet/exhaust termination with no minimum separation distance, as long as the exhaust does not originate in a kitchen and the manufacturer has proven that less than 10% of the exhaust is re-entrained into the supply.

Air inlets should be in locations where they are likely to remain unobstructed by snow or vegetation. The inlets should draw air directly from the outdoors rather than from an attic, crawlspace, garage, or enclosed area under a porch or deck. The ENERGY STAR Certified New Homes program requires inlets to be located at least 2 ft (0.7 m) above grade or above the roof deck (ENERGY STAR 2017a). In areas with more than 2 ft (0.7 m) of regular snow accumulations, a higher location is necessary. The air inlet should not be directly on the roof, where it can draw in odors from asphalt shingles. Air from roofs in the summer is usually hotter than air from other locations, so this air might require additional conditioning (Rudd 2011).

Ventilation inlets can become clogged and should be visually inspected yearly and maintained as needed. Therefore, the best location is one that allows reasonable access by the occupant. Placing the inlet between 2 and 10 ft (0.7 to 3 m) from the ground is most likely to allow such maintenance.

Air inlets should be protected during and after construction from pests and debris. Nests in both intake and exhaust ducts built by birds or bees during construction are quite common before the permanent exterior pest-proof cover is placed. Intrusion by various types of rodents and insects is also common during this time. When construction is complete, the inlet should be covered by a corrosion-proof rodent and insect screen whose mesh does not exceed 0.5 in. (13 mm).

Outdoor Air Intake for Exhaust-Only Ventilation Systems

Exhaust-only ventilation systems are common in dwellings (Strategy 7.1). They typically do not have a designated outdoor air intake but, instead, rely on leakage in the building enclosure to allow outdoor air to enter the dwelling and balance the air removed by the exhaust fan.

Some exhaust-only systems use “trickle vents,” which are designed passive air inlets that can be manually opened or closed by occupants. Like unintended leakage pathways, these inlets rely on the negative pressure generated by the exhaust fan to draw outdoor air in through the vent. Although research has often found these trickle vents to be ineffective in many dwellings, they can work in tightly sealed dwellings (Maxwell et al. 2016).

Trickle vents are normally at the top of a window frame. Bedrooms (where people spend many hours breathing) are often good locations, as long as these vents are not too close to the bed, where hot or cold outside air could cause discomfort. Very cold, very hot, or very humid outdoor air should not be directly introduced into the living space, where it can cause discomfort. Humid or very cold outdoor air can also cause or exacerbate humidity problems. Trickle vents should be located to follow the guidance provided above for all air inlets.

See Strategy 7.1 for a discussion of situations in which trickle vents might not be suitable.

Strategy 3.3 Control Entry of Radon and Other Subsurface Contaminants

Radon

Radon is a colorless, odorless, radioactive gas formed during the radioactive decay of uranium. Uranium is a common component of soils, sands, gravels, shattered shales, limestone, and schist. Because these radioactive elements have unstable atomic structures, they break apart to form new elements and emit radiation in this process. Some of the new elements that are formed are also radioactive and continue the chain of radioactive decay until lead, a stable element, is formed. This breakdown process is slow, and most of its products are solids.

However, radon, one of the compounds formed during this process, is a gas that can enter dwellings through cracks, gaps, or openings in foundations. In 2005, the U.S. Surgeon General issued a radon health advisory because exposure to elevated radon levels indoors increases the risk of lung cancer (HHS 2005).

The dominant radon source in most dwellings is air from the surrounding undisturbed soils and rocks. In a small fraction of dwellings with elevated radon levels, radon enters primarily via well water used for cleaning, cooking, and bathing. In rare cases, granite in countertops or concrete can be a significant source of radon.

Air enters dwellings from below grade when the indoor air pressure is lower than the outdoor air pressure. Negative pressure in basements, crawlspaces, and first floors of houses is caused by the stack effect (movement of air driven by buoyancy and resulting from temperature differences), the operation of exhaust fans, imbalanced air leakage in duct systems (typically return duct leaks in basements), pressure imbalances caused by air distribution systems, and from vented gas appliances that draw combustion air from the home. Some of these factors also increase dilution, so the net effect on radon does not increase radon levels in all homes. The indoor concentration of radon is typically expressed in picocuries per liter (pCi/L) or Becquerels per cubic meter (Bq/m^3). Since 1986, the EPA has recommended mitigation for dwellings with occupied rooms whose measured radon levels are higher than 4 pCi/L (148 Bq/m^3). The World Health Organization (WHO 2014) and ASHRAE 189.1 (ASHRAE 2017f) recommend remediation if radon levels are higher than 2.7 pCi/L (100 Bq/m^3).

Dwellings with elevated levels of radon can be found in every state. The frequency of elevated levels can be estimated using the EPA Radon Zone map (Figure 3.3-A). The EPA also maintains an interactive online map (EPA 2017g) that allows users to zoom in and view state-specific radon information. The map identifies locations with the most frequent radon problems, although high-radon dwellings can be found anywhere.

Facts about radon are as follows:

- Breathing radon increases the risk of dying from lung cancer.
- Radon can be measured, but it cannot be smelled or seen.
- Whether a new house will have elevated radon levels cannot be determined prior to completion of construction.

Some measurement and control considerations for radon and other subsurface contaminants are:

- Measurements of indoor radon levels should follow the EPA guidance for measuring and interpreting radon (EPA 2012a).
- If the EPA guidance suggests reducing the measured indoor radon, sub-slab soil depressurization methods should be used to prevent radon from entering the dwelling.
- Radon-resistant construction methods should be used for new dwellings.
- Other contaminants can enter a dwelling through cracks and gaps in foundations. These can be addressed using similar techniques to those used for radon.

Figure 3.3-A EPA Radon Zone Map

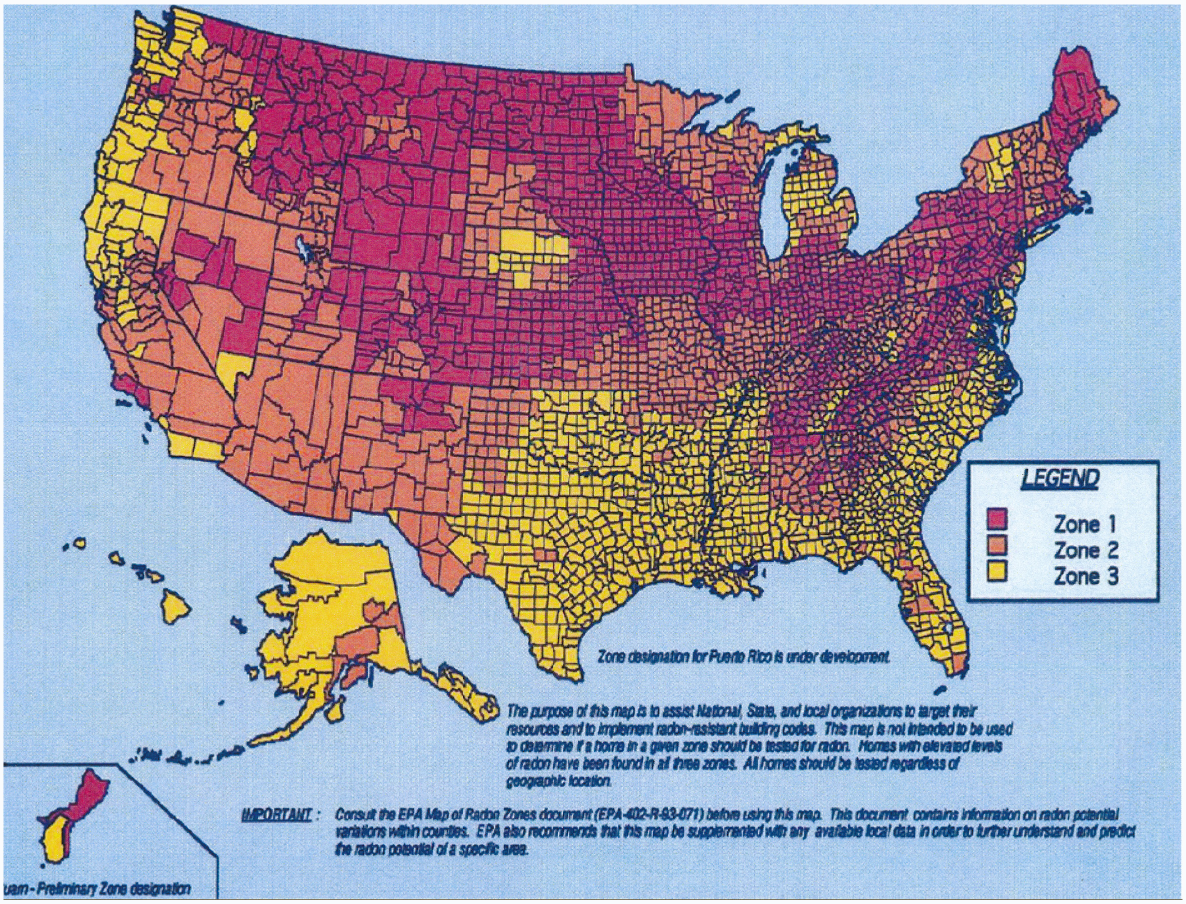


Figure 3.3-A EPA Radon Zone Map
Image courtesy EPA (2017f).

The EPA uses the following descriptions for the three radon zones:

- Zone 1: Counties with predicted average indoor radon screening levels greater than 4 pCi/L (148 Bq/m^3)
- Zone 2: Counties with predicted average indoor radon screening levels 2 to 4 pCi/L (74-148 Bq/m^3)
- Zone 3: Counties with predicted average indoor radon screening levels less than 2 pCi/L (74 Bq/m^3)

Some states have regulations that govern who can measure radon or install a mitigation system. Most states allow occupants to buy and test radon levels in their own dwelling or rental property.

Measuring radon. Unfortunately, it is not possible to determine in advance whether a new dwelling will have elevated radon levels when it is completed. The EPA recommends testing all new and existing dwellings for radon. The EPA Citizen's Guide to Radon contains guidance on measuring radon and interpreting the results (EPA 2012a).

Radon can be measured using passive samplers available at local home improvement or hardware stores and from some state radon and county extension offices. Occupants can buy and make tests in their own dwelling. A good practice is to use a test kit manufactured and analyzed by a firm certified by the National Radon Proficiency Program or the National Radon Safety Board.

Passive samplers intended for occupant use are sold in packaging that is opened and placed in the dwelling, where they collect data for two days to one year. At the end of the monitoring period, they are closed and mailed to a laboratory that reports the average concentration during the test period. It is important to read and follow the instructions on the packaging carefully to avoid tainting the results. Some types of passive samplers are:

- Charcoal canisters that record average radon concentrations for a few days
- Electret detectors that sample radon levels for up to a year
- Alpha track detectors that record average measurements from 30 days to more than a year

Continuous monitors, most often used by radon professionals, measure and record average concentrations for a series of short periods (typically in hourly intervals). Data from continuous monitors reveal changes in radon levels over time and, sometimes, underlying radon dynamics (e.g., whether well water is implicated, whether the radon source is constant or varies widely, and whether windows were opened during the test).

Measurements completed over a few days are less accurate than those made over a month or longer periods of time and should be considered as screening tests. Long-term tests, defined as tests of 90 days or longer, provide better estimates of whether a home has elevated radon levels. Because radon levels can vary by season, a one-year average provides the best indication of occupant exposure. However, if the house has very high radon levels, occupants need to know and address this problem more quickly.

The EPA (EPA 2012a) recommends that occupants conduct a short-term screening measurement over a few days in the lowest lived-in level of the dwelling. The tests should be done in a closed building condition, meaning that windows and doors remain closed, except for normal operation for occupants to enter and exit. Based on the outcome of that initial test, the EPA recommends the following actions:

Step 1. Take a short-term test. If your result is 4pCi/L (48 Bq/m^3)or higher, take a follow up test (Step 2) to be sure.

Step 2. Follow up with either a long-term test or a second short-term test:

- Use a long-term test, if possible, to estimate the year-round average radon level. This test can be done under normal living conditions.

- Use second short-term test when results are needed quickly. This test should also be done in closed-building conditions.

The higher your initial short-term test result, the more certain you can be that you should take a short-term rather than a long-term follow up test. If your first short-term test result is more than twice EPA's 4 pCi/L (148 Bq/m^3) action level, you should take a second short-term test immediately.

Step 3.

- If you followed up with a long-term test: Fix your home if your long-term test result is 4 pCi/L (148 Bq/m^3) or more.
- If you followed up with a second short-term test: The higher your short-term results, the more certain you can be that you should fix your home. Consider fixing your home if the average of your first and second test is 4 pCi/L (148 Bq/m^3) or higher.

This test protocol takes some time to complete. If a dwelling is for sale, the buyer or seller might not have time to complete a series of short-term tests or a screening test followed by a long-term test. In such cases, decisions to mitigate radon are often based only on short-term test or monitoring data. As a result, some dwellings with annual averages less than 4 pCi/L (148 Bq/m^3) are mitigated, and some with annual averages greater than 4 pCi/L (148 Bq/m^3) are not (EPA 2013b). When the radon level in a home is only slightly higher than 4 pCi/L (148 Bq/m^3), covering exposed earth in basements and crawlspaces can sometimes be sufficient for mitigation (EPA 1995).

Radon mitigation. Preventing below-grade air from entering a dwelling is usually the most reliable way to lower its radon level. This is typically achieved using sub-slab soil depressurization to intercept radon-laden air while it is still in the soil and divert it to outdoors.

In concept, sub-slab depressurization is simple. A small, low-wattage exhaust fan is used to remove air from under the house foundation. The fan maintains a lower air pressure in the soil and fill around the foundation than in the house. This reduces indoor radon levels in two ways:

1. The direction of airflow is reversed so that air in the surrounding soil no longer carries radon into the house. Instead, air from the house flows out through cracks and openings in the foundation.
2. Soil gas is pulled through the duct by the exhaust fan and sent outdoors, thereby bypassing the indoor space where it could accumulate.

Sub-slab depressurization is illustrated schematically in Figure 3.3-B. Depending on the site and foundation conditions, the capacity of the fan and the number of suction pits needed to effectively lower indoor radon levels might vary. For example, a single 19-watt fan that removes 40 CFM (19 l/s) of air from under a slab at a single location can reduce very high levels of radon to below the action level of 4 pCi/L (148 Bq/m^3) as long as the drainage layer under the slab allows air to move through it easily and the slab and footings on its sides are fairly airtight. Dwellings with less permeable drainage layers might require a larger fan or more removal points to achieve the same effect.

A drainage layer of 0.5 in. to 1.5 in. (1.3 to 3.8 cm) stone with no fines (finely crushed or powdered stone) laid on undisturbed earth, bound at the edges by concrete footings, and capped with a 4 in. (10.2 cm) concrete slab is quite permeable to the flow of air and distributes the induced low pressure to all points under the slab. As a result, the indoor radon level can drop by more than

Figure 3.3-B Sub-slab Depressurization to Stop Radon-Laden Air

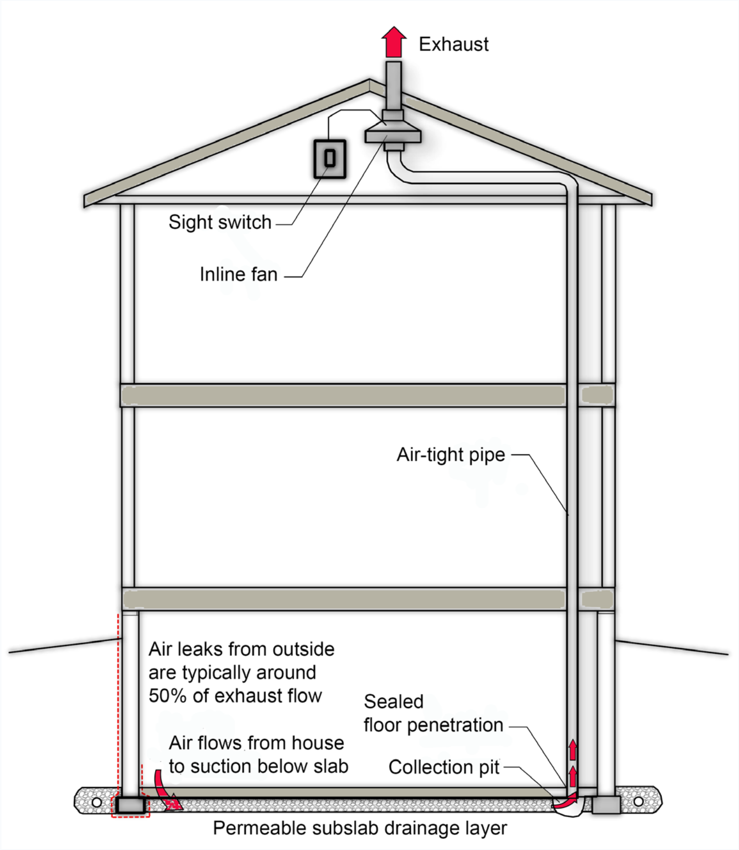


Figure 3.3-B Sub-slab Depressurization to Prevent Radon-Laden Air from Under and Beside the Foundation from Entering a Dwelling
Illustration by T. Brennan.

99% using a single fan and suction point. An interior perimeter perforated drainpipe in the fill under the slab also contributes to good air distribution there.

Conditions that interfere with distribution of the low-pressure field and reduce the effectiveness of sub-slab depressurization systems include:

- Slabs poured directly on undisturbed earth or fill consisting of clay, silt, sand, or gravel that includes a significant proportion of fines
- Footings that divide the sub-slab drainage layer into chambers
- Air leaks into the layer under the slab resulting from:
  - Gaps at the perimeter of the slab that allow outdoor air or house air to flow under the slab
  - Open sumps (water collection pits) connected to interior or exterior drainpipe (sealed covers are available to address this)

- Air-permeable materials under the drainage layer (e.g., shattered shale, glacial till, river-run gravel, or solution pipes [vertical tubes or cones in limestone])
- Ductwork under the slab

Sealing air leaks through the foundation to the soil makes the low-pressure field under the slab stronger and extends it farther. For example, air sealing the joint between the concrete slab and the surrounding foundation wall, sump basins, and open cores at the top of concrete masonry unit foundation walls helps strengthen the low-pressure field under the slab. Many air leaks in finished basements are hidden behind walls and are often only sealed if initial mitigation attempts fail.

Fan-powered whole-dwelling ventilation (Strategy 7.1) is less reliable than sub-slab depressurization for radon reduction. These systems work to remove radon by diluting the indoor radon concentration. Whole-dwelling ventilation is most likely to be successful in tight dwellings with moderately elevated levels of radon (4–8 pCi/L). Bringing in outdoor air in quantities larger than that recommended in Strategy 7.1 has potential disadvantages, such as increasing energy use and indoor humidity problems (EPA 2013a).

Weatherization of existing dwellings without mechanical ventilation can result in slight increases in radon (Pigg et al. 2014). But weatherization combined with whole-dwelling mechanical ventilation can result in decreased radon (Pigg et al. 2014, Francisco et al. 2017), even when that ventilation is exhaust only (Strategy 7.1).

Radon measurement and mitigation in multifamily buildings. Measuring and mitigating radon in multifamily housing can be particularly complex. Responsibility for radon control lies with building owners, and many occupants in multifamily buildings do not own their dwelling units (ELI and EPA 1996).

Radon levels can vary widely between one dwelling unit and another, depending on their locations in the building. For example, radon levels are most likely to be elevated in basement and first-floor units. However, AHUs in basements or crawlspaces can transport radon to upper floors. On rare occasions, elevated radon levels on upper floors have been linked to concrete used in floor slabs and walls or from granite countertops.

The U.S. Department of Housing and Urban Development sets radon policy for some of its multifamily buildings (HUD 2013). The policy, a good example of a best practice for radon measurement and mitigation in multifamily buildings, includes the following requirements:

- Radon testing in at least 25% of units and, if elevated radon levels are found, mitigation
- Notification for tenants of radon measurement and mitigation efforts
- Requirement that radon measurement and mitigation be done by professionals certified by the National Radon Proficiency Program of the American Association of Scientists and Technologists (AARST NRPP 2017), the National Radon Safety Board (NSRB 2017), or the state
- Radon measurements in accordance with the ANSI/AARST Protocol for Conducting Radon and Radon Decay Product Measurements in Multifamily Buildings (AARST 2017)

When radon mitigation is needed, it must be conducted in accordance with ASTM E 2121-13 (ASTM 2013), ASTM E 1465-08a (ASTM 2008), or ANSI-AARST RMS-MF 2018 (AARST 2018).

Radon measurement and mitigation in new construction. Installation of a sub-slab depressurization system without a fan (sometimes referred to as "radon-resistant new construction") can offer a one-time opportunity to mitigate high radon levels in new buildings at very little additional cost (Figure 3.3-C). See EPA 402-K-01-002 for guidance on installing radon-resistant features (EPA 2001). These systems also allow some radon to escape the soil passively, thus reducing the likelihood that the dwelling will experience high radon levels once construction is complete.

Figure 3.3-C Radon-Resistant Construction Features

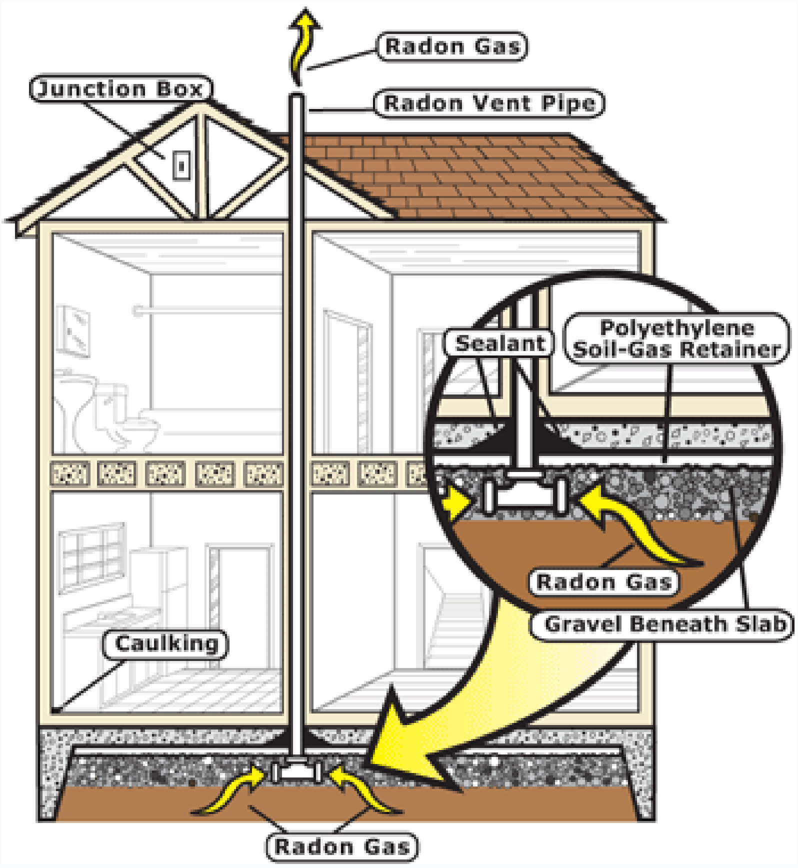


Figure 3.3-C Radon-Resistant Construction Features
Image courtesy of EPA.

Radon-resistant new construction measures for new dwellings (EPA 2001) are as follows:

- Use a 4-in. (10 cm) layer of clean, coarse gravel below the slab to allow all gases in the soil, including radon, to move freely underneath the house. In regions where gravel is too expensive or unnecessary, alternatives (e.g., a perforated pipe or a collection mat) can be used instead.
- Place heavy-duty plastic sheeting (0.15 mm or 6 mil. polyethylene) or a vapor retarder on top of the gravel to prevent the soil gases from entering the dwelling and keep the concrete from clogging the gravel layer when the slab is poured.

- Run a 3 to 4-in. (75 to 100 mm) solid PVC Schedule 40 pipe, such as the ones commonly used for plumbing, vertically from the gravel layer (stubbed up when the slab is poured) through the dwelling's conditioned space (parts of the dwelling that are intentionally heated and/or cooled to achieve comfort conditions) and roof to safely vent radon and other soil gases outside and above the house. This pipe should be installed by a plumber or certified radon specialist and labeled "Radon System." The National Radon Proficiency Program (AARST NRPP 2017), National Radon Safety Board (NSRB 2017), and state radon coordinator (EPA 2017g) provide lists of local service providers.

- Seal all openings, cracks (including the slab perimeter crack), crevices in the concrete foundation floor, and walls with polyurethane caulk to prevent radon and other soil gases from entering the dwelling.

- Install an electrical junction box (outlet) in the attic for a fan if depressurization is needed.

- Conduct radon testing after construction is complete and add the fan if the test results indicate that radon mitigation is needed.

Other Soil Contaminants

In addition to radon, several other contaminants enter dwellings through foundations from the surrounding soil, fill, foundation drainage systems, and bedrock. Those of greatest concern are below-grade contaminants related to human activities, such as:

- Gases released by the chemical and biological decomposition of materials in landfills
- Vapors from petroleum product spills in the soil or floating on nearby water tables
- Industrial solvents and cleaners released from chemical plants or commercial cleaners

In 2002, the EPA estimated the United States had 374,000 contaminated or potentially contaminated sites (EPA 2002). The contaminants are drawn into buildings by the pressure differences between indoor and outdoor air that also draw radon into houses (Figure 3.3-D). These contaminants differ from radon in several ways:

- Their sources are often chemical contamination of the soil and groundwater rather than natural radium deposits.

- Some of the contaminants are regulated by state governments.

- Exposure might involve detectable odors or cause immediate health effects, including skin or respiratory irritation or neurologic effects, whereas the only known health effect of radon exposure is an increased risk of lung cancer.

- Unlike radon, which can be measured using samplers (as described above), these other contaminants can only be measured by trained individuals using expensive sampling equipment.

Four generally approved methods are available for preventing entry of underground contaminants into buildings (EPA 2015d):

1. The below-grade contamination can be removed by excavation of contaminated soil or collection from the surface of contaminated groundwater.

Figure 3.3-D Typical Flows of Vapor from Chemical Sources Through Soil

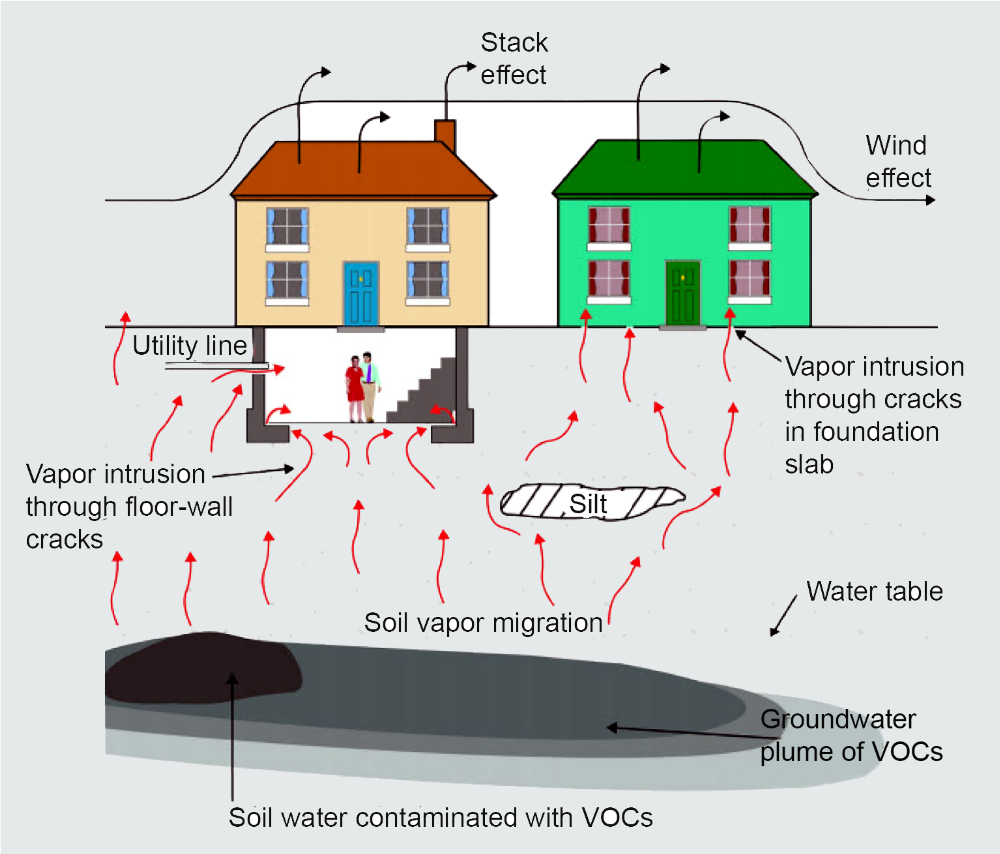


Figure 3.3-D Typical Flows of Vapor from Chemical Sources Through Soil and into Houses
Image courtesy EPA.

2. Passive barriers, or physical membranes, isolate the building from the contaminated soil (EPA 2012b).

3. Sub-slab depressurization is similar to radon control systems, but the system might need to be designed to carry explosive or corrosive gases.

4. The ventilation system can be used to pressurize a building or at least its lower portion. It is more difficult to maintain positive pressurization in a building than to depressurize the below-grade drainage layer. Above-grade pressurization requires constant operation of the ventilation systems and closure of windows and doors. Ordinary occupant and building operator behavior can inadvertently interfere with pressurization, especially in residential buildings.

For construction on sites known to be contaminated, the EPA provides detailed technical guidance for assessing and mitigating vapor intrusion problems (EPA 2015d). In addition, many states have their own guidance or regulations for vapor intrusion (Geosyntec 2017).

Strategy 3.4 Use Doormats to Keep Out Contaminants

3.4

Introduction

Dirt and moisture transported into a dwelling 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, can foster the indoor growth of biological contaminants. Roughly 30–40% of contaminants in a dwelling are brought in from outdoors (Ferguson and Kim 1991). Such contaminants as pesticides, lead, and other heavy metals have been found in tracked-in dirt. Tracked-in dirt and moisture also increase the need for indoor cleaning and thus indirectly degrade IAQ through the unnecessary release of contaminants associated with cleaning (Strategy 5.3). The best way to reduce the IAQ impact of these tracked-in pollutants is to implement effective barrier systems.

Barriers to tracked-in dirt begin with the building's exterior and include appropriate landscaping materials and plants (Strategy 2.4). Because pesticides applied outdoors can be readily carried into a dwelling on footwear, well-considered pest control strategies are also important (Strategy 3.6). A durable, non-vegetated path along the primary entry route reduces tracking of soil, plant materials, and lawn chemicals into the dwelling.

Tips on the use of doormats to keep contaminants out of the dwelling include the following:

- Entrances to multifamily buildings need good combination track-off systems to keep contaminants out of dwelling units.
- Single-family dwellings benefit from doormats just outside and just inside the entrance, but these mats must be used regularly to be effective.
- Shoe removal at the door, especially when someone enters a dwelling from a dirty outdoor location, is a good idea.

Multifamily Dwellings

To prevent dirt accumulation on footwear, well-designed and well-laid-out walkways made of textured paving materials need to be installed. An effective building maintenance and cleaning strategy also needs to be included in the operation and maintenance documentation and training (Strategy 1.5) so that building entranceways are kept clean and, to the extent possible, dry. No landscaping materials that release flowers or berries that can be tracked into the building should be planted near walkways.

Installation of effective dirt track-off (or walk-off) systems (see description below) at the most heavily used entrances is essential for a building's IAQ strategy and is required for multifamily buildings of four or more stories above grade by ASHRAE Standard 189.1 (ASHRAE 2017f). An increasing number of jurisdictions are adopting this standard or the related Green Construction Code (ICC 2015b). In addition to decreasing the amounts of outdoor contaminants brought into the building, track-off systems increase the life expectancy of flooring materials by reducing dirt abrasion of flooring materials.

Properly designed dirt track-off entry mat systems include specific combinations of mat materials, textures, and lengths. A three-part system (Figure 3.4-A) is usually recommended for multiunit housing:

- The scraper mat is an initial section with knobby or squeegee-like projections installed outside building entrances that removes loose dirt and water or snow.

- The absorption mat (also called the trapper or wiper section) is made of stiff-bristled nylon or a nylon-polypropylene blend, is located immediately inside the entryway, and removes additional dirt and moisture by brushing and scrubbing shoes.

- The finishing (or duster) mat completes the process by removing particles left after the scraper and adsorption mats.

Figure 3.4-A Recommended Doormat Layout for High-Traffic Entrances

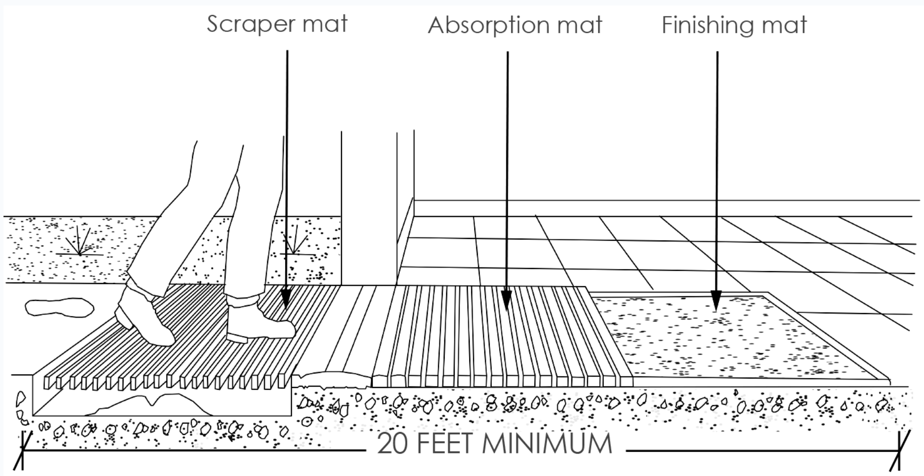


Figure 3.4-A Recommended Doormat Layout for High-Traffic Entrances
Image courtesy of EPA.

Both the scraper and absorption mats should be at least 6 ft (1.8 m) long, and the finishing mat should be a minimum of 8 ft (2.4 m) long. These lengths are based on the assumption that individuals will not wipe their shoes on the mats but, rather, walk across them (EPA 2017c).

The final design of the track-off system needs to take into consideration traffic loads and aesthetics as well as local environmental and climactic conditions. Systems in snowy climates, for example, typically require longer scraper mats, whereas longer absorption portions are needed in rainy regions.

Good outdoor design will keep people from walking in muddy locations. However, when walking on muddy surfaces is unavoidable (e.g., in athletic fields or construction sites), all three track-off zones need to be longer than described above.

Single-Family Dwellings

The recommendations for multifamily section above can be used to guide the selection of effective doormats for single-family homes, although 20 ft (6 m) lengths are not usually practical. As a rule, a coarse scraper mat, rubber fingertip, or “grate-like” drainable mat should be used outside the entrance; a shorter fiber one should be used inside; and everyone who enters the dwelling should be encouraged to use them. Water-resistant floor materials should be used near every door (Strategy 2.3).

Strategy 3.4 Use Doormats to Keep Out Contaminants

3.4

All Dwellings

The tracking of lead on shoes into dwellings has been extensively studied, and the findings are instructive about ways to reduce levels of other contaminants as well. The Washington Toxics Coalition found that removal of shoes at the door, use of high-quality doormats, and thorough vacuum cleaning can reduce the lead in rugs by a factor of 10 or more (Toxic Free Futures 2014). Shoe removal might reduce the lead in rugs by six times, and walk-off mats might result in tenfold reductions, although these estimates and approaches are based on limited scientific evidence (EPA 2000).

Strategy 3.5 Use Design, Building, and Maintenance Strategies to Resist Pests

3.5

Introduction

Pest species that colonize dwellings affect the indoor environment in several ways:

- They can be sources or vectors of environmental hazards. For example, molds, dust mites, insects, and rodents can be sources of allergens, asthma triggers, or disease triggers.
- Some organisms (e.g., rodents and cockroaches) produce objectionable odors.
- Their presence can trigger inappropriate use of legal or illegal pesticides, which may expose occupants to these pesticides.

It is possible to design and construct dwellings that are resistant to colonization by pests. All colonizing organisms need access to enter the dwelling; sources of food and water within or near the dwelling; protected locations where they can eat, rest, and find a mate (harborage); and passages that allow them to safely move between entryway, food, water, and harborage. Left to their own devices, a colonizing organism population will expand until it reaches equilibrium with the available food, water, and harborage. Each dwelling therefore has a specific carrying capacity for each colonizer (Figure 3.5-A).

If pesticides or trapping alone are used to reduce the population, it will return to carrying capacity when the trapping or pesticide use stops. If, however, the entry points to the dwelling, nest sites, food, and water locations are sealed, the carrying capacity will drop (Figure 3.5-A). Removing pest food or storing human food (and food waste) in pest-proof containers further lowers carrying capacity. Pest-proofing a dwelling can drastically reduce the need for pesticide use.

The steps to design a dwelling that resists colonization are as follows:

1. Identify the organisms likely to colonize the dwelling.
2. In the design, identify the likely entry routes, food and water sources, harborage sites, and passageways between them. Kitchens and garbage handling areas are likely to provide food for many different organisms.
3. Consider using pesticides during construction of the dwelling. For example, a termiticide or bait system is needed in many climates to prevent termite colonization.

In occupied dwellings, problem species can be identified through inspections for signs of biological growth, wood-destroying insects, nests, feces, urine, gnaw marks, or carcasses and by trapping. Entry points and harborage sites can be identified by inspection.

Techniques to prevent pests from entering a dwelling include the following:

- Create a strip of ground surrounding the dwelling that offers no harborage because it is open and therefore frightening for pests to cross and is difficult for burrowing species to tunnel through.
- Form tight seals between the foundation, exterior walls, and roof or ceiling to make a complete, continuous barrier.
- Install continuous pest barriers around kitchens, food storage rooms, and trash-handling areas.
- Supplement architectural interventions, when needed, with the judicious use of appropriate pesticides during construction.
- In multifamily buildings, train staff or find a pest control contractor that is well versed in integrated pest management exclusion methods and is willing to implement them.

Figure 3.5-A Effect of Changing the Carrying Capacity for a Pest Species

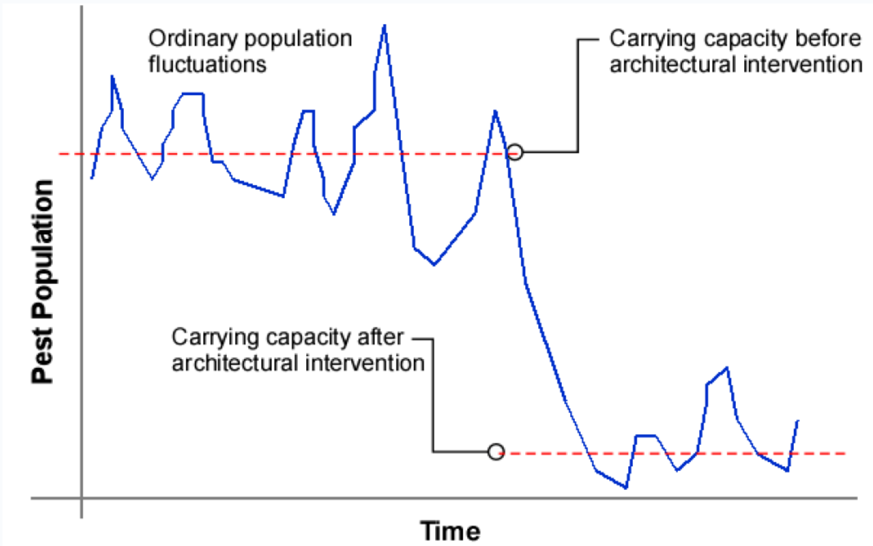


Figure 3.5-A Effect of Changing the Carrying Capacity for a Pest Species

Pests of Concern

Some pests are of concern only in specific climates. For example, scorpions, rattlesnakes, and Formosan termites are problems in only some geographical areas. Red squirrels and white-footed mice are more common in rural dwellings than in urban ones.

Local offices of the U.S. Department of Agriculture's Cooperative Extension System are good sources of information on vertebrates, insects, and fungi that are likely to colonize dwellings in a particular location (CES 2008). Other good sources are county extension offices (USDA 2009), building inspectors, and vector control staff at local health departments.

The most common pest species in dwellings include:

- Mammals: Rats, mice, squirrels, and bats
- Birds*: English sparrows, starlings, and pigeons (all other bird species are federally protected in the United States and may not be killed).
- Arthropods: Cockroaches, ants, termites, yellowjackets, dust mites, and bedbugs

General principles for controlling these pests are described below. Detailed information on the identification, biology, habits, and control approaches for specific organisms can be found in other sources (Ebeling 1978; Olkowski et al. 1991; CDPR 2007; EPA 2008a, EPA 2008b).

In existing dwellings, specific pests can be identified by observing the creatures, damage they

have caused, and nests they have built. Traps can also be used to monitor pests. Pests can often be found inside walls; under or behind cabinets; in basements, crawlspaces, and attics; in waste bins; under baseboards; and, for insects, in warm cavities, such as inside television sets, computers, and smoke alarms. Figure 3.5-B shows two mice that climbed into a waste basket and could not climb back out (the small black dots are waste droppings). Figure 3.5-C shows cockroach droppings in a kitchen cabinet.

Figure 3.5-B Mice & Figure 3.5-C Droppings

Figure 3.5-B Two Mice Caught in a Wastebasket

Figure 3.5-C Cockroach Droppings in a Kitchen Cabinet

Pest Entry

To colonize a dwelling, creatures must get inside, find food and water, and find a place to meet and mate where they will be hidden from occupants who will crush them or spray them with pesticide if they draw notice.

Pest species enter dwellings by several different routes, including through:

- Open doors and windows
- Gaps around doors and windows
- Gaps between the foundation and the upper portion of the dwelling
- Below-grade openings in crawlspaces and basements
- Drainage and sewer pipes
- Intermediate areas, such as porches, sheds, basements, crawlspaces, attics, and attached garages, which often offer safe harborage for pests because they are poorly sealed against entry and because of hidden openings between them and the main part of the dwelling

Some pests, such as dust mites, cockroaches, and bedbugs, are carried into dwellings on people or in boxes, bags, or furnishings.

Rodents, insects, and birds that cause problems in dwellings usually enter through gaps and openings in the dwelling enclosure. Stopping them requires identifying and sealing the likely

entryways and discouraging entry by making the approach to the dwelling less appealing.

Steps to make the exterior of a dwelling less appealing to pests are as follows:

- Create a strip of ground surrounding the dwelling that offers no harborage because it is open and therefore frightening for pests to cross and is difficult for burrowing species to tunnel through.
- Keep dumpsters and garbage cans at least 20 ft (6 m) from the dwelling.
- Place pesticides or bait stations for termites in the soil near the dwelling.

Figure 3.5-D Sealing a Potential Entry Route Where Refrigerant Lines Run Through a Wall.

Barriers in the Dwelling Enclosure

Keeping pests out of building materials requires tight seals between the foundation, exterior walls, and roof or ceiling to make a complete, continuous barrier. Many of the same approaches described in Strategy 2.1 for constructing an air barrier can be used to accomplish this.

The first step is to trace a continuous pest control barrier from the middle of the roof around the walls and down to the middle of the foundation floor. The next step is to identify the materials in each assembly that present a barrier to pest migration. Building materials offer varying levels of protection from different creatures. Examples are as follows:

- Concrete, masonry materials, and steel are impervious to damage by all pests.
- Many building materials, such as plywood, gypsum board, siding, OSB, and windows, are good barriers to the entry of birds, bats, and many insects.
- Plywood, OSB, and aluminum flashing usually keep out rodents.
- Concrete, galvanized steel lath or hardware cloth, and copper or steel mesh to stuff gaps and holes are very resistant to rodent damage (see Figures 3.5-D, 3.5-E, and 3.5-F).

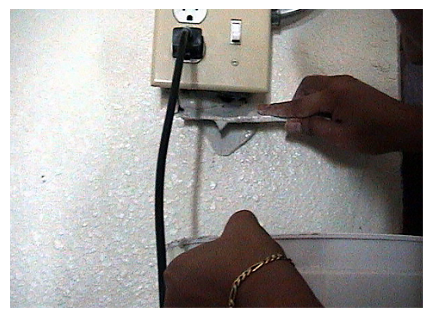


Figure 3.5-E Sealing a Hole in a Plaster Wall Using Plaster Patch

Figure 3.5-F Copper Mesh Used to Stop Openings

However, if rodents want to enter a dwelling, perhaps because it contains a kitchen or a garbage storage area, they can gnaw

through plywood, OSB, and even aluminum flashing. Materials used to fill the gaps and seal the cracks also have vulnerabilities. Foam insulation and caulk, for example, can block insects but not rodents.

The pest control barrier materials used should be based on the species to keep out and the attractiveness of the food, water, and harborage resources inside the dwelling. Materials used to seal gaps between building materials and exclude pests must be durable. For example, a rodent can enter a gap between two treated boards that form a mudsill on top of a foundation wall. A mouse can enter through a gap as small as ¼ in. by 3/8 in. (6 mm by 10 mm). A rat can enter a gap as small as 5/8th in. by 5/8th in. (16 x 16 mm).

If the dwelling offers entry to conditioned harborage with few food resources, these openings can be sealed with aluminum flashing or pieces of wood. Because dwellings have kitchens where food is stored and eaten in the building, resistant materials, such as galvanized steel flashing, copper or stainless-steel mesh, or concrete filling are suitable options. Special effort should be made to create pest barriers around all potential food sites inside the dwelling (see “Additional Barrier-related Pest-Control Steps” below).

Creating barriers to the entry of most insects (except for termites) is both easier and harder in some ways than for rodents. It is easier because many common building materials (e.g., caulk, gypsum board, plywood, and OSB) are barriers to flies, wasps, cockroaches, beetles, and many species of ants. However, insects can squeeze through much smaller openings than the smallest rodents. A 0.2-in. (5 mm) crack is large enough for an adult cockroach to enter. Careful sealing of joints and gaps with caulks, adhesive membranes, or high-density rigid foams can prevent many insects from entering the dwelling. A list of materials that are useful for sealing gaps and openings to prevent pests from entering dwellings is presented in Table 3.5-A.

Recommendations for blocking, sealing, or eliminating pest entry points as part of the design and building process include the following (Frantz 1988; Merchant 2009; Simmons 2007a, 2007b; EPA 2008a, EPA 2008b):

- Seal gaps or flaws in foundations or slabs, or where wall framing meets the foundation or slab floor (see Figure 2.1A).
- Extend foundations below ground vertically by 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 dwelling.
- 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).
- Seal utility entry points (e.g., pipes, cables, electrical conduit, ducts, exhaust vents, louvered vents, underground electrical lines, and external meter boxes) on the dwelling’s exterior.
- Place screens over air intake and exhaust vents for HVAC systems. When possible, use screens on doors, hatches, skylights, and other openings. Cover fan and vent openings with galvanized mesh that has openings of 1/4 in. (6 mm) or smaller.
- Design exteriors so that they provide no access to wall cavities (e.g., have no holes larger than 0.25 in. [6.4 mm] in diameter); modify weep holes with screening to prevent insect access.

Table 3.5-A Materials that can be used to seal or block gaps

Type of Material	Target Pests	Size of Cap Material Can Fill	Advantages	Other Considerations
Polyurethane foam sealant	Birds, bats, and rodents (if reinforced with metal mesh)	Irregular openings larger than 3in. (75 mm)	Easy yo use, cures to rigid plastic foam	Can provide harborage for insects if not protected; codes limit use due to flammability
Caulking	Insetc, bats, and rodents (if reinforced with metal mesh)	Gaps of up to 0.4 in (10 mm)	Flexible, easy to use, available in a variety of materials and application methods	Durability varies by caulking type
Corrugated plastic weep hole inserts or board stock	Insects, bats, birds, and some rodents	Gaps of 1/4 to 1/2 in (6.4 to 50 mm)	Easy to use, does not become corroded, maintains drainage and ventilation through weep holes, boared stock can double as a means for water to drain from the wall cavity	N/A
Metal screening	Insects, bird, rodent, and bats	Unlimited	Blocks openings but allows ventilation	Needs to be sized appropriately for type of pest; because screening restricts airflow, could require vent resizing
Copper or stainless steel woven mesh louvers	Insects, birds, rodents, and bats	Can be stuffed into gaps of 1/8 to 1 in. (3 to 25 mm), can be used for larger gaps if combined with caulk or foam, can be used to seal openings up to 4 in. (102 mm) wide	Flexible, easy to use, allows ventilation, can be used to rein-force caulk or foam	Might need to be secured so that rodents cannot re-move it, should only be used if metals are corrosion resis-tant, code-required on ventilation inlets and outlets

Table 3.5-A Materials That Can Be Used to Seal or Block Gaps and Holes in Dwellings
Sources: Frantz (1988) and EPA (2008b).

Insect control. It is difficult to prevent insects from using the space behind sidings as harborage or nesting sites because sidings are usually designed to drain rain and allow the space behind them to dry. Yellowjackets, honeybees, cluster flies, and solitary wasps often make nests behind brick veneers, horizontal or vertical sidings, and panels. They can be kept out of the cavities behind brick veneers by plastic insert vents in weep holes and by mortar and caulks to seal window, door, and utility penetrations.

Table 3.5-A Materials that can be used to seal or block gaps (cont'd)

Type of Material Cont.	Target Pests Cont.	Size of Cap Material Can Fill Cont.	Advantages Cont.	Other Considerations Cont.
Sheet metal	Birds, rodents, bats, and some insects	Openings and cracks from a fraction of an inch to several inches	Resists rodents well	Can be made of steel or aluminum
Concrete, mortar, brick, cement masonry, or mortared stone	Insects, birds, rodents, and bats	1/4 inch (6 mm) or larger	Durable, structural materials; can fill large openings	Usually used to seal holes in concrete or masonry walls or floors; can be used to fill abandoned pipes
Plastic netting	Bats and birds	Almost unlimited	Strong, stable in ultraviolet light, durable for outdoor use	Can be installed in a way that allows removal for maintenance and inspection
Needle strips or wires	Bats, birds, and rodents	N/A	Slightly more flexible uses than plastic netting	Can interfere with dwelling appearance

Table 3.5-A Materials That Can Be Used to Seal or Block Gaps and Holes in Dwellings (cont'd)
Sources: Frantz (1988) and EPA (2008b).

It is more difficult to keep insects out of the space behind clapboards, vertical board, and batten or panel sidings because many linear feet of cracks and openings need to be sealed, some are difficult to seal effectively, and the cracks and joints are often an essential for controlling rainwater. Effectively preventing insects from entering the space behind siding requires careful detailing and installation of barriers at joints. Copper or stainless-steel mesh, stainless-steel screening, and corrugated plastic vent strips are good for sealing sidings because they cannot be damaged by insects and allow rain to drain along with air movement for drying. Whether sealing the cavity behind siding is worthwhile to keep insects out depends on the extent of potential damage as well as the work and costs involved.

Dust mites, which are approximately 0.12 in. (0.3 mm) long, and bedbugs travel into dwellings on people and their belongings. Dust mite control consist of dusting, vacuuming, changing bed linens, limiting clutter and humidity control. Bedbug populations are concentrated in U.S. cities that have many international travelers, such as New York, Washington, DC, and San Diego. Travelers who return from bedbug-infested areas should inspect their luggage and clothing, wash clothing in hot water and dry it in a hot dryer. Treatment for bedbugs once there is an infestation is complex. (EPA 2018b).

Additional barrier-related pest-control steps. Occupants should make a list of the possible sources of food (e.g., kitchens, trash cans, trash compactors, trash chutes, and pantries). The exclusion methods used on the enclosure can be used in these areas. Continuous pest barriers should be installed around kitchens, food storage rooms, and trash-handling areas. Kitchens and pantries

should be easy to clean and have few cavities for pests to live in. Trash rooms, chutes, and storage areas need to be particularly well shielded from pests. Recommendations for reducing pests' access to food and water as part of the design and build process include the following (Simmons 2007a, 2007b; EPA 2008b):

- See that new kitchen appliances and fixtures have a pest-resistant design (e.g., an open design with few or no hiding places for cockroaches or freestanding sections on casters for easy and thorough cleaning).
- Provide space under and around appliances and equipment in kitchen areas to allow maximum ventilation and ease of (steam) cleaning, and slope kitchen floors to provide good drainage after cleaning.
- Use cove molding at floor-to-wall junctures to minimize build-up of debris and facilitate cleaning. Be sure the molding fills the corner, fill the cavity with mortar or caulk, or consider dusting the cavity with boric acid (see section below on pesticides for more information about boric acid).
- In kitchens 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 or animal rooms.
- See that all pipe insulation has a smooth surface without gaps between pieces.
- Place outdoor garbage containers, dumpsters, and compactors on hard, cleanable surfaces, and, where possible, at least 50 ft [15 m] from doorways.
- Use a solid enclosure for the trash and recycling site that extends to the ground. Use smooth metal or synthetic materials to prevent rodents from gnawing and climbing on the enclosure.
- See that trash storage areas can be closed off from the rest of the dwelling.
- Equip storage areas with self-closing doors.
- Insulate pipes in areas that are prone to condensation, a significant source of water for pests.
- For landscaping, choose plants that shed a minimum number of seeds and fruits that can attract and support insects, rodents, and undesired birds.
- Place concrete or asphalt pads along the exterior walls to help prevent rats from burrowing into the building.

Pesticides

Architectural interventions might need to be supplemented with the judicious use of appropriate pesticides during construction (e.g., if a persistent pest population needs to be reduced before or after use of exclusion techniques). Whenever possible, the least-toxic pesticide should be chosen. Any supplemental pesticides used should be approved for the intended purpose by local and other authorities. Regulations for the storage, application, and disposal of pesticides used at the

site and worker safety should be followed. Pesticide use is worth considering for cockroaches and termites, and pesticide use is sometimes required by law for termites. More detailed information on pesticides and other treatment options is available elsewhere (Olkowski et al. 1991; EPA 2008b).

Pregnant women should be especially careful to avoid exposure to lawn-care pesticides because each of the five most popular lawncare pesticides is associated with birth or reproductive effects (EHHI 2003). If these products must be used, recommended precautions should be followed during use, and only limited quantities should be purchased to avoid the need to store them.

A multistep approach can be very effective at keeping cockroach and rodent infestations out of food and garbage storage sites. A qualified pesticide applicator should apply the lightest dusting of a low-toxicity pesticide (e.g., one containing boric acid) in the most vulnerable cavities (e.g., the kick space or wall cavities containing plumbing or gas lines connected to kitchen sinks, dishwashers, and gas ranges). Each cavity is then carefully sealed, and all entries to the cavities (e.g., gaps around pipes and conduits and joints between gypsum board and wall framing) are sealed with caulk. Copper mesh is then stuffed into gaps large enough for mice to enter, and the gaps are sealed with caulk. This approach provides a double defense, and pests are unlikely to enter. If cockroaches do enter these spaces, they are killed within a few days. Only pesticides approved by the EPA for indoor use should be considered.

Some food resources in and around dwellings are attractive to pests but not people. Wool and grains are attractive to clothes and meal moths, and wooden materials are food for termites. In the United States, termite control usually involves a combination of exclusion, preemptive pesticide and bait application, monitoring for infestation, and treatment of the nest when infestation occurs. To prevent termite infestations, building codes call for foundation materials and mud sills in contact with these pests to be made of materials that are resistant to attack. Low-toxicity treatments made with boric acid that are effective against termites are available for wooden materials indoors. Some termiticides are effective in exterior soil treatments where water reduces the effectiveness of boric-acid–based treatments.

Desirable characteristics for termiticides applied to soil are:

- Long-term effectiveness in below-grade conditions
- Greater toxicity to termites than to mammals or fish
- Inability to be detected by termites (to make less-than-perfect coverage far more effective)
- Low mammalian toxicity (reported lethal dose 50% [LD50] greater than 200 mg/kg when tested by ingestion using rodents)

In Australia, some termite control systems use exclusion techniques only (e.g., application of fine stainless-steel mesh and mastic, a plant resin, to all probable entry routes). Some of these products are available in the United States, but they must have local and state building code approval before they are used, and they might also need to be acceptable to insurance companies. They are intended for use in new construction rather than existing homes.

Pests can find harborage and food and water in ancillary spaces, such as garages, sheds, and crawlspaces. For example, rats, mice, ants, cockroaches, snakes (attracted by the rodents), starlings, English sparrows, and bats might make their dwellings in these spaces, and they might

venture into the dwelling or outdoors for food. If a large pest population lives near a dwelling, a tiny fraction that enters the dwelling could seem like a large infestation. For example, if the soil next to a dwelling with a slab-on-grade foundation has several hundred springtails (tiny insects) per cubic inch, hundreds or thousands of springtails might enter the dwelling every day. They cannot colonize the dwelling, but they must still be dealt with. Several species (e.g., book lice and storage mites) do colonize dwellings because of mold (often inside wall cavities). Following the moisture control guidance in this document can prevent colonization by these organisms (Strategy 2.1).

Pest Control for Multifamily Buildings

Pest control in multifamily buildings and rental properties is more complex than in single-family, owner-occupied buildings. The integrated pest management principles are the same, but there is a division of responsibility between the property manager and the residents. Depending upon the agreed upon division of responsibility, either party may need to perform activities to block pest entry, eliminate harborage sites, and clean the building and landscape.

Most multifamily building managers hire pest control contractors to respond to infestations, but different contractors devote different amounts of attention to sealing pest entry routes. Managers must therefore train their own staff or find a pest control contractor that is well versed in integrated pest management exclusion methods and is willing to implement them. The scope of services for contractors to bid on can include sealing and cleaning the building.

Individual unit residents can be allies or sources of problems. If the manager makes it easy for them to report pest problems and responds effectively when problems arise, residents are more likely to help manage pests by, for example, helping keep the trash disposal system clean and functioning. If, however, residents decide that their manager is not responding appropriately, they might use harmful or illegal pesticides or use them improperly.

In multifamily buildings, the exclusion principles must be applied to the interior walls, floors, and ceilings that separate dwellings from neighboring spaces (e.g., other units, corridors, shafts, stairwells, trash storage rooms, trash chute rooms, mechanical rooms, electric and gas meter rooms, and tenant storage areas) and the entire building enclosure. Apartments can be sealed during construction and renovation, but sealing is far more difficult in occupied buildings because it requires occupants to move their possessions away from the walls so that all baseboard and ceiling trim can be inspected, cleaned, and sealed.

ASHRAE has previously published case studies of compartmentalizing apartments (ASHRAE 2009).

Strategy 3.6 Control Entry of Contaminants from Unoccupied Spaces

3.6

Introduction

Garages, attics, crawlspaces, and basements are the most common attached unoccupied spaces that can transfer contaminants and moisture into a dwelling's living space. Of these, only garages can be detached, which usually eliminates their risk of contaminating the living space.

Effective contamination-control strategies for unoccupied spaces include reducing contaminants in these spaces, air sealing the interface with the living space, maintaining favorable pressure differences (Strategy 6.3), and not installing air ducts in these spaces. New dwellings offer the greatest opportunity to implement these strategies.

For existing dwellings, any obvious IAQ problem in one of these adjacent spaces should be fixed immediately. It is not enough to exhaust air from a moldy crawlspace and air seal its interface to the house. The moisture problem must first be addressed and the mold remediated.

Some dwellings have other unoccupied spaces, such as workshops, spa rooms, greenhouses, and hobby rooms. These spaces should be detached from the dwelling, if possible. If they must be attached, the approaches described here can also be applied to them.

The best ways to avoid transferring contaminants from garages, attics and basements into the home are to do the following:

- Install an exhaust fan in the garage.
- Air seal the interface between the house and garage.
- Do not install any HVAC equipment or ducts in the garage.
- Always open the garage door before starting the car and do not idle the car in the garage even if the door is open.
- Do not store hazardous materials in the garage, attic or basement.

Garages

Attached garages can be a source of vehicle contaminants, including carbon monoxide, nitrogen oxides, and benzene. Air transfer can be more pronounced when the garage shares a large surface with the dwelling or is under it, especially during cold weather and windy conditions.

Contaminants can migrate from the garage to attics and crawlspaces and then into the dwelling (Figure 3.6-A). Passive vents or intentional openings in the garage are not a reliable way to vent garage contaminants to the outdoors. A much better approach is to air seal the walls and ceilings between the garage and house and between the garage and other unoccupied spaces. The air sealing should include weather stripping of the door between the house and garage, sealing of any piping or electrical penetrations, caulking on the bottoms of walls, and air sealing of the band joist area. Access hatches between the garage and attic or crawlspace should be constructed of an airtight material and weather stripped, and any other penetrations to these spaces should be sealed (Merrin et al. 2017).

HVAC equipment and ductwork in the garage should be avoided because they provide a pathway for the transfer of large amounts of air even if the ducts are air sealed. In existing dwellings, duct sealing can be helpful but is not sufficient to prevent contaminant migration from the garage. AHU cabinets are often leaky and difficult to air seal completely (Cummings et al. 2003). Adding a continuous depressurization fan in the garage is especially important when the garage has ducts or air handling equipment (Merrin et al. 2017).

Figure 3.6-A Pathways for Contaminant Flow from a Garage to a Dwelling

Figure 3.6-B shows a crawlspace access hatch in a garage floor. The door is not airtight and can allow garage contaminants to migrate into the crawlspace and eventually into the living space above.

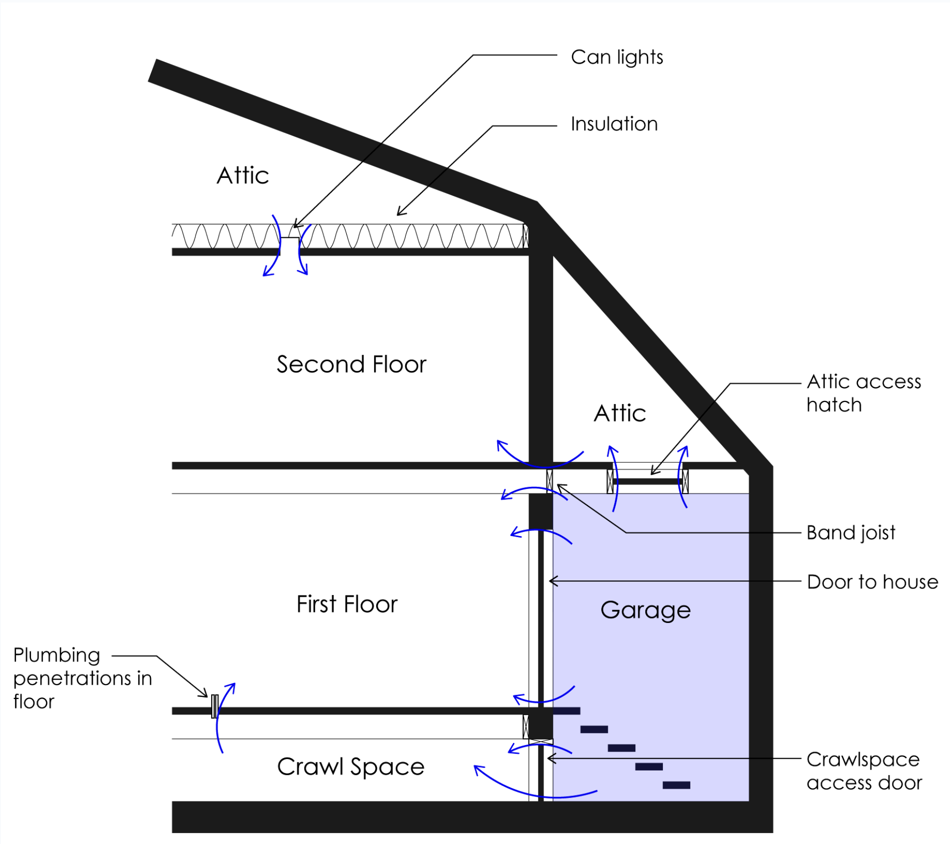


Figure 3.6-A Pathways for Contaminant Flow from a Garage to a Dwelling

Using a fan to exhaust air from an attached garage is a best practice to limit migration of contaminants into the dwelling. This strategy is included in such programs as EPA's Indoor AirPLUS and LEED for Homes. The continuous-exhaust fan (or combination of exhaust fans) should remove a total of 100 CFM (47 l/s) of air per vehicle bay from the garage to the outdoors. Spaces inside garages that are not intended for vehicles (e.g., workshop areas) should be considered in calculations of the number and strength of exhaust fans needed. Control strategies that operate the fan(s) based on door operation or contaminant concentration rather than continuously have less consistent results; therefore, a continuously operating fan is best (Merrin et al. 2017).

Hazardous materials, such as paints and pesticides, should be stored outside, away from doors and windows, and not in an attached garage. The best practice for most occupants is to avoid storing these materials. Modern paints can be easily color matched if needed for touchups, and

stored paint usually dries out anyway. Hazardous materials can pose other risks, including risks of fire and poisoning. Homeowners who insist on storing these materials should buy, build, or rent a shed that is separated from the dwelling.

Figure 3.6-B Crawlspace Access in a Garage Floor—A Pathway for Contaminant Flow

Vented Attics

Attics that are vented to the outside should be air sealed and insulated at the attic floor to separate them from the occupied space below. Air sealing the attic floor reduces energy loss and the transfer of contaminants (including dust, insulation fibers, and humid air) and pests into the living space.

Details on air sealing the interface between attics and other attached spaces can be found in the Department of Energy's weatherization standard work specifications (Office of Energy Efficiency & Renewable Energy 2017), EPA healthy indoor environment protocols for home energy upgrades (EPA 2017m), and, for multifamily buildings, EPA Energy Savings Plus Health guidelines for multifamily buildings (EPA 2017e).

Duct leakage is a major route of entry for attic contaminants into a dwelling. AHUs and ductwork, which are frequently located in attics, are never perfectly airtight and are often quite leaky. Some regions have duct-testing requirements in their building codes, and strict enforcement of these requirements results in tight ductwork. Above-code programs, such as ENERGY STAR and LEED, also require ductwork testing for airtightness (Strategy 1.4).

Even when an AHU is not operating, leakage in the AHU itself and in ducts and gaps around the boots where the ductwork enters the living space can allow contaminants to passively enter the dwelling. When the HVAC system is on, leakage in return ductwork increases this air exchange as air from the attic is pulled into the system and distributed to the living space (Figure 3.6-C). For all these reasons, HVAC equipment and ductwork should not be placed in a vented attic (Strategy 1.2).

The most important steps to prevent contamination of existing dwellings from attached garages, crawlspaces, basements, and attics are:

- To the extent possible, air seal the boundary between these spaces and the occupied portions of the home.
- Air seal the ducts and AHUs in unconditioned spaces.
- Add a garage exhaust fan, especially if the garage has ducts.
- Avoid storing paints, pesticides, or other hazardous materials in these spaces.
- Inspect these spaces at least twice a year for signs of high humidity or moisture problems.

Unvented Attics

Unvented attics solve some but not all of the problems of vented attics. An unvented attic becomes part of the conditioned dwelling and is thermally isolated from the outdoors with an

airtight enclosure at the roof level. The attic has no insulation in the floor, so its thermal conditions are much closer to those of the dwelling below. Other potential benefits of unvented attics include the following:

- Air sealing at the roof level is usually more effective than at the ceiling level. The result is a more airtight enclosure and less introduction of outdoor contaminants, pests, and humidity from outdoors.
- The absence of insulation in the attic floor allows cleaner storage or activity in the space without introducing insulation fibers into the dwelling. Insulation installed at the roof level is usually less prone to damage by occupants.
- The conditions in an unvented attic are more suitable for installation of HVAC equipment and ductwork. However, duct sealing is still important to prevent large pressure imbalances between the attic and dwelling.

Unvented attics can sometimes experience elevated humidity levels, particularly in hot and humid climates and when humid outdoor air enters the attic because of weather-driven pressure differences. If the attic has air-conditioning ducts, condensation can develop on their surfaces. If possible, the air seal of the attic roof should be improved, and a small amount of supply air from the air-conditioning system should be supplied into the attic. It is not necessary to collect return air from an unvented attic. However, in rare cases, a dehumidifier might be needed.

Figure 3.6-C Distribution of Attic Contaminants Caused by Return Leakage

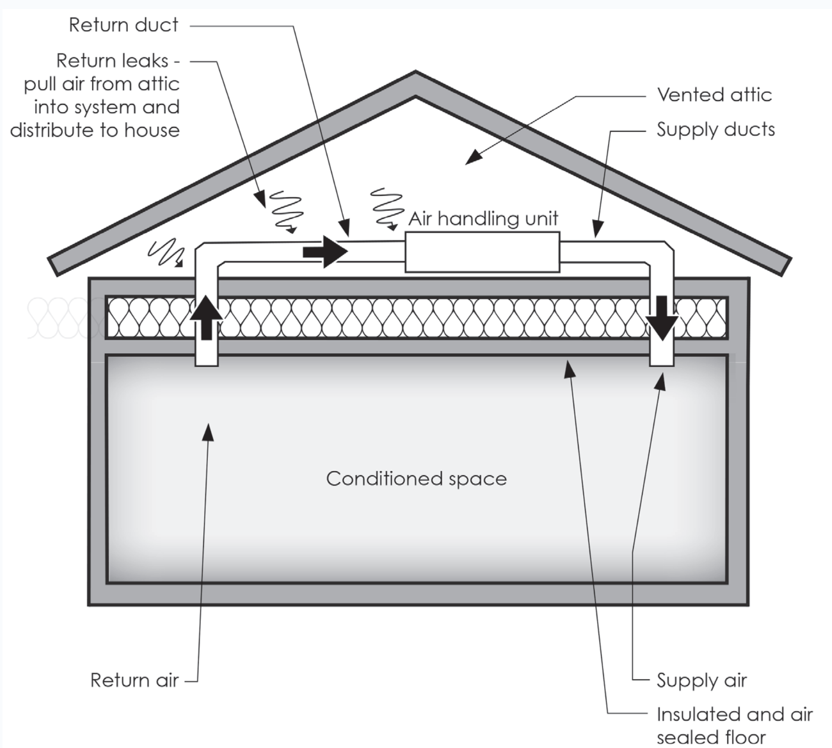


Figure 3.6-C Distribution of Attic Contaminants to the Living Space Below Caused by Return Leakage

In the winter, the temperature and humidity inside an unvented attic are usually very close to those inside the living space, so an unvented attic is unlikely to experience different or worse wintertime moisture problems than the living space. Wintertime humidity problems are discussed in more detail in Strategy 2.2.

Vented and Sealed (Unvented) Crawlspaces

Crawlspaces are popular because they are less expensive locations than basements for piping and utilities. HVAC systems should not be placed in vented crawlspaces for reasons described below. The ability to reach these systems allows flexibility in the living space and convenience if repairs are needed. Crawlspaces are also more flexible than slab-on-grade construction and, in some regions, are useful storm shelters. However, they are prone to moisture problems in many climates. Strategy 2.1 discusses management of moisture in building enclosures in more detail. Because moisture is the main source of contaminant in-migration from crawlspaces, additional details are provided here on how to reduce the potential for the transfer of these contaminants to the living space.

Regardless of the crawlspace type, moisture problems in crawlspaces might not be detected for a long time because occupants rarely look inside them. All crawlspaces should be checked at least twice a year for signs of water intrusion or plumbing leaks, and they should be sloped to a floor drain or sump pump that can remove water if it does collect inside. The grading around the dwelling should slope away, and vents should be high enough that surface water does not enter.

Vented crawlspaces. When a crawlspace is vented, the floor above the crawlspace forms the dwelling's thermal and pressure boundary (the insulation and air barrier layers, described in Strategy 2.1). The floor is air sealed to prevent energy loss and the transfer of contaminants into the living space, particularly in cold weather. Piping, duct, and wiring penetrations, often under or behind sink cabinets, are the most common sites of air leakage in the floor. Dimensional lumber subflooring or plank flooring with no subfloor allows leakage along each crack between boards. Working from the crawlspace side to seal the floor is the most effective strategy because the leaks usually cannot be seen from the occupied space. However, air sealing the floor can be difficult in older dwellings that do not have a continuous subfloor.

Do not leave any exposed earth in the crawl space (Advanced Energy 2005). As with a vented attic, HVAC equipment and ductwork should not be placed in a vented crawlspace to avoid spreading contaminants and humid air into the living space.

In dry climates, vented crawlspaces are common and rarely develop moisture problems. In flood-prone areas, crawlspaces are designed with vents that allow them to flood and drain.

In all other circumstances, vented crawlspaces are not recommended because they are more prone to high humidity and pest intrusion than unvented ones. Moisture problems are common when vented crawlspaces are used in humid and semi-humid climates. Humid outdoor air enters through the crawlspace vents and forms condensation on cool surfaces inside the crawlspace, including on the floor, and other metal surfaces.

Crawlspace problems can become severe because they often persist for a long time before anyone notices them. One telltale sign of airborne dampness in a crawlspace is that the tips of

flooring nails (seen from the crawlspace) penetrating through the floor surface become rusty.

Sealed crawlspaces. Sealed, intentionally dehumidified crawlspaces have been shown to reduce the likelihood of moisture problems (Davis and Dasfur 2004) and the related transfer of these contaminants to the occupied part of the dwelling. Less than 60% RH inside the crawlspace is a good target. They can also save energy by tightening the building enclosure, making the insulation and air barrier assembly more effective, and reducing duct leakage to the outdoors. Several approaches are available to successfully seal a crawlspace (Figure 3.6-D), and details on strategies for new and existing dwellings are available elsewhere (Advanced Energy 2005, 2017).

Figure 3.6-D Sealed Crawlspace with Wall Insulation

When a crawlspace is sealed, the two biggest decisions are where to locate the insulation and which dehumidification method to use. The insulation for a sealed crawlspace can be on its walls or the floor above it. This decision is usually based on cost and local custom. Floor insulation is often less expensive in dwellings on steep sites with very tall crawlspaces. For wall insulation, a fire-rated rigid insulation board or closed-cell spray foam with an ignition barrier must be used. These types of insulation can be expensive when the wall is large. In heating-dominant climates (where more energy is used for heating than cooling), floor insulation has a modest energy efficiency advantage, particularly if the crawlspace is tall, because of the additional wall surface area. In climates where more cooling is used, insulating the crawlspace walls is more energy efficient. For most dwellings, the difference in energy use between the two methods is not large enough to be the only factor to consider when choosing an insulation approach.

The dehumidification method used in a sealed crawlspace is often a critical climate-specific decision. Four methods allowed by building codes include:

1. *Supply conditioned air to the crawlspace.* This method is effective in climates with a long cooling season during which the dwelling's air conditioner operates. This strategy is automatically implemented by the air conditioner, which the occupants are likely to repair if it develops problems. However, this method might not provide enough dehumidification in climates with mild but humid spring and fall seasons, when the air conditioner does not operate regularly. Dwellings in these climates might need supplemental dehumidification in the crawlspace.

2. *Install a permanent dehumidifier in the crawlspace.* This method allows the crawlspace to be dehumidified whenever its humidity level is high, regardless of whether the air conditioner is on. Disadvantages are the additional cost of the dehumidifier and the possibility that occupants might not detect equipment failure immediately.

3. *Use a fan to exhaust air continuously from the crawlspace.* This strategy requires the crawlspace walls to be tighter than the floor that connects the crawlspace to the dwelling, thus drawing conditioned air from the house into the crawlspace. This method creates a relative negative pressure in the crawlspace, reducing the transfer of crawlspace air to the dwelling above. The fan runs all the time, regardless of HVAC operation. However, more air must be moved than in the first strategy because transfer air from the dwelling contains more water

vapor than supply air from an air conditioner. As with the second method, occupants might not detect equipment failure quickly.

4. *Use a fan to transfer air from the conditioned space into the crawlspace (excess air will leak back into the dwelling and to the exterior).* Like the third method, more air must be moved than in the first method, and occupants might not detect equipment failure immediately.

More than one dehumidification approach can be used to yield a more robust effect. For example, a combination of the first two strategies allows the dehumidifier to operate during swing seasons and provides automatic dehumidification from the air conditioning system that has a low likelihood of undetected equipment failure. Although several of these methods involve transfer of air from the living space to the crawlspace, air should never be intentionally returned from the crawlspace to the living space or the AHU.

One downside to sealed crawlspaces is that they can allow radon to enter the living space because they lack vents that let the radon escape to the outdoors. Radon testing should be performed after a sealed crawlspace retrofit (Strategy 3.3). The same radon remediation methods are employed as for a dwelling with a slab floor, with the plastic crawlspace floor treated in the same way as a basement slab.

All crawlspaces should be inspected regularly to identify and address any moisture problems before they become severe. A best practice is to install a humidity sensor in a sealed crawlspace with a remote indicator in the dwelling.

Basements

Basements can experience many of the same contamination problems as other unoccupied spaces. Occupants should never store anything in their basements (e.g., paint cans, pesticides, gas cans, or gas-powered lawn equipment) nor perform activities (e.g., painting, etc.) that they do not want to contaminate their indoor air. Basements are also prone to many of the moisture problems of crawlspaces, but these problems are typically less pronounced because basements are usually unvented. If a basement is sealed as rigorously as an intentionally sealed crawlspace, the strategies described above for sealed crawlspaces can also be effectively employed.

Objective 4

CONTROL MOISTURE AND CONTAMINANTS RELATED TO MECHANICAL SYSTEMS

Mechanical systems in dwellings, which consist of HVAC and plumbing systems, play an important role in providing good IAQ through ventilation, air cleaning, and comfort conditioning. However, because mechanical systems carry water or become wet during operation, they can also amplify and distribute biological growth, which can cause building-related symptoms in occupants, such as nasal and throat irritation. In rare cases, this biological growth can cause building-related illnesses, such as Legionnaires' disease or humidifier fever, an influenza-like illness resulting from inhalation of microbial material growing in a humidifier. The strategies in this objective can help reduce the likelihood of IAQ problems related to mechanical systems.

Strategy 4.1 Control Moisture and Dirt in Air-Handling Systems explains how to keep air handling equipment clean and dry primarily by managing condensate from cooling coils and humidifiers and filtering out particulate matter.

Strategy 4.2 Control Moisture Associated with Piping, Plumbing Fixtures, and Ductwork identifies ways to prevent damage from water leaks, use of insulation and vapor retarders to prevent condensation, and ways that duct and piping systems can exacerbate problems with high indoor humidity and leaky building enclosures

Strategy 4.3 Provide Access to HVAC Systems for Inspection, Cleaning, and Maintenance addresses equipment location, clearances, and other access issues.

Other important mechanical system–related issues pertaining to moisture control are discussed in the following strategies:

- Strategy 1.3 – Schedule and Manage Construction and Renovations to Facilitate Good IAQ
- Strategy 1.5 – Effectively Operate and Maintain the Dwelling to Maximize IAQ
- Strategy 2.1 – Avoid Water Penetration and Moisture Problems in the Enclosure
- Strategy 2.2 – Control Indoor Humidity
- Strategy 2.3 – Select Suitable Materials, Equipment, and Assemblies for Unavoidably Wet Areas
- Strategy 6.3 – Maintain Proper Pressure Relationships Between Spaces

Strategy 4.1 Control Moisture and Dirt in Air-Handling Systems

4.1

Introduction

Air-handling systems and air handling units (AHUs) need to be clean and dry to keep the living space clean and free of biological growth. An AHU consists of a fan or blower that draws air in one side; passes it through components that heat, cool, and/or alter its humidity; and blows it out the other side. Easy access to these systems increases the likelihood that they will be kept clean. Regular maintenance should include cleaning the inside of the AHU cabinet, outdoor air intakes, and return air grille(s); changing the filter(s); and clearing the condensate drain. Duct cleaning is rarely necessary.

This strategy describes ways to keep AHUs clean and dry. For more information about controlling humidity in the entire dwelling, see Strategy 2.2. Strategy 4.2 discusses moisture control in the ductwork associated with the AHU, which is a closely related topic.

Types of AHUs typically found in residential buildings include:

- Central warm air furnaces or heat pumps with or without cooling capability (see Figure 4.1-A for a schematic diagram that labels the typical parts of the AHU and Figures 4.1-B, and 4.1-C for photos of typical residential air-handling systems)
    - Heat might be provided by gas or fuel oil, electric resistance heat, or a heat pump.
    - A refrigerant coil connected to an outdoor air conditioner or heat pump usually provides cooling.
    - The system might have a humidifier or dehumidifier.
    - A filter is usually included to keep system components clean and is usually also intended to remove particulate matter for occupant health (see Strategy 7.2).
    - AHUs are typically located in attics, basements, crawlspaces, or mechanical closets. This guide recommends locating them inside the building enclosure.

- Multiple smaller systems that can be ductless or might have short ducts, including minisplit heat pumps that provide heating and cooling or minisplit units that provide cooling and electric resistance heat (Figures 1.2-B and 1.2-C)

- Heat (or energy) recovery ventilation systems with heat exchangers that transfer energy between the outgoing exhaust air and the incoming outdoor air (described in more detail in Strategy 8.1)

The following considerations are important for controlling moisture and dirt in air-handling systems and AHUs:

- Moisture and dirt in AHUs can lead to mold and microbial growth, which can produce odors and cause allergen-related problems.
- AHUs should be kept clean and dry.
- New AHUs should have drain pans that slope to a drain, access panels for inspecting and cleaning cooling coils, and air filter slots that accommodate 2-in. (50 mm) thick filters.
- Existing AHUs should be checked for dirt; biological growth; and problems with filters, drain pans, and cooling coils.
- AHUs need to be cleaned and repaired as needed.

Figure 4.1-A Typical Residential HVAC System

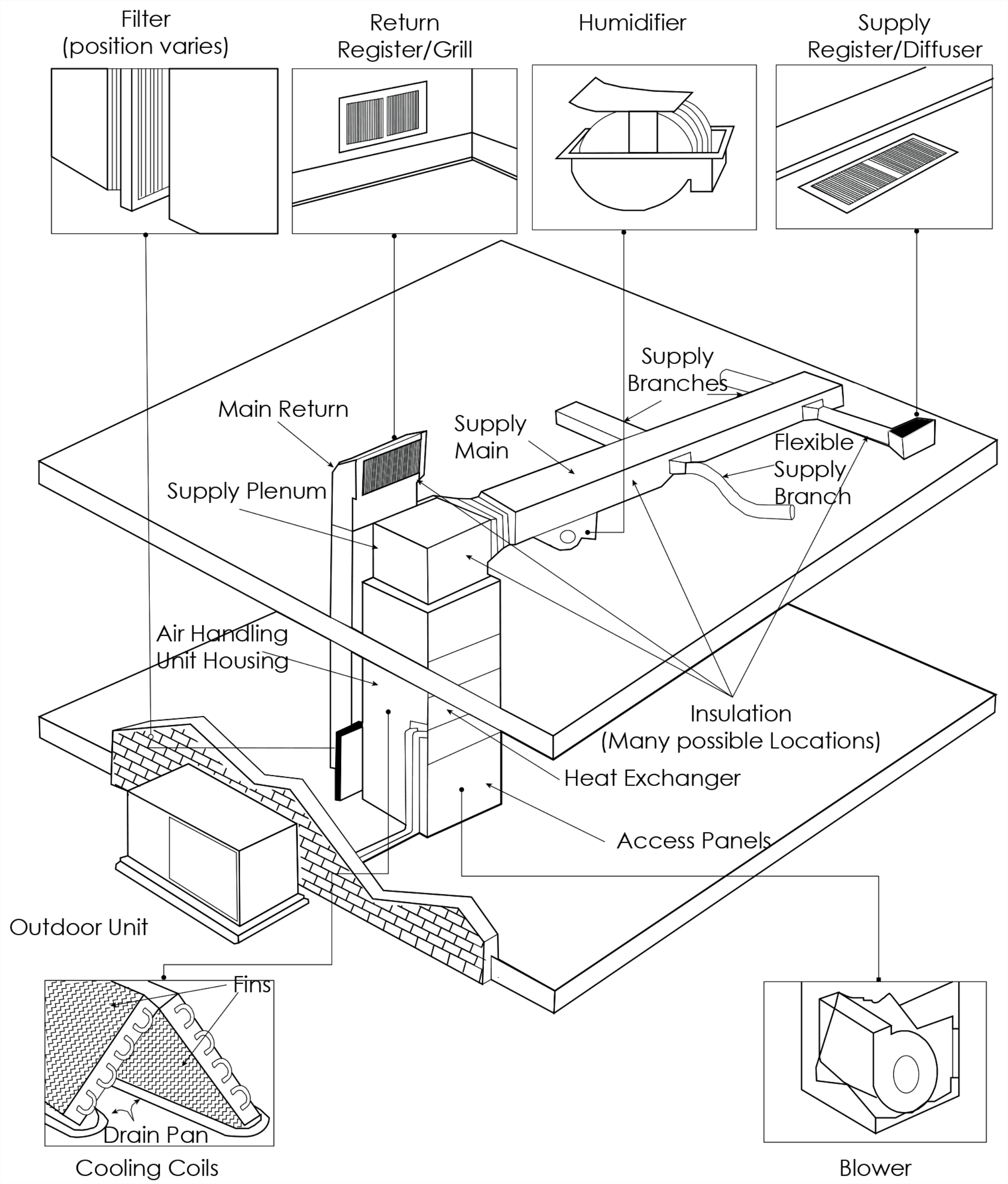


Figure 4.1-A Typical Residential HVAC System
Image courtesy of EPA (1997).

Figure 4.1-B Gas-Fired Warm-Air Furnace with Cooling Coil

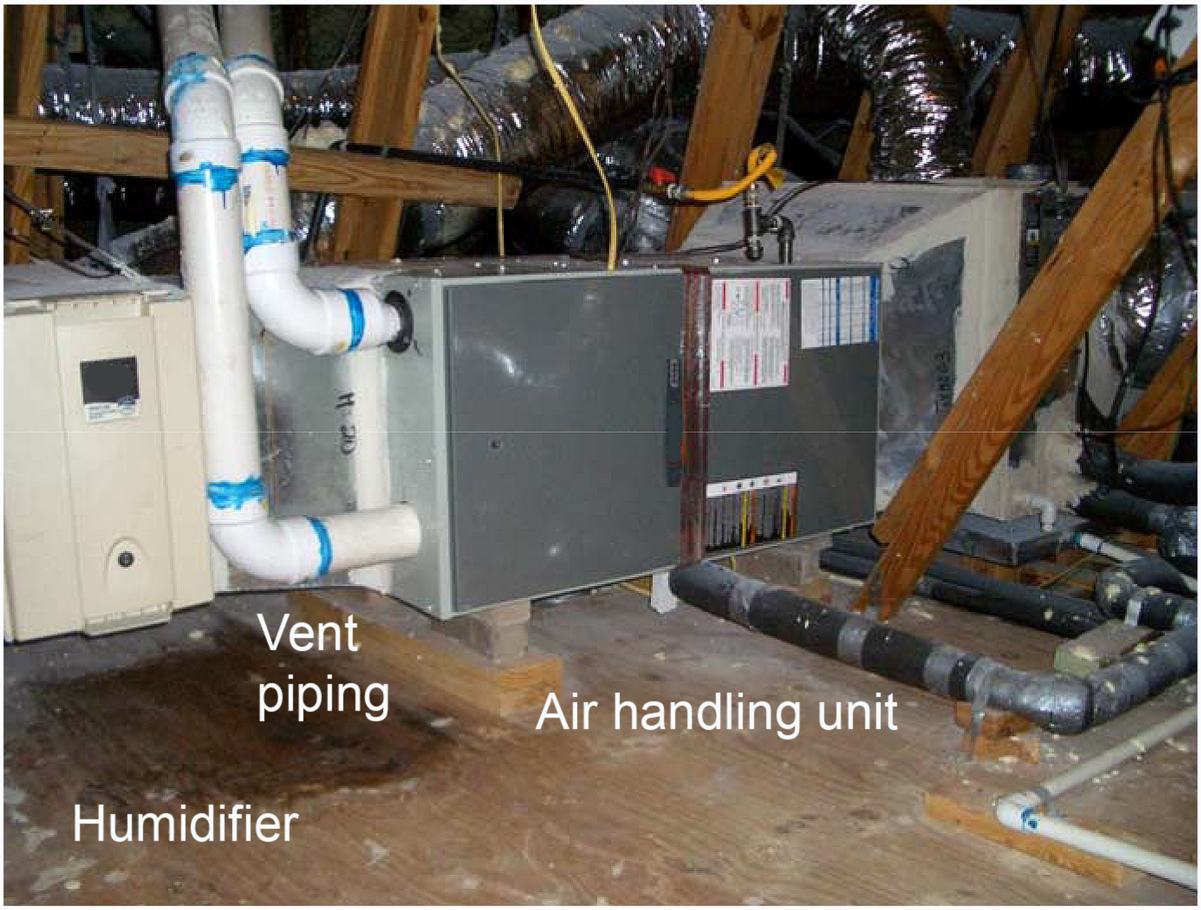


Figure 4.1-B Gas-Fired Warm-Air Furnace with Cooling Coil

Figure 4.1-B shows a gas-fired warm-air furnace with a cooling coil in an attic in a hot, humid climate. This unit has an inline humidifier to provide additional humidification capacity.

Figure 4.1-C shows a vertical gas-fired warm-air furnace with a cooling coil in a mechanical closet. This unit has a properly designed condensate drain and an access panel that is easy to remove for inspection and cleaning of the cooling coil. None of the pipe penetrations pass through the removable panel.

When pipes must pass through the access panels, one way to create access to the cooling coil is to divide the access panels so that pipes enter through locations that are isolated from the access panel. Figure 4.1-D shows a corner of an access panel that has been separated from the remainder of the panel, allowing the panel to be removed for access while the section containing the pipe penetrations remains in place.

Figure 4.1-C Vertical Gas-Fired Warm-Air Furnace

Indoor air contains particles and fibers, some of which can support biological growth. The movement of air through an air-handling system can result in the deposition of particles inside the system when they are blown or dropped (when the air velocity is low) onto surfaces in the ductwork, AHU, heating coils, cooling coils or heat exchangers, and supply ductwork and registers.

Filtration is primarily included in AHUs to keep the AHU clean. Depending on the filter type, they may also remove small particles such that they directly improve IAQ (see Strategy 7.2 for more details). Cleanliness is important to avoid biological growth because cooling coils in air conditioners and dehumidifiers become wet with condensation whenever the entering air is humid enough, meaning that the dew point is higher than the temperature of the coil, which is typically when the indoor RH is greater than about 50%. Condensation drips off the coil into a pan that collects the water. The pan has an outlet (e.g., a plumbing drain for a central HVAC system, or a drain line that passes through the wall and drains outside the building for a minisplit), which should be at the low point, that drains the condensate out of the pan to a safe disposal. For a through-wall or window air conditioner, the bottom of the unit usually forms the drain pan, and the unit should be tipped toward the outside so that the water drains properly.

Figure 4.1-D Pipe Penetrations in an AHU

Condensation in air conditioners and dehumidifiers is part of normal operation, but it can result in problems if it is not properly managed. For example, deposited particles on wet coils and drain pans can be colonized by biological growth. Furthermore, water droplets on the coil can be blown off, especially if the air is moving quickly (e.g., more than 550 ft per minute [2.8 m/s]). The droplets can moisten the cabinet and supply duct downstream of the coil, again resulting in biological growth.

If the air conditioner is oversized, it might not remove much moisture because air conditioners typically need to operate for 5–10 minutes before condensate begins to form (this is discussed in detail in Strategy 2.2). In addition, drain pans might not drain properly because of improper design or clogs (see Strategy 1.5 for information on clearing a clog). The

overflow might wet the floors, ceilings, or walls, resulting in moisture damage, wood decay, and biological growth. Some systems have float valves that shut the unit down when condensate stops draining from the pan, which prevents overflow but disables the cooling systems. It is not always possible to drain condensate using gravity alone from an HVAC system to a safe disposal site. In this situation, a condensate pump consisting of a container, a pump, and a float switch is used to drain the system. The condensate pan drains into the container, the float turns the pump on when water raises it high enough, and the water is pumped to safe disposal. Figure 4.1-E shows a condensate pump designed to serve an air-handling system in a basement room that lacks a floor drain.

Figure 4.1-E Condensate Pump

Some central air-handling systems have humidifiers. Humidifiers increase the indoor RH and are typically installed to alleviate symptoms associated with dry air (e.g., static electricity and dry skin, lips, nose, and eyes) or because a doctor has recommended humidification. However, the addition of a humidifier to a central air-handling system can contribute to moisture and biological growth problems in AHUs and ductwork. Biological growth is least likely in humidifiers that inject water vapor into the air and most likely in those with reservoirs of stagnant water whose droplets they disperse into the air.

Condensation can also occur inside the dwelling and within the building enclosure if the homeowner operates the humidifier at too high an indoor setting. Houses are driest when outdoor air is cold. Adding humidity to the indoor air can result in condensation on materials in colder parts of the dwelling. Common condensation sites are attics, ceilings along exterior walls, exterior walls behind furniture or in closets, and windows. Strategy 2.2 provides more details about when and how to safely incorporate humidification into a dwelling's HVAC system.

System-integrated dehumidifiers are most often needed in hot, humid climates. Strategy 2.2 describes situations in which a dehumidifier is likely to be needed, and ways to integrate a dehumidifier into an air handling system.

Strategy 4.1 Control Moisture and Dirt in Air-Handling Systems

4.1

New Air Handling Systems

An AHU should:

- Allow easy access for inspection and cleaning of the cooling coil and drain pan

- Be easy to clean and have a hard-surface interior (e.g., made of corrosion-resistant metals or plastics)

- Have a drain pan that slopes to a drain at a low point

- Have racks that accommodate a filter that is 2 in. (5 cm) wide or thicker. A filter with at least MERV 8 efficiency should be installed to keep system components clean, and a higher efficiency should be used to filter particles for human health. See Strategy 7.2 for explanation of the MERV rating system for filters and guidance on the use of filters in dwellings.

- Have ducted returns and supplies should be used instead of building cavities

- Be installed in accordance with ACCA Standard 5 (ACCA 2015a).

Existing Air-Handling Systems

Contractors and skilled homeowners can find guidance for inspecting, cleaning, and fixing moisture-related problems associated with existing AHUs from the ACCA (ACCA 2013, ACCA 2015a and b) and the National Air Duct Cleaners Association (NADCA 2013).

Existing AHUs and ductwork should be inspected for moisture problems and biological growth. The only wet area should be the cooling coil and the pan underneath it. Repairs and modifications can include the following:

- *Soiling and mold growth:* Clean hard surfaces and remove and replace contaminated porous insulation (ACCA 2015b, NADCA 2013).

- *Inadequate access:* Add a sealed access hatch to avoid air leakage and allow inspection and cleaning of the cooling coil.

- *Drain pans and line problems:* Level the unit so that the drain is at the lowest point in the drain pan, and modify or replace the drain line so that it drains properly (ACCA 2015b).

- *Condensate blowing off the coil and wetting downstream surfaces:* Remove any interior fibrous insulation from the affected area, and insulate this portion of the duct on the exterior.

- *Inadequate dehumidification:* See Strategy 2.2.

- *Air leaks between the filter and the blower (especially at the filter door):* Add an airtight cover if the filter access does not have one.

A performance assessment in accordance with ACCA (2015a) can be considered. The first step is an inspection of the outdoor air intake (if present) to assess:

- *Location:* If the location is poor, consider moving the outdoor air intake.
- *Clogs:* Clean debris from louvers and screen.
- *Dirt, moisture, and biological growth:* Clean using hot water and detergent.
- *Filter presence, location, and condition:* Replace dirty or damaged filters. If the central AHU does not filter outdoor air, modify it so that it does filter this air or add a filter to the outdoor air ductwork.

If the dwelling has a central humidifier, this unit and the ductwork where humidity is injected should be inspected and cleaned. If the humidifier is not needed, its water should be drained, and the unit should be disconnected.

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

4.2

Introduction

Piping, plumbing fixtures, and ductwork can cause moisture problems through water leaks, condensation on cool surfaces, or by providing a pathway for humidity to enter the dwelling. Careful design, installation, and maintenance are needed to avoid these problems. This section discusses moisture problems that are specific to these systems and can interact with and amplify indoor humidity problems (Objective 2).

Pipes, plumbing fixtures, and ductwork can contribute to moisture problems in homes through:

- Water leaks
- Frozen pipes
- Condensation on cold piping or duct surfaces
- Air and moisture leakage where pipes and ducts pass through exterior walls, floors, and ceilings
- Introduction of humidity via leaky ducts located in unconditioned spaces

Water Leaks in Plumbing Systems

Water leaks cause problems beyond wasted water. Slow drips and leaks that are undetected can cause biological growth and moisture problems, and sudden catastrophic leaks can quickly cause extensive and costly damage. A catastrophic water leak under a bathroom sink, for example, could flood the entire dwelling and lead to costly insurance claims. In Figure 4.2-A, a restoration contractor is attempting to dry hardwood floors that had been flooded

Figure 4.2-A Drying Flooded Hardwood Floors

Home insurers recommend using the strategies in occupied dwellings that are listed below to prevent or at least minimize the damage from water leaks (USAA 2015, AARP 2017):

- Change washing machine hoses every 5 years, and use reinforced, steel-braided, not rubber, hose.

- Conduct annual inspections or continuous observations to identify drips and leaks under water heaters, radiators, sinks, refrigerators, and dishwashers. Corrosion around pipes and cracked or warped flooring can indicate a leak, even if no water is visible. Fix any leaks promptly.

- Do not buy a refrigerator with an automatic icemaker and if the dwelling has one, consider not using it and closing the valve feeding the small water line that connects to the icemaker. These water lines often leak though metal tubing is more durable. If it must be used with the plastic hose, check at least annually if it is cracked or discolored.

- Install a water detection alarm, preferably one with an automatic shutoff that will react to a catastrophic leak. These alarms are typically installed where water service enters the dwelling and near the water heater tank. Web-enabled devices are now available that alert occupants of a leak.

- Check drain pans in AHUs for signs of a clogged drain (Strategy 1.5).

- Keep gutters clean to prevent overflow, and check downspouts annually to be sure that they are directing water away from the dwelling's foundation.

- If a toilet is no longer level, fix it promptly to prevent leaks where it seals to the floor.

- Inspect toilets quarterly for condensation around the bowl or signs of leakage. Condensation can be caused by water running between uses, which is usually caused by a flapper that needs to be replaced.

When a new dwelling is being constructed, the supply and drain side of the water systems should be pressure tested in accordance with the International Residential Code (IRC) or International Plumbing Code, as required by most jurisdictions (ICC 2018a and 2018b). Clothes washers, water heaters, and AHUs should be placed on drain pan that drains water from these appliances to the sewer or outside or on water-tolerant flooring that slopes to a floor drain.

Frozen Pipes

A best practice is to locate pipes inside the thermal enclosure of the dwelling rather than burying them in exterior floors or walls, especially in climates that have freezing outdoor temperatures. Locating pipes inside the thermal enclosure prevents them from freezing and compromising the insulation in exterior walls or floors. When pipes must be placed in an exterior wall or floor, the following steps can help reduce the likelihood of frozen pipes:

- Keep pipes that feed exterior hose bibs short and install a drain on the inside, especially in very cold climates.

- Insulate the pipes.

- Instruct the resident(s) to turn off the water in winter and drain the pipe to the hose bib.

- Fill the wall or floor cavity with continuous insulation around the pipes. Make sure that the insulation is not damaged and that at least half the insulation is on the exterior of the pipes.

- Install pipes deeply enough inside a wall, ceiling, or floor cavity to prevent a gypsum board screw from reaching the pipe.

- Take extra care with pipes in exterior floors (such as those over vented crawlspaces or dwellings on piers). Sloping sewer pipes must remain encapsulated in enough insulation to prevent them from freezing. Check the lowest point of the pipe to make sure that insulation to the outside is adequate.

Condensation on Cool Surfaces

Everyone is familiar with the condensation that forms on a glass holding an iced drink on a hot, humid summer day. This happens because the glass is colder than the dew point of the outdoor air, causing moisture in the air near the surface of the glass to condense. The same phenomenon can occur on ducts and pipes when they become cool enough. Ducts and pipes in unconditioned spaces (e.g., vented attics and crawlspaces or attached garages) experience greater ranges of temperature and humidity than those inside the insulated dwelling and are more vulnerable to condensation problems. The solution is to either raise the surface temperature of the ducts or pipes or to place them in less humid locations.

Air conditioning ducts are designed to carry cold air. To prevent condensation, ducts must be covered with duct wrap, or insulated flexible ductwork must be used so that when the surface is exposed to warm, humid air, its temperature will be higher than that air's dew point. Duct wrap can consist of fiberglass insulation with a vapor retarder facing outward or a closed-cell flexible foam pipe wrap that provides insulation and a vapor barrier in one material. Flexible ductwork comes pre-insulated and wrapped with an exterior vapor retarder.

The performance of insulating materials is rated using the R-value. Air conditioning supply ducts inside conditioned space should be insulated to at least R-6. Outside conditioned space, ducts should be insulated to at least R-8. Workmanship is important. Bends, transitions, supply plenums (cavities in a building that are part of an air-handling system) at the AHU, and duct boots all need to be insulated so as to create a continuous air-sealed wrap. If humid air can infiltrate the ductwork behind the insulation, condensation will form on the duct surface and damage the insulation.

The inside surface of ductwork that carries conditioned air is very cool. If humid outside ventilation air from an ERV, HRV, or separate supply fan is injected into the ductwork, condensation can occur. Air from these ventilation systems should instead be injected into the return ductwork, which is warmer. The fate of this humid outside air delivered to the return depends on how the system is operating:

- If the system is cooling the dwelling, the humid air passes through the cooling coil and is dehumidified along with recirculated air from the dwelling.
- If operation of the AHU fan is interlocked with the ventilation system so the fan is running but the cooling is not activated, the humid air mixes with return air that is warmer and probably less humid. The now less humid mixed air is less likely to condense when it passes to the supply ductwork.
- If the AHU is not interlocked so neither the fan nor the cooling is activated, the airflow resistance of a MERV 8 or higher filter is usually enough to force the air into the dwelling through return ducts. Because the return ducts are warmer than supply ducts, condensation is less likely (Rudd 2011).

Strategy 7.1 discusses ventilation solutions for humid climates in more detail, including situations in which dwellings might be better served by dehumidifier ventilators, which eliminate the risk of ventilation-related condensation inside the ducts.

All ducts, including heating-only and return ducts, should remain within the conditioned enclosure. Uninsulated ducts outside the enclosure can experience wintertime condensation inside, especially in Climate Zones 5, 6, 7 and 8 (Figure 1.2-A). Supply ventilation ducts and exhaust ducts from ventilation systems and exhaust fans should be insulated if they are outside the dwelling's conditioned enclosure (e.g., in a vented attic). This prevents condensation on the insides of ducts carrying warm, humid air through cold spaces and on the outsides of ducts carrying cool air through warm, humid spaces (Rudd 2011).

Sometimes, the bigger problem is high humidity where the pipes or ducts are located. Strategy 2.2 discusses ways to maintain appropriate indoor humidity.

Pipes, Wires, and Ducts Penetrating Through the Enclosure

When piping, wiring, and ductwork pass through the building enclosure, they create a hole that must be air sealed to prevent humid outdoor air from infiltrating the dwelling at this location. In addition to humidity, outdoor air pollutants (including particulate matter) and pests can enter the dwelling, and substantial energy losses can occur. See Strategy 2.1 for techniques to air seal the building enclosure.

Dwellings undergoing renovation, repair or getting new telecommunications service are especially vulnerable to this problem because a plumber, electrician, technician, or other person performing the work might not possess the tools, materials, or knowledge necessary to return the building enclosure to its original state or to seal the penetration in an airtight manner.

Common locations of unsealed penetrations in the building enclosure are:

- Floors over basements and crawlspaces, especially at plumbing penetrations (see Figure 4.2-B, which shows a hole cut in a basement ceiling by a plumber that was not air sealed and floor insulation that was not replaced)

- Ceilings in dwellings with vented attics, especially at the tops of duct chases (vertical shafts among floors of a multistory building to accommodate ducts, wires, or plumbing), which might not be capped

- Walls between dwellings and garages (see Figure 4.2-C, which shows pipe and duct penetrations added to a brick wall separating a garage from the conditioned enclosure of an older dwelling that have not been air sealed)

- Walls where cable television service enters the dwelling, which is often installed, even in new dwellings, after the dwelling is complete and the general contractor is no longer onsite to make sure that the holes are sealed

Figure 4.2-B Hole Cut in a Basement Ceiling by a Plumber

Many of these penetrations are never sealed, or someone attempts to seal the penetration but uses an inappropriate material. Large holes should be blocked with solid blocking,

such as sheathing, dimensional lumber, sheet metal, or drywall. These materials should then be air sealed using caulk or foam products that are intended for use as sealants. Stuffing fiberglass into an opening does not stop the flow of air. In Figure 4.2-D, the duct and pipe are insulated, but an attempt was made to air seal the site where they penetrate the wall between the conditioned basement and an adjacent vented crawlspace using stuffed fiberglass. This material does not stop the flow of air and humidity into the living space.

Figure 4.2-E shows condensation and visible biological growth in a hot, humid climate. The dwelling pressure is negative because of the exhaust in the bathrooms. The plumbing chase has big leaks to outdoor air, and the cabinet is chilled by air conditioning.

Ducts offer another pathway for humidity to enter the dwelling. Leakage in the return duct can pull humid air directly into the HVAC system, and leakage in any part of the duct can create pressure imbalances that increase the infiltration of humid air from the outdoors or adjacent unconditioned spaces. For example, if a duct system outside the dwelling's conditioned enclosure has large supply leaks, the HVAC system returns more air from the living space than it supplies. As a result, the living space maintains a negative pressure with respect to the outdoors, and the dwelling experiences more infiltration. Additional air enters the dwelling from the outdoors and attached spaces (e.g., garages, crawlspaces, basements, and attics). Interactions with these spaces are discussed in more detail in Strategies 3.6 and 6.3.

Even if the ductwork is air sealed and entirely inside the conditioned space, a central return can depressurize portions of the dwelling when bedroom doors are closed and the central AHU is running. For example, if the bedrooms have supply diffusers but no return or exhaust grilles, the portion of the dwelling where the central return is located will have negative pressure relative to the outdoors when the bedroom doors are shut, drawing hot, humid air into the living area. Installing HVAC returns in the bedrooms or passive return paths between the bedroom and adjacent hallway can alleviate this problem (see Strategy 6.3).

All of these issues point to the best practice for HVAC systems, which is to place the AHU and ductwork entirely within the conditioned enclosure. This results in fewer penetrations in the building enclosure and eliminates duct leakage to outdoors from the AHU and ducts. The AHU will not bring humid air into the dwelling and is less likely to cause pressure imbalances. With advance planning, this can be accommodated at little

Figure 4.2-C Pipe and Duct Penetrations in Wall Separating a Garage from an Older Dwelling

Figure 4.2-D Ineffective Attempt to Air Seal Duct and Pipe Penetration into Wall

Figure 4.2-E Condensation and Visible Biological Growth in a Hot, Humid Climate

additional cost (Fonorow et al 2010). This practice can be particularly important in multifamily buildings, where duct leakage outside the conditioned enclosure can exacerbate the transfer of smells between units.

For existing dwellings where bringing the AHU and ductwork into conditioned space might not be practical, sealing the ductwork is important for both energy conservation and IAQ. The amount of duct leakage should be as low as can be practically achieved. A maximum duct leakage of 4 CFM per 100 ft^2 (113 L/min per 9.29 m^2) of conditioned space, when tested with a pressurization or depressurization fan at 0.10 in. w.g. (25 Pa), is a good target (ICC 2015a). Duct leakage testing is explained in more detail in Strategy 1.4.

Air Duct Cleaning

Research on duct cleaning has not shown that it has any significant health benefits (EPA 1997, Zuraimi 2010). However, improperly maintained ducts in commercial and institutional buildings are associated with an increased risk of sick building syndrome symptoms (Sieber et al.1996, Mendell et al. 2008). Duct cleaning should be considered under the following conditions:

- Visible biological growth inside the ducts or AHU is substantial and the surfaces are hard and non-porous (sheet metal). If the surfaces are made of soft or porous materials, they should be replaced.
- Ducts are infested with rodents, cockroaches, or other pests.
- Ducts or coils are clogged with excessive amounts of dust or debris (e.g., after construction).

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

4.3

Introduction

HVAC systems require periodic inspection, cleaning, and maintenance. The occupant needs access and education to prevent and solve problems related to these systems.

HVAC system features that make equipment accessible are as follows:

- Lightweight access door large enough for a person to fit through easily
- Space in front of the equipment large enough for a person to work in comfortably
- Unimpeded path for removal or replacement
- Access to perform the work without a ladder
- Controls with obvious functions or additional labeling

Accessible HVAC Systems

An HVAC system is accessible when a homeowner or technician can enter the space where the equipment is located with reasonable ease and the equipment can be removed and replaced at the end of its life. The door or access hatch to the space where the equipment is located must be large enough to allow a technician to remove and replace the equipment. A clear path must be available for removal that is unimpeded by other equipment (e.g., the water heater). Enough space must be adjacent to the equipment's removable panels so that a technician can perform repairs. Manufacturers' specifications and the building codes typically specify minimum clearances of 30–36 in. (0.8-1 m). For maintenance frequently performed by homeowners (e.g., filter changes), the homeowner should be able to easily and safely perform these tasks using a 6 ft household stepladder or, ideally, without a ladder.

Location of HVAC and Ventilation Filters and Air Intakes

The HVAC and ventilation system filters are the portions of the HVAC system that homeowners most frequently need to reach. Filters can be placed at return grilles or at the AHU. If one of these is not easily accessible, the filters may need to be placed in the more accessible location. For example, if return grilles must be placed in a high ceiling that cannot be easily reached using a 6 ft (1.8 m) stepladder, filters should not be placed in the return grilles. However, if the return grilles are in the floor or a low sidewall and are easily accessed from the living space, they might provide a better location for the filters than an AHU in a short crawlspace that can only be reached by crawling on one's hands and knees.

Strategy 7.2 discusses the consequences of filter location in more detail, including the importance of sealing the return ducts well when return grille filters are used because any air that enters downstream of the filter is unfiltered. Many high-efficiency filters are designed for installation at the AHU, and a single filter for the whole system can be less costly and more convenient than multiple filters at the returns.

When the AHU is inside a closet or mechanical room that can be entered from the conditioned space, the unit is usually more accessible than if it is in an attic or crawlspace. If the AHU is located in an attic, a drop-down staircase and solid flooring should be adjacent to the unit to facilitate safe access, the access door should be large enough to allow a technician or the occupant to enter comfortably, and the unit should be near the access.

Strategy 3.2 provides guidance on locating outdoor air intakes in locations that will keep them free of debris, but that can be easily inspected by the homeowner while standing on the ground or on a short stepladder placed on a stable surface.

Access to Ventilation Systems and Controls

Ventilation systems and their controls should also be accessible to the occupants. ASHRAE Standard 62.2-2016 (ASHRAE 2016b) requires whole-house ventilation systems to have a readily accessible override control (e.g., an on-off switch or dedicated circuit breaker) with a label or icon indicating the system's function. Multifamily dwelling units are required to have an override control, but it does not have to be readily accessible to the occupants. The override system allows the occupants to turn off the system when the outdoor air quality is poor (e.g., because of smoke from a nearby wildfire) or for maintenance. Occupants might also turn up the ventilation if additional capacity is available and the situation calls for it (e.g., if the dwelling is being painted). Because of this requirement, the occupants need to be aware of the ventilation system, why it is needed, the location of the override control, and how to use it.

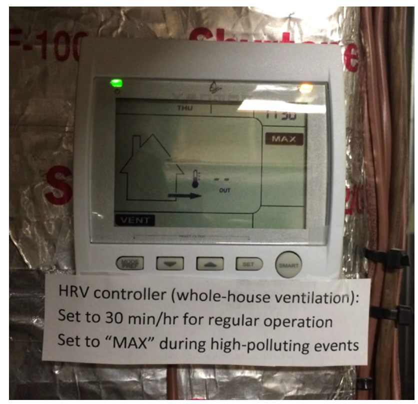
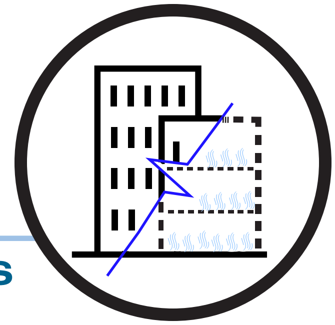


Figure 4.3-A Ventilation System Controller with Instructions for Operation

A best practice is to label the controls so that occupants know the correct setting for normal operation and other settings available for high-polluting events as well as how to turn the system off (Figure 4.3-A).

Objective 5



LIMIT CONTAMINANTS FROM INDOOR SOURCES

A variety of indoor activities, appliances, building materials, finishes, cleaning products, and furnishings emit allergens, combustion products, volatile compounds, biological contaminants, and particles that can cause discomfort, irritation, or more serious health effects. More information on specific health effects and the contaminants that cause them is available in the EPA's online Introduction to Indoor Air Quality (EPA 2017j). Normal occupant activities, such as cleaning and maintenance, also contribute contaminants and can increase the amount of a contaminant (e.g., formaldehyde) emitted by building materials in a dwelling. Materials, finishes, and furnishings that are difficult to clean might require strong cleaning agents that contribute to IAQ problems.

Some emissions are benign on their own but react with other compounds in the air, such as ozone, to form harmful secondary products, and contaminants can act synergistically. Once occupants become sensitized by high exposures, they sometimes stop tolerating lower-level exposures. Although scientific understanding of these issues is still evolving, the strategies presented here provide practical methods to limit the IAQ effects of these contaminants based on current knowledge.

Strategy 5.1 Select Appropriate Building Materials offers succinct recommendations for selecting building materials along with guidance on collecting and evaluating product emission data to minimize contaminant emissions inside a dwelling.

Strategy 5.2 Limit the Impact of Emissions from Materials and Activities outlines steps to limit the impact of unavoidable emissions (including from unusual contaminant sources) on IAQ, such as airing out items that emit high levels of contaminants and using local exhaust systems.

Strategy 5.3 Minimize Effects of Cleaning and Maintenance on IAQ addresses the importance of selecting materials and finishes that are easy to clean, storing and handling cleaning materials, and other ways to reduce the effects of cleaning on IAQ.

Strategy 5.4 Avoid Certain Sources of Contaminants describes products that should not be used indoors, including gasoline-powered equipment and electronic air cleaners that generate ozone. This strategy also describes the impact of smoking and vaping on IAQ.

Objective 5

LIMIT CONTAMINANTS FROM INDOOR SOURCES

Other important information about contaminants generated indoors is discussed in the following sections:

- Strategy 1.5 – Effectively Operate and Maintain the Dwelling to Maximize IAQ
- Strategy 2.2 – Control Indoor Humidity
- Strategy 3.4 – Use Doormats to Keep Out Contaminants
- Strategy 3.6 – Control Entry of Contaminants from Unoccupied Spaces
- Strategy 6.2 – Provide Effective Bath and Kitchen Exhaust
- Strategy 7.2 – Provide Particle Filtration and Air Cleaning

Strategy 5.1 Select Appropriate Building Materials

Introduction

Building materials and home furnishings, especially when they are new, release contaminants. The most common pollutants emitted by building materials are those broadly classified as VOCs and SVOCs. Hundreds of these compounds exist in the indoor air, and understanding of their health effects (both individual and synergistic) is incomplete.

Figure 5.1.A provides examples of building materials that are common sources of indoor contaminants in dwellings.

Choosing materials that emit few contaminants is almost always the least expensive and most reliable way to reduce occupant exposure. Recent toxicology and indoor chemistry advances in sampling and analyzing indoor contaminants have increased understanding of the type of pollutants that affect dwelling occupants and their effects. In parallel, advances in the techniques used to measure the emission (also known as "off-gassing") properties of materials and products used in building construction, finishing, and furnishing have made it possible to more clearly identify their chemical "fingerprints" in indoor environments and thus their impact on IAQ.

Ways to choose appropriate building materials include the following:

- Choose materials that emit few contaminants, which is almost always the least expensive and most reliable way to reduce occupant exposure.
- Use solid wood when possible, ensure that all composite wood products have low emission certification, and do not use pressure-treated wood indoors.
- Select paints, primers, and wood or other floor finishes with low-VOC certification.
- Avoid polyvinyl chloride-based flooring materials that might come into contact with damp concrete.
- Select low-emitting furnishings, cabinets, paint, carpet, glues, scented products, and personal care products.
- Consult product labels from third-party labeling programs, such as those developed by the federal government or consumer groups.

Dwelling Construction and Renovation Materials

When a new dwelling is built, the design team needs to set expectations and identify low-emission building materials to use before construction begins. The builder or designer should request documentation on VOC emission rates (if available) or of compliance with the relevant standards or rating programs for these products. Products with manufacturer claims that are vague or difficult to verify should be chosen with caution. "Greenwashing," for example, occurs when a company makes claims that give the impression that the product is more environmentally friendly or nontoxic than it actually is. Just because a company is a member of the U.S. Green Building Council does not mean that all of its products meet the council's "green" product criteria. Furthermore, some green products that have recycled content or are energy efficient emit high levels of contaminants. The selected products should be fully described in the project specification (see, for example, NIST 2015), and the builder must make sure that the correct product is purchased and installed.

The sheer number of building materials and the contaminants they may contain can feel overwhelming to builders, designers, and homeowners. Many certification and other regulatory programs set emission limits for building materials, but it can be difficult and time consuming to sift through them to find those that are most relevant. The EPA's Indoor airPLUS technical specifications contain detailed requirements by product category (EPA 2017i), and the Indoor airPLUS website offers examples of products that comply with the program's requirements (EPA 2015c).

Strategy 5.1 Select Appropriate Building Materials

Figure 5.1.A Common Building Material Sources of Indoor Contaminants

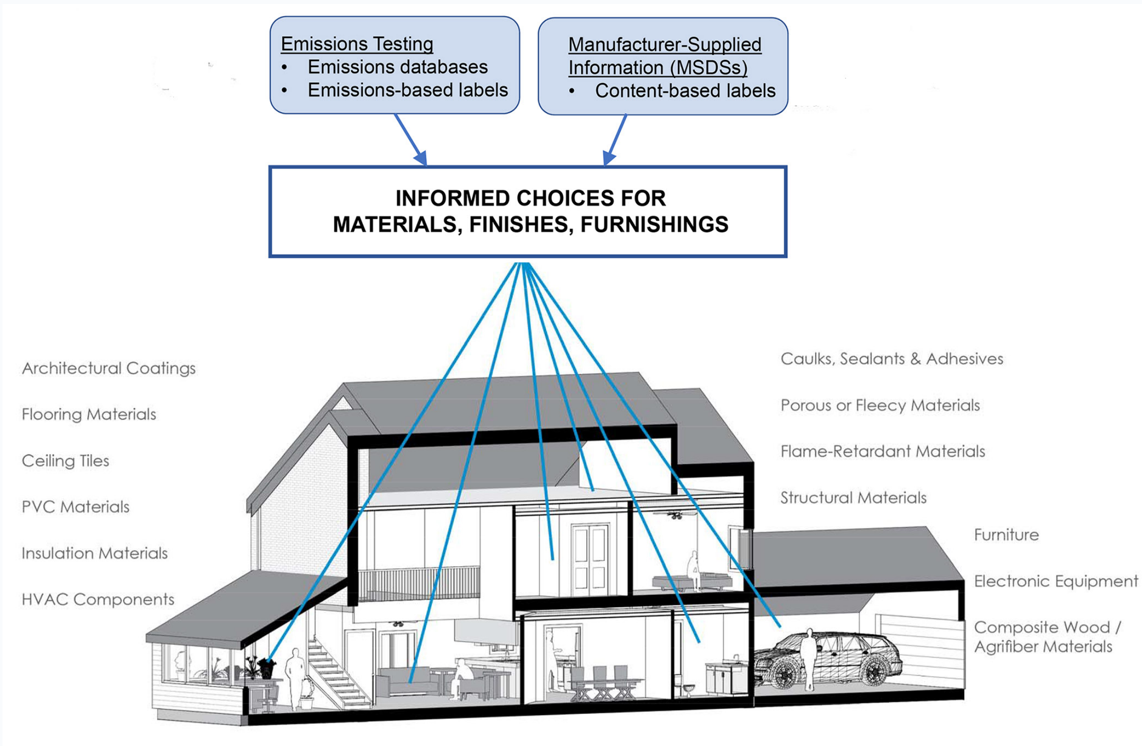


Figure 5.1.A Common Building Material Sources of Indoor Contaminants in Dwellings

Recommended resources and strategies for obtaining low-emitting building materials for important categories in new construction are described below. Selecting emission rates is a complex process that this Guide does not recommend to residential designers, builders and occupants. For this reason, it is best is to rely on certifications and standards given below.

Wood products. Wood products are commonly used in wall and roof sheathing, floors and subfloors, structural panels, cabinets, closet shelving, trim, doors, and stair treads. Solid wood should be used when possible, and all composite wood products should have low emission certification. Pressure-treated wood should never be used indoors, and its use outdoors should be minimized in areas where indoor air could be exposed to it. All edges of material constructed with particleboard should be sealed.

Certifications and markings that indicate wood with low emissions include:

- California Airborne Toxics Control Measure for formaldehyde emissions from composite wood products listed as compliant with the California Air Resources Board's Phase 2 (CARB 2017)

- Composite Panel Association Standard certification criteria for no added formaldehyde or ultra low-emitting formaldehyde (Decorative Surfaces 2017)

- Greenguard or Greenguard Gold certification (Greenguard Certification 2017)

- ANSI standards A208.1 for particle board (ANSI 2016a), standard A208.2 for medium density fiberboard (ANSI 2016b), and ANSI and Hardwood Plywood and Veneer Association standard HP-1-2009 for hardwood plywood (HPVA 2009)

- Kitchen Cabinet Manufacturers Association's Environmental Stewardship Program (KMCA 2017)

Paints and finishes. Paints, primers, and wood or other floor finishes should have low-VOC certification. Because these products are rarely free of contaminants, the dwelling should be ventilated before it is occupied. Relevant certifications include the following:

- Greenguard or Greenguard Gold (Greenguard Certification 2017)

- Scientific Certification Systems Standard EC-10.2-2007 Indoor Advantage Gold (SCS Global Services 2017)

- California Department of Public Health Standard Method V1.1-2010, Section 01350 (California Department of Health 2010)

- Green Seal Standard GS-11 (Green Seal 2015) or GS-36 (Green Seal 2013)

- Green Wise or Green Wise Gold (Green Wise 2017)

- Master Painters Institute Green Performance Standards X-Green, GPS-1, or GPS-2 (PaintInfo 2017)

Flooring: See Strategy 5.3 for information on porous and fleecy materials as well as how to clean these materials. All carpets and carpet pads should meet the Carpet and Rug Institute's Green Label Plus standard (CRI 2017). Polyvinyl chloride-based flooring materials should be avoided if they might come into contact with damp concrete that could, through hydrolysis, result in the release of undesirable (secondary) emissions.

Adhesives and sealants. These are covered by some of the same standards as paints and finishes. In addition, the South Coast's Air Quality Management District rule 1168 (SCAQMD 2005) applies to these products.

All building materials should be durable and low maintenance (requiring less use of cleaning chemicals), and their surfaces should be easy to clean. Detailed installation, maintenance, and cleaning instructions should be part of the material specification process. The product installation practice should conform to the project specifications. Builders and designers should provide detailed maintenance and cleaning instructions to the owners or occupants (Strategy 5.3).

Linings should not be used on interior surfaces of air distribution and ventilation ducts if they can absorb contaminants and catch and hold dust particles. Low-emission cleaning agents should be used to remove residual oils on the interior surfaces of metal ductwork before installation. All duct materials and fittings should be clean and dry before installation, and contamination during construction should be prevented.

Existing Dwellings

Residents should be as careful to select low-emitting products as builders and designers when they purchase furnishings, cabinets, paint, carpet, glues, scented products, and personal care products. New chemicals are continuously being developed, and determining their effects takes time. As a result, rating systems for chemical emissions do not yet cover all products used in dwellings. Nevertheless, as with all chemical exposure, exposure to fewer chemicals is better.

The following practical advice for preventing exposure to chemicals in dwellings comes from the Agency for Toxic Substances and Disease Registry of the U.S. Department of Health and Human Services (ATSDR 2017).

- Check products for harmful ingredients in the Household Products Database (U.S. Department of Health & Human Services 2017) and use the safest products. This website allows supports searches for product material and safety information.

- Read product labels and follow the manufacturer's directions carefully. Some household chemical labels and safety data sheets require those working with these materials to wear a mask, gloves, or other protective clothing to reduce their exposure. If a chemical requires such protection, it should probably not be stored in a dwelling's living space, and it should only be used in well-ventilated, unoccupied space, such as a detached garage, work shed, or, better yet, outside.

- Store strong household chemicals—such as cleaners, paints and finishes, degreasers, and strippers—safely. Some of these products should not be stored indoors. Buy these products in limited quantities to avoid the need to store them. The stronger the product, the more important it is to keep it separate from the rooms where residents spend most of their time. Prevent chemicals from spilling, leaking, or coming into contact with children and pets.

- Avoid tracking chemicals you are exposed to on the job into a dwelling. If you wear personal protective gear for your job, remove and wash contaminated footwear and clothing at the workplace or before entering the dwelling.

- Select furniture that has low emissions. Furniture with hard surfaces typically emits lower levels of contaminants than upholstered surfaces. Be aware of the concerns about composite wood products used in furniture (see information above on wood products). The ANSI/BIFMA X7.1 standard (BIFMA 2011) for formaldehyde and TVOC emissions covers furniture.

- Choose personal and home care products that have minimal amounts of fragrances, chemicals, and other additives.

- Avoid clothing made with flame retardants.
- Air out dry-cleaned clothes before bringing them indoors.
- Avoid paradichlorobenzene moth repellants.
- Do not use air fresheners, candles, incense, or other scented products. In addition to emitting VOCs, candles and incense are a significant source of indoor particulate matter.

Product Labels

Product labels are sometimes incomplete and misleading, and nonexperts might find understanding and comparing labels difficult and time consuming. The websites of responsible labeling programs clearly identify which organization manages the label and the label's requirements. In general, third-party labeling programs (such as those developed by the federal government or consumer groups) are more robust than those developed by a single company for its own products or by a manufacturing industry group.

Product labels describing emission properties provide far more information than content-based product labels, which merely report the percentage of VOCs by weight. When choosing between products, occupants should favor those with lower emission rates.

The TVOC emission rate, although widely reported, is increasingly recognized as a poor indicator of the true impact on IAQ of any given material. This is largely due to the wide range of effects of individual VOCs; some VOCs have significant odors or toxicological effects or act as irritants at low concentrations, whereas others are harmless at high concentrations. Therefore, occupants should choose products with labels that indicate emissions rates for individual compounds, not only for TVOCs.

Safety Data Sheets (Formerly Known as Material Safety Data Sheets or MDSs)

The Occupational Safety and Health Administration's safety data sheets (OSHA 2013) provide detailed safety information about a wide variety of substances used in dwellings and workplaces, including cleaning products. They list known hazards, safety precautions for storage and use, and emergency procedures. Although intended for use in workplaces, they are an accessible source of information on the chemical composition of products and safety information.

Long-term emissions of SVOCs, such as plasticizers, stain and water repellants, fire retardants, polymers, antimicrobial additives, wood preservatives, and pesticides, affect human health and should be considered in the evaluation of material properties. Even foods and their packaging are sources of some SVOCs (Berkeley Lab 2017a).

Chemical emission rates vary significantly over time. Some chemicals in a product decay rapidly (within hours or days), whereas others release contaminants at nearly constant rates for many months (Zhang et al. 1999, Zhu et al. 1999). When a product is selected, the effects of acute exposure (over less than a day) and chronic exposure (over more than a day) should be taken into account. Chronic exposure typically affects health conditions that develop over time, such as those involving growth, reproduction, or behavior.

After compounds enter indoor air, chemical reactions (e.g., reactions with ozone, described in Strategies 3.1 and 7.2) can change these compounds, sometimes resulting in more harmful substances. Rating systems do not yet address these advanced aspects of indoor air chemistry, but such systems might be developed in the future.

When product emissions are considered, the other materials in the systems in which these products will be used should also be considered. For example, carpeting comes with padding, adhesives, tapes, or subflooring. Because of chemical interactions, emissions from a system might be markedly different than those from individual constituents.

Contaminant emissions from materials often rise in higher temperatures and humidity levels. This is an important consideration for those selecting building materials, designing the HVAC system, and selecting setpoints for a thermostat and humidistat.

Research on Contaminants in Dwellings

IAQ guidelines and standards for specific contaminants, especially at concentrations typically found in dwellings, are currently sparse. A few published studies are summarized here.

In a literature review, Levin and Hodgson (Levin and Hodgson 2006) found that only a small number of more than 100 reported VOCs in dwellings and office buildings and measured in studies published between 1990 and 2001 exceeded levels of potential concern for comfort (odor and sensory irritation) and health. The most significant of these, in terms of health effects and typical concentrations, were formaldehyde, acetaldehyde, and acrolein. Logue et al. (Logue et al. 2012), in a more recent report, also found that of the indoor air contaminants studied, particulate matter, acrolein, and formaldehyde accounted for most of the disability-adjusted life years lost.

Formaldehyde and VOCs

The EPA reports that guidelines or recommendations have been set by various organizations for formaldehyde concentrations, but no federally enforceable standards have been set for VOCs in non-industrial settings (EPA 2017q). More information is available from the Lawrence Berkeley National Laboratory's Indoor Air Quality Scientific Findings Resource Bank (Berkeley Lab 2017a).

Hodgson and colleagues (Hodgson et al. 2000) found that in both manufactured and site-built, unoccupied dwellings, the predominant airborne compounds were α-pinene, formaldehyde, hexanal, and acetic acid. The dwellings had similar types and concentrations of VOCs, whose main sources tended to be plywood subfloors, latex paint, and sheet vinyl flooring.

In a 2011 study of 108 California homes, ventilation was insufficient to control formaldehyde in homes to acceptable levels, even for homes with relatively low emission rates, suggesting that even further reductions in emissions will be required (Offerman 2011).

Strategy 5.2 Limit the Impact of Emissions from Materials and Activities

Introduction

In new dwellings, thorough screening of materials, furnishings, equipment, and consumer products can greatly reduce indoor emissions. However, in both new and existing dwellings, contaminant sources can remain after screening. These sources might include the following:

- Several ordinary occupant activities are sources of airborne particles and chemical compounds (see Strategy 5.3 for guidance on exposures related to cleaning).
- Pets are sources of allergens and bacteria, and pet food and water can attract colonizing insects and rodents.
- Existing furniture and building materials that are too expensive to replace can be sources of contaminants.
- Construction in occupied dwellings introduces construction-related contaminants.

This section describes a variety of strategies that occupants and contractors can use to reduce the negative impact of these contaminant sources.

The simplest and most effective way to limit the impact of emission from materials and activities is to avoid those that release airborne contaminants into the home.

- When this is not possible, do the following:
- Cover materials with coatings or veneers to block contaminant release.
- Air out materials and products that release odors before bringing them into the dwelling.
- If spray polyurethane foam is being installed, use installers with third-party certification.
- Air out the home after new materials have been installed.
- When renovations are conducted in an occupied dwelling, isolate the occupied portion from the construction area.

Covering Problem Materials with Coatings or Laminates

In occupied buildings, if existing furniture or cabinets emit VOCs, coatings or coverings can be used to reduce or eliminate the emissions. For example, medium-density fiberboard, particleboard, or plywood can be covered with laminates, self-adhering foil, or liquid-applied or dry-powder coatings. The application of self-adhesive foil, plastic film, or low-VOC odor barrier paint to the insides of cabinets and bottoms of drawers or tables can also reduce VOC emissions. However, this approach can only be used with materials that are accessible.

In new buildings, the most effective and practical way to limit the effects of emissions from indoor materials is through rigorous screening that avoids those with known emissions (Strategy 5.1).

Airing Out High-Emission Items

Airing out new materials, furnishings, and belongings in a well-ventilated, clean space (e.g., a screened-in porch or garage with open doors or windows) before bringing them into a dwelling can reduce emissions from new products and materials. If a product has a problematic odor for more than a month, the owner should contact the manufacturer.

Materials that benefit from airing out before being brought into the dwelling include the following:

- New furniture that is releasing VOCs
- New shelving made of medium-density fiberboard or particleboard
- Dry-cleaned clothing

Polyurethane Foam Insulation

Two-component spray polyurethane is used as moisture-tolerant insulation in crawlspaces, basements, and attics in new dwellings and those being retrofitted or remodeled. This product mixes two sets of chemicals together onsite using a spray gun to produce rigid, stable foam insulation. This product is different from the single-component foam that is available in retail stores, which is more suitable for sealing gaps, and can be applied by dwelling occupants.

Correctly applied two-component foam releases contaminants during application and for hours afterward. Anyone in the building during application must therefore be protected by personal protective equipment or engineering controls (EPA 2017l). Specifically, the two fluids must be mixed in the proper ratio and applied by spray foam installers who are certified by the product's manufacturer or a third-party certification program (e.g., Air Barrier Association of America or Spray Polyurethane Foam Alliance) in accordance with the manufacturer's instructions.

If polyurethane foam insulation appears to be the source of problem odors, the occupant should contact the installer and manufacturer to determine whether the product was correctly applied. If the installer and manufacturer cannot resolve the issue, a third-party inspector might be needed. An assessment of polyurethane foam quality should include examination of the foam for cracks, blisters, surface characteristics, and color (see ACC 2013; Fennell 2012).

Exhaust Systems for Unavoidable Emissions

Activities in kitchens and bathrooms are some of the major sources of indoor air contaminants. An effective strategy to limit their impact on IAQ is to install a local exhaust system in the same room as the contaminant source (Strategy 6.2). Local exhaust systems are more effective if the door between the room and the rest of the dwelling can be closed so that the contaminants cannot spread to the rest of the house. This strategy is most effectively applied during the design phase for new dwellings, but it can be applied to existing kitchens, bathrooms, and workshops. Local exhaust systems for cabinets might be appropriate for highly sensitive residents, but these systems must be used with caution to avoid creating moisture problems (CMHC 1998; Rafuse 1995).

Unusual Sources of Indoor Air Contaminants

Unusual sources of contaminants in residences often result from occupant activities. For example, some hobbies, avocations, and home businesses involve use of paints and varnishes, solvents, pesticides, ceramic kilns, and soldering or welding equipment. Some occupants have unusual pets. The strategies listed below can be used alone or in combination to manage air contaminants from unusual sources.

- If a dwelling activity can also be done in an occupational setting, identify and apply the relevant occupational health and safety requirements. For example, if a dwelling has a woodworking shop, review the Occupational Safety and Health Administration requirements for woodworking (OSHA 2017).

- Provide local exhaust ventilation as close to the source as possible. Many point sources (sources of pollution that can be attributed to a specific physical location) can be treated using a dust collection shroud attached to the tool or an exhaust hood above the source. For example, a dust collection system can be used on a table saw in the basement or an exhaust system can be used for a ceramic kiln (see Strategy 6.2).

- Provide additional dilution ventilation (Strategy 7.1) when needed, such as when several sources of air contaminants are spread out over a large area in an art studio or greenhouse. If the work area with unusual sources is contained, a combination of exhaust ventilation and air sealing can prevent migration of air contaminants from the work area into the house (see Strategy 3.6).

- Use personal protective equipment in addition to ventilation if the above strategies do not provide adequate protection. However, anyone planning to use a respirator (a type of personal protective equipment) should consult their physician because respirators are not appropriate for people with heart conditions, respiratory disease, or claustrophobia.

Staged Entry of Materials

Porous, fleecy materials, such as carpets and ceiling tile, can absorb large amounts of contaminants released during construction. To the extent possible, these materials should be stored and installed after completion of construction activities that release high levels of VOCs (e.g., painting or staining and application of caulks, adhesives, and sealants) or fine particles (e.g., sanding or grinding). Otherwise, these materials can act as contaminant reservoirs and reemit these contaminants into the indoor air for months or years.

Building Flush-Out

Immediately after a new dwelling is built or a remodeling project is completed, contaminant emissions from building materials and interior surfaces are typically highest. It is useful, therefore, to operate ventilation systems at high settings or keep windows open for a few days to help flush these contaminants out before and during the first few weeks of occupancy.

The specific flush-out procedure employed must be adapted to local climatic/seasonal conditions. One flush-out strategy is to open all the windows for two to three days. Another is to set the ventilation systems higher, while keeping indoor conditions at 60-80°F and less than 60% RH. The HVAC system capacity and seasonal weather conditions limit the extent this strategy can be used. Raising the temperature during the flushing out does not appear to be beneficial.

Occupants sometimes cannot or do not want to leave the windows open for several days, and they might be anxious to move into a new dwelling without taking the time to follow all of the required steps. Any flushing out that can be done is worthwhile. At minimum, occupants should run the ventilation fans at their highest settings continuously for the first two weeks after they move into a new dwelling. Filtration and air cleaning strategies are even more important during the flush-out period and immediately following construction.

Limiting Occupant Exposure to Contaminants During Remodeling and Retrofitting

Many sources of indoor air contaminants might be present during remodeling. Demolition releases high levels of airborne particles, which can include hazardous construction materials (e.g., lead in paint, polychlorinated biphenyls in caulking, or asbestos in floor and ceiling tiles or plaster).

Builders and contractors can minimize occupant exposure to contaminants in occupied dwellings during remodeling or retrofitting by following these steps:

- Assess the potential of remodeling activities to produce air contaminants.
  - Identify potential sources of lead, asbestos, and polychlorinated biphenyls in the dwelling that could be disturbed by the work.
  - Identify potential IAQ hazards. For example, sanding, grinding, sawing, and soldering release high levels of airborne particles. Also, glues and other adhesives, lubricants, cleaners, paints, and varnishes release volatile compounds.

- Follow the recommendations in the EPA retrofit guide to protect IAQ during energy efficiency retrofits (EPA 2018a).

- Use low-VOC-emission materials, equipment, and appliances in the remodeling (see Strategy 5.1).

- Use a sander with a built-in dust collector or one that can be connected to a vacuum cleaner with a good filter.

Strategy 5.2 Limit the Impact of Emissions from Materials and Activities

If any existing hazards or remodeling tasks have significant potential for contamination, builders and contractors should follow these steps:

- Physically close off work areas from the rest of the dwelling by closing doors or installing temporary walls.

- Seal air-handling diffusers and return grilles in the work area.

- Use exhaust fans to induce negative air pressure in the work area relative to the rest of the dwelling.

- Remove furnishings, equipment, and appliances from the work area or wrap them in protective coverings.

- Maintain access to a safe emergency exit in the work area.

- Thoroughly clean the work area before taking the temporary walls down.

Strategy 5.3 Minimize Effects of Cleaning and Maintenance on IAQ

5.3

Introduction

To minimize the effects of cleaning and maintenance on IAQ:

- Select durable materials and finishes that are simple to clean and maintain.
- Use cleaning products that have minimal emissions.
- Store cleaning products properly.
- Operate local exhaust systems during cleaning.
- Use a central vacuum cleaning system that emits exhaust air to the outdoors or uses a high-efficiency filter.

A clean indoor environment is a requirement for good IAQ. Unless particulate matter from outdoor or indoor sources that settles on surfaces, including carpets, is removed by cleaning, it can become airborne again. Biological contaminants can also become overgrown in dirty environments.

Recognition is growing, however, that some cleaning agents and/or practices can have detrimental effects on indoor air. Materials and designs that minimize the need for cleaning and facilitate cleaning with nontoxic agents can help achieve a clean and healthy indoor environment. Following the manufacturer's instructions for cleaning is also important.

A preferred initial strategy is to prevent dirt and contaminants from entering the dwelling in the first place, thus reducing the need for cleaning. This strategy pays additional dividends by reducing cleaning labor and can be achieved through effective dwelling design, maintenance, and operation. An example is the use of doormats to keep contaminants and dirt localized in small areas near the entrance that can be cleaned more often (Strategy 3.4). An airtight building enclosure reduces infiltration of contaminated outdoor air (Strategy 3.1) and introduction of outdoor moisture (Strategy 2.2). Highly effective filters in the heating and cooling system remove particles from the air before they can settle (Strategy 7.2).

See Figure 5.3.A for a summary of cleaning strategies that minimize threats to IAQ.

Use of Durable Materials and Finishes That Are Simple to Clean and Maintain

Interior materials and finishes should allow cleaning without use of strong chemical agents and be durable enough to reduce the IAQ effects of replacement or refinishing. Particular attention should be paid to flooring materials and surfaces used in kitchens, bathrooms, other toilet rooms (any rooms that contain a toilet), and laundries. Low-emission, hard-surface materials, such as tile or stone, are durable and easy to clean and disinfect, but they require proper installation. Furthermore, grout that is improperly sealed or loose holds contaminants, and moisture flows must be considered (see Strategy 2.3).

Use of Cleaning Products with Minimal Emissions

Just as it is important to avoid materials that emit high levels of VOCs, the use of cleaning products with high emissions should be minimized. Cleaning is an ongoing and essential requirement in any dwelling. Cleaning products have diverse functions and chemical compositions, and some ingredients can be irritating or harmful to occupants. Some cleaning products, most notably those with terpenes (components of pine and citrus oils), can result in formation of highly irritating secondary byproducts when used in the presence of indoor oxidants

(such as ozone; CARB 2008a). Cleaning products should be selected to avoid these potential problems, equipment that generates ozone should not be used, and carbon filters should be used in regions with high outdoor ozone levels (Strategy 3.1).

The EPA's Safer Choice Label program (EPA 2017o) can help consumers choose cleaning products that have safer chemical ingredients without sacrificing quality or performance. A separate label certifies products that have no fragrances. The program's website supports searches for products that have met the label requirements.

As with anything else, if the marketing claims about a product seem too good to be true, they probably are. Occupants should be wary of cleaning products whose manufacturers boldly claim that maintenance can be avoided or that these products produce chemical reactions that eliminate contaminants. These products might be ineffective, or worse, the chemical reactions could produce even more irritating compounds than the cleaning products alone.

Figure 5.3-A Cleaning Protocols that Maximize IAQ

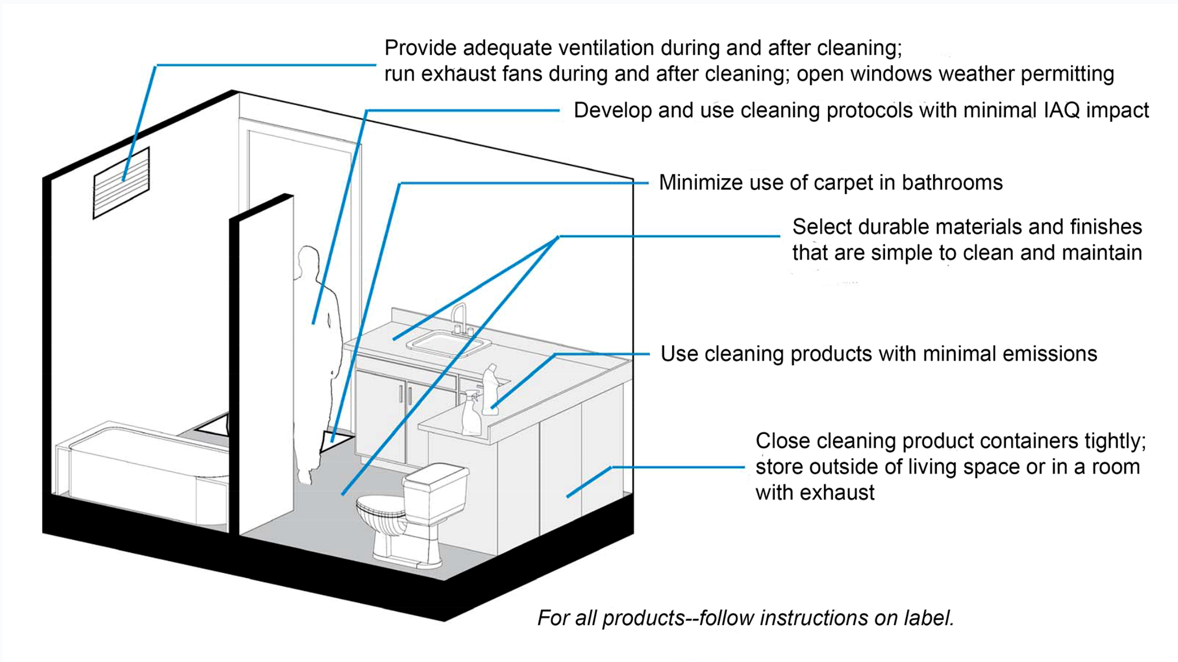


Figure 5.3-A Cleaning Protocols that Maximize IAQ

Cleaning Product Storage

Cleaning product containers should always be tightly sealed during storage, and these products should be stored outside the living space when possible, as long as they will not freeze. When this is not feasible, cleaning products should be stored safely in a room where an exhaust system is often turned on, such as in a bathroom or other toilet room, laundry room, or kitchen.

Local Exhaust Ventilation During Cleaning

Local exhaust systems should be turned on and in areas where cleaning agents emit airborne contaminants. This step will minimize IAQ effects in the cleaning area and reduce the spread of airborne contaminants to other areas inside the dwelling.

Vacuum Cleaning Systems

Central vacuum cleaning systems that exhaust to outside the dwelling reduce indoor particle contaminant levels by removing dirt, dust, pollen, dander, and dust mites or other allergens. In dwellings with no central vacuum cleaning system, a vacuum cleaner with a high-efficiency particulate air (HEPA) or other equally effective filter should be used (Consumer Reports 2016c).

Strategy 5.4 Avoid Certain Sources of Contaminants

Introduction

Some sources of indoor contaminants should not be used in dwellings because they present avoidable health hazards. These sources are discussed below.

Tips for avoiding certain contaminant sources are as follows:

- Do not smoke or "vape" indoors.
- Do not use appliances intended for outdoor use, such as grills and camping stoves, indoors.
- Locate generators 25 ft downwind from the dwelling.
- Do not use appliances indoors that generate ozone.

Carbon Monoxide

Carbon monoxide is a colorless, odorless gas produced by burning fuel. The initial symptoms of carbon monoxide poisoning are similar to those of the flu and include dizziness, fatigue, headache, nausea, and irregular breathing. Exposure to high levels of carbon monoxide can be deadly, and carbon monoxide poisoning from fuel-burning appliances kills more than 170 people in the United States each year. Some common causes of carbon monoxide poisoning are burning charcoal inside a dwelling, garage, vehicle, or tent or when cars are left running in an attached garage. Cars should never be left running in a garage.

The U.S. Consumer Product Safety Commission and the Federal Emergency Management Agency have joined forces to warn residents not to use gasoline-powered generators or charcoal grills indoors or in attached garages because of the risk of carbon monoxide poisoning (United States Consumer Product Safety Commission 2003).

Gasoline-powered portable generators should be kept in level areas that have no risk of flooding and are as far from the dwelling as possible. Studies have shown that these generators might need to be up to 25 ft (7.5 m) away from any openings in the dwelling, and they should be downwind of the dwelling if possible (NIST 2009). The National Fire Protection Association has codes and standards for the safe installation and operation of permanently installed generators (NFPA 2017 and 2018b).

Indoor Ozone Generators

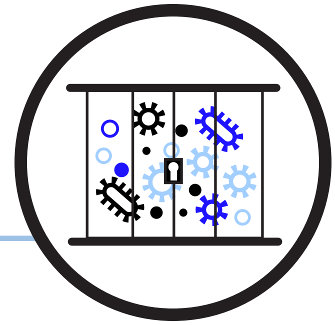
A variety of other types of consumer products can release ozone (Zhang 2017). For example, some electronic air cleaners produce ozone, sometimes in hazardous amounts, and they should never be used because ozone causes health problems, including respiratory tract irritation and breathing difficulties (ARB 2015). The EPA regulates it as an outdoor air contaminant. Even at concentrations less than the ambient air quality standard of 70 parts per billion, ozone can cause health problems by itself and when it reacts with indoor VOCs in the air or on indoor surfaces including human skin to produce different VOCs and significant amounts of fine and ultrafine particles (Norgaard 2014, Rai et al. 2013, 2014). For more information on ozone in dwellings, see Strategy 7.2. and the California Air Resources Board website (CARB 2008a; CARB 2008b; ARB 2015; ARB 2016).

Smoking and "Vaping"

No one should ever smoke indoors, especially when doing so exposes others to secondhand smoke. A large body of evidence has identified the dangers of exposure to secondhand smoke (HHS 2006). Parents who do not smoke in front of their children but do smoke elsewhere in the dwelling still expose their children to harmful secondhand smoke. Furthermore, smoking indoors leaves residue on clothing and other indoor surfaces, which exposes others to "thirdhand smoke." Zhang et al. (2003) found that overwhelmingly the VOCs measured in smoking homes were from the smoking residuals. Smoke from cigarettes used on a balcony or near a door or window can enter the dwelling, so smoking in these areas is not a good solution. The best place to smoke is outside, far from anyone or any building.

"Vaping" with electronic cigarettes has not been studied as well as tobacco smoke, but this practice should be avoided indoors until more conclusive evidence is available (Chapman 2018, Logue et al. 2017; Shahab 2017).

Objective 6



KEEP CONTAMINANTS IN THEIR PLACE

Equipment and activities in the dwelling can be significant sources of indoor air contaminants. Among these are combustion products from fuel-burning equipment and cooking; exhaust from vehicles in enclosed garages; air pollutants from personal care products; particles and fumes from shop as well as arts and crafts activities; and odors from various sources. It is always best to move pollutant-generating activities outdoors (Strategy 5.4). When this is not possible, the next best option is to remove pollutants where they are generated using vented appliances (Strategy 6.1) or local exhaust systems (Strategy 6.2).

The strategies for Objective 6 cover various means of isolating and removing contaminants, including the use of exhaust systems and vented appliances to remove indoor air contaminants produced by fuel-burning and other equipment and activities from a dwelling:

Strategy 6.1

Properly Vent Combustion Equipment discusses methods to direct the moisture and gasses generated by combustion to the outdoors and to provide furnaces and water heaters with adequate air for combustion.

Strategy 6.2

Provide Local Capture and Exhaust for Point Sources of Contaminants describes techniques to reduce exposure through well-designed exhaust systems and proper use of such systems.

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Strategy 6.3

Maintain Proper Pressure Relationships Between Spaces describes methods to control pressure differentials that can cause combustion appliances to malfunction or increase contaminant transfer from attached spaces, such as crawlspaces, garage, and attics.

Other strategies that address exhaust systems and space depressurization include the following:

- Strategy 1.2 – Select HVAC Systems to Manage the Energy Effects of Ventilation
- Strategy 2.2 – Control Indoor Humidity
- Strategy 3.3 – Control Entry of Radon and Other Subsurface Contaminants
- Strategy 3.6 – Control Entry of Contaminants from Unoccupied Spaces
- Strategy 5.2 – Limit the Impact of Emissions from Materials and Activities
- Strategy 7.1 – Choose Outdoor Air Ventilation Strategy and Quantity

Strategy 6.1 Properly Vent Combustion Equipment

Introduction

Fuels are burned indoors to heat buildings in cold weather. They are also burned to heat water for drinking, cooking, and bathing; to cook food; and, in fireplaces, to enhance dwelling ambiance. The primary fuels burned in buildings are natural gas, propane, fuel oil, firewood, and wood-based pellets. The combustion of these fuels releases air contaminants in a dwelling, including carbon dioxide, carbon monoxide, water vapor, fine particulate matter, nitrogen dioxide, polycyclic aromatic hydrocarbons, and formaldehyde. Some of these contaminants can result in immediate eye, nose, and throat irritation; asthma events; or carbon monoxide poisoning. In other cases, health effects (e.g., heart disease, respiratory disease, or cancer) show up only after years of exposure. Water vapor does not directly compromise IAQ, but it can lead to conditions conducive to biological growth or other threats to IAQ.

> Burning fuels releases air contaminants in the form of particles and gases and water vapor.
>
> The following steps are important for properly venting combustion equipment:
>
> - The combustion equipment used should collect and exhaust the combustion contaminants.
> - For new dwellings, mechanical draft or direct-vent appliances should be used that comply with the applicable codes and standards.
> - Steps for existing dwellings are to:
>   - Inspect combustion equipment safety.
>   - Repair, remove, or replace combustion equipment and address any deficiencies as needed to meet the applicable codes and standards.
>   - Replace unvented combustion heating appliances with new vented equipment.

There are several ways of reducing exposure to contaminants released inside buildings:

- Do not burn anything inside unless it is directly vented to the outside.
- Contain the combustion and its pollutants and vent them out of the dwelling using one of the ventilation systems described in the subsections below (ICC 2015c).
- Choose combustion equipment that produces the smallest amount of pollution.
- Use carbon monoxide alarms to alert you if a combustion source is producing unacceptably high carbon monoxide levels (Strategy 5.2).
- Follow the manufacturer's instructions for installing, maintaining, and operating all equipment.
- Never use portable combustion equipment (e.g., generators and other power tools that have engines, grills, camping stoves or kerosene space heaters) indoors.

This strategy focuses on properly venting combustion equipment used for space heating, hot water heating, or ambiance. Please note that local, state, and federal codes and regulations pertaining to ventilation of emissions from combustion equipment supersede any guidance in this document.

Strategy 6.1 Properly Vent Combustion Equipment

Methods to Vent Contaminants from a Combustion Device

Several methods can be used to vent combustion contaminants from a combustion device. The following definitions from the International Mechanical Code (ICC 2015b) are used in the subsections below to describe the methods that can be used to vent combustion contaminants from a combustion guide:

- Direct-vent appliance: Appliance (Figure 6.1-A) constructed and installed so that all air for combustion comes from the outdoors and all flue gases are discharged to the outdoor atmosphere.
- Mechanical draft system: A venting system (Figure 6.1-B) designed to remove flue or vent gases by mechanical means .
- Natural draft system: A venting system that relies on a draft produced by the difference in the density of gases inside a chimney or vent and the density of air outside the chimney or vent to convey combustion products outside (Figure 6.1-C).

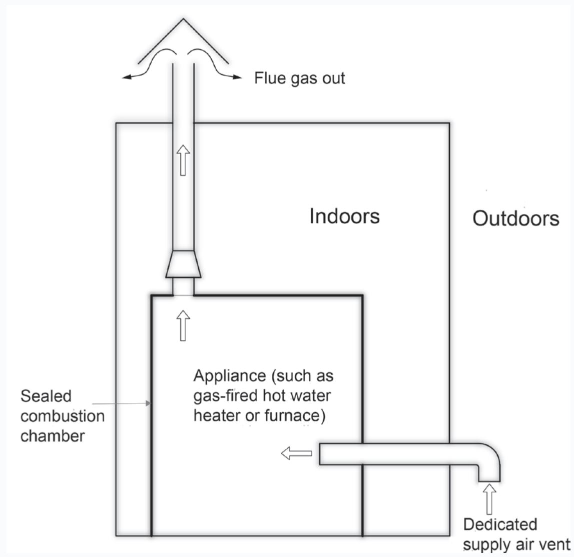


Figure 6.1.A Direct-Vent Appliance Setup

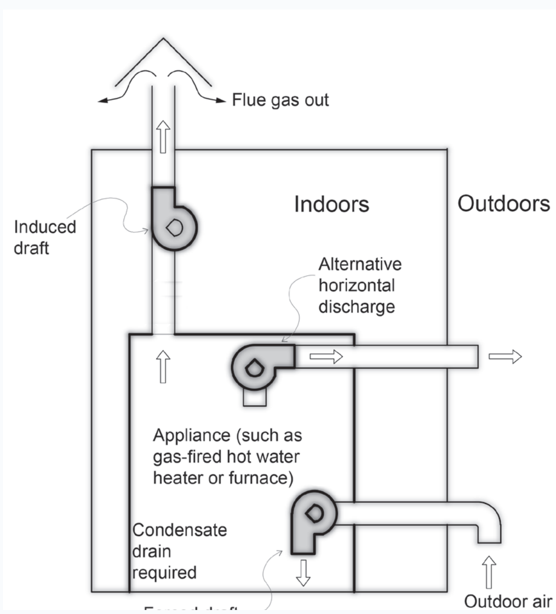


Figure 6.1-B A Mechanical Draft System

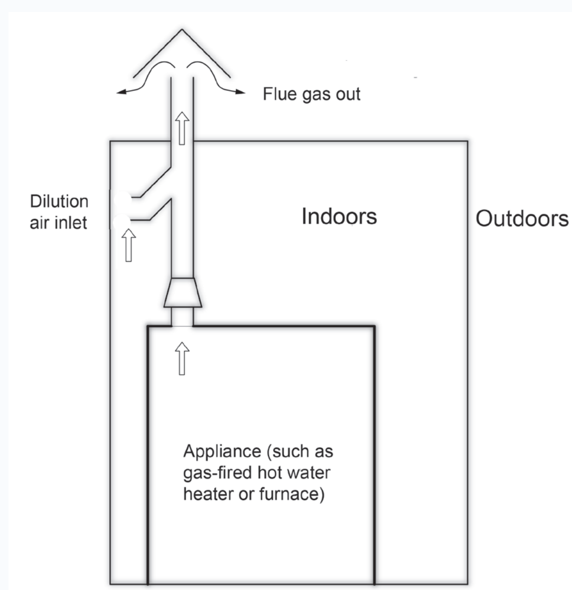


Figure 6.1-C Natural Draft System

New Dwellings

For new dwellings, the best practice is to use a mechanical draft system or direct-vent appliance to vent all combustion equipment—including furnaces, boilers, space heaters, water heaters, and

fireplaces—used for dwelling heating, water heating, or ambiance.

The EPA Indoor airPLUS program requires mechanical drafting or direct venting in new dwellings (EPA 2017i) except for natural draft systems in warmer zones (Climate Zones 1–3, Figure 1.2-A) if an energy rater has conducted the RESNET combustion safety tests, (RESNET 2010) This guidance can also be applied to existing dwellings, particularly when equipment is replaced.

All fireplaces and other fuel-burning and space-heating appliances should meet the following energy efficiency and emissions standards and restrictions:

- *Masonry heaters (also known as masonry stoves, kachelofens, Russian fireplaces, Finnish fireplaces, Swedish stoves, tile stoves, contra-flow fireplaces, radiant fireplaces, and mass-storage fireplaces):* Masonry heaters as defined by ASTM E1602 (ASTM 2017b) and section 2112.1 of the 2012 International Building Code (ICC 2012) are acceptable. These stoves use a maze of flue baffles to warm the surrounding masonry, which then emits heat for 18 to 24 hours. The temperature inside some masonry heaters can reach 2,000°F (1100°C) compared with a maximum of 700°F (370°C) inside a metal stove. Traditional masonry fireplaces designed for open fires should not be used in dwellings.

- *Factory-built wood-burning fireplaces:* These fireplaces should have tight-fitting, gasketed glass doors and a dedicated outside air supply. Factory-built wood burning fireplaces meeting the requirements of the EPA's wood-burning fireplace program (EPA 2017b) are a good choice.

- *Wood stove and fireplace inserts as defined in section 3.8 of UL Standard 1482 (UL 2011b)*: These inserts should meet the certification requirements of UL Standard 1482 and the emission requirements of the EPA's new source performance standards for new residential wood heaters (EPA 2015a).

- *Pellet stoves:* These stoves should meet the requirements of ASTM E1509 (ASTM 2017a) and the emission requirements of the EPA's new source performance standards (EPA 2015a) for new residential wood heaters.

- *Natural gas and propane fireplaces*: These fireplaces should have a permanently affixed glass front or tightly sealed door and be mechanically vented or direct vented in accordance with ANSI Z21.88/CSA 2.33 (CSA 2016).

- *Decorative gas logs as defined in ANSI Z21.84 (ANSI 2017b)*: These should not be used.

Existing Dwellings

All or, at the very least, older unvented combustion appliances should be removed from existing dwellings (ASHRAE 2012). The EPA (EPA 2011) recommends a safety assessment of all vented combustion appliances in the dwelling (e.g., furnaces, boilers, space heaters, and water heaters). This assessment should include clearances, venting system condition, potential for backdrafting, integrity of fuel lines, and safety of electrical connections.

Strategy 6.1 Properly Vent Combustion Equipment

For gas-fired appliances and equipment, this assessment should use applicable installation standards, including the National Fuel Gas Code, ANSI Z223.1/NFPA 54 (NFPA 2018), the applicable ANSI Z21 (ANSI 2017a) gas-fired appliance safety standard, and the manufacturer's instructions. As part of the assessment, a determination should be made of whether gas-fired appliance installations comply with the requirements in Section 9.3 of the National Fuel Gas Code (NFPA 2018) for proper venting. For oil-fired appliances and equipment, the assessment should be based on applicable installation standards, including the ANSI/NFPA standard for the installation of oil-burning equipment (National Fire Protection Association [NFPA 2016b]), the applicable ANSI/UL oil-fired appliance safety standard (UL 1994), and the manufacturer's instructions.

All new combustion equipment should be installed in accordance with the ANSI/ACCA HVAC quality installation specifications (ACCA 2015a) and the recommendations for new dwellings above. When equipment is removed that is deficient or not code compliant, it must be disposed of properly to prevent its reinstallation elsewhere.

Backdraft problems should be addressed by having sufficient openings to allow combustion air to enter and avoiding problems caused by excessive exhaust (Strategy 6.2). If a whole-house fan is used for cooling at night, several windows should be opened before the fan is turned on.

When existing dwellings are tightened, weatherized, or have larger exhaust fans installed, combustion appliances should tested to identify combustion safety issues. See that the appliances draft properly and do not emit carbon monoxide under worst-case depressurization. See BPI-1100-T-2014, Section 7 (BPI 2014).

Relevant Guidance and Standards

Relevant guidance and standards are as follows:

- ACCA Standard 5 HVAC Quality Installation Specification (ACCA 2015a)
- ANSI Z223.1/NFPA 54: National Fuel Gas Code (NFPA 2018)
- ANSI Z21 Series Standards for Residential Gas-Fired Appliances (ANSI 2017a)
- ASHRAE Standard 62.2 Ventilation and Acceptable Indoor Air Quality in Residential Buildings (ASHRAE 2016b)
- BPI-1100-T, Combustion Appliance Testing section (BPI 2014)
- BPI Technical Standards, Technical Standards for the Building Analyst Professional, CAZ Depressurization Limits Table (BPI 2012)
- Carbon Monoxide (CO) and Other Combustion Appliance Emissions (EPA 2011)
- EPA Indoor airPLUS Specification 5.1 (EPA 2015c)

- NFPA 31, Standard for the Installation of Oil-Burning Equipment (NFPA 2016b)

- NFPA 211, Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances (NFPA 2016a)

Strategy 6.2 Provide Local Capture and Exhaust for Point Sources of Contaminants

6.2

Introduction

Kitchens and bathrooms are two common locations where pollutants—including VOCs, combustion byproducts, and pollutants generated by people—are formed in every dwelling. These rooms are also significant sources of water vapor, which is often described as a contaminant. However, water vapor is always present as a constituent of air and only causes comfort or biological growth problems at high concentrations. Therefore, the impact of water vapor in these rooms and the importance of exhaust strategies to remove it depend on climate conditions.

This strategy focuses on local exhaust systems that remove contaminants where and when they are generated. To effectively remove particles, gases, and moisture, local exhaust systems must be correctly sized, properly located, installed with good workmanship, and operated as intended.

Kitchen Exhaust Systems

An effective kitchen exhaust system removes contaminants emitted by the food being cooked and the cooking surface or fuel as well as water vapor and heat generated during cooking.

Why it is needed. Regardless of the cooking fuel used, food releases contaminants into the air during cooking in types and quantities that depend on the food and cooking method. Gas cooktops and ovens generate combustion byproducts, including water vapor, carbon dioxide, carbon monoxide, nitrogen dioxide, and ultrafine particles (Lunden et al. 2015). Traditional electric cooktops and heated cookware emit ultrafine particles from the burn-off of dust and food particles and from detergents used to clean cookware (Wallace et. al 2015). The surfaces of electric induction cooktops remain cooler than those of traditional electric cooktops during cooking, which is likely to reduce some but not all of this burn-off because cookware is still heated during cooking. Gas ovens can introduce combustion byproducts into the dwelling, especially when they are first turned on. Occupants should use their kitchen range hoods whenever they are cooking on the stovetop or using the oven.

Strategies to reduce pollutant exposure in kitchens are as follows:

- Use a hood-style exhaust system that covers the cooktop.
- Cook on the burners closest to the exhaust fan, which are usually in the back of the stove.
- Increase the flow rate of the exhaust fan.
- Install a quiet exhaust fan to encourage frequent use.
- Install controls that automatically operate the exhaust fan when the cooking appliance is used or manually operate the fan whenever the cooktop or oven is used.
- Consider installing an induction cooktop.

How much air? ASHRAE Standard 62.2-2016 (ASHRAE 2016b) requires that all cooktops have either an exhaust hood with at least a 100 CFM rating or another type of exhaust system with at least a 300 CFM rated fan airflow (this includes downdraft fans, such as the one pictured in Figure 6.2-B). These are minimum airflows, and higher rates should be used when recommended by the manufacturer of the cooktop. If no recommended airflow rate is available for a cooktop, the best practice is to install at least a 200 CFM hood-style exhaust system that covers the cooking surface. Many exhaust fans fail to achieve their rated airflow when they are installed, and a 200 CFM hood-style exhaust system provides a good margin above the recommended minimum airflow of 100 CFM. Following the duct sizing guidelines in ASHRAE Standard 62.2 is a good strategy to help obtain fan airflow rates that are close to their rated levels.

Large systems and makeup air. The manufacturer's required airflow rate can be quite large, often in excess of 400 CFM, for commercial-style or gas ranges. Exhaust systems with very large exhaust volumes use more energy, are expensive to install and operate, and can contribute to pressure imbalances in dwellings that have negative effects on IAQ (Strategy 6.3). For this reason, intentional makeup air (described below) is required when these large fans are used. In many cases, the simplest and best solution is to select a different range that can operate with a lower flow-rate hood that does not require makeup air.

When a large volume of exhaust air is required, the resulting negative pressure inside the dwelling may cause gas appliances to backdraft (Strategies 6.1 and 6.3), lead to problems with fireplace draw, or produce noise and possible building enclosure or humidity problems (Strategy 2.2). Dwellings with natural-draft gas appliances (described in Strategy 6.1), very tight building enclosures, and fireplaces have a particularly high risk and might need compensatory outside air at even lower airflow rates.

Dwelling unit ventilation is never enough to balance the airflow quantities needed for a large hood, even if a supply-only ventilation system is used. As discussed in Strategy 7.1, a typical dwelling needs less than 100 CFM of dwelling unit ventilation, whereas some large residential kitchen range hoods have an airflow rate as large as 1,200 CFM. A 100 CFM supply-only ventilation system does little to counterbalance flow rates this large. A balanced whole-house ventilation system would have no effect on dwelling pressure, and an exhaust-only system would add to the problem.

For these reasons, large exhaust fans need makeup air from outdoors to balance the large quantity of air that the hood exhausts out and to prevent negative pressure in the dwelling. Many jurisdictions have codes requiring makeup air to be automatically supplied when the kitchen exhaust fan is operated.

When makeup air is needed, design challenges include finding an intake location, whether and how to condition the makeup air, and the accessibility and reliability of the system. All of these can add significantly to the cost and space needs of the project. There is no universally accepted rule for when a makeup air system is needed. Some thresholds used by various programs and codes are:

- Kitchen hood rated airflow greater than 400 CFM (189 l/s) (ICC 2015c)

- Sum of rated airflow of largest two exhaust fans in dwelling larger than 15 CFM/100 ft^2 (75 l/s per 100 m^2) of conditioned floor area (maximum allowed by ENERGY STAR New Homes (ENERGY STAR 2017a) for dwellings with naturally drafted fireplaces). ASHRAE has a similar requirement (ASHRAE 2016b).

- Measured negative indoor/outdoor pressure difference meeting RESNET's or BPI's limits in the combustion appliance zone with exhaust fans operating (RESNET 2010; BPI 2015)

- The first two criteria above might be most useful for new dwellings under construction. The third criterion might be easiest to implement in dwellings that already have exhaust fans.

Capture efficiency. Hoods located directly above the cooktop that cover the entire cooktop surface (Figure 6.2-A) tend to be the most effective. In general, downdraft systems that exhaust air from

a location to the side or underneath the cooktop (Figure 6.2-B) are the least effective type in tests (Consumer Reports 2016b). Tests of commercial hoods have demonstrated that hoods over island cooktops need more air than those against a wall and that side panels make hoods perform even better. Island hoods should be 6 in. larger than the cooktop (Consumer Reports 2016b) to achieve a 3 in. overhang on all sides A hood height of 18-30 in. (46-76 cm) above the cooktop is recommended for optimal capture of cooking contaminants.

Figure 6.2-A Preferable Exhaust System: Hood Covers the Cooktop Surface

Capture efficiency ratings that would quantify how well a hood removes cooking contaminants are not currently available for consumer cooktop hoods. However, research is being conducted to develop test methods that will enable development of such ratings in the future (Singer et al. 2011b). Higher airflow rates improve capture efficiency and can be used to partially compensate for less effective configurations (Singer et al. 2011a), which is why ASHRAE Standard 62.2-2016 (ASHRAE 2016b) requires a higher airflow rate for kitchen exhaust systems other than hoods (such as downdrafts).

Recirculating kitchen hoods that introduce air back into the kitchen are common but ineffective because their grease traps do not remove most contaminants.

Figure 6.2-B Less Effective Exhaust System: Downdraft Kitchen Exhaust Setup

Use and operation. The kitchen range hood (or exhaust system) should be used whenever someone is cooking on the stovetop or using the oven. If the oven is far from the hood, the exhaust system will be less effective. Likewise, the effectiveness of a kitchen exhaust system at removing contaminants from cooking with countertop appliances is limited when the appliances are located away from the hood or exhaust intake.

Unfortunately, many occupants are not aware of the importance of using the kitchen exhaust, or they choose not to use it because the fans can be loud. Interlocking kitchen exhaust systems to operate automatically when cooking takes place can help ensure that the exhaust fan is used consistently. Systems are currently available that automatically turn the hood on using a temperature sensor, but they do not turn on immediately and might not turn on at all during low-temperature or oven cooking. Smart hoods currently in development will turn on whenever the range is used, and they should be on the market within the next few years.

If the exhaust system does not cover all of the burners equally or if a downdraft exhaust system is used, the burners that have the best coverage (usually the ones in the back) or are located closest to the fan should be used.

Sound. Quieter products are more likely to be used regularly. The Home Ventilating Institute (HVI 2017) maintains a certified products directory that provides consumer information on sound ratings for many exhaust fans. Unfortunately, the institute does not include most microwave hood fans, but this is likely to change in the future. Sound ratings for fans are measured in sones, and fans with lower numbers of sones are quieter. The best practice is to choose a fan with the lowest sound rating possible. Standard 62.2 (ASHRAE 2016b) requires fans that are located in the occupied space to have sound ratings of less than 3 sones. Since few large fans are this quiet, an effective strategy to reduce sound when a very large exhaust fan must be used is to mount the fan remotely, as shown in Figure 6.2-C.

Figure 6.2-C Remotely Mounted Kitchen Exhaust Fan

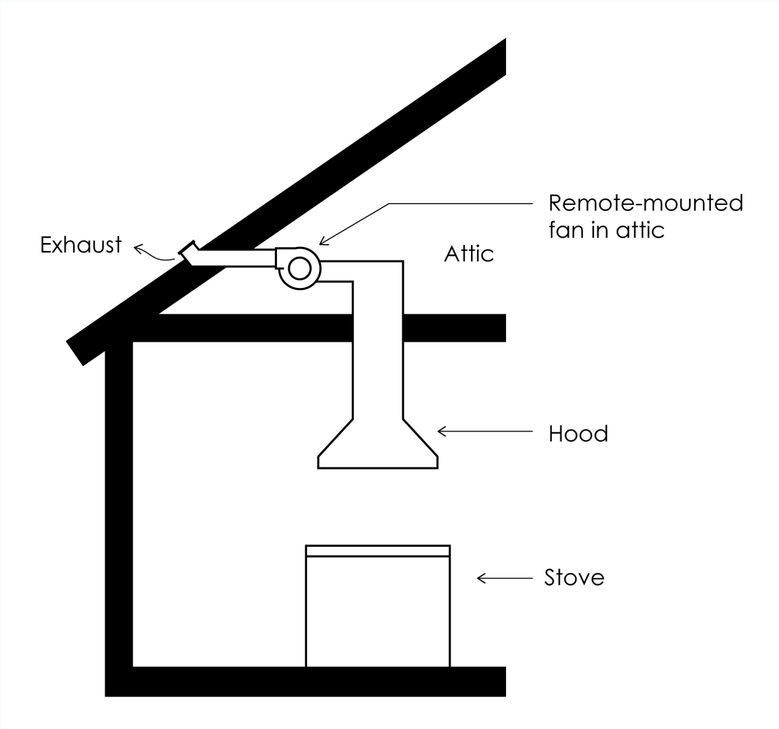


Figure 6.2-C Remotely Mounted Kitchen Exhaust Fan

Kitchen exhaust not over the rangetop. In lieu of an exhaust hood or downdraft, it is possible to ventilate a kitchen by diluting the kitchen air, although doing so is not recommended. ASHRAE Standard 62.2-2016 (ASHRAE 2016b) allows this to be accomplished by installing an exhaust fan that removes a volume of air greater than or equal to five air changes per hour from any location in an enclosed kitchen. The strategy is not allowed for non-enclosed kitchens, such as those open to a larger great room or living area. Even in a relatively small kitchen, the airflow rate for such a system can become quite high, increasing the energy required to move and condition this air. When the exhaust system is not at the cooking location, the capture efficiency is much lower and occupants in the kitchen will have higher contaminant exposures. However, it is better than no system and might be the most viable option for a retrofit situation, particularly if the kitchen is enclosed and small.

Bathroom Exhaust Systems

One role of bathroom exhaust systems is to remove personal odors and pollutants from cleaning and personal products. In many climates, however, the role of a bathroom exhaust system in removing moisture from the bathroom is even more important. Bathrooms tend to be cleaned more often than other rooms and used to store cleaning products, so exhausting air from bathrooms helps remove VOCs emitted by those products. ASHRAE Standard 62.2 (ASHRAE 2016b) requires a mechanical exhaust fan in all bathrooms (rooms containing bathtubs, showers, spas, or similar moisture sources).

ASHRAE Standard 62.2 and most building codes also require an operable window or a fan in any room that contains a toilet. A fan is the best option for removing odors in toilet rooms. When disease transmission is a concern, another helpful practice in dwellings is to close the toilet lid before flushing it.

The minimum requirements of ASHRAE Standard 62.2-2016 (ASHRAE 2016b) are to provide a 50 CFM (23.6 l/s) rated intermittent or 20 CFM (9.4 l/s) rated continuous exhaust system in each full bathroom. As with kitchen fans, compliance with the duct sizing requirements in ASHRAE Standard 62.2 is important to help the fan operate near its rated airflow rate, but it is also helpful to install a larger fan than the minimum size. An 80 CFM (37.8 l/s) rated fan with ductwork that meets the standard's requirements is a good design strategy for achieving a 50 CFM (23.6 l/s) installed airflow rate.

Removal of moisture from bathrooms is very important to prevent IAQ problems, such as biological growth, in all but the driest climates. In warm humid climates, bathroom moisture can add to the humidity load that the air conditioner and/or dehumidifier must control. In cold climates, bathroom moisture can raise the indoor humidity level in tight dwellings and contribute to window condensation problems. Dwellings in climates zones 3–5 (Figure 1.2-A) are at risk of both problems depending on the season.

Strategies to enhance moisture removal in bathrooms are as follows:

- Locate the exhaust fan in the ceiling or high on a sidewall in the shower enclosure.
- Use a low-flow showerhead. Showers with rain showerheads or multiple showerheads with water flow of more than 2.5 gpm (9.5 l/min) aerosolize more water vapor.
- Use shower doors rather than an open shower design.
- Use a higher exhaust fan airflow rating than the minimum required.
- Close the bathroom door and run the exhaust fan during every shower and for 15 minutes afterward.
- Use a timer, occupancy sensor, delay setting, and/or humidity control so that the fan runs while the bathroom is used and for at least 15 minutes afterward.
- If a continuous-run 20 CFM (9.4 l/s) fan is used, install a "boost" setting that allows the occupant to temporarily increase the flow rate to at least 40 CFM (18.9 l/s).

As with kitchen fans, the sound rating of bathroom exhaust fans is important. In addition to being more likely to be used by the occupants, quieter fans tend to be more efficient, of higher quality, and more likely to deliver airflows close to their rated airflow rate. Sound data are available for nearly all bathroom fan models on the market and can be found printed on the packaging of new fans or in the Home Ventilating Institute certified products directory (HVI 2017). ASHRAE Standard 62.2-2016 requires intermittent fans to have a rating of less than 3 sones, and continuous-run fans should have a rating of less than 1 sone. Fans with ratings of less than 1 sone are widely available and should be installed as a best practice, even for intermittent applications. Selecting a fan with an ENERGY STAR rating is an easy way to find a fan that is both quiet and efficient.

Bathroom fans are particularly vulnerable to impeded function due to poor installation. In many cases, an electrician installs the fan, an HVAC contractor installs the ducts, and a siding contractor installs the cover on the dwelling's exterior. The person coordinating all of this construction needs to understand the importance of these fans and supervise all aspects of the installation.

Figure 6.2-E Twisted Duct (Which Reduces Exhaust Effectiveness)

Best practices for maximizing bathroom fan performance are as follows:

- When the fan is installed, the duct connection should be aimed toward the outdoor penetration so that bends are not needed.
- Some fans have an internal damper that can become caught on the duct, especially if the attachment has a sharp bend or if a flexible duct is bunched up close to the fan.
- The duct size should be determined using ASHRAE Standard 62.2 (ASHRAE 2016b) for the selected fan size and duct length.
- Ducts should have no visible holes, tears, or loose joints at ductwork connections, and they should be constructed of durable materials.
- Ducts should be as short and straight as possible (see Figure 6.2-E for a duct that does not follow this recommendation).
- Rigid duct is recommended. If a flexible duct is installed, it should be pulled to its full length to avoid compression and supported to avoid sags, and the bend radius should be at least one duct diameter (ADC 2010).

Figure 6.2-F Airflow Hood Used to Measure Flow Rate of a Bathroom Exhaust Fan

- If spray foam insulation is installed around a flexible duct, care should be taken to avoid crushing the duct.
- The exterior penetration should be covered as soon as the duct is installed and throughout construction to keep animals and debris out.
- When the siding is completed, the flexible duct should be gently pulled through the opening, and any extra length should be cut off. The duct should be permanently attached to the opening, the temporary covering should be removed, and a low-restriction cover that is pest proof should be installed.

Following these steps will dramatically reduce the likelihood that the fan will fail to deliver the intended airflow rate. A best practice is to measure each bathroom fan using a flow hood to verify the flow rate (Figure 6.2-F). If a flow hood is not available, a simple go/no-go test can be used: if the fan holds toilet tissue against its surface, it is drawing air.

Other Local Exhaust Fans

Some dwellings have other spaces—including attached garages, craft rooms, shops, and utility rooms—where local exhaust fans can be helpful. Unless a space is large, a bathroom-sized exhaust fan is usually adequate. Strategy 3.6 discusses exhaust fan options for garages in more detail.

Dryer vents are essential, and homeowners should be careful to keep lint traps and dryer vents clean. Failure to do so can be a fire risk and increase drying time and energy consumption.

When possible, activities that generate high levels of pollution should be done outdoors. However, if an accident occurs, food is burned, or an unusual cleanup is needed, use of exhaust systems (e.g., multispeed kitchen fans) and operable windows are helpful.

Exhaust Air Outlets

Exhaust air should be delivered directly to the outdoors—not to the attic, eaves, wall or ceiling cavity, or back into the dwelling. Furthermore, exhaust air should always be removed from the space via ductwork and not routed through wall or ceiling cavities. Bathroom exhaust fans in many existing dwellings deliver air to the attic, which can cause moisture problems. Sometimes, the duct becomes disconnected in the attic and no one notices.

The exhaust outlet should not be close to windows or doors that might be open. If the dwelling has a ventilation system with an outside air intake, that intake should be at least 10 ft (3 m) from the exhaust fan or, even better, around a corner to prevent the exhaust air from reentering the space. Exhaust outlets should be located in areas where they will not become obstructed by snow, vegetation, or other materials.

If multiple fans in the same dwelling unit share a common exhaust duct, backdraft dampers should be used to prevent backflow of air from one exhaust point to another.

In multifamily buildings, exhaust systems must not inadvertently deliver the exhaust air to another living unit, and the correct quantity of exhaust air must be removed from each living unit. When each dwelling unit has a fan, each unit should have its own exhaust duct. When a single fan removes air from multiple units, commissioning should be performed to verify that the correct airflow is achieved in each unit. If a fan serving multiple units does not operate continuously, backdraft dampers should be used to prevent air exchange between units when the fan is not operating.

Existing Buildings

Many existing buildings do not have kitchen and bathroom exhaust fans ducted to the outdoors. Appendix A of ASHRAE Standard 62.2 (ASHRAE 2016b) provides an alternative option for these dwellings to meet the standard. When this method is used, a local exhaust airflow deficit is calculated and a method is applied to increase the whole-dwelling ventilation rate (Strategy 7.1) to compensate for the airflow deficit. This method is based on the fact that contaminants from the kitchen or bathroom mix with the dwelling unit air, and additional dwelling unit ventilation dilutes them. Although this is an acceptable compromise for existing dwellings, the best practice is to provide local exhaust systems meeting the same requirements as those in new dwellings when possible.

Strategy 6.3 Maintain Appropriate Pressure Relationships Between Spaces

Introduction

Air moves from a space with higher air pressure (force delivered by air molecules bumping into a surface) to one with lower pressure. Air flowing from outdoors to indoors or from one room to another can transfer contaminants and result in moisture problems, thermal discomfort, frozen pipes, or ice dams.

Air Pressure Differences: Figure 6.3-A & Figure 6.3-B

Air pressure differences between indoor spaces and the outdoors or between one indoor space and another can be caused by fans (Figure 6.3-A), wind (Figure 6.3-B), or the stack effect (Figure 6.3-C).

Figures 6.3-A and B show how fan-driven air pressure differences can contribute to IAQ problems. Figure 6.3-A shows a section of part of a dwelling, where a central AHU supplies air to a bedroom with a closed door, but does not return air directly from the bedroom, instead relying on a return located in the hallway. This results in a lower pressure in the hallway than is present outdoors, in the bedroom, and in the crawlspace. As a result, contaminants from the crawlspace can be pulled into the living space.

Figure 6.3-B is a floor plan that shows the air pressure relationships in a ranch house with three bedrooms and two bathrooms. The dwelling has airflow problems caused by an AHU with a central return in the living space and no returns in the bedrooms or bathrooms. The plus signs indicate positive air pressure with respect to the adjoining space, and the negative signs indicate negative air pressure. The arrows show the direction of the airflow.

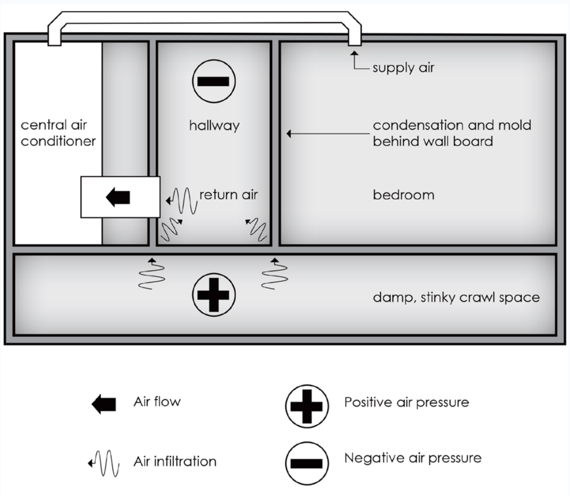


Figure 6.3-A Impact of Fan Operation on Air Pressure in Different Spaces

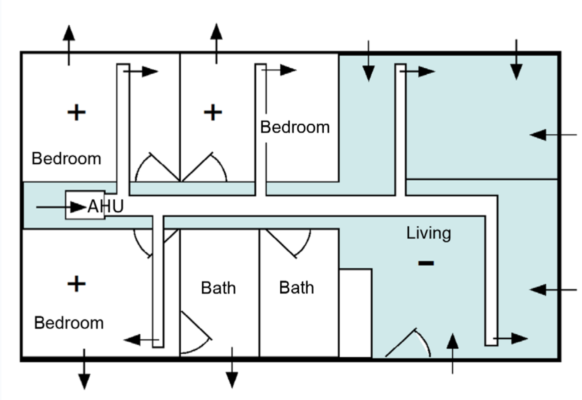


Figure 6.3-B Floor Plan of a Ranch House with Airflow Problems

Air Pressure Differences: Figure 6.3-C & Figure 6.3-D

Figure 6.3-C shows how wind influences the air pressure, air infiltration, and air exfiltration experienced at the exterior walls of a dwelling. The windward side experiences a higher pressure outdoors and air will move into the dwelling, while the leeward side experiences a lower pressure outdoors and air will move out of the dwelling.

Figure 6.3-D shows how stack effect influences the air pressure, air infiltration, and air exfiltration experienced at the exterior walls and ceiling of a dwelling when the outdoor temperature is colder than the indoor temperature (the direction of the airflows are reversed in hot weather). The natural buoyancy of the warm indoor air creates a lower pressure inside the lower portion of the dwelling relative to outdoors, and infiltration occurs. In the upper portion of the dwelling, this buoyancy creates a higher indoor pressure relative to outdoors, and produces exfiltration. The pressures are largest at the highest and lowest points in the dwelling.

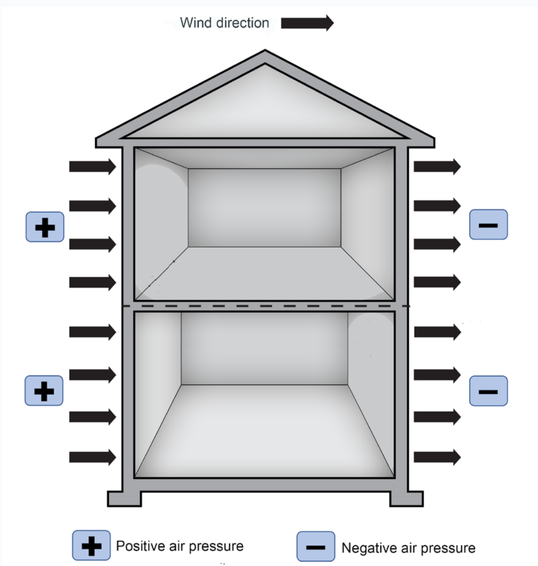


Figure 6.3-C Effect of Wind on Air Pressure at the Dwelling Enclosure

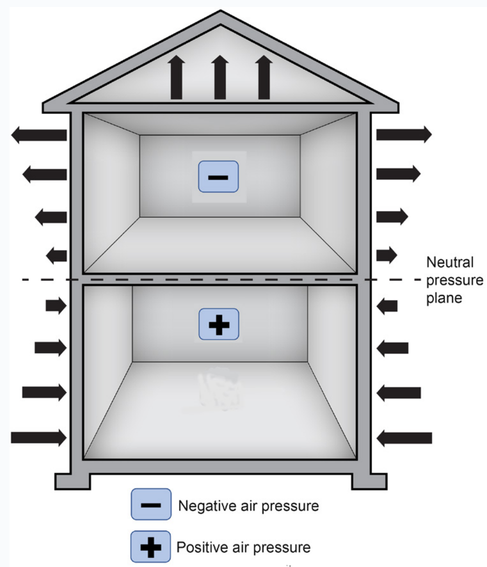


Figure 6.3-D Impact of Stack Effect on Air Pressure at the Dwelling Enclosure During Cold Weather

Fan-driven airflow is usually intentional, such as when exhaust fans are used to remove contaminants or for cooling. All dwellings experience some air movement between spaces and to or from outdoors, but serious problems can sometimes occur, as the following examples show.

- When a central AHU is running, a closed door between air supplies and returns will cause the rooms with supplies only to pressurize and rooms with returns to depressurize (Figures 6.3-A and B). Air is drawn from a damp, moldy crawlspace into the rooms and wall cavities upstairs. The damp air drawn up into the wall cavities condenses on the backside of the gypsum board, promoting hidden biological growth.

- In a dwelling with leaks in return ducts or a central AHU located in a vented crawlspace, attic, or garage, air will be drawn into the return side and blown into the dwelling when the AHU runs, which will pressurize the dwelling.

- A natural-draft water heater is in a room that becomes depressurized by a fan. Instead of going out through the vent pipe, the water heater combustion gases move from the heater into the dwelling when the heater turns on (Section 6.1), causing dangerously high carbon monoxide levels.

- During cold weather, the stack effect in a two-story dwelling draws air in through an attached lower-level garage (as in Figure 6.3-C), bringing contaminants from the automobile and lawnmower into the dwelling.

- The return plenum of a central air conditioner depressurizes the exterior wall cavities around it because it is not air sealed. Hot, humid outdoor air is drawn through air leaks in the exterior walls bringing air into contact with interior surfaces that the air conditioning system has chilled to below the outdoor air dewpoint and moisture problems result.

- A thoughtful smoker opens a window in a multifamily building that has exhaust ventilation in each dwelling unit. The smoker's exhaust ventilation no longer depressurizes the unit. Air is drawn through the utility chases from the smoker's dwelling into the dwelling of the nonsmoker living in the unit above whose windows are closed.

Air flows between one indoor space and another or between an indoor and outdoor space can result in air contaminant or moisture problems.

To control these air contaminant and moisture problems:

- Prevent the airflows from causing problems by sealing the leaks between two spaces and reducing or eliminating the airflow between them by managing the pressure difference between the two spaces.
- Minimize pressure differences between indoor spaces and between indoor space and the outdoors caused by AHU operation by balancing return and supply airflows in each room or open zone.
- Air seal all ductwork.

These examples have three things in common:

1. The air pressure between two spaces or between an indoor space and outdoors is different.

2. The walls, ceiling, or floors separating the spaces have an unintended hole or passage.

3. The resulting airflow carries air contaminants, water vapor, hot air, or cold air that creates an IAQ problem.

Prevention and Correction of Airflow Problems Created by Unintended Pressure Differences

Several strategies can be used to prevent these problems in new construction and correct them in existing dwellings.

The best practice for spillage from combustion devices is to follow the guidance for new and existing buildings in Strategy 6.1 using direct vent whenever possible. When not possible, see that negative pressure does not occur in the room containing the combustion equipment. Also see

that the combustion equipment is in good condition and meets the applicable codes and standards listed in Strategy 6.1. For example, if the negative pressure is caused by a large kitchen exhaust fan, it might be possible to replace it with a smaller fan or switch it to a lower speed. If the kitchen fan is the right size and needs to be remain, makeup air could be added to the room to reduce the negative air pressure. Strategy 6.2 discusses the appropriate sizing of kitchen exhaust fans and ways to add makeup air in more detail.

Figure 6.3-E Jump Duct Viewed from Below

The imbalances in room pressures described in the examples above that are caused by a central AHU can be prevented using one of the following methods (which are required by the ENERGY STAR for New Homes (ENERGY STAR 2017a) program):

- Locate a dedicated return duct in the main living space and in rooms (e.g., bedrooms) that are likely to have closed doors, and balance the supply and return airflows.

- Construct a return path using two grilles and a "jump duct" (Figures 6.3-E and 6.3-F) that allows air to pass from a bedroom through a duct to an adjacent room that has a central return. The jump duct is hidden above the ceiling or in a wall cavity. Details on designing and constructing jump ducts are available from the Building America Solution Center (U.S. Department of Energy 2017).

- Achieve a measured pressure differential of less than 0.012 in. w.g. (3 Pa) between the room and the adjacent living area where the central return is located. This can be accomplished for smaller rooms by cutting a thin slot (1/2 in. or 13 mm) between the door and the threshold, a so-called "door undercut." For rooms or suites with more than 60 CFM of supply air, a larger door undercut or one of the two methods above must be used.

Figure 6.3-F Jump Duct Installation

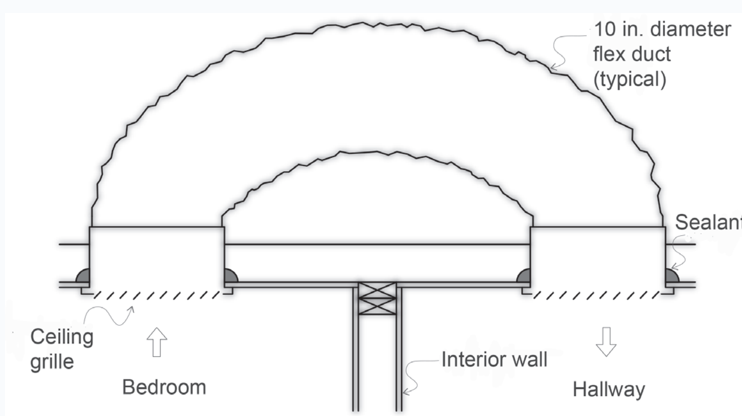


Figure 6.3-F Jump Duct Installation

Strategy 6.3 Maintain Appropriate Pressure Relationships Between Spaces

It is never desirable to bring air containing mold spores, musty odors, water vapor, or contaminants from a crawlspace, attic, or garage into the living space. The first step to prevent this problem is to address the air quality problem in the attached space (e.g., a damp crawlspace with biological growth). The next step is to install an air barrier and seal gaps in walls and floors that separate the attached space from the living space. For more information on these steps, see Strategy 3.7.

Leaky ductwork can also create pressure imbalances in dwellings. When the AHU is on, air leaks in the return ductwork draw air from the crawlspace or attic and blow it into the dwelling. Large leaks in the supply ductwork can also cause problems beyond energy loss of the heated or cooled air. If supply air is lost to a crawlspace or attic, the dwelling air pressure can experience negative pressure, causing the problems described in the examples above. Duct sealing can be difficult (because many air leaks in the system might be covered by duct insulation) but is often worth the effort in order to save energy and improve IAQ.

The conventional way to seal the HVAC system ductwork is to remove the insulation, seal the leaks, and reinstall the insulation. A product exists that uses sticky airborne particles to seal the HVAC air leaks from the inside without removing the insulation.

New construction. For new construction, the builder or designer should use the following guidelines:

- Pressure balance the air distribution system using dedicated returns or return air passages in main living spaces and in every bedroom.

- Locate AHUs and ductwork inside the insulated enclosure (thermal boundary) of the dwelling, which is the best location, whenever possible (e.g., in a conditioned basement with all ductwork between conditioned floors). Air seal ductwork to a leakage rate based on conditioned floor area of less than 8 CFM/ft^2 (40 l/s-m^2) measured at 0.1 in. w.g. (25 Pa).

- The next best choice is to install AHUs and distribution systems in unvented crawlspaces or attics. Air seal ductwork to a leakage rate based on conditioned floor area of less than 6 CFM/ft^2 measured at 0.1 in. w.g. (25 Pa).

Do not install AHUs in vented crawlspaces, unconditioned basements, or attics. If no other location is available, air seal the ductwork to a leakage rate based on conditioned floor area of less than 4 CFM/ft^2 (20 l/s-m^2) measured at 0.1 in. w.g. (25 Pa).

An additional best practice is to test, balance, and commission the finished dwelling (Strategy 1.4).

Multifamily buildings. Some pressure imbalances in multifamily buildings are caused by the design and construction of the building and AHU equipment, and some are caused by the residents. Also, pressure differences caused by stack effect are likely to be larger in multi-story buildings.

In new construction, each dwelling unit can be air sealed to make it more difficult for air to flow from one dwelling to another. The amount of net exhaust or outdoor air to each dwelling unit can be balanced to reduce the pressure differences between units. Multifamily buildings designed and constructed in this way can prevent problems and make it easier to fix problems if they do occur.

Strategy 6.3 Maintain Appropriate Pressure Relationships Between Spaces

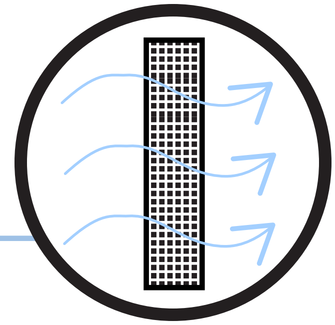
The ENERGY STAR Multifamily High-Rise program (Energy Star 2017b) and ASHRAE 62.2 (ASHRAE 2016b) have requirements for compartmentalization.

In existing multifamily buildings, solving pressure imbalance problems is more difficult. Options include air sealing and rebalancing the AHU equipment and ductwork. However, the air leakage sites are hidden in walls, shafts, and ceiling cavities and are therefore difficult to reach without breaking through walls and ceilings. Furthermore, the AHUs and ventilators often serve many units, and changes in one unit can affect others.

In the example of the thoughtful smoker above, potential improvements include:

- Change the smoking policies to prohibit smoking in or near the building.
- Seal the pathway between the units.
- Change the air pressure relationship between the units by pressurizing the neighbor's unit or depressurizing the smoker's unit.

In occupied buildings, sealing the air leaks between apartments has never been demonstrated to prevent secondhand smoke transfer but it can reduce the effect. If smoking policies cannot be changed, then changing the air pressure relationships might be accomplished by running continuous exhaust in the smoker's apartment.



Objective 7

REDUCE CONTAMINANT CONCENTRATIONS THROUGH VENTILATION, FILTRATION, AND AIR CLEANING

Dilution ventilation is the process of delivering outdoor air, which usually has lower concentrations of contaminants than indoor air, to the dwelling. For information about cases where contaminants in outdoor air are of concern, see Strategy 3.1.

How much the indoor concentrations of contaminants are reduced by ventilation, filtration, and air cleaning depends on how much outdoor air is mixed into the indoor air, how clean it is, how good the filtration is, and how much air is circulated through the filter.

The strategies for Objective 7 address ways to dilute indoor air contaminants using outdoor air or remove contaminants from indoor air using filtration and air cleaning.

Remember the three states of matter: solid, liquid, and gas? Particle filtration removes particles (also known as "aerosols") that are usually solid but are sometimes liquid and that are so small that they remain suspended in air and circulate with it. Gas-phase air cleaning removes gas molecules, such as ozone and VOCs.

Strategy 7.1 Implement Appropriate Outdoor Air Ventilation Strategies and Quantities describes strategies for providing outdoor air ventilation, as required by building codes and standards, and how much of this ventilation to provide.

Strategy 7.2 Provide Particle Filtration and Air Cleaning discusses the health effects of PM, the origins of PM in dwellings, and ways to reduce PM, including filtration strategies; and briefly discusses gas-phase air cleaning.

Other strategies that are relevant to reducing the concentration of contaminants in dwellings include the following:

- Strategy 3.1 – Determine Regional and Local Outdoor Air Quality
- Strategy 6.1 – Properly Vent Combustion Equipment
- Strategy 6.2 – Provide Local Capture and Exhaust for Sources of Contaminants

Strategy 7.1 Implement Appropriate Outdoor Air Ventilation Strategies and Quantities

7.1

Introduction

Limiting indoor contaminants, also known as source control, is the most efficient and effective approach to improve IAQ. In this guide, Objectives 2 through 6 cover source control by providing guidance for reducing contaminants related to moisture, the outdoors, mechanical systems, indoor sources, household equipment, and occupant activities. Much of that discussion focuses on preventing specific contaminants from entering the living space or removing their sources from the indoor environment. However, not all contaminant entry can be prevented.

Indoor air contains many substances whose sources and emission rates might be difficult for designers to identify or prevent and whose health effects might not yet be well understood. Additionally, residents bring contaminants into homes via household products and activities such as cooking, tracking in, from pets, etc. To dilute all these indoor air contaminants, whether or not they are identified and understood, outdoor ventilation air is needed.

Dilution ventilation is an inefficient way to remove contaminants compared with removing them at the source. Increasing outdoor air ventilation requires significant energy to move, mix, and condition the air; thus, diluting a strong contaminant source requires impractical amounts of ventilation air. However, dilution ventilation is needed for sources that are spread out, mobile, or otherwise unpredictable or unknown.

A minimum outdoor air ventilation rate is essential for all buildings and is therefore required by building codes and standards. This strategy discusses techniques for providing it and how much to provide.

In modern dwellings, the benefits of building a tight enclosure and providing mechanical ventilation far outweigh the costs. This "build tight and ventilate right" strategy helps achieve a durable and pest-free dwelling, removes contaminants of outdoor origin by filtration and air cleaning (use of absorbent filter material, such as activated carbon, to collect gas-phase air contaminants, such as ozone and VOCs, Strategy 7.2), and, in most climates, reduces humidity problems and substantially decreases energy consumption.

There are different ways to deliver the ventilation air to a dwelling. Each method has benefits and limitations, and not all are appropriate in all climates. Table 7.1-A and the discussion later in this section cover this issue in detail.

Dwelling-unit ventilation (also referred to as whole-house or whole-building ventilation) systems use a fan and/or natural forces to bring in outdoor air that dilutes indoor contaminants in the entire

How to implement an outdoor air ventilation strategy:

For designers and builders:

- Determine the ventilation rate needed to meet ASHRAE Standard 62.2 (ASHRAE 2016b) and comply with local codes.
- Choose a dilution ventilation system type: balanced, supply, or exhaust.
- Decide whether to integrate the ventilation system into the central AHU.
- Consider adding enhanced distribution or mixing.
- Verify that the design ventilation rate is provided.

For occupants and operators:

- Find out what type of ventilation you have.
- Operate the ventilation system as intended and make adjustments for changing conditions.
- Perform preventive maintenance and filter changes according to a schedule and arrange for repairs when needed.
- Open windows and doors when needed for high-polluting indoor events.

dwelling unit. The intention is to replace a portion of indoor air with outdoor air, which usually is cleaner. Inadequate outdoor air ventilation can result in poor IAQ, discomfort, and adverse health effects.

These ventilation systems are designed to operate on a continuous basis or with regular cycle times. They provide ventilation independently of residents' use of windows or leakage through the building enclosure, which vary substantially with weather and might not be sufficient to meet the need for dilution ventilation.

Leaky dwellings were once the norm, and many older leaky dwellings remain. Outdoor air enters these dwellings through cracks in the building, driven by natural forces. Relying on natural leakage is an unreliable method of ventilation because it moves very large quantities of outdoor air thorough the dwelling when the weather is extreme and provides very little outdoor air when the weather is mild. Engineered natural ventilation, however, remains an appropriate strategy in some limited circumstances (Strategy 8.2).

As of 2017, ASHRAE has only one relevant standard that covers residential dwelling units in all types of buildings (ASHRAE 2016b). The standard (Figure 7.1-A) is best known for its information on ventilation rates, but it also contains important guidance on such topics as local exhaust ventilation, dwelling unit compartmentalization, and air sealing.

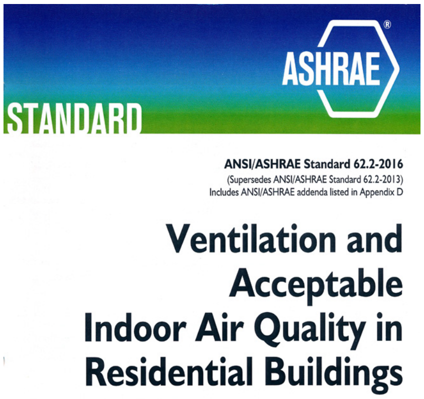


Figure 7.1-A Cover of ASHRAE Standard 62.2

Ventilation Rates

ASHRAE Standard 62.2 (ASHRAE 2016b) requires the dwelling unit's ventilation rate to be based on total floor area and number of bedrooms. A user's manual with sample calculations is available (ASHRAE 2017a). The ventilation rates in the standard have evolved over time because of ongoing debate about the "right" ventilation rate. The rates in the standard were developed by experts and with public comment; they thus constitute the best available requirements to follow.

For detached and horizontally attached dwellings, the standard allows a reduction in the whole-house ventilation rate if the air leakage of the building enclosure is measured. This reduction recognizes that infiltration produces a dilution effect. In dwellings that are extremely leaky, the effect can be so large that no mechanical system is required. This does not mean that leaky dwellings have good ventilation; a tight dwelling with a mechanical ventilation system is always the best choice. No infiltration credit is allowed for multifamily buildings with vertically attached units because of the complexity of determining the impact of infiltration on individual units in these buildings.

Many jurisdictions have legal requirements for the minimum mechanical ventilation rate in new residential construction (and sometimes for renovations). However, some local jurisdictions amend or interpret the model codes so that they do not require mechanical ventilation, particularly in multifamily buildings. This is not a good practice. The two most common model codes covering residential ventilation in the United States are the IRC (ICC 2015d) and the International Mechanical Code (IMC; ICC 2015c).

The 2015 IMC, which covers most multifamily dwelling units (those not covered by the IRC, discussed below), requires all occupiable spaces to have natural or mechanical ventilation. It also requires mechanical ventilation in dwelling units with an air infiltration rate of less than 5 ACH50 when tested with a blower door (described in detail in Strategy 1.4). If the jurisdiction also adopts the ICC Code (ICC 2015c) without amendments, a blower door test of 5 ACH50 or less is required, but the IMC does not require it directly. Even if both codes are adopted, this cross-referencing of the two codes can be easily overlooked or neglected, creating an effective loophole. As a result, many multifamily dwellings still rely in whole or in part on operable windows and doors to provide the code-required ventilation. This is not good practice because in many locations including in the U.S. people do not open windows often enough to meet ventilation requirements.

The IRC (ICC 2015d), which covers detached one- and two-family dwellings and townhouses not more than three stories high with their own entrance from the street, has a section on energy efficiency that requires air leakage of 5 ACH50 or less in all climate zones (Figure 1.2-A) and specifically requires mechanical ventilation. Increasing numbers of jurisdictions continue to adopt requirements for mechanical ventilation for new dwellings. The latest versions of ASHRAE Standard 62.2 (ASHRAE 2016b) and local codes provide the minimum ventilation rate for a particular dwelling unit.

It can take time for the model codes to adopt rates published in ASHRAE Standard 62.2 and even more time for local jurisdictions to adopt the model codes. Jurisdictions also sometimes edit the model codes before adopting them. Therefore, the ventilation rates in ASHRAE Standard 62.2 are often higher than those required by local codes. This guide recommends that the minimum rates in ASHRAE Standard 62.2 be adopted as a best practice.

Existing dwellings. ASHRAE Standard 62.2 applies to all dwelling units, unlike codes, which usually apply only to new dwellings and to existing dwellings undergoing substantial renovation. The ASHRAE standard is frequently applied to dwellings and other dwelling units that are undergoing weatherization, and it should be considered an important strategy for optimizing IAQ in any dwelling.

Because existing dwellings are often less airtight than new ones, a best practice is to arrange for a blower door test (Strategy 1.4) on the dwelling so that the ASHRAE Standard 62.2 ventilation rate can be reduced based on infiltration. Doing so also provides the opportunity to identify and air seal large sources of leakage in the building enclosure.

Some people believe that it is better not to air seal an existing dwelling to avoid the need for mechanical ventilation. The consensus among building science and air quality experts is that a tightly sealed dwelling with a properly designed and operated mechanical ventilation system is always the best choice. In addition to the large differences in infiltration in extreme versus mild weather, existing dwellings are more likely than new ones to receive contaminated infiltration air from attached spaces, such as attics, crawlspaces, and garages. Of course, the best designed ventilation system does no good if it is not maintained and operated (Strategy 1.5).

Cycling ventilation. The ventilation rates in most codes and standards are for continuously operating systems. Sometimes, it is desirable to operate the system for less time at a higher airflow rate. There are several reasons to cycle systems. For example, when the fan used for ventilation is also used for heating or cooling, it can consume significant amounts of energy. Cycling the system to turn on for 20 minutes or less per hour is a good energy-saving strategy,

particularly when it is combined with a smart controller that accounts for system runtime when the system is heating or cooling the dwelling. A smart controller set for 20 minutes per hour will only add system runtime if the system doesn't operate for at least 20 minutes per hour to provide heating or cooling. Another reason to cycle a system is that standalone ventilation fans (e.g., exhaust fans and energy recovery ventilators) are available in discrete size increments, and cycling allows use of larger fans than are needed, without over-ventilating the dwelling.

Most mechanical ventilation systems that use cycling operate for a designated number of minutes each hour at a proportionally higher flow rate. For example, a dwelling unit that needs 50 CFM (23.6 l/s) of continuous ventilation could be served by 150 CFM (70.8 l/s) of ventilation air for 20 minutes each hour. Fan-cycling controllers are readily available for both supply and exhaust fans. Most controllers are designed for one-hour cycles, and the occupant can adjust the number of minutes the fan is on each hour. Some controllers also allow occupants to increase the length of the cycle to more than one hour.

Mechanical ventilation systems that are designed to operate in cycles must be designed to move more air than those that run continuously. One benefit of this extra capacity is that the fan can temporarily run continuously when a highly polluting activity, such as painting or cleaning, is done indoors.

Cycle times longer than one hour can be used in locations with a significant energy or IAQ penalty associated with operating the ventilation system at certain times of day. For example, a large energy advantage can be associated with ventilating a dwelling in a desert climate at night, when the air is cooler. In some locations, outdoor ozone or PM concentrations can be elevated at certain times of day, and ventilating the dwelling at other times can be beneficial (Strategy 3.1). Because longer cycles can raise short-term contaminant concentrations, ASHRAE Standard 62.2 (ASHRAE 2016b) requires more total ventilation when the cycle is longer than three hours. The standard includes a calculation that accommodates a variety of approaches.

Choice of Ventilation System Type

There are many different ways to use supply and exhaust air to deliver the desired quantity of ventilation air to a dwelling. Some of these methods are not appropriate in certain climates, and each has potential benefits and limitations. The designer should select a system based not only on its cost but also on its suitability for the climate, ability to filter contaminated outdoor air, compatibility with the heating and/or cooling systems, potential to exacerbate moisture problems, acceptability to occupants, and energy use. Examples of each type of system are described in Appendix A.

Figure 7.1-B Balanced Ventilation System

Balanced ventilation systems. Balanced systems (Figure 7.1-B) include one or more supply and exhaust fans that bring in outdoor air while exhausting out an approximately equal amount of air. The most common systems are HRVs and ERVs, which are discussed in Strategy 8.1. These self-contained units transfer heat and/or moisture between the outgoing and incoming airstreams, which can reduce the energy and humidity loads associated with ventilation. The units can be separately ducted, or they can be integrated into the ductwork of a central AHU. If a balanced system delivers outdoor air to the dwelling without being heated, cooled, or dehumidified, care must be taken to prevent discomfort and moisture problems.

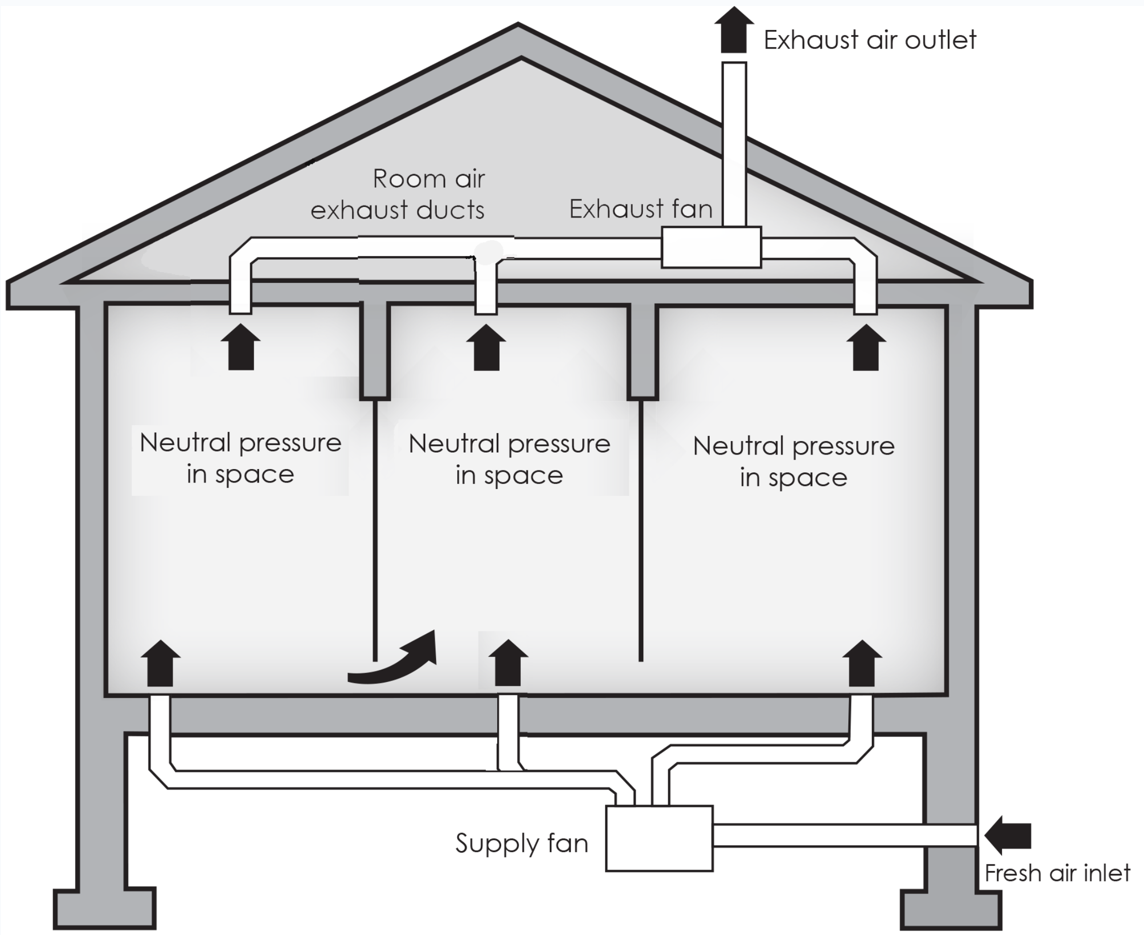


Figure 7.1-B Balanced Ventilation System

Other types of balanced ventilation systems include:

- Balanced ventilators with no heat or energy recovery that have a similar function to ERVs and HRVs but do not provide the energy or humidity benefit.
- Ventilators that dehumidify incoming air and exhaust air to the outdoors.

- Supply and exhaust strategies described below that are combined and controlled to operate simultaneously and create a balanced ventilation system. For example, a controller can turn an exhaust fan on while a supply-only controller pulls outside air into the return side of the AHU.

Exhaust-only ventilation systems. An exhaust-only ventilation system includes one or more exhaust fans, which usually also serve as bathroom or kitchen fans, and no fans to directly supply outdoor air. These fans depressurize the dwelling, thereby inducing infiltration through the building enclosure or through trickle vents (but see caveats about trickle vents below). Where the infiltration air enters depends on many factors, such as where the leaks in the enclosure are, the wind effect, the stack effect, HVAC system leaks, or pressure imbalances.

Figure 7.1-C Exhaust-Only Ventilation System

Exhaust-only ventilation systems (Figure 7.1-C) have the lowest cost of all the options for both new and existing dwellings. They can utilize existing bathroom fans, although this might require a fan upgrade (see below on ratings for sound and continuous operation). These systems can work well in relatively dry climates and are the most common system in existing dwellings.

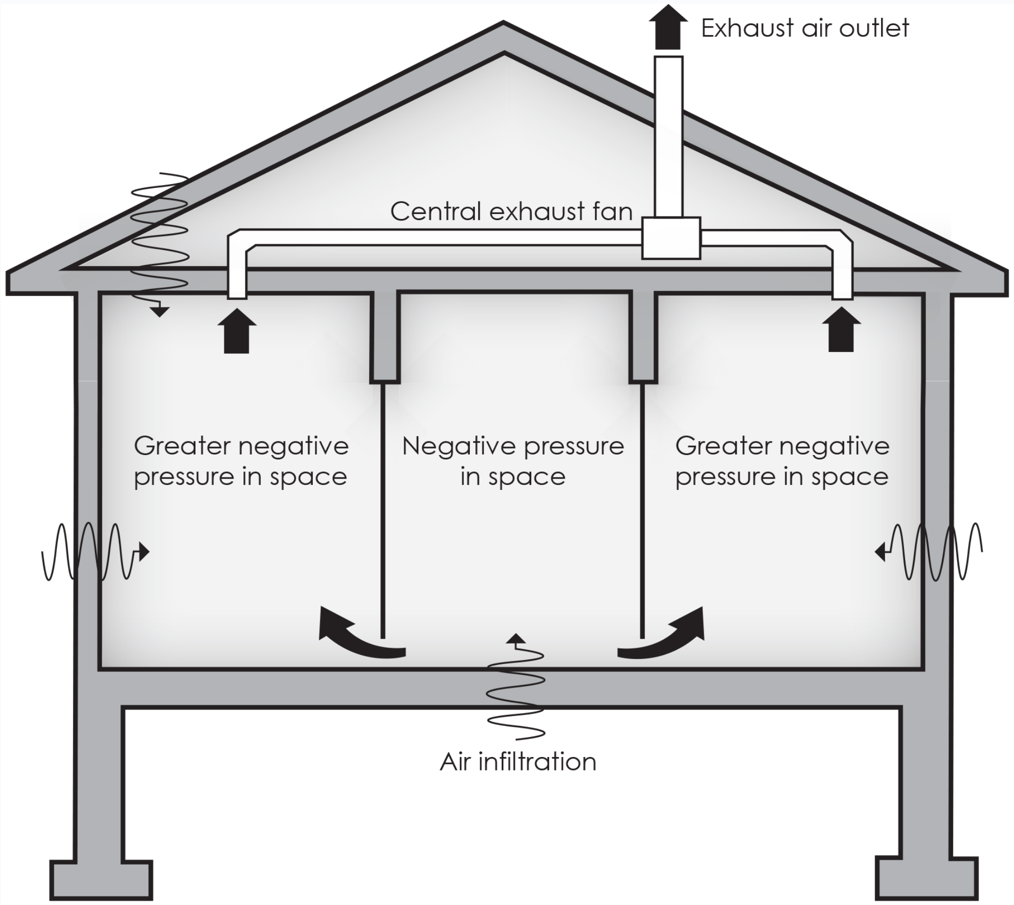


Figure 7.1-C Exhaust-Only Ventilation System

Exhaust fans located inside the living space must be quiet so they do not disturb occupants and cause them to disable the fan. For this reason, occupants must understand the purpose of the fan so that they do not think it is malfunctioning and try to turn it off. Fans used for this purpose should have a rating of 1 sone or less or be mounted remotely. The sone rating is a measure of sound, and is discussed in more detail in Strategy 6.2. A lower number of sones is associated with a quiet fan.

Bathroom exhaust fans with multiple speed settings are widely available; a high speed can be used to exhaust air when the bathroom is in use (Strategy 6.2), and the low speed can be used for continuous dwelling unit ventilation. Except in extremely humid climates, occupants often notice improved moisture removal from the bathroom as a side benefit.

Precautions for exhaust ventilation. Air that infiltrates a dwelling can pick up contaminants from an attached garage, crawlspace, attic, or dwelling unit. For dwellings that have a large adjacent surface area or large leakage paths to such spaces, this type of system might not be the best choice. If one of these adjacent spaces is unusually contaminated or damp, the first solution should always be to remediate the problem in the adjacent space (Strategy 3.6). Air sealing the building enclosure between the indoors and these adjacent spaces is especially important when an exhaust-only ventilation system is used.

Concerns that exhaust-only ventilation systems increase indoor radon levels (by drawing more air into the dwelling from the ground) are unfounded. Most of the air that these systems draw comes from the outdoors, and the net effect is to dilute the indoor radon concentration (Seifert and Schmid 2002; Sherman 1992, Francisco et al. 2017).

In multifamily units with exhaust-only ventilation systems, compartmentalization is essential to reduce cross-contamination between units. This level of airtightness is practical to achieve only in new buildings. Air that comes from other indoor spaces is unlikely to be as clean as outdoor air and is less effective for diluting indoor contaminants. It is difficult to calculate how much additional exhaust air is needed to increase the likelihood that the required air will come from outdoors because the amount depends on how airtight and compartmentalized the units are, the outdoor temperature, and the building height. Maxwell and colleagues (Maxwell et al. 2016) provide an estimate for a specific case, but no generic recommendation has been developed.

Because the exhaust strategy creates a (usually small) negative pressure in the dwelling, a combustion safety check should be performed, particularly when such a system is added to a dwelling that has atmospherically vented gas appliances. Combustion safety checks are discussed in more detail in Strategy 6.1.

“Trickle vents” are sometimes used with exhaust-only ventilation systems. Like unintended leakage pathways, these inlets rely on the negative pressure generated by the exhaust fan to draw outdoor air in through the vent. To obtain a substantial portion of a dwelling’s fresh air through these vents, the dwelling needs to have an unusually high level of airtightness (Maxwell et al. 2016). Furthermore, the designated vents add another pathway for infiltration or exfiltration (uncontrolled outward leakage of air through cracks and interstices in any building element and around windows and doors) in windy or extreme temperature conditions. For those considering trickle vents, Maxwell et al. (Maxwell et al. 2016) describe the additional steps necessary to use them successfully.

Figure 7.1-D Supply-Only Ventilation System

Supply-only ventilation systems. A supply-only ventilation system uses one or more supply fans to bring outdoor air into the dwelling unit. This type of system (Figure 7.1-D) creates positive pressure in the dwelling unit, pushing exhaust air out as exfiltration through leakage paths in the building exterior.

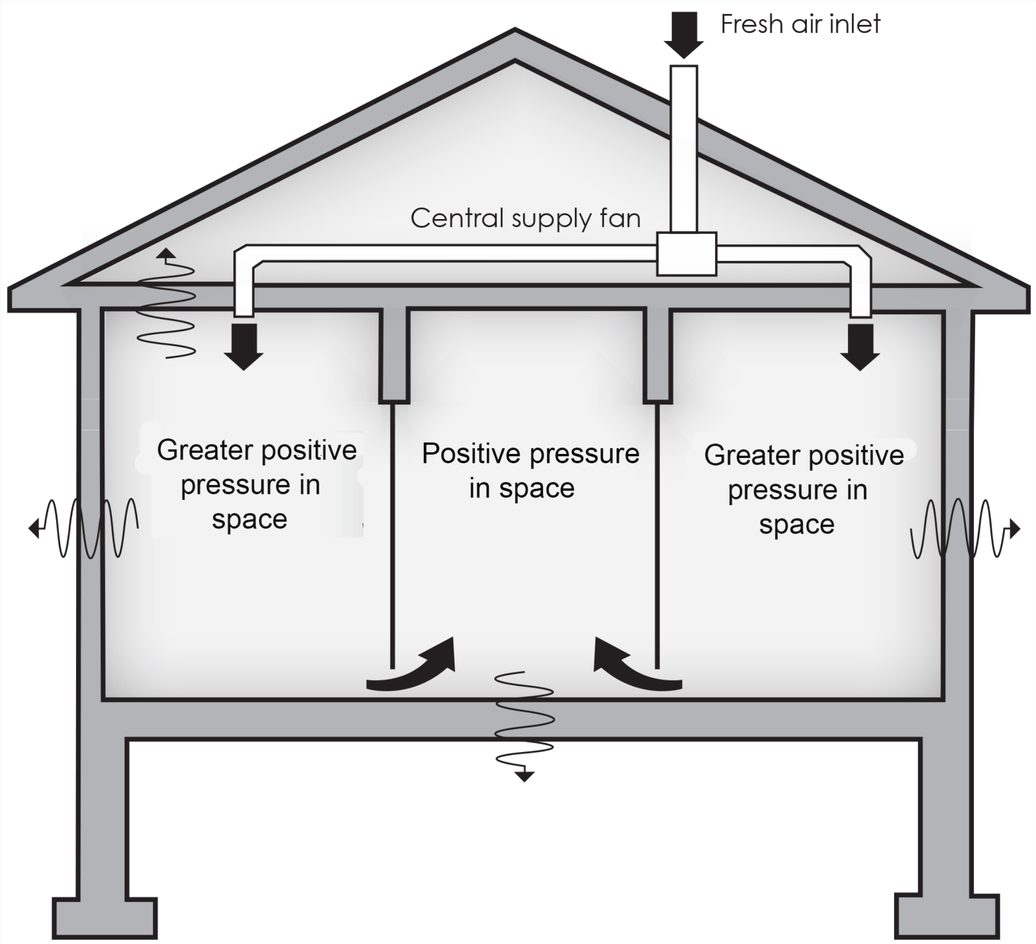


Figure 7.1-D Supply-Only Ventilation System

A common approach to implement supply-only ventilation is to introduce the outside air into the return side of a central HVAC system so that it can pass over the heating and/or cooling coils. To provide reliable ventilation, the fan must operate regularly, even when heating and cooling are not needed. To save energy, the system should operate for 20 minutes per hour or less. The system should also have an efficient fan with an Electronically Commutated Motor (ECM) and a damper that closes to prevent overventilation when the system operates in heating or cooling mode for longer than the ventilation cycle time.

Alternatively, ventilation air can be conditioned (heated, cooled, and/or dehumidified) independently of the central HVAC system. In some climates, the air can be mixed with room air

in a manner that prevents comfort problems. For example, very small through-the-wall fans can be used in each room to supply air on a distributed basis. These fans typically supply very small quantities of air in the range of 10 to 20 CFM (4.7 to 9.4 l/s) in locations (such as a high sidewall) where occupants are unlikely to feel the air directly.

Care must be taken to avoid introducing very cold, hot, or humid air directly into the living space where it could cause discomfort or moisture problems. Examples of how to do this include:

- Introducing the air in small quantities and in multiple locations throughout the dwelling
- Choosing a location where occupants are unlikely to feel the air
- Delivering the air using the central AHU so that it is mixed with indoor air and thermally conditioned before delivery to the living space
- Choosing a location for potentially humid air where it is unlikely to contact cold surfaces that could develop condensation

In humid climates, supply-only ventilation systems can introduce substantial humidity into the dwelling, so using a dehumidifier is a good idea. Supply systems that incorporate a dehumidifier often recirculate some house air through it to provide additional dehumidification.

Depending on where contaminants are generated, supply-only ventilation systems can help spread these contaminants around, rather than removing them. For example, if the supply ventilation air is delivered to the kitchen, which is also a primary source of a particular contaminant, the pressure difference generated by the ventilation system will help spread the contaminant to the other rooms of the dwelling.

Other Concerns About Ventilation System Design

Many people believe that exhaust-only and supply-only ventilation systems cause pressure imbalances that can lead to moisture problems in building enclosures. These fears are largely unfounded. Poor enclosure design and inadequate indoor humidity control (in particular, failure to adequately dehumidify the dwelling in the summer) are much more likely causes of these problems. All dwellings experience some infiltration and exfiltration through the building enclosure due to weather conditions. A well-designed building enclosure can typically withstand the modest increase in infiltration or exfiltration resulting from the typically small pressure differentials created by these ventilation systems. For very tight dwellings, such as those with less than about 1.5 ACH50, a balanced ventilation system might be preferable to limit the impact on pressure differences between the indoors and outdoors. See strategy 1.4 for more detail on airtightness testing.

Distributing ventilation air to heavily occupied rooms (sleeping areas and main living spaces) is usually better than introducing all the air in one location, and can be done in the following ways:

- Separately duct ventilation air to multiple locations. The ventilation system fan should accommodate the pressure drop for the length of planned ductwork. Some smaller fans are not properly sized to distribute air over long distances.

- Distribute air using the dwelling's central AHU fan with a supply-only or balanced strategy that mixes the air with recirculated air from the dwelling and distributes it to all of the spaces that the system heats and cools.

- With an exhaust strategy, use multiple exhaust fans (e.g., in every bathroom), which allows the system to remove local contaminants from more than one location and increases the system's effectiveness at removing contaminants that are primarily generated in the rooms where the exhaust vents are located.

These strategies can be combined when balanced ventilation systems are used to deliver outdoor air to frequently occupied rooms (bedrooms and living areas) and remove exhaust air from rooms that are likely to contain contaminant sources (e.g., kitchens and bathrooms).

Multifamily buildings require special considerations and offer special opportunities. ASHRAE has one ventilation standard that applies to dwelling units (ASHRAE 2016b) and another for corridors, lobbies, and other areas in the same buildings (ASHRAE 2016a). The system should be designed to deliver air directly to each dwelling unit and not only the corridor. If a shared ventilation system is used for multiple units, the design must also provide a means for controlling and verifying delivery of the correct amount of air to each unit.

The factors to consider in choosing a system for an individual dwelling or multifamily building are summarized in Table 7.1-A.

Verifying Airflow

ASHRAE Standard 62.2 (ASHRAE 2016b) calls for required outdoor and exhaust airflow to be measured and tested in all modes of operation that occupants will use to provide the required ventilation. In jurisdictions that have not adopted ASHRAE standards, installers often rely on factory airflow ratings, especially when access and space constraints make reliable and repeatable outdoor airflow measurements difficult or not feasible. However, factory airflow ratings are often not realized in practice. RESNET Standard 380 (RESNET 2016) describes several methods for measuring airflow in mechanical ventilation systems.

Ducts serving ventilation systems have many of the same challenges as those described in Strategy 6.2. As with bathroom exhaust fans, the ductwork serving ventilation systems almost always delivers less air than the rating on the equipment. Some designers choose equipment with supply fans that are larger (say 20%) than required and that are adjustable to have a reasonable likelihood of delivering the desired quantity of air.

Installers should verify the airflow of new systems (measurement techniques are described in Strategy 1.4). Many systems have adjustable airflow rates or timers that need to be set based on the measured airflow rate. For example, a multispeed bathroom fan should be tested and set at the speed that delivers the desired airflow rate. Likewise, the airflow rate of a supply-only system that is integrated with the AHU should be tested, and the timer controller should be set to operate the AHU fan for the appropriate cycle time to achieve the target airflow rate.

Table 7.1-A Overview and Evaluation of Whole-Building Ventilation

Exhaust-Only Ventilation System	Supply-Only Ventilation System	Balanced Ventilation System

• Air exhausted by one or more exhaust fans (usually in bathrooms or the kitchen) from the dwelling continuously or periodically with a timer
 	
• Fan sound levels:
  ○ ≤1.0 sones inside or near the room
  ○ ≤3.0 sones for remote locations
	• Outdoor air ducted into central HVAC system with a motorized damper and timer
	
	• Separate supply fan(s) used with conditioning or mixed with room air
	
	• Might include a dehumidifier in humid climates
		• Has supply and exhaust fans (ERVs, HRVs, or ventilators)
		
		• Hybrid supply and exhaust systems that run simultaneously
		
		• Might be standalone or integrated with central AHU

Advantages: • Simple and inexpensive to install and operate • Small fan, so typically uses little energy • Good for removing pollutants near the fan, which is often in a bathroom or kitchen • If installed in a bathroom, helps remove moisture • If installed in a kitchen, helps remove moisture and cooking contaminants • Can use local exhaust system already in place	Advantages: • Simple and inexpensive to install • Can use existing central duct system • Draws air directly from the outdoors • If connected to a central AHU, offers better outdoor air distribution throughout the dwelling • Can filter and condition outdoor air	Advantages: • Neutral effect on dwelling air pressure, so has no combustion safety concerns • Recovery of up to 70% of heat and moisture by HRV or ERV • Does not rely on enclosure leakage to balance airflow • Can be ducted separately or integrated into existing ductwork • Draws air directly from the outdoors

Table 7.1-A Overview and Evaluation of Whole-Building Ventilation Systems

Owners of existing dwellings cannot easily test their own systems. However, if the supply and/or exhaust points are accessible, they can spot major failures by holding up a piece of paper to the fan inlet or outlet. Of course, this does not guarantee that the flow is sufficient. Owners should periodically check their systems to make sure that they still operate properly, and they should repair or replace systems that do not work.

Table 7.1-A Overview and Evaluation of Whole-Building Ventilation (cont'd)

Exhaust-Only Ventilation System (Cont.)	Supply-Only Ventilation System (Cont.)	Balanced Ventilation System (Cont.)
Advantages (cont.): • Can be used with any HVAC system, including a ductless system		Advantages (cont.) • If connected to central AHU, provides better outdoor air distribution throughout the dwelling • Can filter and condition outdoor air
Design and Installation Issues: • Outdoor air could enter from attached contaminated areas • Induces small negative indoor pressure, which can threaten combustion safety • Inability to filter incoming air or recover heat or energy from departing air • Unpredictable outdoor air distribution • No energy recovery	Design and Installation Issues: • If air is delivered directly to the living space, care is needed to protect thermal comfort and proper humidity • Still need bathroom and kitchen exhaust systems • Often requires a large fan that consumes more energy • No energy recovery	Design and Installation Issues: • Higher initial cost and more costly maintenance • Preplanning required for unit, vent, and duct locations • Requires special controls when integrating a central AHU fan • If serving as bathroom exhaust system, typically requires HRV

Table 7.1-A Overview and Evaluation of Whole-Building Ventilation Systems (cont'd)

Strategy 7.2 Provide Particle Filtration and Air Cleaning

7.2

Introduction

Indoor particulate matter (PM) is a diverse category of contaminants that have significant health effects. PM in indoor air is composed of tiny solid particles, clumps of particles, or droplets. It includes combustion byproducts, allergens, dust, bacteria, molds, and even human skin cells. In most of North America, about half the PM in indoor air originates outdoors. In many locations around the world, severe outdoor pollution is the primary source of indoor exposure to airborne particles.

PM is categorized by size. Coarse PM has a diameter larger than 2.5 microns, fine PM ($PM_{2.5}$) has a diameter of 2.5 microns or less, and ultrafine particles (UFP) have a diameter of less than 0.1 micron.

Indoor particulate matter originates from:

- Outdoor air that comes indoors unintentionally or as ventilation air
- Smoking
- Indoor sources of combustion
- Cooking
- People and pets
- Pests
- Devices, including irons and printers

Much of the health research about indoor PM focuses on $PM_{2.5}$ (particles with a diameter of 2.5 microns or less), which has emerged as the indoor pollutant with the most widespread chronic health impact based on disability-adjusted life years (Logue et al. 2012). The primary health risk is cardiovascular, and everyone is at risk, not just those with allergies and asthma. A regulatory, scientific, and instrumentation complex has been built around the 2.5 micron distinction and measurement of its mass concentration, but there is no magic about any particular number. Increasing evidence indicates that exposure to even low levels of $PM_{2.5}$, below the levels regulated by EPA for outdoor air, contribute to harmful health effects (Shi et al. 2015).

This section discusses the health effects of PM, the origins of PM in dwellings, ways to reduce it at the source, and best-practice filtration strategies to remove it. Objectives 3, 5, and 6 cover specific sources of PM and source reduction strategies in more depth. Removing PM requires much more than an ordinary furnace filter, and removal is extremely important for human health. Gas-phase filtering technologies to remove other contaminants, such as ozone and VOCs, are less common in dwellings and are discussed briefly below.

Health Effects

In 2005, outdoor levels of $PM_{2.5}$ were responsible for an estimated 130,000 premature fatalities in the United States (Fann et al. 2012). Many studies seek to correlate health effects with *outdoor* PM2.5 because the data are easier to obtain, but their conclusions are relevant to *indoor* $PM_{2.5}$ exposure because most people spend 90% of their time indoors (Klepeis et al. 2001), and approximately half the PM measured indoors originates outdoors (Stephens and Siegel 2012; Turpin et al. 2007). As a result, much of the exposure to outdoor PM actually occurs indoors.

Health impacts are often measured using disability-adjusted life years (DALYs), which combine estimated years of life lost with years spent living with a disability to provide a quantitative measure of public health burden. A detailed description of the sensitivity and uncertainty of DALY can be found elsewhere (Mathers et al. 2006). A study of 15 common indoor air pollutants (Logue et al. 2012) found that $PM_{2.5}$ had the highest DALY rate (700 per 100,000), and the pollutant with the next highest DALY rate was secondhand tobacco smoke (100 DALYs). Therefore, $PM_{2.5}$ has

seven times the impact of the next most impactful known pollutant, secondhand tobacco smoke, which is a more specific category of PM.

PM enters the body through the respiratory system. Coarse PM is cleared out of the respiratory system in a few hours, but ultrafine and fine particles can take weeks to be cleared from the body (Hildemann 2016).

Long-term exposure to PM is strongly correlated with cardiovascular disease and mortality, and short-term exposure during pollution spikes increases the rate of cardiovascular events. PM is believed to contribute to cardiovascular disease by causing systemic inflammation, activating coagulation, and direct transfer into the circulatory system. In the respiratory system, PM contributes to oxidative stress and inflammation and has been correlated with asthmatic symptoms and the need for asthma medication. PM has also been correlated with reduced lung function in children and susceptible adults, including those with asthma, older adults, and individuals with chronic obstructive pulmonary disease (Anderson et al. 2012).

Many studies have assessed whether removal of particles with filtration reduces the rates of these health effects. A review of earlier studies (Fisk 2013) found the following:

- Particle filtration produces statistically significant improvements in markers that predict adverse coronary events. The economic benefit of this improvement in health far exceeds the costs of filtration.
- Particle filtration has modest respiratory health benefits for patients with asthma and allergies, especially in dwellings with pets.
- Studies have not shown that particle filtration in buildings has a significant effect on respiratory symptoms in people without allergies and asthma.

The overall conclusion from this research is that the primary societal benefits of filtration are in coronary health, and filters should not be used only for patients with allergies and asthma. Fine particles and UFP are difficult to filter, and filtration strategies that remove these can also remove allergens, which are typically larger.

Origin of Indoor PM

A 2007 study (Turpin et al. 2007) of indoor, outdoor, and personal (breathing-zone) air in 219 non-smoking dwellings in three U.S. cities found that the median indoor and outdoor concentrations of $PM_{2.5}$ were roughly equal to one another. About half the indoor particles originated in the outdoor air, and the remainder was generated indoors. Particles of outdoor origin accounted for one-quarter to one-third of the particles in the breathing-zone air. A few dwellings in the study had some environmental tobacco smoke sources, and their indoor $PM_{2.5}$ concentrations were nearly twice those of non-smoking dwellings.

Outdoor PM (discussed in more detail in Strategy 3.1) comes from traffic, agriculture, construction, soil, electricity generation, industrial processes, fires, mold spores, and pollen. Coarse particles and UFP are removed by the building enclosure relatively well as outdoor air is infiltrated to the indoors. Particles between 1 and 2.5 microns penetrate the building more easily,

so the $PM_{2.5}$ indoors comes from a mix of indoor and outdoor sources (Weschler 2016). Gao et al. (2015) found that particles of 0.05 –1 µm are most penetrable for wood framed and residential walls. Air sealing is an effective way to reduce or eliminate this source of particle exposure.

A modeling study (Zhao et al. 2015) showed that for particularly leaky dwellings, air sealing can reduce indoor PM of outdoor origin more thoroughly than a high-efficiency filter in the central AHU. Filtration is the best way to remove particles of indoor origin. However, air sealing is an effective and durable way to reduce exposure that does not require subsequent effort by the homeowner and increases the effectiveness of filtration in very leaky dwellings. Air sealing can be incorporated into the construction of a new or renovated dwelling or can be part of a weatherization project for an existing dwelling. It can also be applied to multifamily dwellings, where sealing between units can be as important as sealing to the outside.

Indoor sources of PM are discussed in more detail in Objective 5 and include:

- *Combustion sources:* Smoking, candles, incense, wood burning, cooking, and heating
- *Allergens:* Dog, cat, cockroach, and mite allergens; molds; and bacteria
- *Occupant activities:* Ironing with steam, laser and three-dimensional printers (Stephens 2016)
- *Vacuum cleaning*
- *Particle resuspension:* Walking, crawling, or moving in bed can cause significant resuspension. Infants and shorter individuals are closer to the floor and can have higher exposures due to resuspension. The concentration in their breathing zone can be up to five to 10 times higher than the concentration in the bulk air (Boor 2016).
- *Human skin flakes:* Contribute significant PM, bacteria, and fungi to the air. As a result, occupied spaces can have 80 times more bacteria in their PM than unoccupied spaces (Weschler 2016).

Many indoor sources of PM (e.g., smoking, candles or incense, dwelling heating, and wood burning) can be easily avoided or reduced through the use of properly vented combustion equipment (Strategy 6.1). Exposure to PM generated during cooking can be significantly reduced using a well-designed local exhaust fan (Strategy 6.2). Exposure during vacuuming can be reduced by using a vacuum with a HEPA filter.

Types of Particulate Filters

This section describes the most common types of filters available for residential use (NAFA 2007).

Mechanical and electrostatically charged filter media.
This is the most familiar type of residential filter and is typically found in central HVAC systems. Usually disposable, the “mechanical media” are made of fiberglass, polyester, or cotton fiber. They might be pleated to provide more surface area for capturing particles. Most residential filters

are also electrostatically charged to better attract particles. These types of filters range from those with very low efficiency that remove only very coarse dust and debris to high-efficiency filters that remove a high percentage of fine particles.

The efficiency of mechanical and electrostatically charged media filters can be evaluated using the MERV rating. ASHRAE developed the MERV rating system to evaluate filter performance for PM of three size ranges (0.3 to 1.0 microns, 1.0 to 3.0 microns, and 3.0 to 10.0 microns). To achieve a good MERV rating, a filter must meet the rating system's target performance in each size range.

- Low-efficiency filters (MERV 6 and under) have low filtration efficiency, can remove some coarse particles, but have little impact on fine particles.
- Medium-efficiency filters (MERV 8-12) are widely available and can remove fine particles from the air without significant cost, energy use, or system considerations.
- Higher-efficiency filters (MERV 13 and up) are increasingly able to remove fine particles and ultrafine particles, but they usually require more fan pressure or are larger than a standard filter, so they might not be practical as a drop-in replacement in systems that are not designed for them.

Buying Filters

- For disposable filters, the MERV rating describes the filter efficiency.
- Change the filters three to four times per year.
- Make sure that the filter fits tightly in its enclosure so that air cannot bypass it without being filtered.
- When buying a room air cleaner, choose one with a clean air delivery rate that is appropriate for the size of the room.

Many filters sold for the residential market use brand-specific comparison scales, which can make it difficult for consumers to compare the filters of different brands. Comparing only MERV-rated filters is an easy way to find out whether the filters have been tested according to a method developed by an independent group. Some store-brand filters are MERV rated, and some filters rated with a brand-specific scale also have a MERV rating on their packaging. For filters that are not MERV rated, comparison scales are available online. However, very little information is typically available on the brand-specific scales, and these filters might not have been tested using the same particle size ranges that are included in MERV testing. It is best to err on the side of better performance when buying a filter that is not MERV rated.

A new filter efficiency standard, ISO 16890 (ISO 2016), has recently been published. Few residential filters rated using this standard are available at this time, but more might be developed in the future. This standard can be used to test filters in different size categories of PM (less than 1 micron, less than 2.5 microns, less than 10 microns, and "coarse" particles—categories that health experts usually use for particles) instead of the MERV rating system. Because of these size categories, the ISO 16890 and MERV scales cannot be compared with one another, but the filtration efficiencies for particles in the smaller size ranges can be roughly compared.

Electronic air cleaners. Electronic air cleaners are another type of particle-removal device. These cleaners have an initial ionizing section, where particles receive an electrostatic charge, and a collector section, where the particles are removed from the air through attraction to charged plates. These devices can produce ozone, an indoor air pollutant, but typically in very small amounts. If these devices are cleaned and operated according to the manufacturer's instructions,

Table 7.2-A MERV Levels for Different Filter Types

Table 7.2-A has photos of various MERV-rated filters and describes their ability to remove PM of various sizes.

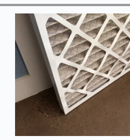
MERV Level	Dust Spot %	Typical Particulate Filter Type	% 0.3-1 pm	% 1-3 pm	% 3-10 pm	Example Filter
1	N/A	Low-efficiency fiberglass and synthetic media disposable panels, cleanable filters	Too low efficiency to be applicable to ASHRAE Standard 52.2 (ASHRAE 2007) determination			
2	N/A					
3	N/A					
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	

Table 7.2-A MERV Levels for Different Filter Types

most can remove particles effectively while posing minimal risk from ozone (see discussion below on ozone generators, which are a different product category that should never be used). If they are not cleaned, the efficiency of these devices drops, and they can produce more ozone. California has adopted regulations to limit ozone emissions from air cleaning devices, and its Air Resources Board maintains an online database of certified air cleaners (ARB 2018). Purchasing only electronic air cleaners that are listed in this directory is a reliable way to ensure that the device will produce minimal ozone.

Electronic air cleaners have advantages. For example, they typically produce a lower pressure drop than mechanical filters. Although they need to be cleaned, the homeowner does not need to purchase new filters regularly. However, they cannot be rated reliably using the MERV scale, making it difficult to compare their efficiencies with those of other types of filters. Their efficiencies are often described as removing “up to” a given percentage of particles. They lose efficiency as they become loaded with contaminants between cleanings, so their performance when they are clean might not reflect their overall performance. One way to overcome this limitation is to purchase a product that combines a medium-efficiency mechanical filter with an electronic air cleaner. Following the manufacturer’s recommended cleaning schedule is also very important.

If the efficiency of an electronic air cleaner was tested using the ASHRAE dust spot efficiency test (ASHRAE 1992), Table 7.2-A can provide a rough comparison of the air cleaner's "best case" performance to that of MERV-rated mechanical filters. These air cleaners can also be tested using the ANSI/AHRI 680 standard (AHRI 2009). This standard assigns particles to 12 different size categories in initial and "loaded" conditions, and it groups the size categories so that they can be roughly compared with the categories in the MERV standard.

Ozone generators. Ozone generators are a different product category that should never be used. Ozone is an air pollutant that irritates the respiratory tract and triggers asthma symptoms. Such devices have been marketed to reduce odors because ozone can break down certain compounds in the indoor air. However, they break these compounds down into other indoor air pollutants, and they are ineffective at removing biological aerosols, although they have been marketed for this purpose (Grinshpun 2016). They are sometimes marketed as "air purifiers" using product descriptions that lead to confusion with other types of electronic air cleaners. Buying only electronic air cleaners that are listed on the California Air Resources Board database of certified air cleaners (ARB 2018) is a good way for consumers to avoid this confusion.

Figure 7.2-A Portable Air Cleaner

Portable air cleaners. Portable air cleaners (Figure 7.2-A) contain either a mechanical or electronic air cleaner, and they have a built-in fan to move air through the filter. These cleaners are commonly sold for use in rooms for localized filtration. Their performance is typically characterized using the clean air delivery rate (CADR), a voluntary measure developed by the Association of Home Appliance Manufacturers (AHAM) that can be used to select the correctly sized unit for a room. The CADR is based on both the efficiency of the filter and the volume of air moved through it, and it describes performance in terms of equivalent clean air. For example, a filter with a CADR of 250 for dust particles can reduce dust concentrations by the same amount as the introduction of 250 CFM of clean air into the room. Portable devices using the association's testing method are listed online with removal rates for pollen, dust, and tobacco smoke (AHAM Verifide 2017).

Filtration is not an acceptable alternative to smoking bans in dwellings. However, the CADR for tobacco smoke is a good way to compare filter efficiency for other types of fine particles. The searchable tool on the AHAM website is based on room size. The list includes products designed to reduce particle concentrations by 80% in the room, which is a meaningful reduction (EPA 2009).

Some portable air cleaners also have activated carbon odor removal capability. The most significant impact of this option is typically to reduce ozone levels. In locations where outdoor ozone is high, this option can be helpful.

Filter Effectiveness

Measures of filter efficiency, like MERV, are defined by the fraction of particles removed as they pass through a filter, but they do not tell the whole story about a filter's *effectiveness* in a given application. Filter effectiveness is influenced by the amount of air that passes through the filter, the timing of that airflow, and the source and destination of the filtered air. For example, dwellings that use supply or balanced ventilation systems can remove outdoor particles effectively by placing a filter in the intake air duct to treat the incoming ventilation air directly, before it has a chance to mix with indoor air. This approach is especially helpful in locations where the outdoor $PM_{2.5}$ level is high.

High-efficiency filters at the AHU return can remove particles from indoor and outdoor sources but are more effective when the AHU operates continuously or a timer turns the AHU fan on at regular intervals (e.g., 20 minutes each hour) to achieve regular airflow through the filter. If the AHU fan operates only under thermostatic control, less air moves through the filter and it is less effective, especially in mild weather.

A filter is also more effective if it is installed in a tight-fitting filter frame that does not allow unfiltered air to travel around the filter's edges, thus avoiding filtration (a process known as "filter bypass"). When a highly efficient filter is used, filter bypass can allow more particles to remain in the air than the filter does. For this reason, highly efficient commercial and industrial filters (such as HEPA filters) are sealed into their frames. Some high-efficiency residential filters have gaskets or weather stripping that provide a seal between the filter and its housing, and weather stripping can be added to a filter to prevent filter bypass. Of course, the filter should be of the correct size for the application, meaning that it fits snugly into its location. The more efficient the filter is, the more important it is to seal its edges. Not doing so can defeat much of the purpose of a filter.

Integration with Dwelling Unit HVAC and Ventilation Systems

Several studies have evaluated and compared various HVAC systems, outside ventilation air, and filter combinations. Some of the relevant findings are summarized below.

MERV 12-14 provides substantial benefits. A modeling study (Zhao et al. 2015) estimated the reduction in morbidity and mortality associated with outdoor PM in 22 cities using 11 different types of filters in a central AHU. The greatest improvements were in dwellings with leakier building enclosures and in cities with higher outdoor PM. Filters in the MERV 12-14 range had substantial benefits, and returns were somewhat diminished for higher MERV ratings.

When the filter is in the AHU, runtime matters. Several studies have shown that if AHUs are turned on only when heating or cooling is needed, the average runtime is approximately 20% (Thornburg et al. 2004; Stephens et al 2011; Cetin and Novoselac 2015). Low runtimes reduce the ability of high-efficiency filters to remove particles because fewer particles move through the filter. Modeling studies have shown that filtration as part of the HVAC system can meaningfully reduce indoor levels of particles that originate outdoors, even when the HVAC system operates only for heating and cooling, but the efficacy of this approach varies. Leakier dwellings with longer HVAC runtimes benefit more from the filtration (Azimi et al 2016).

Strategy 7.2 Provide Particle Filtration and Air Cleaning

Direct filtration of ventilation air is a common-sense strategy for reducing indoor levels of outdoor PM. Filtration of ventilation air introduced by a supply-only or balanced ventilation system reduces PM introduced into the dwelling via ventilation. When a supply-only or balanced ventilation system is used, positive pressurization of the dwelling can also reduce infiltration of outdoor particles.

A study of two test dwellings in Texas showed an approximately 80% reduction in 0.3–2.0 micron particles using central fan integrated supply-only ventilation compared with exhaust ventilation without AHU operation. The central fan integrated supply ventilation system had MERV 9 filters and operated 20 minutes per hour (Rudd and Bergey 2014).

Because outdoor $PM_{2.5}$ concentrations vary significantly around the world (particularly outside the United States), more efficient filters are needed to reduce the impact of outdoor PM*2.5* on the indoor air. A modeling study (Stephens et al. 2016) determined the filter efficiency needed to reduce the impact of outdoor PM and provide a similar indoor impact as outdoor air that meets the U.S. National Ambient Air Quality Standards and World Health Organization guideline (WHO 2016) levels. The results of this study are the basis for the recommendations in this guide for areas with high outdoor $PM_{2.5}$ concentrations.

The most successful strategies combine filtration of outdoor air with minimum settings for AHU runtime. A study (Singer et al. 2016) evaluated the effectiveness of several combinations of ventilation system and filter options in a test dwelling at removing particles generated outdoors and indoors from cooking. The three systems with the best performance for both outdoor and indoor particles were:

- Supply ventilation on a timer operating 20 minutes per hour using the forced air system with a MERV 8 filter on the outdoor air supply and a MERV 16 filter at the forced air unit

- Exhaust ventilation with a MERV 13 filter at the return of a minisplit heat pump that operates at low continuous speed

- Exhaust ventilation with a MERV 13 filter at the return of a forced air system on a timer operating 20 minutes per hour

Best Practices for Filter Selection and System Design

The system combinations in Figures 7.2-B, 7.2-C, 7.2-D, and 7.2-E can be used in new or existing dwellings as best practices that go beyond codes and standards. ASHRAE Standard 62.2-2016 (ASHRAE 2016b) requires only MERV 6 filters for forced-air systems with ducts longer than 10 ft (3 m) to keep the system and ducts clean. This standard requires no air filtration at all for ductless air conditioners and ductless heating systems, which does not address occupant exposure to PM. The IMC (ICC 2015c) requires heating and air conditioning systems to have filters, but it does not require filters to meet specific performance criteria.

When filters with a MERV rating of 13 or higher are recommended in an AHU, new systems should be designed to accommodate the associated pressure requirements. Existing systems should be evaluated to determine whether a MERV 13 filter can be added; if not, a MERV 11 filter can be used. Most existing systems can accommodate a MERV 11 filter, as long it is changed regularly. Because existing dwellings with leaky building enclosures often benefit the most from filtration, using a strategy that does not rely on the central AHU is a good choice when a MERV 13 filter in the central AHU is not appropriate.

Best Practice Filter Guidelines

Best practice filter guidelines for systems with and without central AHUs are:

- MERV 13 (or higher) filter at the central AHU, with a thermostat or timer/controller that turns the AHU fan on for at least 20 minutes per hour in combination with one of the following ventilation strategies (Figure 7.2-B):
  - Supply-only ventilation with a MERV 6-8 filter for incoming outdoor air
  - Balanced ventilation with a MERV 6-8 filter for incoming outdoor air
  - Exhaust-only ventilation

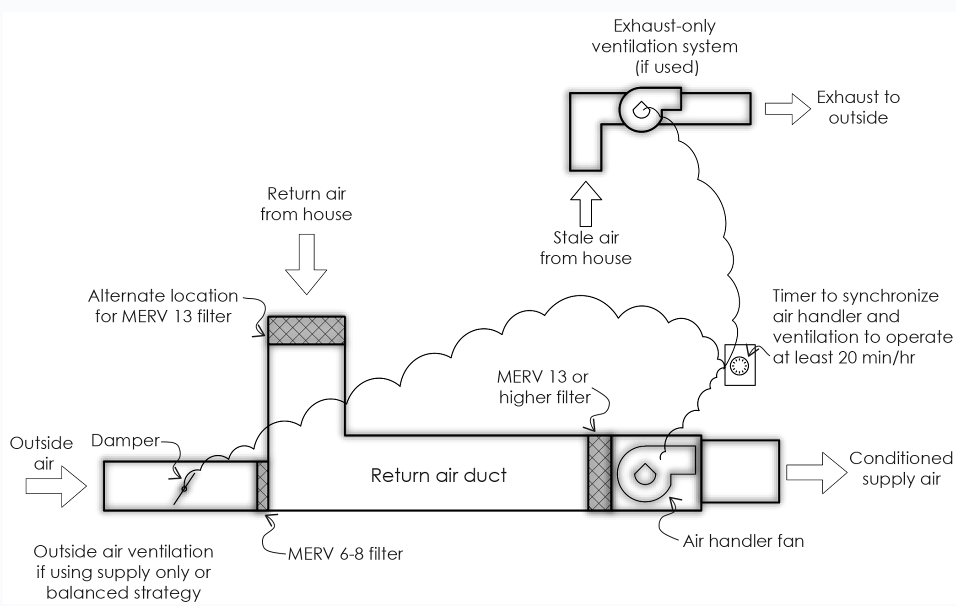


Figure 7.2-B Best-Practice Combination System for Filtration at Central AHU

Best Practice Filter Guidelines

- No central AHU or a central AHU that is not used for filtration:
  - A MERV 13 (or higher) filter that treats both the incoming air of a supply-only or balanced ventilation system and at least one ACH of recirculated indoor air (Figure 7.2-C)
  - Exhaust-only ventilation paired with a MERV 13 (or higher) filter that treats and recirculates indoor air at the rate of one ACH or more (Figure 7.2-D)
  - Portable air cleaners in all sleeping rooms with a tobacco smoke clean air delivery rate greater than or equal to the room volume in ft^3 divided by 12 (or, in SI units, greater than or equal to the room volume in m^3 multiplied by 2.9) (Figure 7.2-E). If used with a supply-only or balanced ventilation system, pass incoming outdoor air through a MERV 6-8 filter.

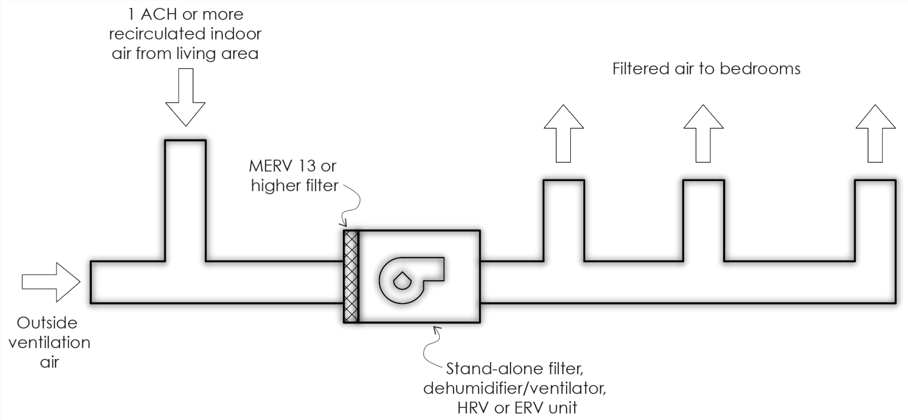


Figure 7.2-C Supply-only or Balanced System Combined with Filtered Recirculation Air

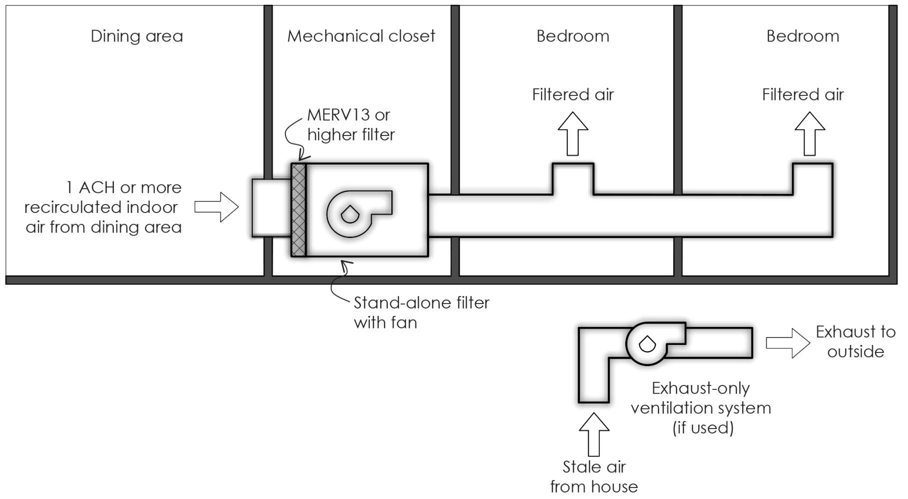


Figure 7.2-D Exhaust-only Ventilation System Combined with Filtered Recirculation Air

Best Practice Filter Guidelines

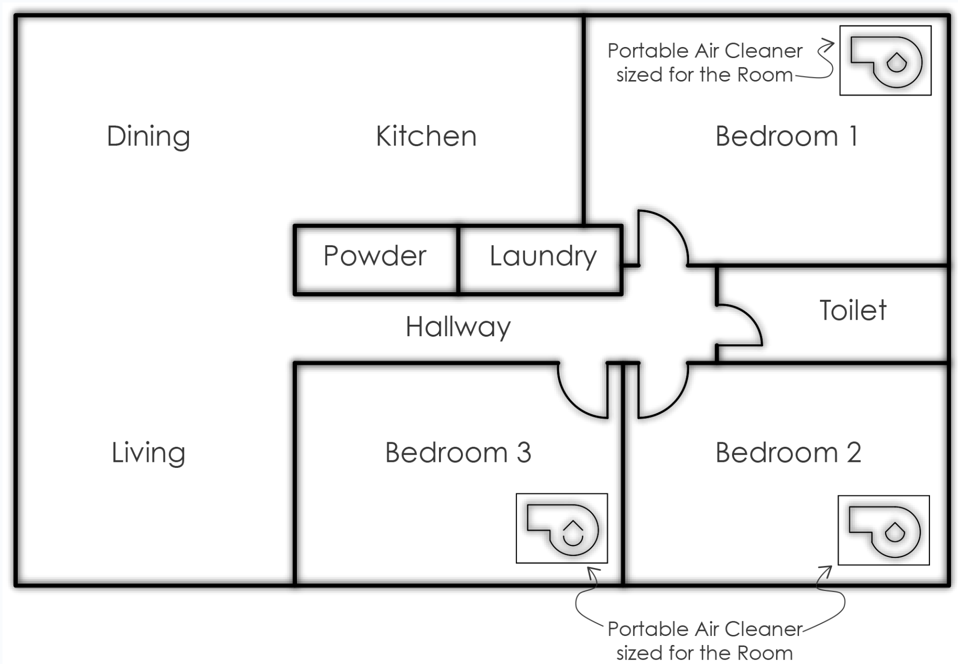


Figure 7.2-E Portable Air Cleaners in Sleeping Rooms

For filtration strategies that use the central AHU, the MERV 13 filter can be located at the filter return grille(s). Placing the filter at the central AHU is often preferable if this location offers convenient access to change the filter and offers the following advantages:

- Only one filter needs to be changed.
- Outdoor air from a system-integrated supply-only or balanced ventilation system passes through the filter en route to the living space.
- The filter pressure drop does not increase leakage in the return duct.

However, if the return grille(s) are in a more convenient location for changing the filter, the filter can be located there. If so, duct leakage should be tested and verified to be less than 6 CFM25 per 100 ft² (170 L/min per 9.29 m²) of conditioned floor area (CFA) served by the system.

Although MERV 13 filters that are 1 in. (2.5 cm) thick are available, a 2 in. (5 cm) or 4 in. (10 cm) filter slot offers more flexibility and allows use of a lower pressure drop MERV 13 filter. The lower pressure requirement can make these filters more compatible with existing systems, but the system might need to be retrofitted with a larger filter slot to accommodate the thicker filter.

For filter systems that recirculate dwelling air but are independent of the AHU, a best practice is to design the system to achieve distribution and mixing throughout the living space. For example, a system might pull air from a main living area and deliver filtered air to all of the bedrooms in the dwelling. Since the kitchen is usually part of the main living space and is a significant source of indoor particles, this configuration usually reduces occupant exposure.

For dwelling units in areas with average annual $PM_{2.5}$ above 15 μg/m^3, additional measures are needed to reduce the impact of outdoor PM in the incoming ventilation air. For these locations, a supply-only or balanced ventilation system should be used, and the outdoor air filter efficiency should be increased to the recommended MERV rating from Figure 7.2-F, which provides the ventilation air filtration levels needed to reduce entering outdoor $PM_{2.5}$ concentrations to the World Health Organization maximum of 10 μg/m^3.

Best practices from ASHRAE Standard 189.1 (ASHRAE 2017f) for filtration in common areas in multifamily buildings are as follows:

- Provide at least a MERV 8 filter upstream of all cooling coils or other wetted surfaces in air-handling systems.
- Provide at least MERV 13 filters or air cleaners in air-handling systems that serve occupied spaces.
- Seal filters, filter tracks, supports, and access doors to prevent filter bypass.
- Provide air-cleaning devices with an ozone-removal efficiency of at least 40% in all buildings in ozone "non-attainment" areas.

Changing or Cleaning Filters

A best practice is to change mechanical filters three to four times per year; one of those times should be in early winter in humid climates (Schoen 2003). Mechanical filters can do a better job of removing some sizes of particles as they become loaded, but the used filter can be a source of contaminants and thus reduce IAQ. Loaded filters also reduce airflow through the system. If a filter is not changed often enough, the system's functionality can be compromised. How often filters need to be changed to prevent loading varies. In some dwellings, less frequent replacements might be adequate, but the filter should be checked at least three or four times per year. Filters that appear to be coated with a layer of dirt should be changed.

Most mechanical filters sold for residential use are electrostatically charged (also known as "electret" filters). Whether a filter is electrostatically charged is often indicated in the detailed product description, and manufacturers sometimes give these filters names that end in "et," "ete," or "ion." The performance of electret filters degrades over time from exposure to fine particles associated with combustion (e.g., diesel exhaust, cigarette smoking, cooking aerosols). Field studies suggest that this efficiency loss is probably less severe when the proportion of recirculation air is high, as is typical in dwellings (Lehtimaki et al. 2005a, 2005b).

There is no way to know what portion of a filter's rated performance relies on the electrostatic charge or whether a filter has lost its charge, which can happen before the filter looks dirty. Many of the strategies in this guide (e.g., use of a kitchen range hood, nonsmoking policies, use of direct vent combustion equipment and EPA-rated wood burning appliances, and elimination of candle use and other unnecessary combustion indoors) can reduce the exposure of residential filters to fine combustion particles. When these strategies are not employed, a high-performance filter that does not rely on electrostatic charge, which might be difficult to find, provides more consistent performance over time.

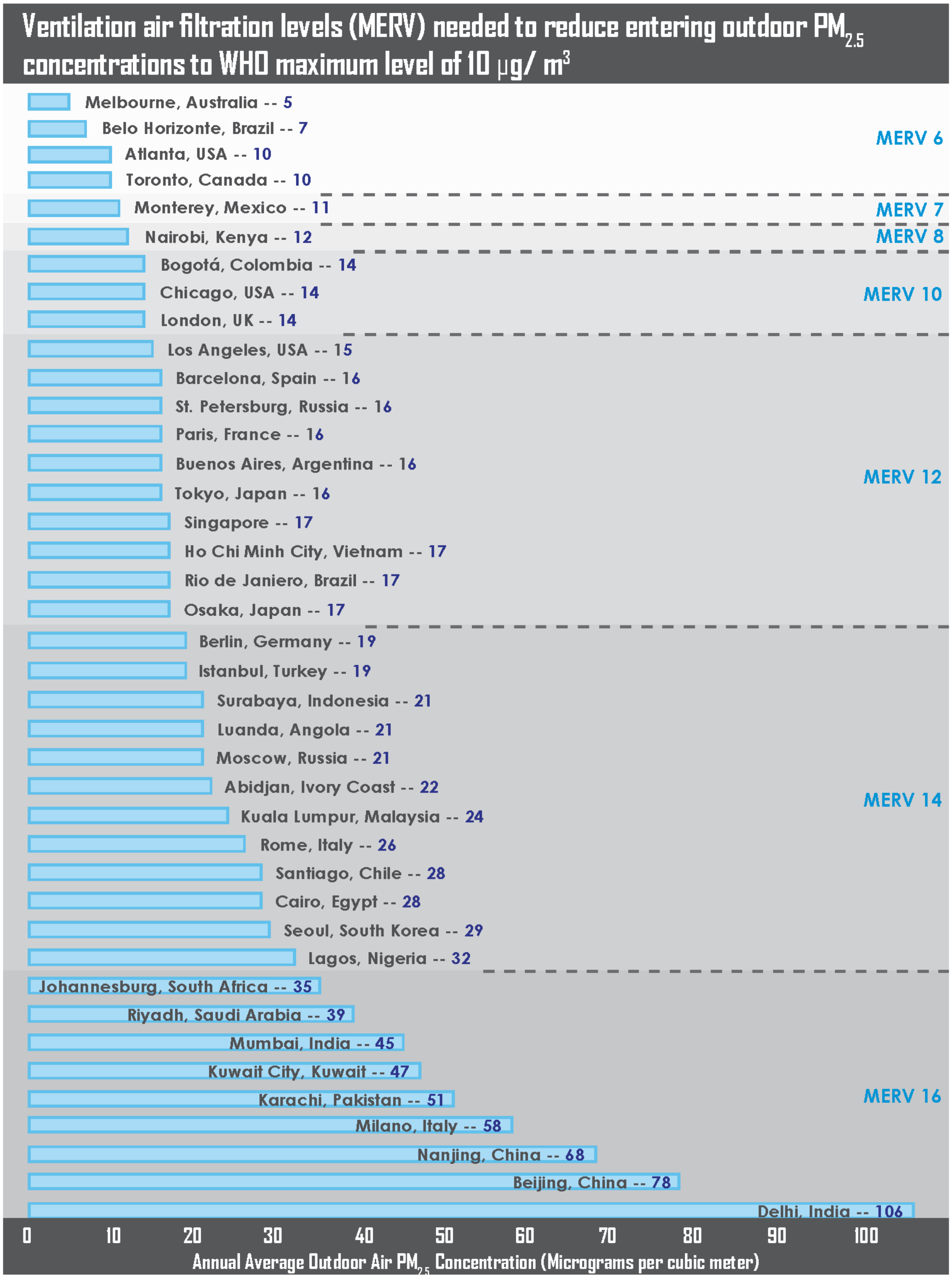


Figure 7.2-F Filtration Levels for ventilation air, to achieve equivalency in areas where outdoor air exceeds World Health Organization Standards
Adapted from Stephens et al. (2016).

For media filters, use of an alarm triggered by pressure loss that notifies the occupant that the filter is loaded and needs to be changed is a best practice, especially for filters with a rating higher than MERV 11 (Walker et al. 2013). Designers must consider filter accessibility in their system designs. Filters—whether in returns, central air-handling systems, or on outside air ducts—need to be accessible to occupants and in an obvious location so that occupants know that these filters exist and need to be changed. Every dwelling should have an operation and maintenance manual that includes filter change location and instructions.

Electronic air cleaners do not have a component that needs to be changed, but they lose efficiency over time as they become loaded and need to be cleaned to maintain effectiveness. The initial cost of these filters is higher, and they require more maintenance labor, but their long-term material cost is lower than that of media filters because they do not require owners to purchase replacement filters. The manufacturer's instructions should be checked to determine the appropriate cleaning frequency; manufacturers typically recommend cleaning three to four times per year. It can be hard to know if electronic air cleaners stop working. If they aren't getting dirty, that should raise suspicions.

Energy Effects of High-Efficiency Filters

Several studies have shown that filters up to MERV 11-12 have negligible effects on HVAC system energy use (Walker et al. 2013; Stephens et al. 2010). MERV 16 and higher filters can use more energy, but the extent of this increase depends on other system characteristics. High-efficiency filters in return grilles can also promote duct leakage because they can increase the return system pressure. MERV 16 and higher filters should only be used in return grilles when the system duct leakage has been tested to limit the energy loss and introduction of contaminants into the return.

For filters in the central AHU, operating the system fan longer than is required to condition the dwelling can significantly increase energy use. Turning the fan on for 20 minutes per hour is a good compromise that provides a basic level of filtration even in mild weather without adding much runtime. A high-efficiency standalone filter can be more energy efficient for removing particles than a filter in the AHU. The fan in this type of filter is often smaller and uses less energy than an AHU fan with longer runtimes (Fisk 2016).

Preparedness for Unusual Events

A high-efficiency (MERV 11 or higher) filter helps prepare residents for unusual outdoor events, such as smoke from wildfires. When such an event takes place, the AHU fan can be set to run continuously so that it removes more particles from the indoor air. Homeowners should temporarily turn off any outside air ventilation systems during such events, unless these systems have a high-efficiency filter for the incoming air. When the event is over, filters should be changed, and fans and ventilation systems should be returned to their original setting.

Gas-Phase Filter Technologies

"Gas-phase" air filters, the most common of which use activated carbon, remove gaseous pollutants, such as ozone and, to a limited extent, VOCs from the air. This process is sometimes called "air cleaning." These filters can be added to the central HVAC system or to portable air cleaners.

The most effective way to control ozone of outdoor origin (Strategy 3.1) is to install activated carbon filters at the outdoor air intake to filter the ozone before it can chemically react, which creates other pollutants. Specialty retailers sell (typically online) both activated carbon-only filters and particle filters combined with activated carbon in 1–4 in. (2.5–10 cm) thick replaceable panels.

Activated carbon filters are usually marketed for removal of odors and VOCs, not ozone, even though they are much more effective at removing ozone than odors or VOCs. A large amount of activated carbon is required to remove significant amounts of odor and VOCs, and this is not practical for dwellings. To control ozone from outdoors, these filters can be used during the hot sunny season only, when ozone concentrations are higher.

Carbon filtration is worth considering for dwellings in areas with high outdoor ozone concentrations. Recent modeling research shows that commercially available carbon filters can reduce ozone levels in dwellings and have a favorable cost-benefit ratio (Aldred et al. 2016). An ASHRAE review of air-cleaning products that remove ozone and their costs and benefits showed that a central HVAC system with activated carbon filters that operated only for thermal conditioning was beneficial in Riverside, California, and Phoenix, Arizona, dwellings (ASHRAE 2014). If the system operated continuously during the ozone season (summertime), it became cost effective in Atlanta, Georgia; Austin, Texas; Buffalo, New York; Chicago, Illinois; Cincinnati, Ohio; Houston, Texas; Miami, Florida; Minneapolis, Minnesota; New York, New York; and Washington, DC.

Activated carbon filters can be useful in most cities when sensitive individuals (such as people with asthma) live in the dwelling. The benefit:cost ratio is better for 2-in. (5 cm) and 4-in. (10 cm) filters than for 1-in. (2.5 cm) filters because of their lower pressure drop and associated energy costs.

Activated carbon filters are also available and sometimes easier to find for standalone filtration units; however, this approach is less effective than filtering outdoor air where it enters the dwelling. Activated carbon cloth or mat hung on walls is not usually aesthetically acceptable, and its long-term performance is unknown.

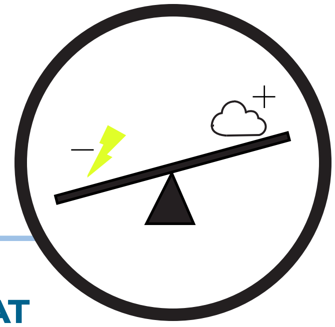
Ultraviolet germicidal irradiation air cleaners use ultraviolet lamps to destroy biological contaminants (viruses, bacteria, and molds). These air cleaners are best used in combination with, and not instead of, a particle filter. They are not commonly used in dwellings, and some units marketed for dwelling use might not yield long enough ultraviolet radiation exposure times to be effective. Currently, there is not enough evidence to recommend widespread use of these cleaners in dwellings.

Photocatalytic oxidation air cleaners are not recommended for dwellings at this time. They combine ultraviolet lamps with a catalyst that reacts with the light to break gaseous pollutants (e.g., VOCs) down into other compounds. The technology shows promise, but it is expensive and not available in a format that is appropriate for dwellings. There is also a concern that VOCs might

break down into substances (e.g., formaldehyde) that are more harmful (Zhong and Haghighat 2015).

Gas phase air cleaning has the ability to remove VOCs (Chen et al. 2015), but this ability is very limited. The primary means to control for VOCs should be to limit their introduction into the dwelling (Strategies 5.1 and 5.2).

Objective 8



MINIMIZE ENERGY USE, MAXIMIZE COMFORT, AND ADDRESS INTERACTIONS OF FACTORS THAT AFFECT IAQ

IAQ and strategies to maintain it have significant effects on dwelling energy use, occupant comfort, and occupants' overall perceptions of the indoor environment. The strategies for this objective can help reduce the energy required to deliver good IAQ. They can also help designers understand interactions among the factors in indoor environments to support their efforts to maximize the impact of their IAQ efforts:

Strategy 8.1 Use Energy Recovery Ventilation Where Appropriate explains the economics of energy recovery ventilation systems as well as how they contribute to humidity control.

Strategy 8.2 Use Natural or Mixed-Mode Ventilation Where Appropriate describes the careful design considerations for meeting ventilation requirements with natural or mixed-mode ventilation.

Strategy 8.3 Enable Residents to Maintain Comfort covers the factors that influence occupants' experience of the indoor environment, including IAQ, thermal conditions, sound, and light.

Strategy 8.4 Consider Interactions Among Factors Affecting IAQ explains how other factors including thermal conditions, humidity, and sound interact to impact indoor air quality and occupants perceptions of it.

Other strategies that are relevant to reducing the energy required to deliver good IAQ include the following:

- Strategy 1.2 - Select HVAC Systems to Improve IAQ and Manage the Energy Effects of Ventilation
- Strategy 2.2 – Control Indoor Humidity
- Strategy 6.1 – Properly Vent Combustion Equipment
- Strategy 6.2 – Provide Local Capture and Exhaust for Point Sources of Contaminants
- Strategy 7.1 – Implement Appropriate Outdoor Air Ventilation Strategies and Quantities
- Strategy 7.2 – Provide Particle Filtration and Air Cleaning

Strategy 8.1 Use Energy Recovery Ventilation Where Appropriate

Introduction

The benefits of using an ERV or HRV for whole-house ventilation include:

- Energy savings due to recovery of heat from outgoing air
- Neutral effect of balanced supply and exhaust airflows on building pressure
- Ability to filter and distribute outdoor air regardless of whether the ventilation is integrated into a central air-handling system

It is good practice for designers to choose equipment that is at least 20% larger than required to have a reasonable likelihood of delivering the desired quantity of air.

Figure 8.1-A Operation of an ERV & Figure 8.1-B Operation of an HRV

ERVs (Figure 8.1-A) and HRVs (Figure 8.1-B) simultaneously supply outdoor ventilation air and exhaust air from the dwelling while recovering energy from the air being exhausted. An ERV or HRV uses a small fan to bring outdoor air into the dwelling. This air passes through a heat transfer medium, where it crosses paths with air that is simultaneously exhausted from the dwelling. The type of medium determines the efficiency of the device and whether it is an ERV or HRV. HRVs transfer only sensible energy; in other words, the incoming air is warmed in winter or cooled in summer, with no transfer of humidity. ERVs transfer both sensible and latent energy (defined in the definitions section), meaning that when it is cool and dry outside (as in winter in many locations), the incoming air is warmed and humidified, and when it is hot and humid outside (as in summer in many locations), the incoming air is cooled and dehumidified. Beyond the heat transfer medium used, the devices are nearly identical. In fact, some models can be changed from ERV to HRV by swapping the heat transfer core.

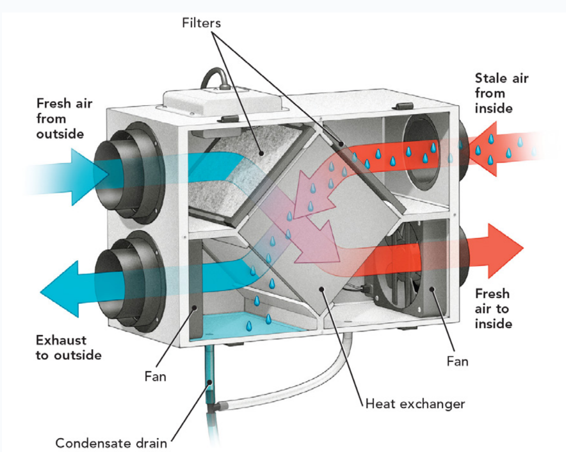


Figure 8.1-A Diagram showing operation of an ERV
Illustration by Christopher Mills, courtesy of Fine Home Building Magazine.

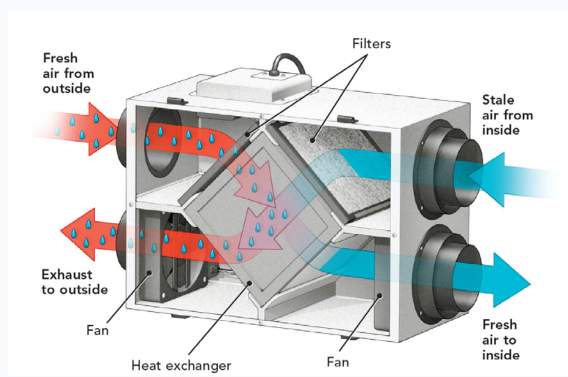


Figure 8.1-B Diagram showing operation of an HRV
Illustration by Christopher Mills, courtesy of Fine Home Building Magazine.

A typical HRV has a sensible heat recovery efficiency of about 70%. This means that if the temperature is 0°F (-17°C) outdoors and 70°F (21°C) indoors, the incoming air is prewarmed to 49°F (9°C). ERVs typically have a sensible heat recovery efficiency of about 50%, and they exchange about 50% of the latent energy (or humidity) in the air. As a result, HRVs are more effective than ERVs in the winter and when no humidity exchange is needed, whereas ERVs are more effective than HRVs in humid summer conditions. The Home Ventilating Institute publishes a directory with efficiency data for many ERVs and HRVs sold in the United States (HVI 2017).

Choosing Between an ERV and HRV

The choice between an ERV or HRV is typically based on climate to achieve the best overall annual efficiency or to exploit the transfer of moisture in a way that improves IAQ in the dwelling.

In a hot, humid climate, an ERV is usually the best choice because it precools the incoming outdoor air and reduces the moisture contribution of the incoming ventilation air. However, an ERV is not a humidity-control device—its effects are limited to reducing the humidity impact of the ventilation air. Some dwellings in humid climates still require a dehumidifier to control humidity. An ERV also reduces the drying effect of wintertime ventilation air in a heating climate. However, this effect is usually small, and it comes at the expense of a lower sensible recovery efficiency. The higher sensible recovery efficiency of an HRV typically makes it the better choice for heating-dominated climates and climates with hot, dry summers.

For mixed humid climates in climate zones 3 and 4 (Figure 1.2-A), ERVs and HRVs usually have similar annual energy efficiency. If the summers are humid, an ERV might be preferable because of the reduced summertime impact of ventilation air on the humidity load. This is especially true if the dwelling might need dehumidification for other reasons, such as being in a humid microclimate or having a low cooling load or finished basement. For dwellings in the cooler zone 4 that are more prone to high winter humidity, an HRV can be a better choice than an ERV. These dwellings usually have ultra-tight construction (less than 1 ACH50) and indoor sources of humidity (e.g., open showers or high occupant density). In this transitional region, no single choice might be best based solely on climate (Holladay 2010).

Integration with Local Exhaust Strategies

To maximize energy efficiency, some designers choose to exhaust bathroom air using an HRV (or, less commonly, an ERV). Another benefit of this strategy is that it can accomplish the two functions of whole-house ventilation and local exhaust with a single piece of equipment. However, this dual purpose means that the design of the system and its controls must meet both goals.

Some HRV models allow up to 10% cross-leakage (exhaust air that mixes back in with air supplied to the dwelling), but an HRV model chosen for a bathroom should have less than 3% cross-leakage. In addition, the exhaust air outlet and the outdoor air inlet should be at least 10 ft (3 m) away from one another on the exterior of the dwelling to avoid cross-contamination. ASHRAE Standard 62.2 (ASHRAE 2016b) allows a combined exhaust/intake termination with less than 10 ft (3 m) separation if it has less than 10% cross-leakage, but not when that system includes exhaust from a kitchen. This guide recommends against using combined inlet/outlets for bath exhaust as well.

For example, a single HRV can be used to exhaust air continuously from one or more bathrooms at a flow rate that meets the requirement for whole-house ventilation (Strategy 7.1). As long as the continuous exhaust from each bathroom is more than 20 CFM (9.4 l/s), the ASHRAE Standard 62.2 requirement for local bathroom exhaust (see Strategy 6.2) is also met. If exhaust air is drawn from more than one bathroom, the ductwork should be designed and the system commissioned to achieve the target airflow in each bathroom. Some designers oversize the HRV so that an occupant-accessible switch in the bathroom can be used to temporarily increase the exhaust flow rate, allowing the system to more quickly remove moisture from the bathroom. This strategy could be applied to the systems in Case Studies 3, 4, or 5 in Appendix A.

Because one of the key goals of local exhaust systems is to remove moisture, an HRV is almost always preferable to an ERV for this dual-purpose strategy because it does not recapture any moisture in the exhaust air and reintroduce it into the dwelling. In extremely humid climates, however, an ERV can be used. Although the ERV recovers some of the humidity from the air being exhausted while the bathroom is in use, it reduces the humidity impact of whole-house ventilation air for the entire day, making the overall net effect on humidity more favorable. An ERV in this situation can also be preferable to a standalone exhaust fan, which creates negative pressure in the dwelling, causing the exhausted air to be replaced with humid outside air without latent recovery.

This guide recommends against exhausting kitchen air through an HRV or ERV because most of these devices are not rated for kitchen grease, and it is more difficult to match the necessary flow rates for continuous kitchen exhaust and whole-house ventilation. Unless the kitchen is very small, the rate for continuous ventilation is often prohibitively large. An intermittent fan mounted in a hood configuration is usually a better solution and more effective for removing kitchen contaminants, as discussed in Strategy 6.2.

Integrating ERVs and HRVs into Central AHUs

Many designers integrate ERVs and HRVs into a dwelling's central AHU. The main advantages are that doing so allows distribution of ventilation air throughout the dwelling using existing ductwork and filtration of this air using the filter in the AHU.

However, this approach has some potentially important disadvantages. Compared to using the ERV or HRV uncoupled from the AHU, this strategy can require more AHU runtime, and the fan energy used to accomplish this can be significant. Also, if the exhaust air draws from the return air ducts and the outdoor air is also delivered into the AHU's ducts, the system will short-circuit if the AHU fan is not operating whenever the ERV or HRV operates, delivering less ventilation air than intended to the living space. In addition, the ducts must be tight; leaky ducts, especially return ducts outside conditioned space, can allow contaminants to be drawn in, which could partially compromise ventilation system function. Finally, outdoor air should never be introduced into the supply ductwork because it can cause condensation in the ductwork during the cooling season. A carefully implemented design and control approach can avoid these problems.

One of the two options described below can be chosen to integrate ERVs and HRVs into central AHUs.

Option 1: Connection of exhaust and outdoor air sides of the ERV or HRV to the AHU's return duct. The exhaust air is pulled from a location in the duct that is at least 10 ft (3 m) away from where the outside air is introduced (unless the ERV's or HRV's installation manual calls for a

different distance). The outside air connection should be closer to the AHU, and the AHU fan must be set to operate whenever the ERV or HRV operates to prevent short-circuiting of the ventilation air and to allow the outdoor air to pass through the AHU filter before being delivered to occupants. In this configuration, the ERV or HRV only needs a coarse filter that can protect it from clogging, and it does not need to filter particles to protect human health.

To avoid using a great deal of energy to operate the AHU fan, the ERV or HRV should be sized so that it does not need to run continuously. The advantages are discussed in Strategies 7.1 and 7.2 of a fan runtime of 20 minutes per hour to minimize fan energy use, particularly when a smart controller accounts for system runtime and only increases fan operation when the weather is mild and the AHU fan is not needed for heating or cooling for 20 minutes during a given hour. Successful implementation of this option requires simultaneous operation of both the ERV or HRV and AHU for 20 minutes per hour. A caveat, however, is that finding and implementing a control strategy that accomplishes this simultaneous operation can be challenging.

Option 2: Direct removal of exhaust air from within the dwelling and connection of outdoor air to AHU return duct (Case Study 4 in Appendix A). This option is simpler than Option 1, but it requires additional consideration of how the ERV or HRV air is filtered.

In this approach, the exhaust air comes directly from the dwelling and is not connected to the AHU. The air might be exhausted from a bathroom, common area or hallway, conditioned basement, or conditioned attic. The outdoor air is delivered into the AHU's return duct without requiring synchronized operation of the ERV or HRV and AHU fans. When the AHU fan operates, it distributes air to all conditioned parts of the dwelling. When the AHU fan does not operate, the ventilation air takes the path of least resistance back through the returns. Because returns are typically in more heavily occupied rooms, such as main living areas and (ideally) bedrooms, this approach distributes the outdoor air in a reasonable way.

This option is best used when the air-handling system has a high-efficiency filter at the AHU (rather than at the returns). The airflow resistance of the high efficiency filter directs the outdoor air back through the return ducts rather than through the AHU, where condensation could occur in the supply ductwork. Because the ventilation air is delivered to the living space without passing through the AHU's filter when the system is not operating, the ventilation air should be filtered using a strategy consistent with the recommendations in Strategy 7.2. Some options are:

- A MERV 13 filter at the AHU operating for at least 20 minutes per hour with a MERV 6-8 filter in the ERV or HRV

- An ERV or HRV with a MERV 13 filter that filters both the outdoor ventilation air and one ACH of recirculated indoor air

ERVs and HRVs can also be used in multifamily buildings. Some buildings have an ERV or HRV for each living unit, with a system design that is not very different from that used in a single-family dwelling. Alternatively, a larger ERV or HRV can process exhaust air and provide supply air for multiple living units and common areas (Holladay 2010). For example, Case Study 9 in Appendix A could be adapted to work with an ERV or HRV.

Strategy 8.2 Use Natural or Mixed-Mode Ventilation Where Appropriate

8.2

What is Natural Ventilation?

A dwelling or some portion of it that has no ventilation fans and whose ventilation relies on natural forces only, such as wind pressure or differences in air density (stack effect), is naturally, or passively, ventilated.

In many locations, particularly in the developed world, whole-dwelling ventilation provided naturally does not meet building codes unless a fan is used as well. In other locations throughout the world, natural ventilation is allowed, can be effective, and might even be common. In climates that are common in North America, natural forces cannot always be relied on to provide sufficient ventilation because they are highly variable. Such natural forces often provide less ventilation in mild weather and more in severe weather, when the ventilation is most energy intensive. These periods of high and low ventilation might not coincide with periods of high and low indoor contaminant generation.

In the past, all residential buildings relied on ventilation from air leakage through the enclosure and through open windows and doors, powered only by natural forces. ASHRAE Standard 62.2 (ASHRAE 2016b) allows this natural ventilation if it provides no more annual exposure to contaminants than a mechanical system, which must be documented using calculations.

Some features of natural ventilation are as follows:

- A dwelling that relies on natural forces only, such as wind, is naturally, or passively, ventilated.
- Natural ventilation and natural cooling have related but separate goals. The former is done to provide acceptable contaminant concentrations; the latter is done to provide a comfortable temperature and air movement.
- Most dwelling units have operable windows and some sort of fan-forced ventilation system. Using these judiciously in combination can improve air quality and comfort.

Ventilation provided by accident is not the same as an engineered natural ventilation system, as discussed in the section below on the history and applications of natural ventilation and natural cooling. A more detailed discussion of the dilemma of choosing intentional versus unintentional ventilation is available elsewhere (Schiavon 2014).

Even when Standard 62.2 requires fan-powered ventilation, it allows the ventilation rate to be reduced to account for air leakage (Strategy 7.1). A fan for local mechanical exhaust from the kitchen or bathroom (Strategy 6.2) is required by ASHRAE Standard 62.2 and usually by code, even if the remainder of the dwelling is naturally ventilated.

Natural Ventilation vs. Natural (Ventilative) Cooling

The purpose of ventilation—whether natural, mechanical, or mixed mode (mix of natural and mechanical approaches)—is to provide acceptable odor and sensory irritation and contaminant concentrations without known health risks. People sometimes use the term “natural ventilation” when referring to air exchange to achieve satisfactory thermal (temperature and humidity) conditions. Many experts prefer to distinguish this process and its goal from ventilation by calling it “natural

Is Air Conditioning Good for Air Quality?

Research shows consistent associations between occupant symptoms and the presence of air-conditioning systems in buildings, although most of these studies focused on office buildings, not dwellings (Mendell 1993). More information about the downsides of air conditioning is available in Losing Our Cool (Cox 2010).

conditioning" or "natural cooling." A related concept is "ventilative cooling" (EBC 2015), which includes natural or mechanical methods of ventilation for cooling purposes. ASHRAE Standard 55 (ASHRAE 2017b) defines naturally conditioned spaces as those where thermal conditions are regulated primarily by occupant-controlled openings.

Thus, although related, contaminant control and thermal control are separate goals (see Strategy 8.4), and natural ventilation can help achieve both of them.

Kolokrotroni and colleagues (EBC 2015) discuss the "climate cooling potential" index, used to estimate the cooling potential of night cooling, and they conclude that the climate has good cooling potential in all of Northern Europe (including the British Isles). In Central, Eastern, and even parts of Southern Europe, the climatic cooling potential is still significant. Dry climates in the western part of North America have climate cooling potential that is similar to that in Europe.

In some cases, natural ventilation for contaminant control can interfere with thermal comfort, such as when a window is opened in wintertime to dilute contaminants from activities such as cleaning, painting, or smoking. In other cases, natural ventilation for thermal purposes can increase indoor contaminant levels, such as when outdoor conditions are mild and windows are opened, yet outside air has high levels of $PM_{2.5}$, ozone, or other contaminants (Strategy 3.1). This issue is especially important in polluted areas; for specific examples of residences in Seoul, Korea, see the article by Park and colleagues (Park et al. 2014).

Mixed-Mode Ventilation

Mixed-mode ventilation is usually defined as a combination of natural (passive) ventilation with mechanical (fan-forced) ventilation. Most dwelling units have some form of this combination, with operable windows and some sort of fan-forced ventilation. Often, passive ventilation uses the same amount or less of energy than mixed-mode ventilation.

In "concurrent operation," whole-dwelling ventilation operates and windows are open in the same space and at the same time. It is possible to turn off the whole-dwelling ventilation when windows and doors are open, but this is rarely done and not necessary. Turning off whole-dwelling mechanical ventilation when windows and doors are open is called "changeover operation," in which the ventilation alternates between purely natural and purely mechanical. In dwellings, occupants typically do this mechanically. A description, tailored primarily to commercial buildings, is available elsewhere (CBE 2017).

Making natural ventilation available through operable windows for unusual events (e.g., burnt food or spills) is advantageous, even if it is not used to meet the minimum ventilation requirement.

When conditions are right (e.g., outdoor pollution and allergen levels are low and outdoor thermal conditions are moderate), opening windows and/or operating exhaust or inlet fans can enhance natural cooling. The bathroom or kitchen exhaust fan, a fan in or near an open window, or a whole-house fan could be used. A whole-house fan usually draws air up and out and is operated when windows are open to draw in replacement air.

Need for Caution

Running a high-volume exhaust or whole-house fan when the windows are closed and combustion appliances (e.g., water heaters, especially those that rely on natural draft; Strategy 6.1) are running can cause the flame to go out or deadly carbon monoxide to enter the living space.

Nighttime ventilative cooling. In locations with strong diurnal temperature fluctuations (hot during the day and cool and dry at night), bringing in outdoor air at night can be a great approach to natural cooling. This is especially true if the dwelling has a large thermal mass (dense, heat-holding materials, such as masonry and stone, in its walls and floors that take longer to heat up and cool down). Nighttime cooling can contribute to moisture problems when used in humid conditions.

The strategy works like this: fans or open windows encourage cooler air at night to flow into the dwelling, cooling not only the room air but also materials like stone and masonry that hold a lot of heat. This can be especially effective at night if windows are open in sleeping rooms. The cooler thermal mass persists into the hot part of the day and helps keep the room air cooler. In addition, the cool surfaces contribute to personal comfort through radiative cooling (losing heat to a cool surface without contacting it—the opposite of how a fire provides warmth through close proximity). Clean outdoor air, which includes nighttime air in many locations, also improves IAQ in the dwelling.

In dwellings that have an air-permeable enclosure, nighttime cooling with the windows closed can force the air through the enclosure, enhancing enclosure cooling. This approach should not be used when air outside is highly humid; this air should not be drawn into the enclosure (Strategy 2.1).

History and Applications of Natural Ventilation and Natural Cooling

Natural forces have been used for thousands of years to ventilate and cool spaces. Examples of ancient building structures that use natural ventilation include the Pantheon in Rome, where the "Great Eye" at the dome's apex is the primary source of ventilation and daylight. Similarly, Persian building structures used wind scoops called "malqafs" and water features to take advantage of the wind, evaporative cooling, and natural buoyancy effects for passive ventilation and cooling (Walker 2008).

Naturally cooled buildings are not designed to achieve constant environmental conditions. They take advantage of, and adapt to, changing outdoor conditions to provide an indoor environment that is comfortable enough for the occupants, even if this environment is not consistent or perfect.

Clearly, some locations are not suitable for natural ventilation or natural cooling. These locations include those that require tight temperature and humidity control or that experience prolonged high outdoor temperatures, high humidity levels, chronic outdoor air pollution, or other severe weather conditions. However, many locations can take advantage of natural ventilation strategies for the entire year or a significant portion of it.

Natural ventilation and natural cooling generally work well with other sustainable strategies; for example, energy-efficient design typically requires the reduction or 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 ceilings are suitable for natural ventilation. In addition, 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, often in the form of masonry and stone, can also be used to temper

incoming air, especially when the building is flushed with outdoor air on cool nights, and it can moderate mean radiant temperature, which improves comfort. Mass provides a thermal flywheel, so the building requires less overall energy for heating and cooling (Willmert 2001).

A promising option for mixed-mode ventilation in cold climates is an outdoor temperature sensor that controls the ventilation system and turns it down when, for example, the temperature is low enough for stack forces to provide ventilation.

As with mechanical systems, natural ventilation can be noisy. Open windows and doors transmit noise from outside to inside. Buildings designed to use natural ventilation or cooling often have large areas of exposed masonry or stone to temper outdoor air (see discussion above), and such large areas of hard surface can cause noise problems.

Dwellings near ground-level pollution might need natural ventilation openings above floor level. Safe and easy access to these openings and their control devices is required.

Strategy 8.3 Enable Residents to Maintain Comfort

Introduction

Some basic information on thermal conditions and how to maintain them is as follows:

- Thermal conditions affect chemical and biological contaminant levels and the intensity of occupants' reactions to these contaminants. However, our knowledge of these effects and their mechanisms is very limited.

- Despite this limited knowledge, achieving a high thermal comfort level is likely to reduce contaminant levels and enhance occupant perceptions of IAQ.

- People's perceptions of IAQ are closely correlated to thermal comfort.

Figure 8.3-A Factors Affecting Thermal Comfort

ASHRAE Standard 55 (ASHRAE 2017b) addresses thermal comfort, yet there is no single right answer for temperature and humidity. The appropriate approach depends on two personal factors (metabolic activity and clothing insulation) and two environmental factors in addition to temperature and humidity—radiation (e.g., from a radiant heater or cold window) and air speed (e.g., from fans and drafts; Figure 8.3-A).

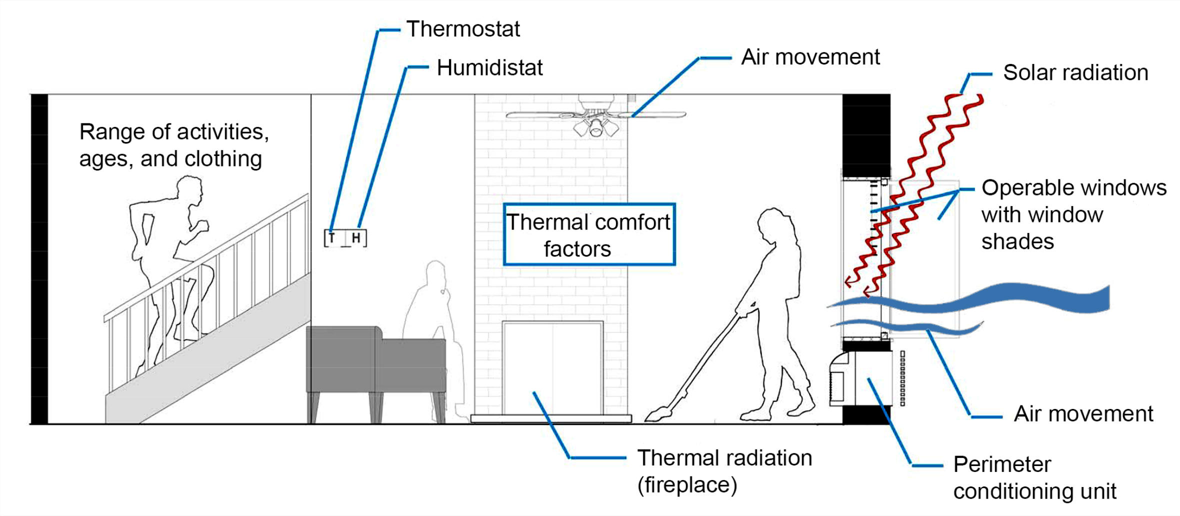


Figure 8.3-A Factors Affecting Thermal Comfort.

Thermal comfort scientists have used data from a broad section of the population to develop a method for predicting comfort. However, because of differences among people, the goal—less than 20% of occupants expressing discomfort—is very low (ASHRAE 2017b). As a result, even if people are dressed identically and doing the same activity, no single condition will satisfy everyone. Such diversity in required conditions is the scientific basis for what we already know, that family members often have different opinions about the optimal thermostat setting.

Occupant Adaptation

Dwellings typically have operable windows, doors, and shading devices that can be used for natural conditioning to supplement, replace, or defer the use of mechanical cooling, known as ventilative cooling (Strategy 8.2). Natural conditioning saves energy.

For example, opening shades on the sunny side of the dwelling can help warm it up on cold mornings. Opening windows when outside conditions are favorable and closing them when they are not can help heat and cool the dwelling. Cross-ventilation can be very effective, even when windows are next to and not across from each other. Even if outside air is not much cooler than inside air, the breeze has a cooling effect.

Furthermore, people's expectations change; they can tolerate hotter conditions indoors when the weather is hot and cooler conditions indoors when the outside temperature is lower. In addition, their perception of air quality is more favorable when they have some control over their environment and can see, feel, and hear the outdoors.

Thermostat Settings

People often have different thermal comfort needs, and they can adjust clothing to fit these needs. The worst thing to do is to change the temperature on the thermostat drastically from hot to cold because this can reduce both the efficiency and effectiveness of the comfort system.

The summer range might seem high, but it is intended for people who are seated, relaxed, and wearing summer clothing. The conditions depend heavily on activity level. For example, the "walking about" activity level is associated with a higher metabolic rate, and keeping all the other parameters (clothing, air speed, humidity, and radiant heat) the same would require an ambient temperature of 66–74°F (19-23°C (average 70°F or 21°C)).

The winter temperature and humidity might also seem high for similar reasons. A relaxed person who is sitting in a room with a temperature lower than 72°F might eventually reach for a blanket, a hot drink, or something else to warm up.

Online Tool

Occupants can check their own thermal conditions using an online tool (Hoyt et al. 2017) to enter their own level of activity and clothing and find out whether it matches their expectations. Many buildings are cooled to well below the optimal comfort range for people wearing seasonal clothing, causing people to wear sweaters in the summer!

To use degrees Fahrenheit, be sure to use the SI IP button near the bottom of the screen. To make the tool simpler to use, avoid considering radiant sources (e.g., a fireplace or cold window) by clicking on the "Use operative temperature" button near the top, which eliminates the information on "Mean radiant temperature" from the screen. Try selecting metabolic rate and clothing level first, and then choose different temperatures first and then humidity levels.

Examples of Online Tool Results for Indoor Comfort Conditions

For sample thermostat settings, see the two sample conditions shown in Figures 8.3-B and 8.3-C, which are for people who are seated, relaxed, and wearing typical clothing in still air without thermal radiation in summer and winter. In summer, the range is about 76-81°F (24-27°C) (average 78°F or 26°C) with 65% RH (Figure 8.3-B); in winter, the range is about 72-78°F (22-26°C (average 75°F or 24°C) with 30% RH (Figure 8.3-C).

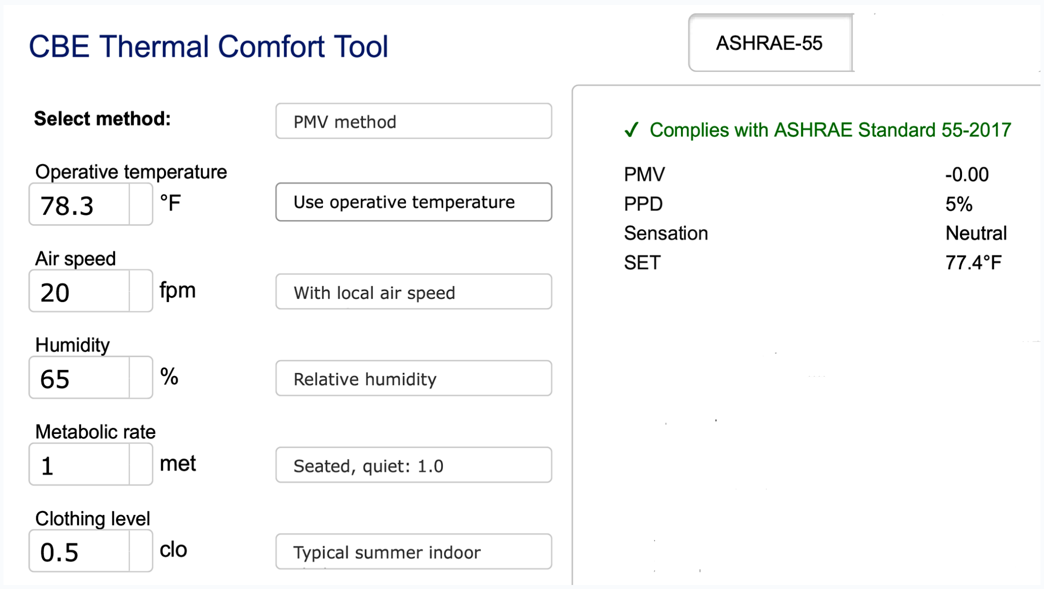


Figure 8.3-B Example of Online Tool Results for Indoor Summer Comfort Conditions
Courtesy of Hoyt (2017).

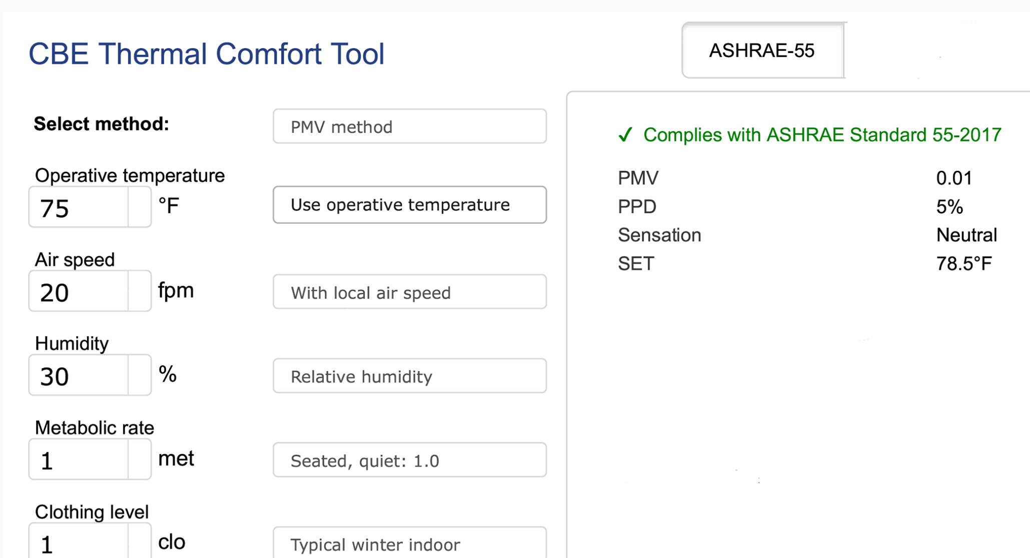


Figure 8.3-C Example of Online Tool Results for Indoor Winter Comfort Conditions
Courtesy of Hoyt (2017).

Of course, whether thermal comfort has been reached is up to occupant. However, designers and builders must meet energy codes and pick reasonable conditions for typical people.

Radiant Heat

The temperatures that occupants want also change with radiant heat exchange. People can tolerate a lower indoor temperature if radiant heat is available, such as from a hot stove, well-vented fireplace (see Strategy 6.1), quartz heater, or warm body nearby. Similarly, thermal comfort is greater in summer when shade is available from trees or fixed overhangs outside or from shades inside. Shades can also prevent the radiation of body heat through windows when the outside temperature is cold, especially at night.

Air Movement

Occupants' perceptions of temperature also change with air movement. Higher temperatures and humidity levels inside are more tolerable when a fan or open window provides a pleasant breeze that cools people off. This breeze can become a draft in cold conditions, however, resulting in the desire for warmer conditions in winter.

Drafts can occur under windows and in other locations where heat loss is concentrated. Some rooms have overhead forced-air heating. If the air comes from too high up or is too warm, it will stay close to the ceiling and be less effective reaching down to where the people are.

Grilles and registers need to have enough air speed to mix indoor and outdoor air sufficiently to prevent hot and cold spots, but the air speed should not be so high as to cause drafts. Ceiling fans can be used to increase beneficial airflow. Conditions that can lead to noise complaints include poorly implemented zone control forcing too much air through a small zone, or locating the forced air fan and return grill right next to an occupied space with a short duct run.

Energy Codes and System Design

Energy codes typically require HVAC systems to be sized so as not to overcondition the space and thus use excess energy. The commonly used International Energy Conservation Code (ICC 2015a), calls for "the interior design temperatures used for heating and cooling load calculations" to be no more than 72°F (22°C) for heating and at least 75°F (24°C) for cooling.

Some designers choose a design with an even higher indoor temperature for air conditioning in summer, such as 78°F (26°C), to conserve energy. Others select a condition, such as 72°F (22°C), to maximize the number of satisfied residents, even though this choice might not be consistent with the energy code. Selecting systems and controls that perform efficiently at partial load, such as those with variable-speed blowers, can mitigate the increased energy demands.

Figure 8.3-D Recommended Thermostat Locations

It is also important to locate the thermostat (Figure 8.3-D) where people spend time and avoid confounding it with solar radiation or other heat sources.

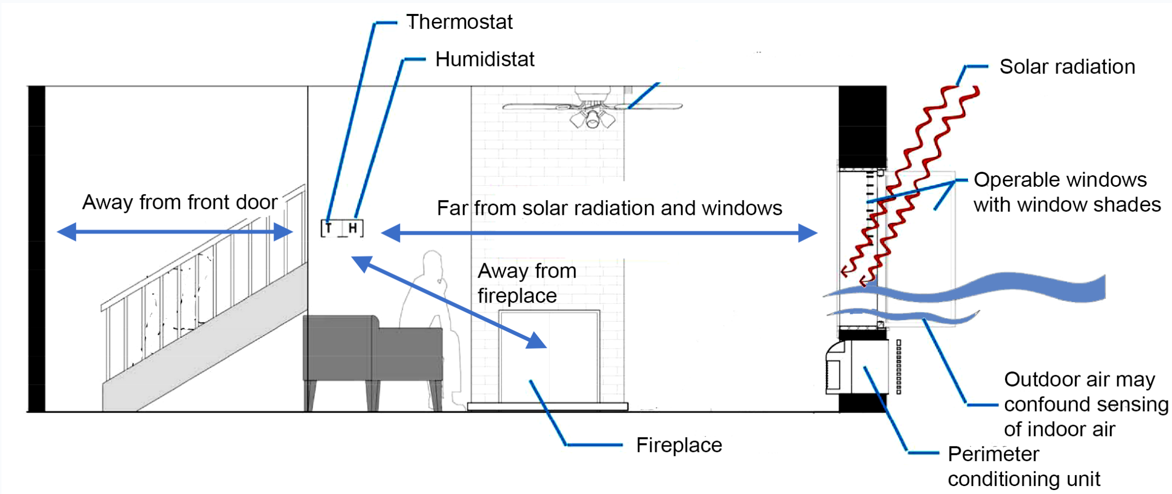


Figure 8.3-D Recommended Thermostat Locations

Individual Control and Zones

Giving each person control over his or her own environment (as can be done in many automobiles and airplanes, for example) is ideal but not easily accomplished in dwellings. Even controls in each room are prohibitively costly for most HVAC system types. A practical alternative for designers and builders is to provide carefully selected zones, each with its own thermostat. See Strategy 1.2 for details on zoning.

Humidity Control for Comfort

Limiting high humidity indoors is a comfort goal that needs to be considered in system designs. When it is humid outdoors, an air conditioning system might need additional capabilities to control humidity. Enhanced humidity control options are discussed in more detail in Strategy 2.2. Controlling moisture is also important to limit condensation and biological growth.

Limiting high humidity indoors is a comfort goal that needs to be considered in system designs. When it is humid outdoors, an air conditioning system might need additional capabilities to control humidity. Enhanced humidity control options are discussed in more detail in Strategy 2.2. Controlling moisture is also important to limit condensation and biological growth.

Low indoor humidity is common in winter when the weather is cold and can be uncomfortable for some people. However, ASHRAE standards for thermal comfort (ASHRAE 2017b) and air quality (ASHRAE 2016b) do not establish a lower limit for humidity, and using a humidifier, especially

Actionable Guidance for Maintaining Comfort

For designers and builders:

- Use separate zones in parts of the dwelling that have a large glass area or a large roof to accommodate heat gains and losses that are very different from those in other areas, such as on different floors.
- Make sure that HVAC systems have sufficient stages of heating and cooling to handle partial loads in addition to peak loads.
- In humid climates, use HVAC systems with enhanced humidity removal capability (see Strategy 2.2).

For occupants:

- Use window shades to keep out the heat (especially when the sun is shining) and the cold (especially at night).
- Open windows when the outside air is clean and mild to reap multiple benefits: thermal comfort, good IAQ, and energy conservation.
- Change thermostat settings, clothing, and activity level for each season.
- Maintain humidifiers and keep the humidistat setting low, or do not use them.
- If the HVAC air system is not zoned, increase airflow in summer upstairs and in other hot areas and in winter downstairs and in other cold areas by partially (or in limited rooms completely) closing grilles in other rooms. However, overdoing this strategy can cause the system to stop running; if this happens, open the closed grilles slightly.
- Change thermostat settings gradually (except when leaving the dwelling, returning, waking up, or retiring); see the discussion above on thermostat settings.

with the humidistat on a high setting, has some risks (Strategy 2.2). If a doctor recommends humidification for a sick child, the best approach might be to take the child into the shower room while the exhaust fan is running (see Strategy 6.2) or to humidify the sleeping room only, which can be done using a tabletop refillable humidifier. Clean drinking water should be used in the refillable humidifier, the water should be changed daily, and the manufacturer's recommendations for cleaning and maintenance should be followed.

Higher levels of particulate matter can cause a feeling of dryness, and improving particle filtration can be helpful (Strategy 7.2). Also consider using beverages, especially at the bedside, to relieve nighttime and morning dryness.

Strategy 8.4 Consider Interactions Among Factors Affecting IAQ

8.4

Introduction

People experience their indoor environments as complex mixtures of experiences and sensations. Therefore, changes in one aspect of the indoor environment can influence not only perceptions, but also sometimes even more objective measures of indoor conditions. ASHRAE Guideline 10 (ASHRAE 2016c) provides a comprehensive overview of how these environmental factors interact to affect occupants, and it forms the basis for most of the content in this section.

Experience of the indoor environment is influenced by multiple factors, including IAQ, thermal conditions, sound, and light. Therefore, many variables can potentially interact. Many aspects of these interactions are not well understood, so the focus of research has been on more common and well-known interactions.

Factors that are known to influence indoor air quality and occupants' perceptions of it include:

- Interactions among indoor air chemicals
- Thermal conditions
- Humidity
- Sound
- Light
- Stressful situations

People integrate their responses to the various factors. They typically give different weights to each factor depending on the situation or task, and one seriously deficient factor can reduce satisfaction with the others. For example, if the thermal conditions are not comfortable, occupants might perceive the IAQ as poor. Other stressors can also affect occupants' perceptions of the indoor environment. Satisfaction or dissatisfaction with the other occupants, windows or views, the aesthetic environment, or ergonomics, can influence perceived IAQ.

Three indoor air contaminants that contribute to lung cancer risk—smoking, asbestos exposure, and radon exposure—can interact with one another. For designers and building managers, this potential interaction offers a strong justification for smoking bans and removal or encapsulation of asbestos as well as for reducing indoor radon levels to the extent practical. For dwellings occupied by smokers, this interaction also justifies the maintenance of lower levels of radon. The EPA estimates that the lifetime risk of developing lung cancer is nearly nine times higher for smokers than for nonsmokers exposed to its "action level" for radon remediation of 4 pCi/L (148 Bq/m^3) (EPA 2012a).

Interactions between the thermal environment and IAQ have been studied extensively and are known to be significant (Berglund and Cain 1989, Fang et al. 1998a, Fang et al. 1998b, and Mølhave 1993). High temperature and humidity cause occupants to perceive the indoor air as stuffier, more odorous, and staler. Higher temperatures can also cause more emissions and higher concentrations of VOCs and formaldehyde. In dwellings where occupants plan to maintain warmer indoor temperatures because of occupant preference or lack of air conditioning, the use of low-emission materials and cleaning products (such as scent-free cleaners) might be particularly important.

Increased humidity levels can cause biological aerosols to survive longer. However, at low humidity levels, the upper respiratory system's defense mechanisms (which are based on moisture and mucosa) become less effective, which can cause particles to penetrate more deeply and be more irritating. Designers of dwellings in very cold climates that do not have a humidifier and are therefore likely to experience dry conditions (less than 20% indoor RH) should pay extra attention to providing high-quality filtration and perhaps even use a MERV 14 or 15 filter instead of the MERV 13 filter recommended in Strategy 7.2 of this guide.

Strategy 8.4 Consider Interactions Among Factors Affecting IAQ

Chemicals in the indoor air can interact with one another in ways that harm IAQ. For example, ozone can react with many common indoor VOCs, such as those that produce the "fresh scents" in cleaning products, to produce certain substances (e.g., formaldehyde and ultrafine particles) that are more irritating or toxic than the original VOCs (Weschler 2000). Reducing indoor ozone levels by not using ozone-producing air cleaners is discussed in Strategy 7.2, and reducing ventilation when outdoor ozone levels are high is covered in Strategy 3.1.

The acoustic environment can also affect IAQ. In dwellings, for example, where fans are loud, occupants are less likely to use them. Kitchen hoods are an unfortunate example because cooking generates many fine particles. Larger gas ranges often require large kitchen range hoods because they can generate more contaminants when multiple burners are operating. These large hoods are often loud, which makes occupants less likely to use them. It can be difficult to find kitchen hoods with a low sound rating, so the best solution is often to use a hood with a remotely mounted motor. See Strategy 6.2 for a more in-depth discussion of exhaust fan sound ratings and where to find quieter fans.

Finally, certain design decisions and system selections described in this guide affect more than one aspect of IAQ. Some of these interactions, such as keeping all ducts inside the conditioned enclosure of the dwelling, are synergistic in that they reduce the transfer of contaminants from unconditioned attics, crawlspaces, or garages while eliminating one cause of pressure imbalances that could cause gas appliances to develop a backdraft. Other choices, such as not installing or using a forced-air system, can limit options in other areas. Without an AHU, filtration and distribution of ventilation air must be accomplished using stand-alone systems.

This guide presents other options that allow dwellings without ductwork to meet these needs, but the choices are more limited and might be costlier. Keeping the "big picture" in mind when planning to maximize IAQ can pay dividends in the form of occupant satisfaction with indoor air.

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Appendix A

VENTILATION AND FILTRATION CASE STUDIES

This appendix presents ten case studies that demonstrate the use of different types of ventilation systems (Strategy 7.1) and filtration approaches (Strategy 7.2). Their main features are summarized in Table A-1, and they are described in more detail below the table. The term “warm and humid climate” in this appendix refers to climate zones 1, 2, and 3 in the “moist” region and climate zones 4 and 5 in the “marine” region of Figure 1.2-A.

Table A-1 Overview of Ventilation System Characteristics in Case Studies

Case Study	System Type	Central AHU Required	Filter Location	Use in Existing Dwellings	Use in Multifamily Dwellings	Applicable Climates
1	Supply	Yes	Central AHU return	If system and access allow	If each unit has a separate AHU	All climates, but should be used with caution in warm and humid climates
2	Exhaust	No	Room air cleaners	Easy to implement	Some concern about transfer of air between units	All climates, but should be used with caution in regions below warm and humid climates
3	Balanced	No	ERV or HRV	If access is available for ductwork	If access allows a separate ERV or HRV in each unit	All climates
4	Balanced	Yes	Central AHU return	If system and access allow	If each unit has a separate AHU	All climates
5	Balanced	No	Room air cleaners	If access allows ductwork	If access allows a separate ERV or HRV in each unit	Cold climates
6	Exhaust	No	Room air cleaners	If access allows ductwork	Some concern about transfer air between units	All climates, but should be used with caution in warm and humid climates
7	Supply	Yes	Central AHU return	If system and access allow	If each unit has a separate AHU	Humid climates
8	Balanced	Yes	Central AHU return	If system and access allow	If each unit has a separate AHU	All climates, but should be used with caution in warm and humid climates
9	Supply	Not in each unit	Room air cleaners or dwelling unit AHU return	Difficult to implement	Only applicable to multifamily dwellings	All climates, but dehumidifier needed in regions warm and humid climates
10	Exhaust	Not in each unit	Room air cleaners or dwelling unit AHU return	Difficult to implement	Only applicable to multifamily dwellings	All climates, but should be used with caution in regions below the warm/humid line in Figure 1.2-A

Table A-1 Overview of Ventilation System Characteristics in Case Studies

Case Study 1 Supply-Only Ventilation at Central AHU with Filter in Return

Description: An outside air intake duct is connected to the return side of the central air-handling unit's (AHU's) ductwork. A motorized damper is installed in the duct and connected to a controller that cycles the AHU fan on when the damper is open. The outside air and recirculated air from the dwelling mix and pass through the dwelling's primary filter at the AHU. The mixed air is then distributed to the dwelling through the supply ductwork.

Appropriate climates: This system (Figure A-1) can be used in all climates, but caution is warranted in warm and humid climates. The additional humidity introduced by this type of system might require additional design measures to prevent problems.

HVAC system: The dwelling is heated and cooled using a central AHU (e.g., air source heat pump, forced-air furnace, and/or air conditioner).

Figure A-1 Supply-Only Ventilation at Central AHU with Filter in Return

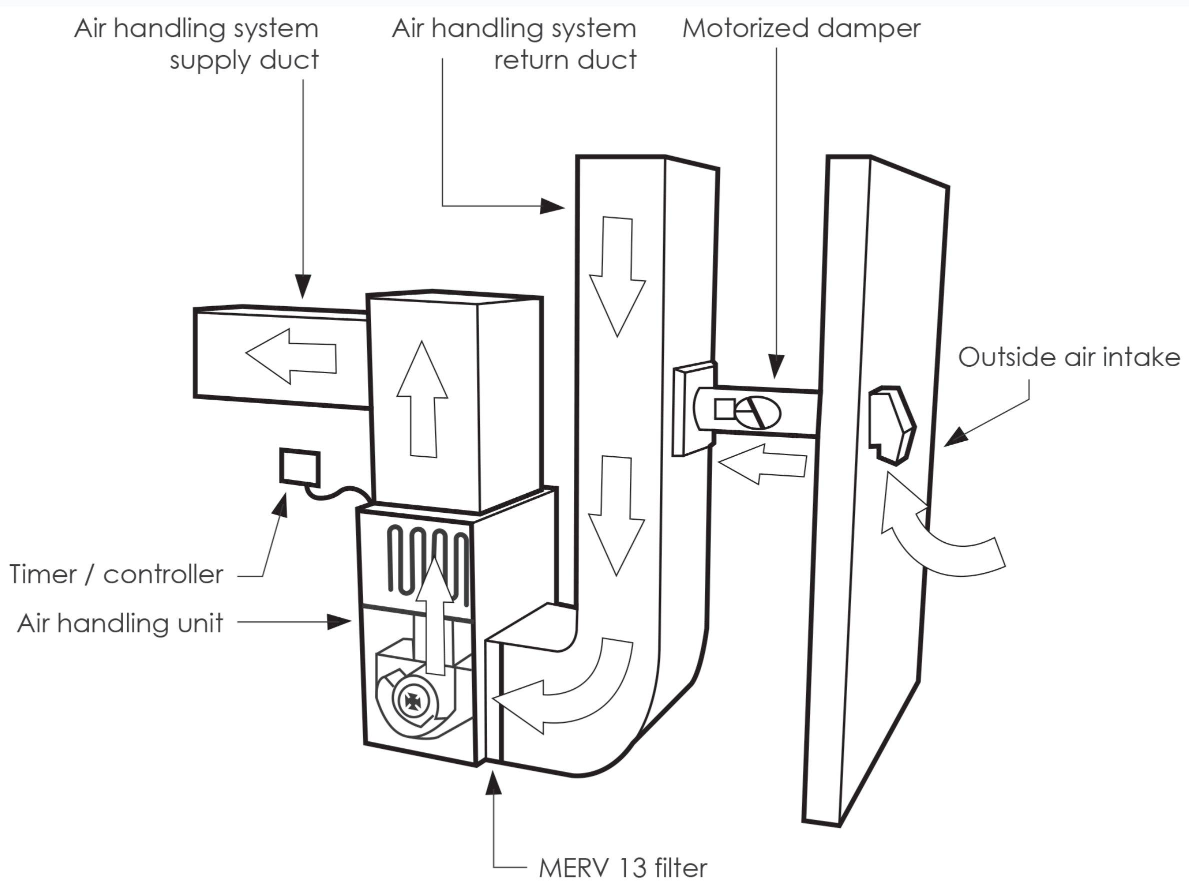


Figure A-1 Supply-Only Ventilation at Central AHU with Filter in Return

Case Study 1 Supply-Only Ventilation at Central AHU with Filter in Return

Ventilation system: An outdoor air duct is connected to the return side of the AHU. A motorized damper is installed in the duct and connected to a controller that cycles the AHU fan on when the damper is open. The ASHRAE Standard 62.2 (ASHRAE 2016b) ventilation rate for the dwelling is 50 cubic feet per minute (CFM) (23.6 l/s) if ventilation is continuous. This system is designed to provide 150 CFM (70.8 l/s) of outside air for 20 minutes each hour. With suitable controls, operation during heating and cooling can count toward the 20-minute run time.

Filter: A minimum efficiency reporting value (MERV) 13 filter is located in the heating, ventilation, and cooling (HVAC) return downstream of the outside air intake. This filter removes particles from both the ventilation air and indoor air that is recirculated through the air-handling system. The use of the timer controller also achieves a minimum turnover of air through this filter.

Why this system works: The system is simple and inexpensive to install and maintain. Only one filter needs to be changed, and the ventilation system uses the AHU fan, which is repaired if it stops working. The 20-minute per hour run time limits energy use and gives the system extra capacity for use during high-polluting events. The central AHU periodically turns over and mixes the indoor air, which can lower occupant exposure to contaminants generated in heavily occupied rooms and passes indoor air through the filter regularly.

Existing dwellings: This system is easily retrofitted into existing dwellings that have a central AHU and access to run a duct from a clean outdoor location to the return duct.

Multifamily: This system can be used in multifamily buildings if each dwelling unit has its own AHU (see Figure A-2).

What can go wrong with this type of system?

- In humid climates, this system can introduce too much moisture into the dwelling. Although the cooling coil in the AHU provides some dehumidification, this dehumidification might not be enough. If the controller causes humid air to be introduced when cooling is not needed, occupants might notice humid air or undesired condensation could occur.

- The outside air delivered should be measured (see Strategy 1.4) to see that the target airflow, in this case 150 CFM (70.8 l/s), is provided when the system is on. If the duct is not large enough or the fan operates at a lower speed when heating and cooling is not occurring, the dwelling can be underventilated. If the run time is increased to compensate for this, the overall energy that the system uses also increases.

- The system can use more energy than other systems. In more severe climates, the lack of heat recovery increases the heating and/or cooling energy needed to condition the incoming air. In addition, the AHU fan uses more energy than fans in most balanced and exhaust systems. This increased energy usage is mitigated somewhat by the 20-minute run time.

- The proper setting for the system is not always intuitive or obvious to occupants. Clear instructions should be provided.

Figure A-2 Supply-Only Ventilation at AHUs Serving Individual Units

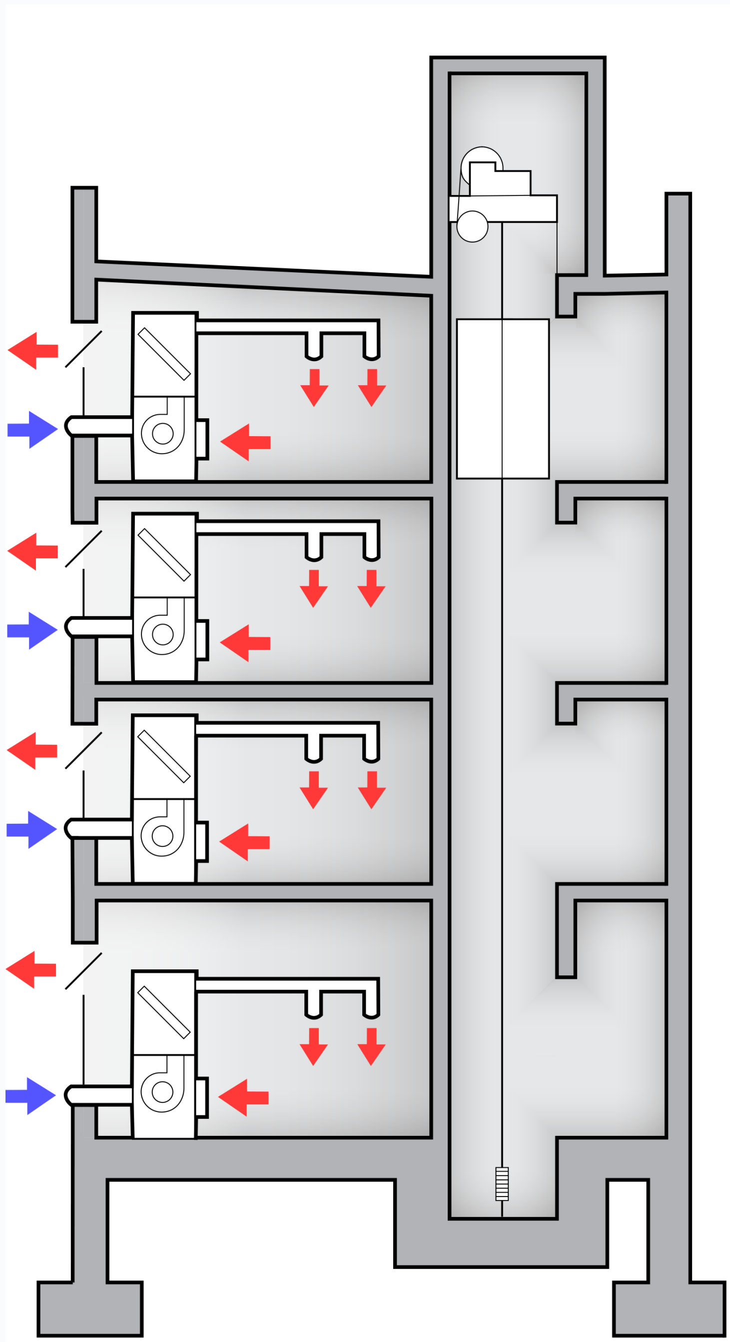


Figure A-2 Supply-Only Ventilation at AHUs Serving Individual Units in a Multifamily Building

Case Study 2 Exhaust-Only Ventilation in the Bathroom, No Central AHU, and Room Air Cleaner Use

Description: A continuously operating fan is placed in one or more bathrooms to provide ventilation. Electronic room air cleaners are used in each bedroom to provide filtration.

Appropriate climates: This system (Figure A-3) can be used in all climates, but caution is needed in warm and humid climates. The additional humidity introduced by this type of system might require additional design measures to prevent problems

HVAC system: The dwelling does not need to have a central AHU (the air might be conditioned, for example, using radiant floor heat or ductless minisplits).

Ventilation system: A continuously running bathroom fan provides exhaust-only ventilation. The fan is in a centrally located bathroom and has a sound rating of 0.3 sones. It also has an integrated ventilation control that offers a low continuous setting to comply with the ASHRAE Standard 62.2 (ASHRAE 2016b) ventilation rate requirement, 45 CFM (21.2 l/s), for the dwelling. The fan can be boosted to its full flow rating of 80 CFM (37.8 l/s) using an occupant-controlled switch.

Figure A-3 Exhaust-Only Ventilation in the Bathroom & Room Air Cleaners

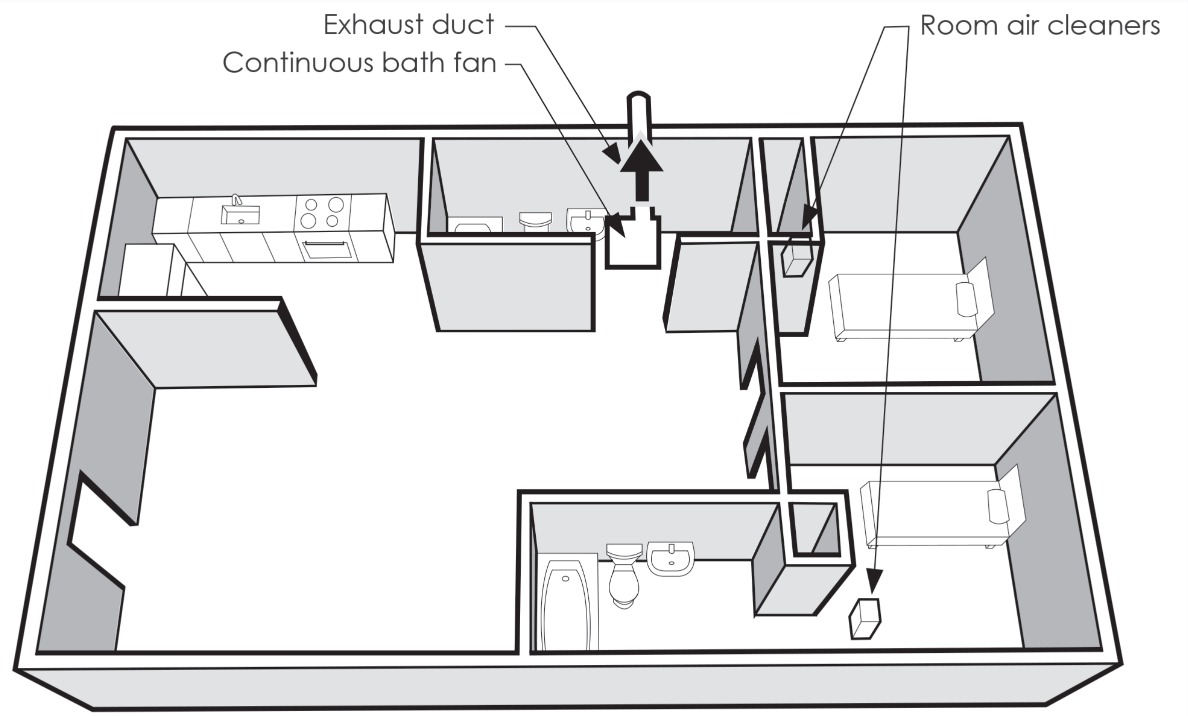


Figure A-3 Exhaust-Only Ventilation in the Bathroom, and Room Air Cleaners

APPENDIX A

Filter: Each bedroom has an electronic room air cleaner (as described in Strategy 7.2) that is rated by the American Home Appliance Manufacturers (AHAM). Each bedroom is 12 ft by 12 ft (3.7 by 3.7 m), with 9 ft (2.7 m) ceilings, so the room air cleaners have a tobacco smoke clean air delivery rate of 108 or higher. (According to Strategy 7.2, the tobacco smoke clean air delivery rate should be at least the room's volume in ft^3 divided by 12, as follows: 12 ft x 12 ft x 9 ft/12 = 108. In SI units, the minimum clean air delivery rate is calculated as the room volume in m^3 multiplied by 2.9: 3.7 m x 3.7 m x 2.7 m x 2.9 = 107).

Why this system works: The system is simple and inexpensive to install and maintain. It does not require a central AHU, although it can be used in dwellings that have central systems. The fan uses little energy, and its continuous operation removes moisture from the bathroom, where it is generated. This system can be enhanced by using multiple continuous fans in different bathrooms, which improves distribution of the exhaust air and moisture removal from multiple bathrooms.

Common system variations: This system has many variations that are functionally very similar to one another.

- For larger dwellings, continuously operating fans in more than one bathroom can be used, and their flow rates can be added together to achieve the target ventilation rate.

- If access allows, a single, remotely mounted inline fan can be used to exhaust air from multiple bathrooms simultaneously.

- A low-sone kitchen fan can be used instead of a bathroom fan.

Existing dwellings: This is one of the easiest systems to retrofit into an existing dwelling. Many existing dwellings already have a bathroom fan ducted to the outdoors that can be easily and inexpensively replaced with a quiet fan set for continuous operation. Dwellings that do not have a bathroom fan are usually easy to retrofit. Because this ventilation system is not integrated into the central AHU, it is a good choice when the central AHU is old and its fan cannot handle a high-efficiency filter or the AHU fan's energy consumption is high.

Multifamily dwellings (Figure A-4): This system is widely used in multifamily dwellings with a suitable fan in each living unit. However, some living units might receive transfer air from other units rather than air directly from outside. This transfer air can be difficult to quantify because the amount depends on the location of the unit in the building, airtightness of the building, separation between units, and weather. For this reason, supply-only and balanced ventilation systems are preferable for multifamily dwelling units.

What can go wrong with this type of system?

- In a very humid climate, this system can introduce too much moisture into the dwelling. Although air conditioning can provide some dehumidification, this dehumidification might not be enough. In this type of climate, a ventilation system with energy recovery or dehumidification might be a better choice.

- If a very quiet fan is not used or the occupants do not understand the purpose of the ventilation system, they might disable it.

- In most dwellings, the negative pressure induced by this type of system is quite small. However, in very airtight dwellings, such a system could exacerbate localized negative-pressure problems with combustion appliances, particularly those that are atmospherically vented (Strategy 6.1).

- Although most people become accustomed to the white noise associated with room air cleaners, this strategy might not be the best choice for occupants who are very sensitive to sound.

- Replacement filters are less likely to be available locally, can cost more, and might need to be ordered by mail or online.

Figure A-4 Exhaust-Only Ventilation System Serving Individual Units

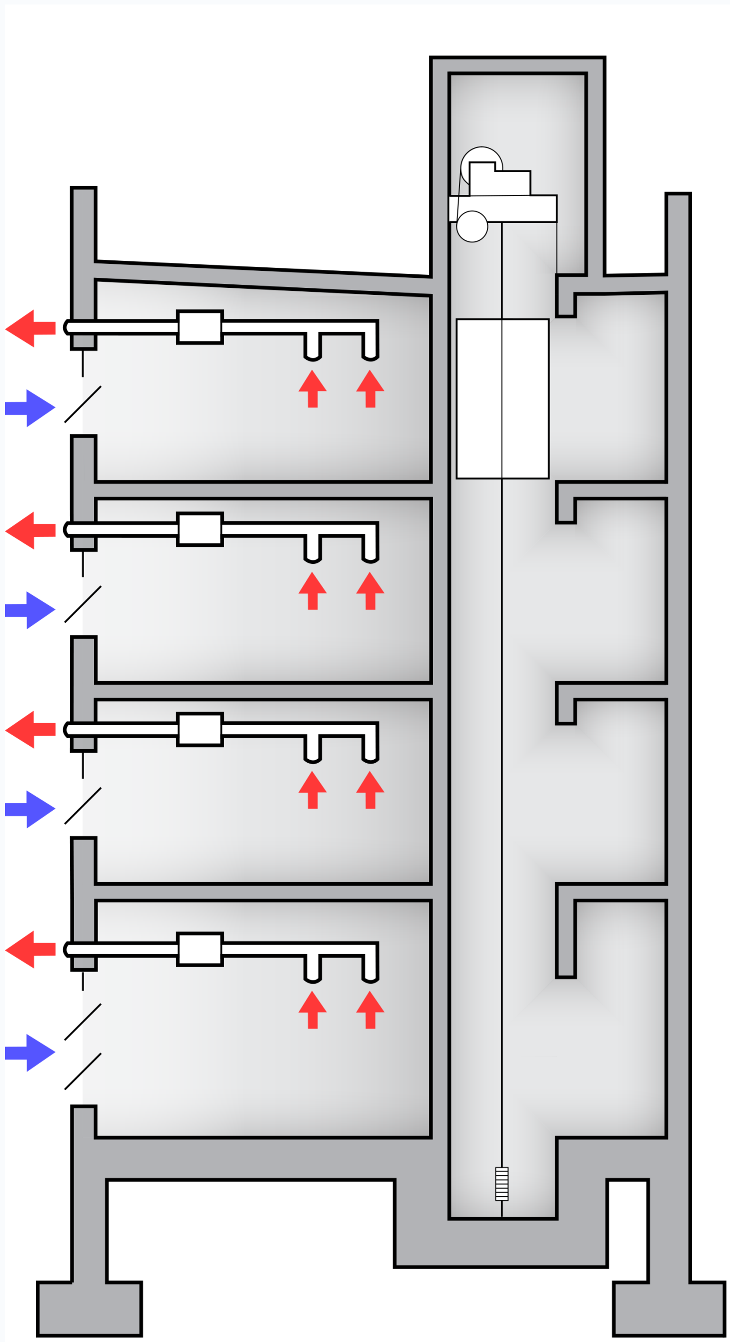


Figure A-4 Exhaust-Only Ventilation System Serving Individual Units in a Multifamily Building

Case Study 3 ERV or HRV with a High-Efficiency Filter and No Central Air-Handling System

Description: An ERV or HRV is installed and controlled to cycle between two modes of operation. The first mode removes air from a central living area and introduces filtered outdoor air to bedrooms. The second mode recirculates indoor air from the central living area, filters it, and delivers the filtered air to the bedrooms.

Appropriate climates: This system (Figure A-5) can be used in all climates. See Strategy 8.1 for a discussion of whether an ERV or HRV is most appropriate for a particular climate or application.

HVAC system: The dwelling does not need to have a central AHU (conditioning might be provided, for example, using radiant floor heat or ductless minisplits).

Figure A-5 ERV or HRV with a High-Efficiency Filter and No Central AHU

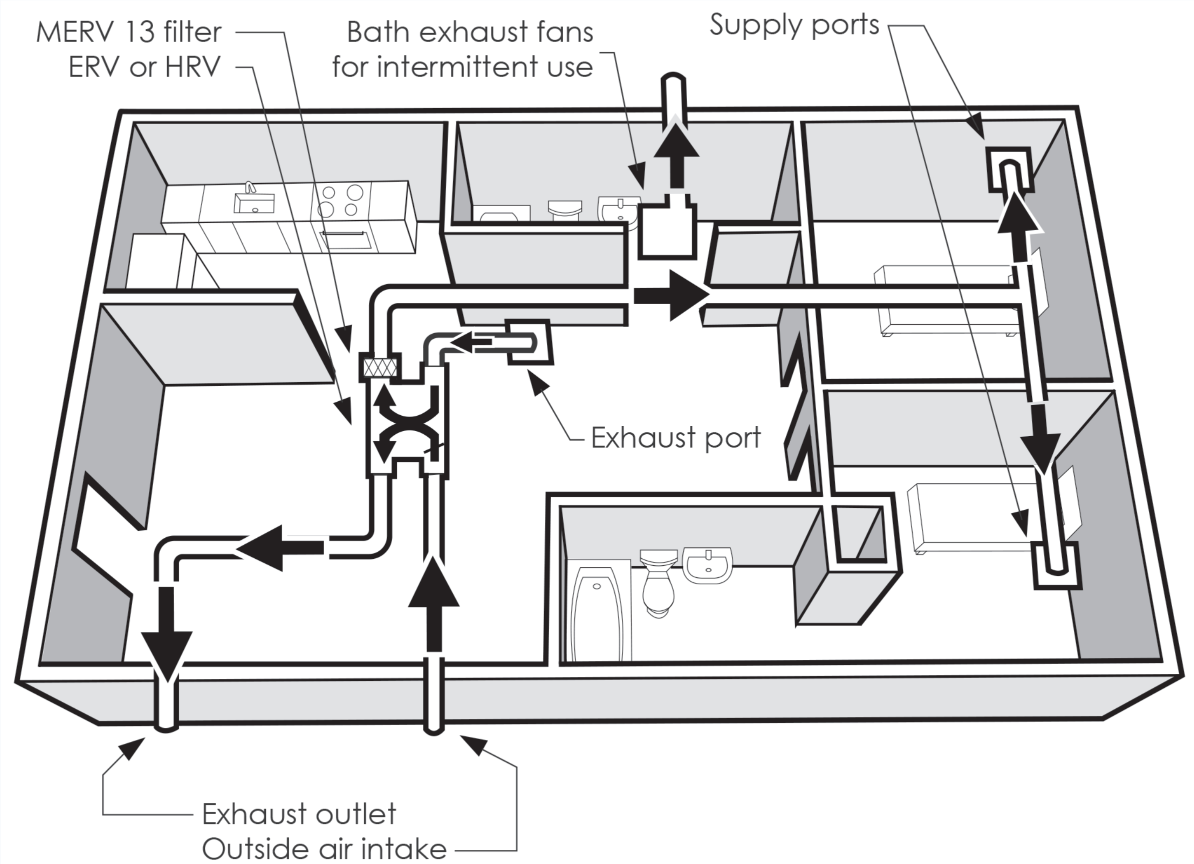


Figure A-5 ERV or HRV with a High-Efficiency Filter and No Central AHU

APPENDIX A

Case Study 3 ERV or HRV with a High-Efficiency Filter and No Central Air-Handling System

Ventilation and filtration: Ventilation is provided with an ERV or HRV that has a MERV 13 filter. This unit is sized and ducted to cycle between two modes:

1. Filter and recirculate one air change per hour (ACH) of indoor air

2. Deliver the ASHRAE Standard 62.2 (ASHRAE 2016b) outside air ventilation rate for the dwelling

Sizing and controls are key to implementing this type of system. This ERV or HRV has a controller that allows it to operate in the first mode with a user-selected recirculation airflow rate of 250 CFM (118 l/s) for 40 minutes per hour. This setting allows 10,000 ft^3 (283 m^3) per hour of indoor air to pass through the filter, filtering one air change per hour for a small dwelling of 1,250 ft^2 (116 m^2) with 8 ft (2.4 m) ceilings. For the remaining 20 minutes per hour, the ERV or HRV operates in the second mode with a user-selected outdoor air ventilation rate of 180 CFM (85.0 l/s)—three times the continuously required rate according to ASHRAE Standard 62.2 for this dwelling of 60 CFM (28.3 l/s) for 20 minutes per hour.

The system is independently ducted, supply air is delivered to the bedrooms, and return air is pulled from a central living space or one or more bathrooms. See Strategy 8.1 for more guidance on determining whether an ERV or HRV is best for a particular dwelling and a discussion about the removal of air from bathrooms using these devices.

Why this system works: This system can be installed in any dwelling and does not require a central AHU. It provides heat or energy recovery to reduce the amount of energy used by the system. By delivering fresh air to the bedrooms and gathering return air from the main living area, it ventilates the most frequently occupied rooms while promoting air mixture inside the dwelling using minimal ductwork.

Existing dwellings: This system can be retrofitted into an existing dwelling regardless of the existence, age, or condition of the central AHU. However, not all existing dwellings have easily accessible space for the system's ductwork.

Multifamily dwellings: This system can be used in individual dwelling units in multifamily buildings where space is available for the ductwork and ERV or HRV.

What can go wrong with this type of system?

- This system is more expensive to install than others, and replacement filters might be expensive or need to be ordered by mail or online. Multiple units or large units might be needed to provide capacity for one ACH of filtration in larger dwellings.

- The system's ductwork results in positive pressure in bedrooms and negative pressure in the living space when the bedroom doors are closed (Strategy 2.3). The airflows are smaller than those associated with a typical AHU, so the pressure differences are not large enough to cause problems in most dwellings. However, in dwellings with very tight interior partitions or atmospherically vented gas appliances, problems are still possible. Adding transfer grilles or jumper ducts to connect the bedrooms to the living area can prevent these problems.

- Strategy 8.1 discusses how ERVs and HRVs influence humidity in dwellings, but expecting them to function as humidity-control devices can lead to problems.

Case Study 4 ERV or HRV That Is Partially Connected to Air-Handling System Ducts and a MERV 13 Filter in AHU Return

Description: Exhaust air for an ERV or HRV is drawn from a central living space (e.g., living room or hallway; Figure A-6). Outdoor air supplied by the ERV or HRV passes through a lower-efficiency filter and is then introduced into the AHU's return. A high-efficiency filter is placed in the AHU downstream of the outdoor air intake, and the system fan is controlled to operate for at least 20 minutes per hour to filter the indoor air for human health.

Appropriate climates: This approach can be used in all climates. See Strategy 8.1 for a discussion of whether an ERV or HRV is most appropriate for a particular climate or application.

HVAC system: The dwelling is heated and cooled using a central AHU (e.g., an air source heat pump, forced-air furnace, and/or air conditioner).

Ventilation system: An ERV or HRV exhausts air from a central living space and supplies outdoor air into the AHU's return. The exhaust and outdoor airflow rates, 75 CFM (35.4 l/s), are calculated

Figure A-6 ERV or HRV Partially Connected, and MERV 13 Filter

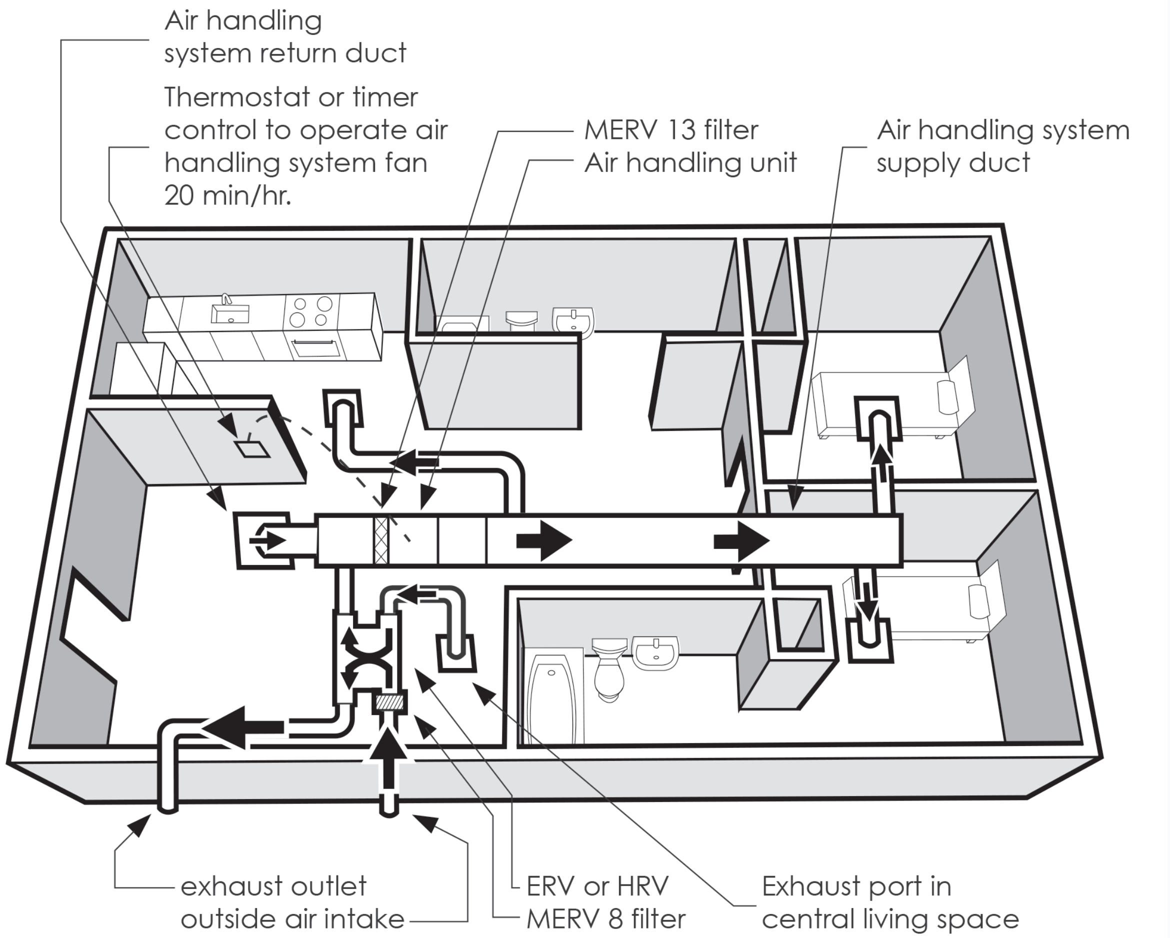


Figure A-6 ERV or HRV Partially Connected to Air-Handling System Ducts and MERV 13 Filter in the Air-Handling System Return

for this dwelling using ASHRAE Standard 62.2 (ASHRAE 2016b). The ERV or HRV can run continuously and does not need to be synchronized with AHU runtime. However, this guide recommends operating the AHU for at least 20 minutes per hour to filter the indoor air.

Filters: A MERV 13 filter (to protect human health) in the HVAC return is installed downstream of the outside air intake. A controller is used to operate the AHU for at least 20 minutes per hour to filter the indoor air using the MERV 13 filter. The outdoor air intake of the ERV or HRV has a MERV 8 filter to keep the equipment clean.

Why this system works: This system is easily integrated into a central AHU and does not require much additional ductwork. The outdoor air from the ERV or HRV mixes with supply air and can be distributed throughout the dwelling when the AHU is operating. When the AHU is not operating, the outdoor air leaks back through the returns, which distribute it to rooms that have a return.

Because the operation of the ERV or HRV does not need to be synchronized with the AHU, a smaller ERV or HRV that runs continuously at 75 CFM (35.4 l/s) can be used. AHU fans can use substantial amounts of energy, so not running the AHU fan continuously saves energy.

Existing dwellings: This system can be retrofitted into an existing dwelling if a service technician determines that the AHU fan can accommodate a MERV 13 filter. The dwelling also needs space and access to install the ERV or HRV and associated ductwork.

Multifamily dwellings: This system can be used in individual dwelling units in multifamily buildings where space is available for the ductwork and ERV or HRV.

What can go wrong with this type of system?

- In areas with high outdoor particulate pollution, the lack of interlock between the ERV or HRV and the AHU fan can allow too much outdoor particulate matter to enter the dwelling in the ventilation air. A strategy like that used in Case Study 3 (in which all of the ventilation air passes through a MERV 13 filter) is preferable for locations with high outdoor pollution levels.
- In very extreme climates or when the ventilation flow rate is high, air leaking back through the returns when the AHU is not operating could cause discomfort.
- The MERV 8 filter on the ERV or HRV intake (needed to keep system components clean) is a second filter that the resident needs to change. If this filter is not changed, the outside air intake becomes clogged and the system only exhausts air from the dwelling.
- Strategy 8.1 addresses how ERVs and HRVs influence humidity in dwellings, but expecting them to function as humidity-control devices can lead to problems.
- Because the MERV 13 filter is in the AHU, the dwelling might not achieve adequate particle filtration if the system is not operated for a minimum runtime regardless of the need for heating and cooling.

ERV or HRV That Is Partially Connected to Air-Handling System Ducts and a MERV 13 Filter in AHU Return

- Introduction of outdoor air can cause condensation in the duct system under certain circumstances, such as when the outside air is humid and is allowed to migrate into the supply side of an AHU that is cool because it recently finished a cooling cycle. The recommended design prevents this condensation by introducing the outdoor air into the return side of the AHU and using a high-efficiency (MERV 13) filter downstream of the ERV or HRV. The resistance to airflow from this filter causes the outside air to remain in the warmer return duct (Strategy 4.2).

- The central return and the ERV or HRV exhaust should be located far enough away from one another to prevent short-circuiting.

Case Study 5 HRV Ducted for Cold Climates and Room Air Cleaners

Description: An HRV pulls exhaust air from either a central location in the dwelling (living room or hallway) or from one or more bathrooms (Figure A-7). Outdoor air supplied by the HRV is introduced into closets. The system operates continuously, and filtration is provided by room air cleaners in bedrooms.

Appropriate climates: This strategy is appropriate for cold climates that do not require air conditioning or have humid summers.

HVAC system: The dwelling does not need to have a central AHU (the air might be conditioned, for example, using radiant floor heat or ductless minisplits).

Figure A-7 HRV Ducted for Cold Climates

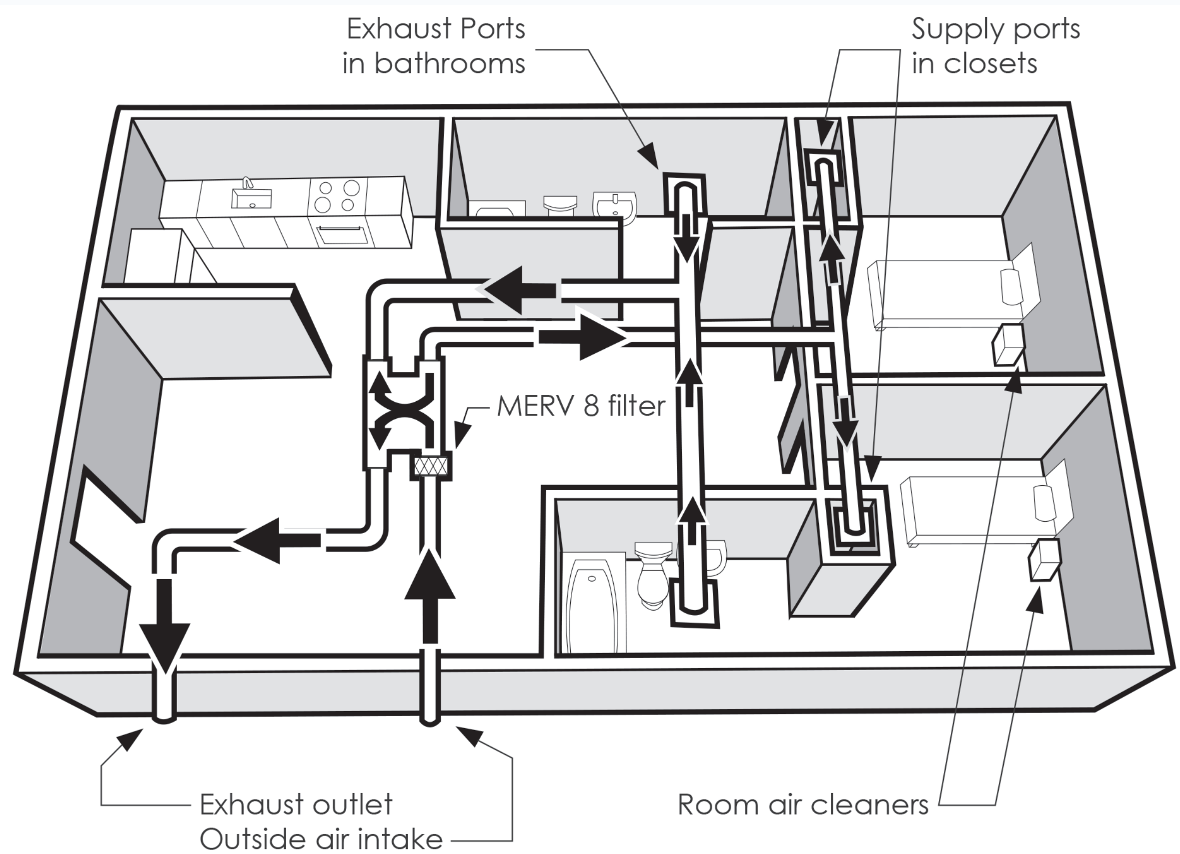


Figure A-7 HRV Ducted for Cold Climates

Ventilation system: The HRV pulls exhaust air from either a central location in the dwelling (living room or hallway) or from one or more bathrooms (Figure 1.7). Outdoor air supplied by the HRV is introduced into closets. The system operates continuously at the ASHRAE Standard 62.2 ventilation rate (ASHRAE 2016b), which is 80 CFM (37.8 l/s) for this dwelling.

Filter: Each bedroom has a room air cleaner (per Strategy 7.2) that is rated by the Association of Dwelling Appliance Manufacturers. Each bedroom is 12 ft by 12 ft, with 9 ft ceilings (3.7 m by 3.7 m with 2.7 m ceilings), so the room air cleaners have a tobacco smoke clean air delivery rate of 108 or higher. (According to Strategy 7.2, the tobacco smoke clean air delivery rate should be at least the room's volume in ft^3 divided by 12, as follows: 12 ft x 12 ft x 9 ft/12 = 108. In SI units, the room's volume in m^3 is multiplied by 2.9 to obtain the clean air delivery rate: 3.7 m x 3.7 m x 2.7 m x 2.9 = 107).

Why this system works: This system can be implemented using a wide variety of commercially available HRVs. Because it operates continuously, the required flow rate is low and less likely to be noticed by the occupants. The strategy can be used to remove air from one or more bathrooms, eliminating the need to install bathroom exhaust fans in those rooms (Strategy 8.1). Introduction of outdoor air into the closets provides airflow to those spaces, eliminating the buildup of contaminants in that location and ventilating the bedrooms.

Existing dwellings: This system can be retrofitted into existing dwellings that have space and access to install the HRV and associated ductwork.

Multifamily dwellings: This system can be used in individual dwelling units in multifamily buildings that have space for the ductwork and HRV.

What can go wrong with this type of system?

- In very extreme climates and those with high ventilation flow rates, cold air delivered to the closets could create discomfort.

- The MERV 8 filter on the ERV or HRV intake, which is needed to keep the system components clean, is an additional filter that occupants need to change. If the filter is not changed, the outside air intake will become clogged and the system will only exhaust air from the dwelling.

- When the outdoor air is humid, an HRV delivers humid air to the dwelling. Delivering humid air into closets is inappropriate in climates with humid summers because it could lead to moisture problems.

- If the system is intended to extract exhaust air from bathrooms and replace bathroom fans, at least 20 CFM (9.4 l/s) of air must be continuously removed from each bathroom (Strategy 6.2). Appropriate operation and maintenance of the system is especially critical in this situation because if the HRV stops functioning, both ventilation air and bathroom exhaust will become compromised.

- Although 20 CFM (9.4 l/s) of continuous exhaust air from bathrooms complies with ASHRAE Standard 62.2 (Strategy 6.2), this airflow might not be enough to quickly remove steam when the shower is used. The system could be enhanced by expanding capacity to temporarily “boost” airflow and increase the amount of exhaust when the resident turns on a switch in the bathroom.

- Although most people become accustomed to the white noise associated with room air cleaners, this strategy might not be the best choice for occupants who are very sensitive to sound.

- Replacement filters are less likely to be available locally, can cost more, and might need to be ordered by mail or online.

Case Study 6 Exhaust-Only Ventilation with Exhaust Ports in Closets and Room Air Cleaners

Description: This system (Figure A-8) is similar to that described in Case Study 2, except that it uses an exhaust fan located outside the living space. This single fan exhausts air from multiple exhaust ports in closets throughout the dwelling. Room air cleaners are used for filtration in the bedrooms. In this example, the bathrooms have separate exhaust fans that are only used for bathroom exhaust and not for whole-house ventilation (per Strategy 6.2).

Appropriate climates: This approach is suitable for all climates, but it should be used with caution in warm and humid climates. The additional humidity introduced by this type of system might require design measures to prevent problems.

HVAC system: This strategy can be implemented in a dwelling with no central AHU or independently from the central AHU.

Figure A-8 Exhaust-Only Ventilation with Exhaust Ports in Closets

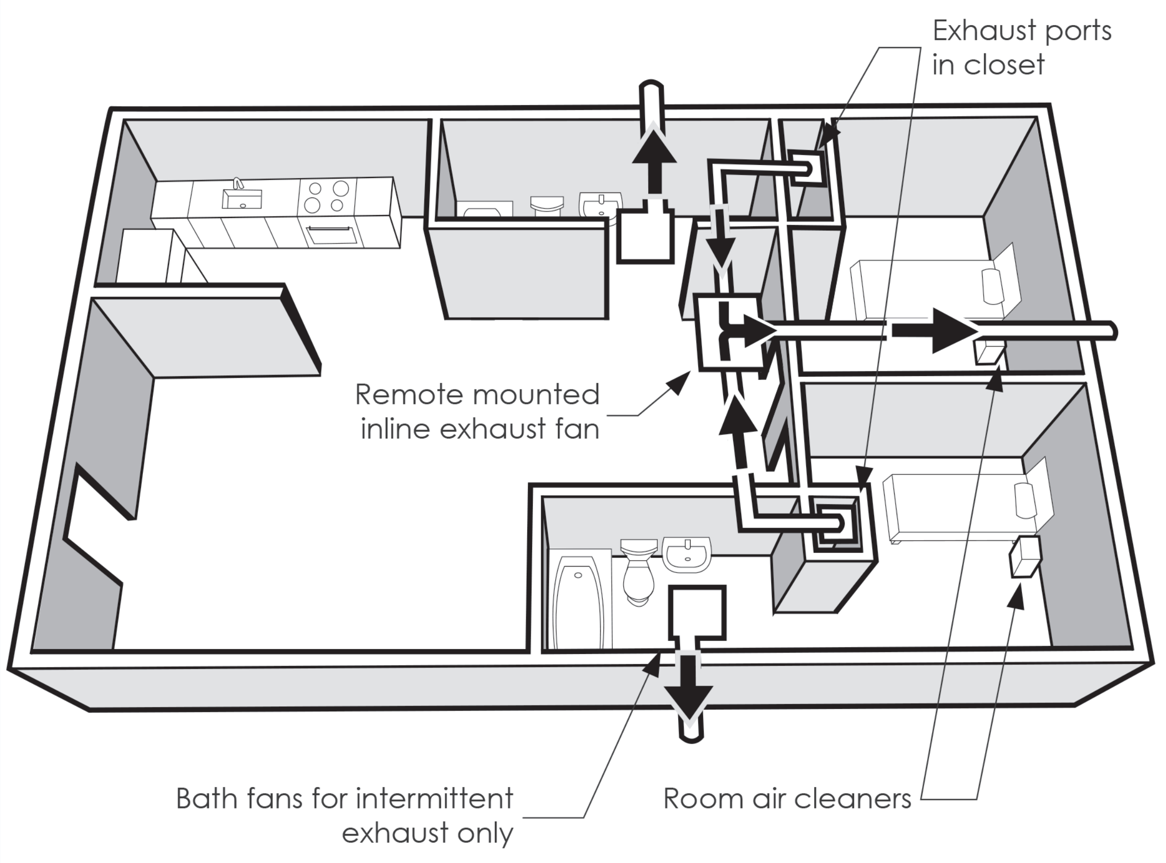


Figure A-8 Exhaust-Only Ventilation with Exhaust Ports in Closets

Case Study 6 Exhaust-Only Ventilation with Exhaust Ports in Closets and Room Air Cleaners

Ventilation system: A single remotely mounted exhaust fan (for example, in the attic) exhausts air from multiple exhaust ports in closets throughout the dwelling. The system operates continuously and has a ventilation rate, 60 CFM (28.3 l/s), that meets the requirements of ASHRAE Standard 62.2 (ASHRAE 2016b) for this dwelling.

Filter: Each bedroom has a room air cleaner (per Strategy 7.2) that is rated by the Association of Dwelling Appliance Manufacturers. Each bedroom is 12 ft by 12 ft, with 9 ft ceilings (3.7 m by 3.7 m with 2.7 m ceilings), so the room air cleaners have a tobacco smoke clean air delivery rate of 108 or higher. (According to Strategy 7.2, the tobacco smoke clean air delivery rate should be at least the room's volume in ft^3 divided by 12, as follows: 12 ft x 12 ft x 9 ft/12 = 108. In SI units, the room's volume in m^3 is multiplied by 2.9 to obtain the clean air delivery rate: 3.7 m x 3.7 m x 2.7 m x 2.9 = 107).

Why this system works: The system is simple and inexpensive to install and maintain. It does not require a central AHU, although it can be used in dwellings that have them. The fan uses little energy. By exhausting air from closets, this system keeps these spaces at slightly negative pressure, providing airflow through them and preventing contaminants from migrating outward into the dwelling. In climates that require air conditioning, this strategy pulls conditioned indoor air through the closet, reducing the likelihood of moisture problems in the closet (although the overall effect of the system is to add humidity to the dwelling).

Locating the fan outside the living space makes it less likely that residents will object to the system's sounds.

Existing dwellings: This system can be retrofitted into existing dwellings that have space and access for the fan and associated ductwork.

Multifamily dwellings: This system can be used in individual dwelling units in multifamily buildings if space is available for the ductwork and fan. However, some dwelling units might receive a substantial amount of transfer air from other units instead of air directly from outside. The amount of transfer air received by these units can be difficult to quantify because it depends on each unit's location in the building, the building's airtightness and separation between units, and the weather. For this reason, supply-only and balanced ventilation systems are preferable for multifamily living units.

What can go wrong with this type of system?

- Using this system in very humid climates can introduce too much moisture into the dwelling. Although air conditioning can provide some dehumidification, this might not be enough. In these climates, a ventilation system with energy recovery or dehumidification might be a better choice.

- If the resident does not understand the purpose of the ventilation system, he or she might disable it.

- In most dwellings, this type of system results in only slightly negative pressure. However, in very airtight dwellings, such a system could exacerbate localized negative-pressure problems with combustion appliances, particularly those that are atmospherically vented (Strategy 6.1).

- Long ducts with many bends or kinks can substantially reduce the flow rate of these fans. If ducts are connected to multiple closets that are far away from one another, it is important to design and commission the system (using methods described in Strategy 1.4) to achieve the necessary flow rate. If the ducts are long, an oversized fan with multiple airflow settings (or one that can be turned on and off using a timer) can provide more flexibility when the fan is commissioned.

- Although most people become accustomed to the white noise associated with room air cleaners, this strategy might not be the best choice for occupants who are very sensitive to sound.

- Replacement filters are less likely to be available locally, can cost more, and might need to be ordered by mail or online.

Case Study 7 Dehumidifier-Ventilator and MERV 13 Filter Integrated with Air-Handling Unit

Description: A dehumidifier ventilator is designed and installed to provide outdoor air for ventilation and dehumidify recirculated indoor air (Figure A-9). The ventilator intake pulls some recirculation air from closets and/or below-grade spaces and simultaneously introduces outdoor air, which passes through a low-efficiency filter. The dehumidified air is introduced into the AHU return. A high-efficiency filter is downstream of the ventilator in the AHU's return to filter air and protect human health.

Appropriate climates: This system is appropriate in climates with humid summers, especially those in warm and humid climates.

HVAC system: This system requires a central AHU.

Figure A-9 Dehumidifier-Ventilator Integrated into AHU

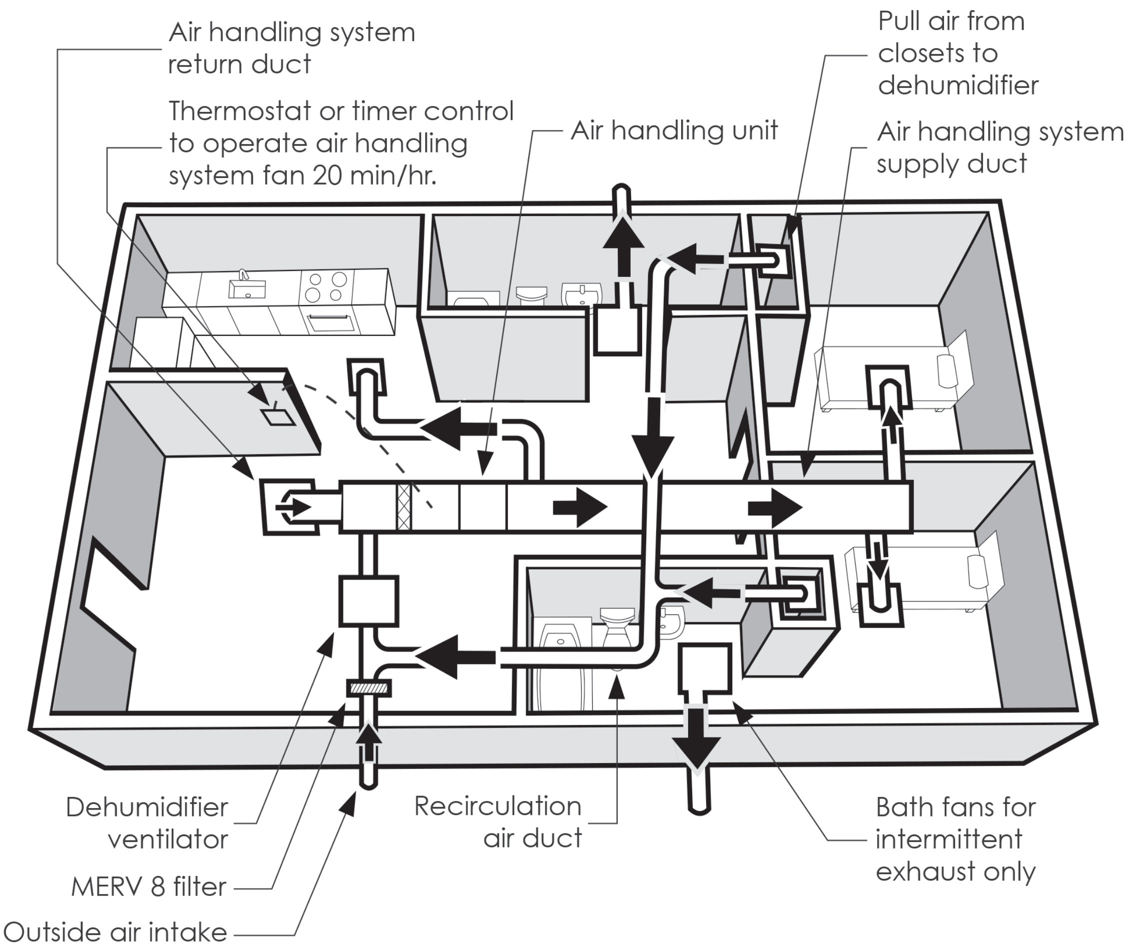


Figure A-9 Dehumidifier-Ventilator Integrated into AHU

Case Study 7 Dehumidifier-Ventilator and MERV 13 Filter Integrated with Air-Handling Unit

Ventilation System: A dehumidifier ventilator is designed and installed for continuous operation (Figure A-9). The ventilator intake simultaneously pulls some recirculation air from closets and/or below-grade spaces and 65 CFM (30.7 l/s) of outdoor air for ventilation (calculated in accordance with ASHRAE Standard 62.2 for this dwelling; ASHRAE 2016b). The mixed recirculated and outdoor air is dehumidified and then introduced into the AHU return. The AHU fan does not necessarily need to be interlocked with the ventilator.

Filter: The HVAC return has a MERV 13 filter downstream of the ventilator to filter air and protect human health. The AHU fan is set to turn on at least 20 minutes per hour to provide filtration regardless of whether heating or cooling is needed. The outdoor air intake for the dehumidifier-ventilator has a MERV 8 filter to provide filtration and protect the equipment.

Why this system works: This system dehumidifies the outdoor ventilation air and provides supplemental dehumidification of indoor air. The recirculated air can be pulled from any part of the dwelling where the air is likely to be particularly humid (e.g., below-grade spaces, closets, or central living areas). A dehumidifier ventilator is the best option for controlling indoor humidity in dwellings that need more dehumidification than the air-conditioning system can provide.

Existing dwellings: This system can be retrofitted into existing dwellings that have enough space and access for the dehumidifier and associated ductwork.

Multifamily dwellings: This system can be used in individual dwelling units in multifamily buildings that have space for the dehumidifier and ductwork.

What can go wrong with this type of system?

- Dehumidifiers used for this purpose should have an ENERGY STAR rating to avoid excessive energy use.

- Occupants need to be able to reach and maintain the MERV 8 filter on the ventilator to achieve proper airflow.

- In areas with high outdoor particulate pollution, the lack of interlock between the dehumidifier ventilator and the AHU fan can allow too much outdoor particulate matter to enter the dwelling in the ventilation air. This problem can be solved by placing a higher-efficiency filter (such as a MERV 13 filter) on the outdoor air intake of the ventilator or interlocking the operation of the ventilator with the AHU fan.

Case Study 8 Combined Supply and Exhaust System Without Energy Recovery

Description: This system combines a supply-only ventilation system (as in Case Study 1) with an exhaust-only ventilation system (as in Case Study 2). In this example, two exhaust fans operate simultaneously with a supply-only ventilation system to provide balanced ventilation without heat recovery (Figure A-10).

Appropriate climates: This system is appropriate for all climates, but it should be used with caution in warm and humid climates. The additional humidity that this type of system introduces might require additional design measures to prevent problems.

HVAC system: This system requires a central AHU.

Ventilation system: This system combines a supply-only ventilation system (as in Case Study 1) with an exhaust-only ventilation system (as in Case Study 2) that operate simultaneously to provide balanced ventilation without heat recovery. ASHRAE Standard 62.2 (ASHRAE 2016b)

Figure A-10 Supply & Exhaust Ventilation System Without Energy Recovery

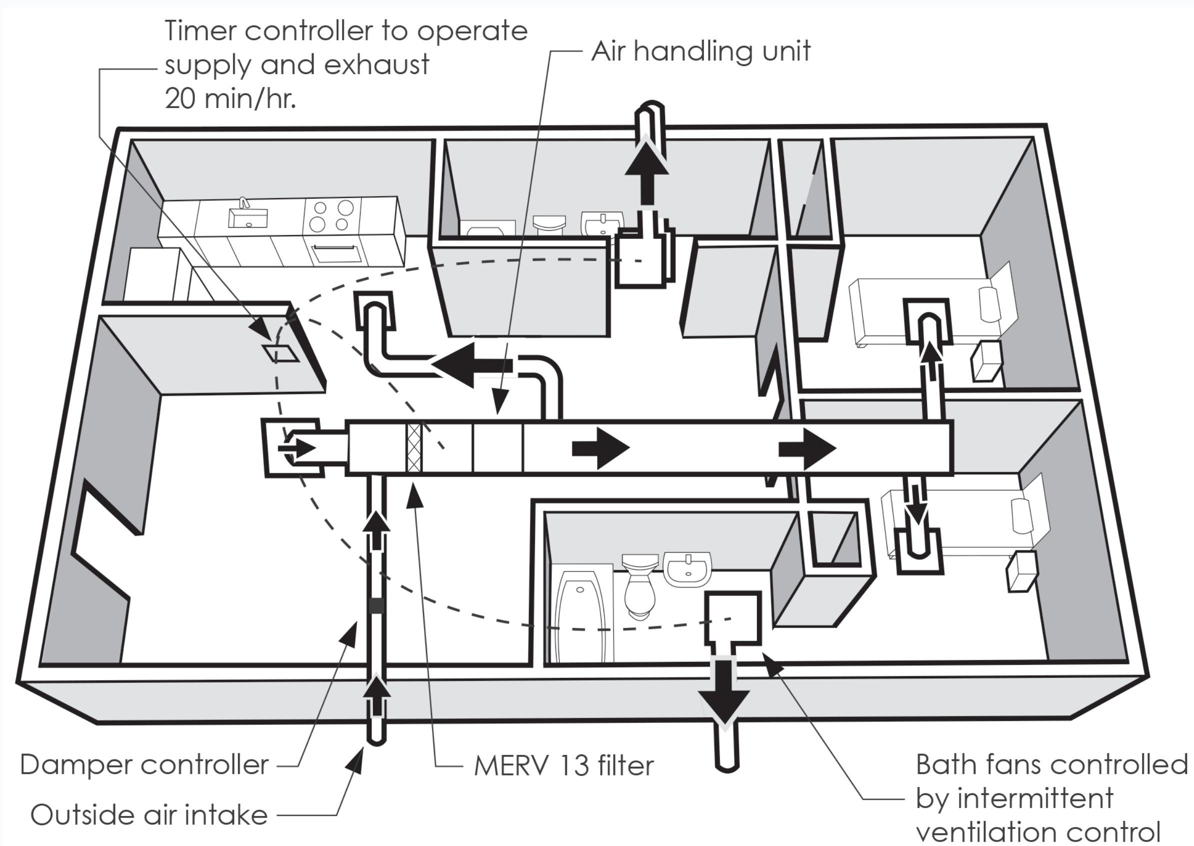


Figure A-10 Combined Supply and Exhaust Ventilation System Without Energy Recovery

APPENDIX A

requires 50 CFM (23.6 l/s) of continuous ventilation for the dwelling. To limit AHU fan runtime, the controller turns the supply-only system on for 20 minutes per hour, and the supply duct is sized to provide 150 CFM (70.8 l/s). Each of the bathroom exhaust fans is sized to exhaust 75 CFM (35.4 l/s), and the fans are controlled to operate simultaneously with the supply-only system.

Filter: The HVAC return has a MERV 13 filter downstream of the outside air intake. (The room air filters in Case Study 2 would be redundant and are not required.)

Why this system works: This system is an inexpensive way to provide balanced ventilation. By combining features of Case Studies 1 and 2, it has many of their advantages. The timer controller limits AHU runtime to 20 minutes per hour to save energy when the weather is mild and the system is not operating to condition the dwelling, but it achieves a minimum circulation of air through the MERV 13 filter.

Existing dwellings: The exhaust portion of this system is typically easy to retrofit into existing dwellings. The supply portion is also easily added to dwellings with access and space for an outside air duct. A service technician should evaluate existing AHUs before adding a MERV 13 filter. If the system cannot accommodate such a filter, a MERV 8 filter could be used in the AHU and room air cleaners could instead be used for filtration (as in Case Study 2).

Multifamily dwellings: This system can be used in individual dwelling units in multifamily buildings where space and access are available and each unit has its own AHU.

What can go wrong with this type of system?

- As with Case Studies 1 and 2, this system introduces outdoor humidity into the dwelling, and it should be used with caution in climates with humid summers.
- The system's supply and exhaust components need to be carefully designed, installed, and commissioned to achieve the target airflow without needing longer runtimes for the AHU, which can significantly increase the amount of energy the system uses.
- As in Case Study 1, the supply part of this system can use a substantial amount of fan energy if the cycle time is longer than 20 minutes per hour.
- In more severe climates, the lack of heat recovery requires more heating and cooling energy to condition the incoming air.
- The proper setting for the system is not always intuitive or obvious to residents. Clear instructions should be provided.
- To achieve balanced system operation, the system controls must be designed and installed to operate the supply and exhaust portions of the system simultaneously.

Case Study 9 Supply-Only Ventilation in Multifamily Building Using a Shared System That Serves Multiple Dwelling Units

Description: A central, remotely located fan delivers outdoor air to multiple dwelling units in a multifamily building (Figure A-11). Filtration is accomplished within the individual dwelling units using any of a variety of possible strategies.

Appropriate climates: This system is appropriate for all climates. For dwellings in areas below warm/humid line in Figure 1.2-A, a dehumidifier should be provided for the supply airstream.

HVAC system: This system is independent of the heating and/or cooling system serving the dwelling units.

Ventilation system: A central, remotely located fan delivers outdoor air to multiple dwelling units in a multifamily building. Dampers in the ducts serving each unit achieve balanced airflow to meet the requirements of ASHRAE Standard 62.2 for each dwelling unit (ASHRAE 2016b). The air can be preconditioned or dehumidified as needed for the climate. Typically, the supply air is delivered into the central living space of each unit.

Filter: At least a MERV 8 filter should be used to filter the outdoor air. If the building is in a city with high outdoor particulate matter levels, a filter with a higher MERV rating should be used (see Figure 7.2-F). Each dwelling unit should also have air filters (e.g., room air cleaners or a MERV 13 filter in an AHU that serves the dwelling unit), as recommended in Strategy 7.2. Filtration is needed in individual units to filter particulate matter generated indoors and that enters the dwelling units via infiltration.

Why this system works: A single ventilation system serves the dwelling units and is therefore easy for the building manager to operate and maintain. The system does not require occupant operation or maintenance.

Existing buildings: Centralized systems are difficult to retrofit into existing buildings unless these buildings are undergoing extensive remodeling that allows installation of a duct chase to accommodate the system.

Multifamily dwellings: This system is intended for multifamily buildings.

What can go wrong with this type of system?

- This system must be designed and commissioned to achieve the target airflow in each dwelling unit.
- In humid climates, the supply-only outdoor air unit should provide dehumidification to avoid introducing too much moisture into the building.
- In climates that experience extremely hot or cold weather, the supply air could make conditions uncomfortable for occupants unless it is preconditioned.
- If the system does not operate continuously, it must have dampers to prevent movement of air between dwelling units.

- Because the need for filtration in individual dwelling units cannot be avoided, education of the residents or a building-level maintenance program is required so that filters are changed according to the relevant schedule.

Figure A-11 Supply-Only Ventilation in Multifamily Building

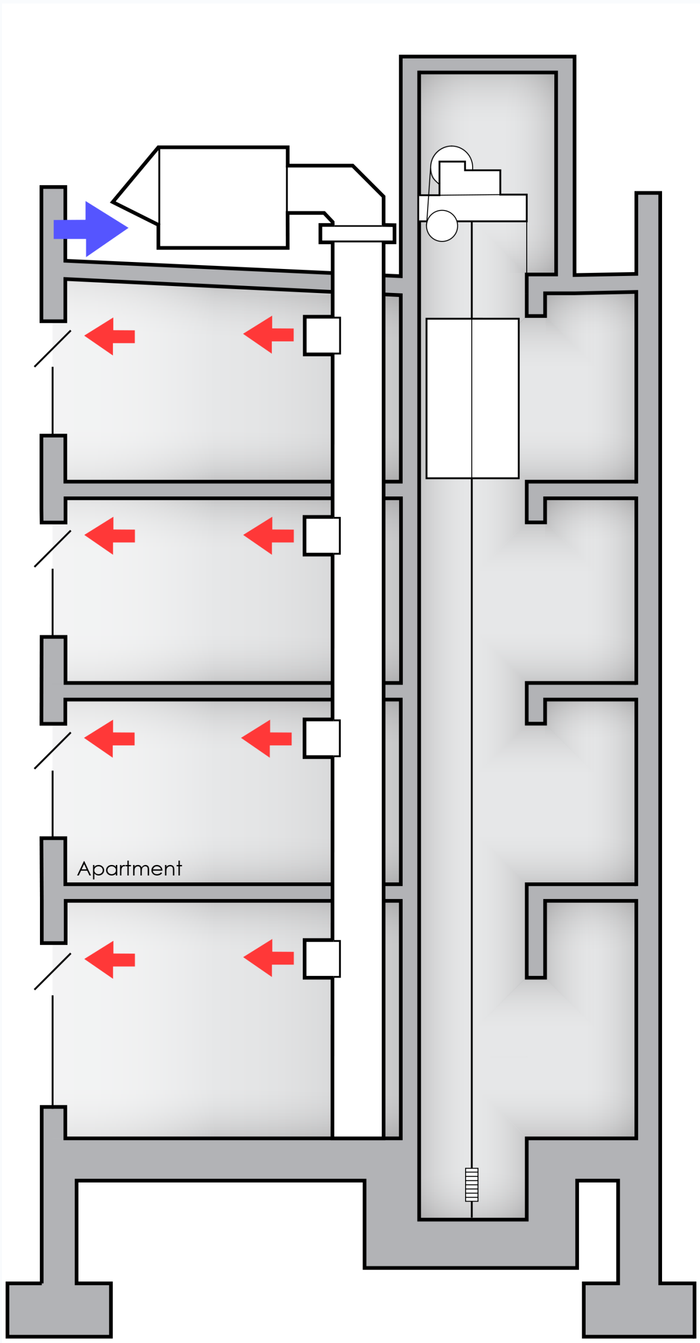


Figure A-11 Supply-Only Ventilation in Multifamily Building Using a Shared System That Serves Multiple Dwelling Units

Case Study 10 Exhaust-Only Ventilation in Multifamily Buildings Using a Shared System Serving Multiple Dwelling Units

Description: A central, remotely located fan exhausts air from multiple dwelling units in a multifamily building (figure A-12). Filtration is accomplished within the individual dwelling units using any of a variety of possible strategies.

Appropriate climates: This system is appropriate for all climates, but it should be used with caution in warm and humid climates (Figure A-12). The additional humidity this type of system introduces might require additional design measures to prevent problems.

HVAC system: This system is independent of the heating and cooling system serving the dwelling units.

Ventilation system: A central, remotely located fan exhausts air from multiple dwelling units in a multifamily building. Dampers in the ducts serving each unit allow airflow to be balanced so that it meets the requirements of ASHRAE Standard 62.2 for each dwelling unit (ASHRAE 2016b). The exhaust air can be removed from the central living space or from bathrooms in each dwelling unit. If the system exhausts air from bathrooms (which is often desirable so that it can serve a dual purpose as a bathroom exhaust system), it needs to operate continuously and remove at least 20 CFM (9.4 l/s) per bathroom (see Strategy 6.2).

Filter: Each dwelling unit should also have air filters (e.g., room air cleaners or a MERV 13 filter in an AHU that serves the dwelling unit), as recommended in Strategy 7.2. Filtration of particulate matter generated indoors and that enters the dwelling units via infiltration is needed in individual units.

Why this system works: A single ventilation system serves all of the dwelling units and is easy for the building manager to operate and maintain. The ventilation system does not require occupant operation or maintenance.

Existing buildings: Centralized systems are difficult to retrofit into existing buildings unless these buildings are undergoing extensive remodeling that allows installation of a duct chase.

Multifamily dwellings: This system is intended for multifamily buildings.

What can go wrong with this type of system?

- Use of this system in very humid climates can introduce too much moisture into the building. A ventilation system with energy recovery or dehumidification might be a better choice in these climates.

- The system must be designed and commissioned so as to achieve the target airflow in each dwelling unit.

- Even when the system is properly designed and commissioned, some dwelling units might not receive the target amount of ventilation directly from outdoors (depending on weather conditions and their location within the building). Instead, these units could receive air from neighboring units. Although the building achieves the target ventilation rate, the incoming outdoor air is not necessarily distributed evenly among dwelling units in the building. This effect can be mitigated with good compartmentalization (air sealing of the common walls) between units, but a balanced or supply-only ventilation system is the only way to prevent this problem.

- In most dwellings, only a small amount of negative pressure is induced by this type of system. However, in very airtight dwellings, this system could exacerbate localized negative-pressure problems with combustion appliances, particularly those that are atmospherically vented (Strategy 6.1).

- If the system does not operate continuously, it must have dampers to prevent movement of air between dwelling units.

- Because the need for filtration in individual dwelling units cannot be avoided, education of the residents or a building-level maintenance program is required so that filters are changed according to the relevant schedule.

Figure A-12 Exhaust-Only Ventilation in Multifamily Building

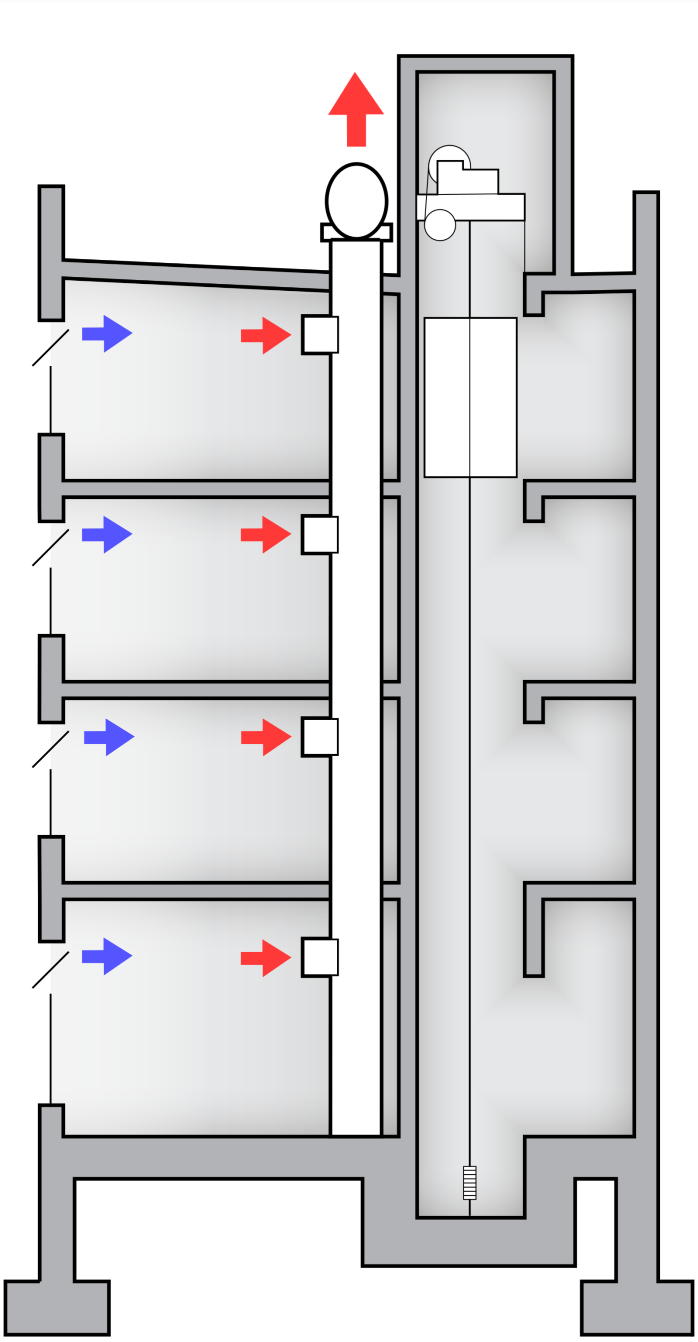
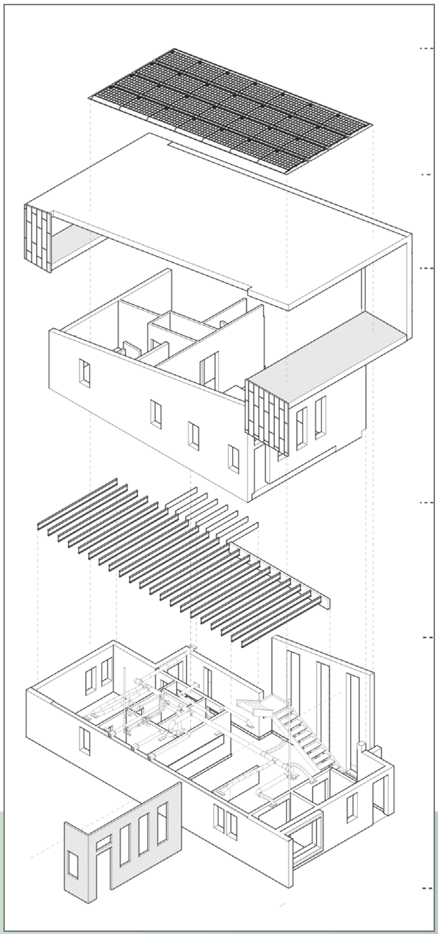


Figure A-12 Exhaust-Only Ventilation in Multifamily Building Using a Shared System Serving Multiple Dwelling Units

Best Practices for Good IAQ



Indoor air quality (IAQ) is one of many factors that make a dwelling healthy, comfortable, and functional. Good IAQ is nearly invisible; poor IAQ can have a negative effect on health and comfort. Achieving good IAQ throughout the life span of a home requires a commitment to indoor air quality when buying, renting, and designing and maintaining that focus throughout construction, operation, and maintenance.

This guide addresses single- and multifamily dwellings, unrestricted by building size or HVAC system type. It was written by experts in residential IAQ and presents best practices to achieve excellent IAQ. It provides information and tools that residents, home designers, and builders can use to integrate IAQ into dwellings while addressing budget constraints and other functional requirements.

This guide presents the best available information to allow informed decision-making, with eight objectives for improving IAQ and detailed implementation strategies:

- Objective 1 – Acquire, Design, Construct, and Operate a Dwelling to Achieve Good IAQ
- Objective 2 – Manage Moisture
- Objective 3 – Limit Contaminant Entry into the Living Space
- Objective 4 – Control Moisture and Contaminants Related to Mechanical Systems
- Objective 5 – Limit Contaminants from Indoor Sources
- Objective 6 – Keep Contaminants in their Place
- Objective 7 – Reduce Contaminant Concentrations Through Ventilation, Filtration, and Air Cleaning
- Objective 8 – Minimize Energy Use, Maximize Comfort, and Address Interactions of Factors that Affect IAQ

ISBN 978-1-947192-02-7 (paperback)
ISBN 978-1-947192-03-4 (PDF)

9 781947 192027

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Telephone: 404-636-8400 (worldwide)
www.ashrae.org

Product code: 90458 6/18