Evaluating and Managing Indoor Air Quality

A Guide for Owners and Occupants

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Table of Contents

We shape our buildings; thereafter they shape us. – Winston Churchill

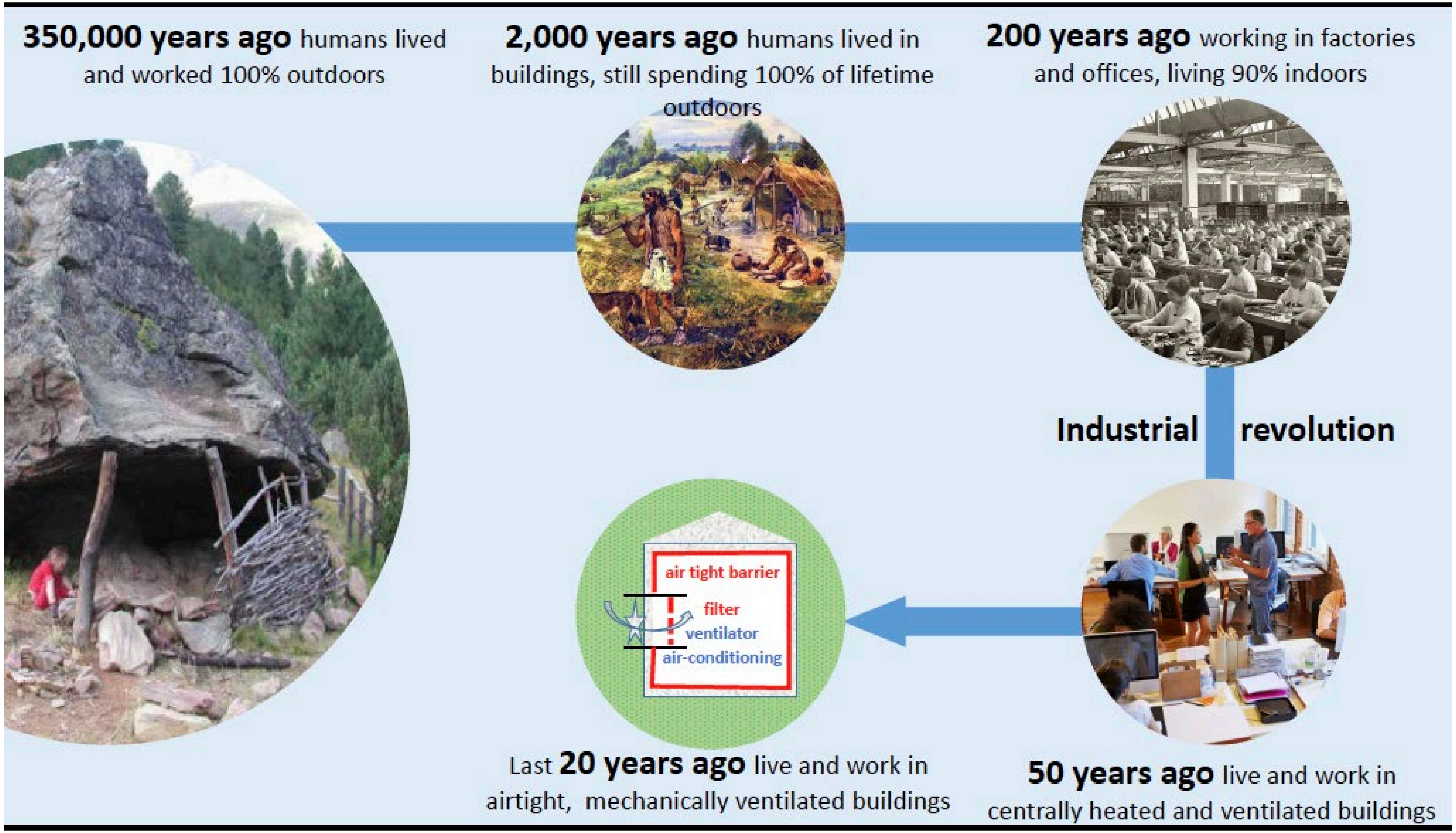


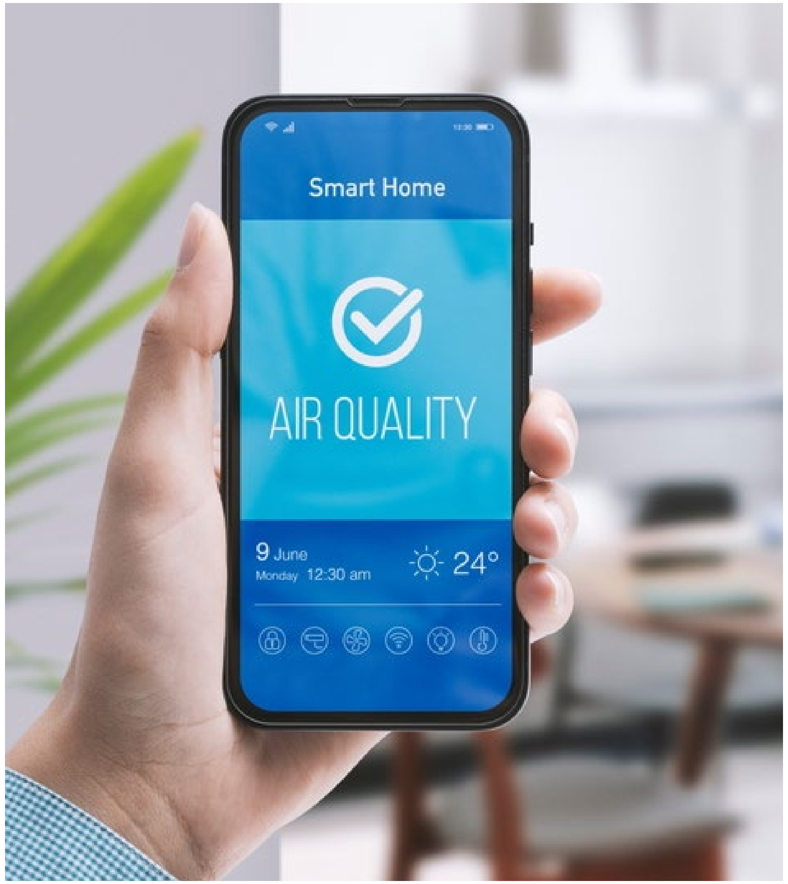
Image courtesy of Stephanie Taylor, M.D.

What is Indoor Air Quality (IAQ)?

I. What is IAQ?
- I. Health
- II. Perception

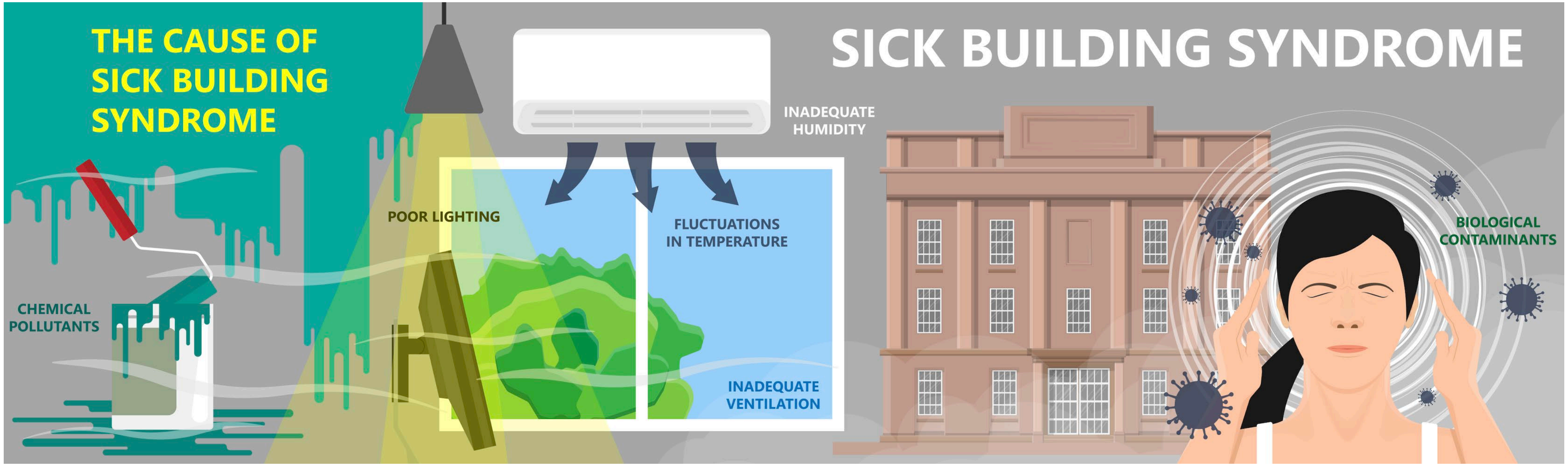
II. Management
- I. Background
- II. Measure
- III. Survey
- IV. Reporting and Data Ownership

IV. ACTION – Control Humidity
V. ACTION – Control Contaminant Concentration
VI. ACTION – Improve Filtration and Air Distribution



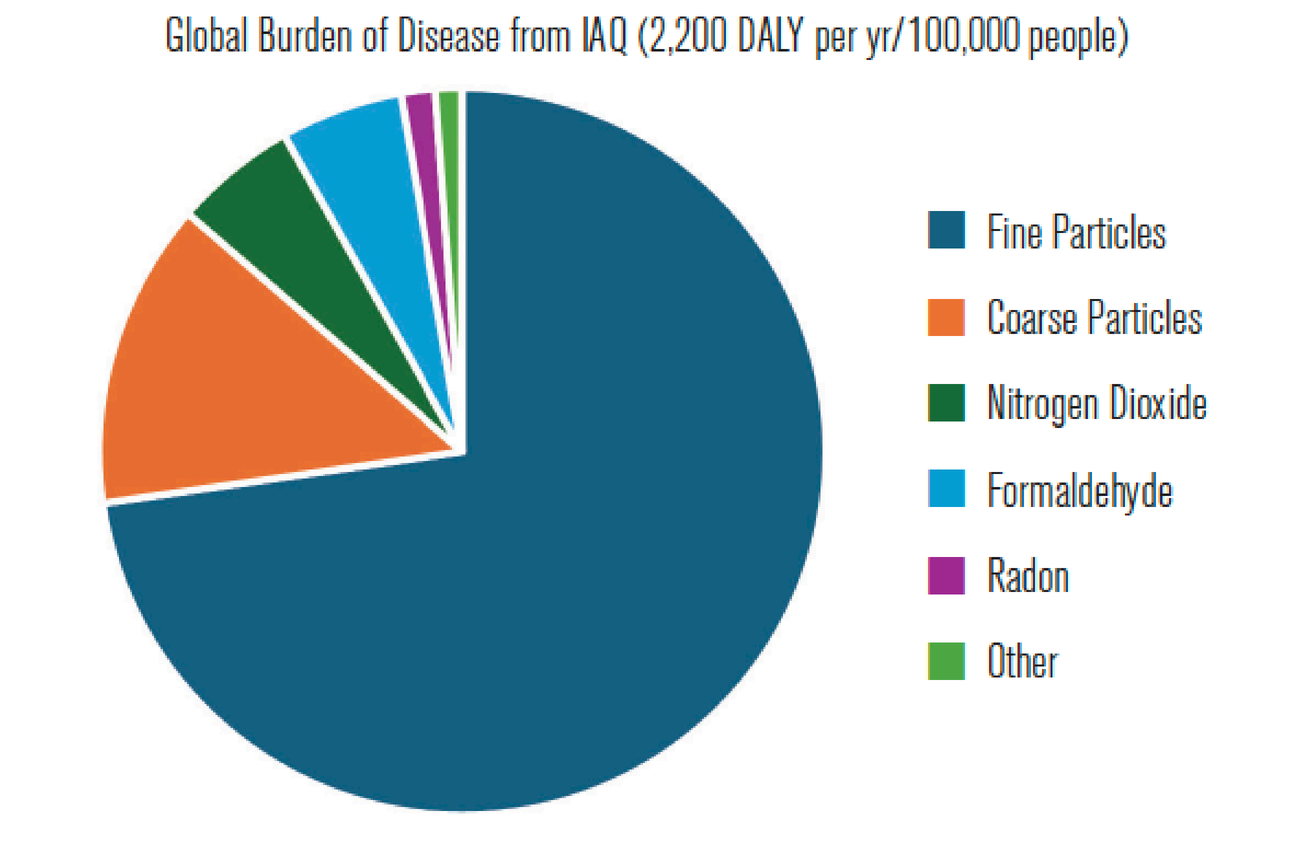
Two Components of IAQ – Health and Perception

- Health effects can be acute or chronic.
- Perception is influenced by environment and culture.



Health Effects - Particles and Chemicals

FIGURE 2 Fraction of global burden of disease for indoor air quality imputed by Morantes. 99% is explained by particles, NO_2, HCHO, and Rn.

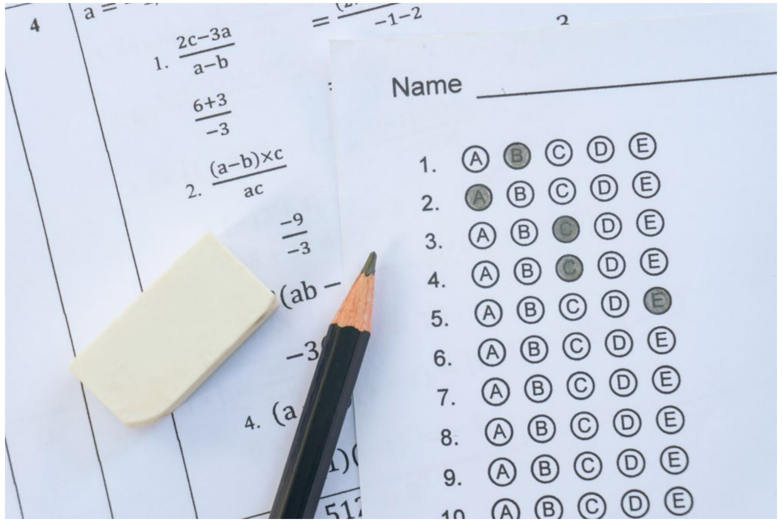


Sherman, M. (2024). IAQ Paradigms — The Next Generation. *ASHRAE Journal.* 66(4), 44-45.

A Slight Increase in $PM_{2.5}$ Harms Our Thinking

Chess players made 26% more mistakes.

Incorrect calls by umpires increased by 2.6%.



The probability of failing an exam increased by 8%.

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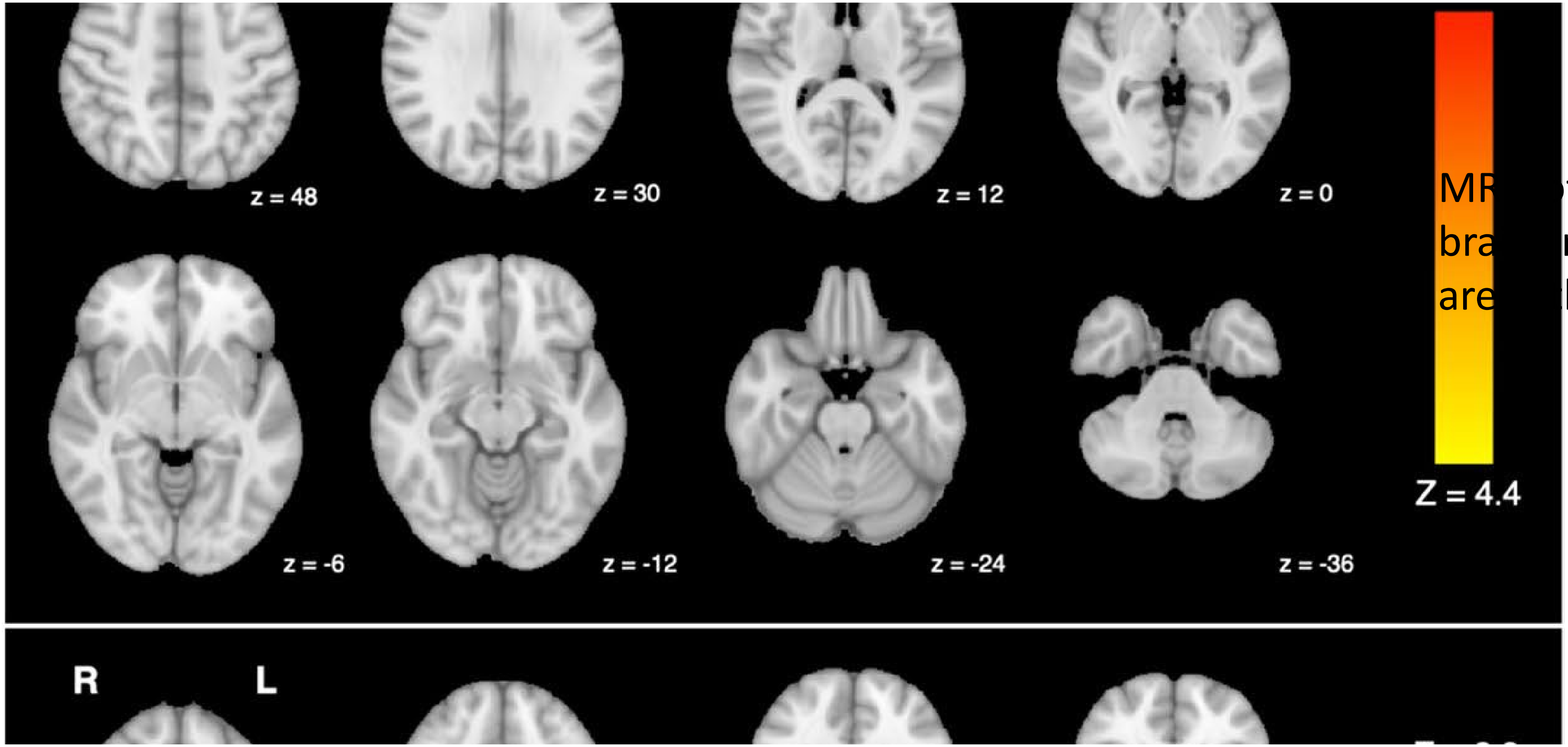
Inhaled Particles Can Evade the Blood/Brain Barrier

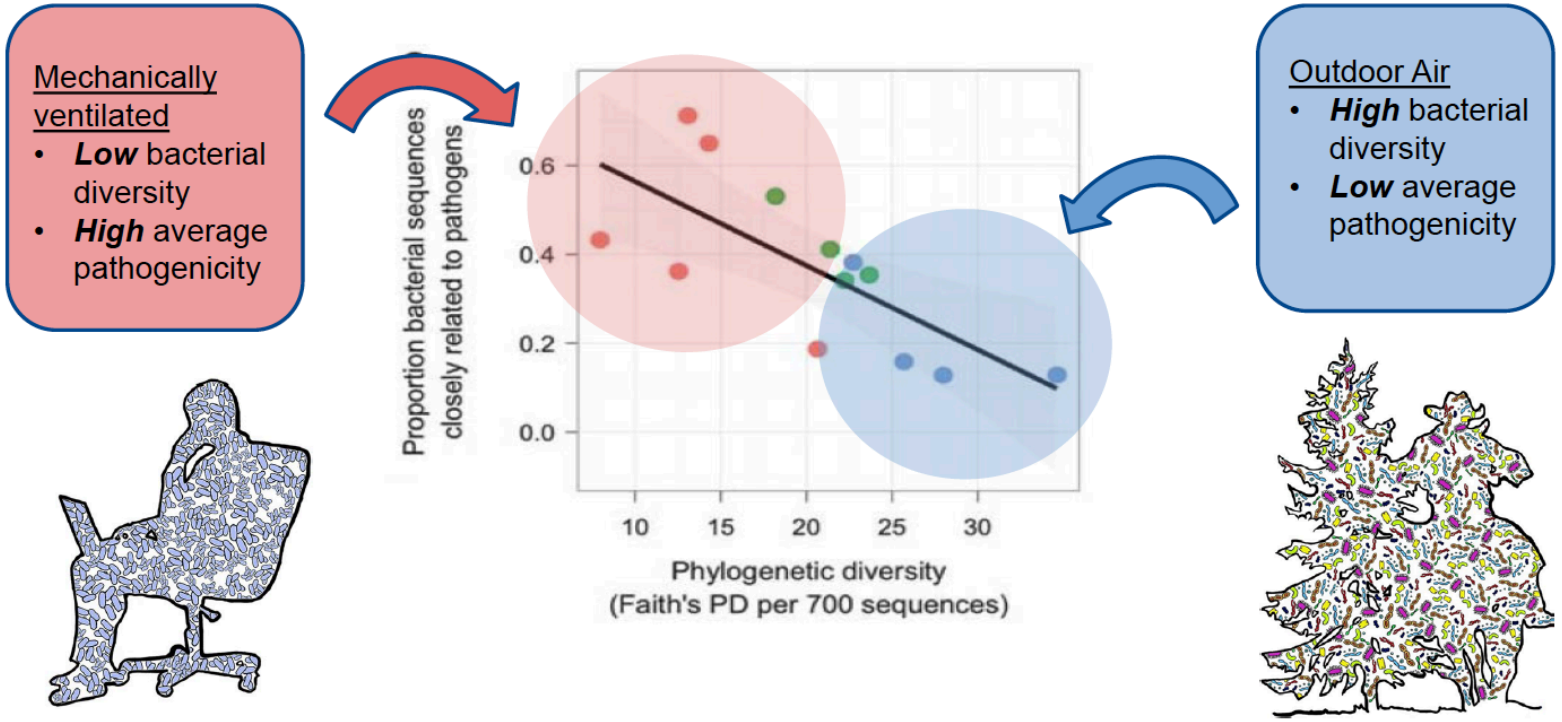


MR f healthy adult
bra reveal damage to
are hat control:

Gawryluk, J.R., Palombo, D.J., Curran, J. *et al.* Brief diesel exhaust exposure acutely impairs functional brain connectivity in humans: a randomized controlled crossover study. *Environ Health* **22**, 7 (2023). https://doi.org/10.1186/s12940-023-00961-4 | Graphics courtesy of Stephanie Taylor, MD

Health Effects - Pathogens

Microbes in mechanically ventilated buildings are more closely related to pathogens



Graphics courtesy of Stephanie Taylor, MD

For more information visit the [Microbiome topic page]

Health Effects – High Humidity

- Microbial Growth – ASHRAE 62.1 Limit is 60degF dewpoint

Microbial Growth

- Microbial growth is best controlled in buildings by limiting humidity.
- In areas within buildings that are unavoidably wet, control the microbe’s food source(s). Examples include filter organic particles from airstreams to keep cooling coils clean or wash commercial kitchen surfaces.
- ”Everything is everywhere, but the environment selects”
- Action - Humidity

Moisture in Envelope Infrastructure Facilitates Growth of Tree Sapling

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

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

Photo courtesy of Phil Morey, *Indoor Air Quality Guide*

Bass Becking hypothesis, LGM Bass Becking, 1934

Microbial Growth

- What are effects of temperature, light, or air movement on microbial growth?
- Microbes will grow at all temperatures in our built environment.
- UV from sunlight harms some bacteria. Some fungi grow using radiation as a food source.
- Air movement distributes spores, food, and adds to or subtracts from water availability.

Health Effects – Low Humidity Triple Whammy

1. Human respiratory immune defenses are significantly harmed by inhalation of dry air.

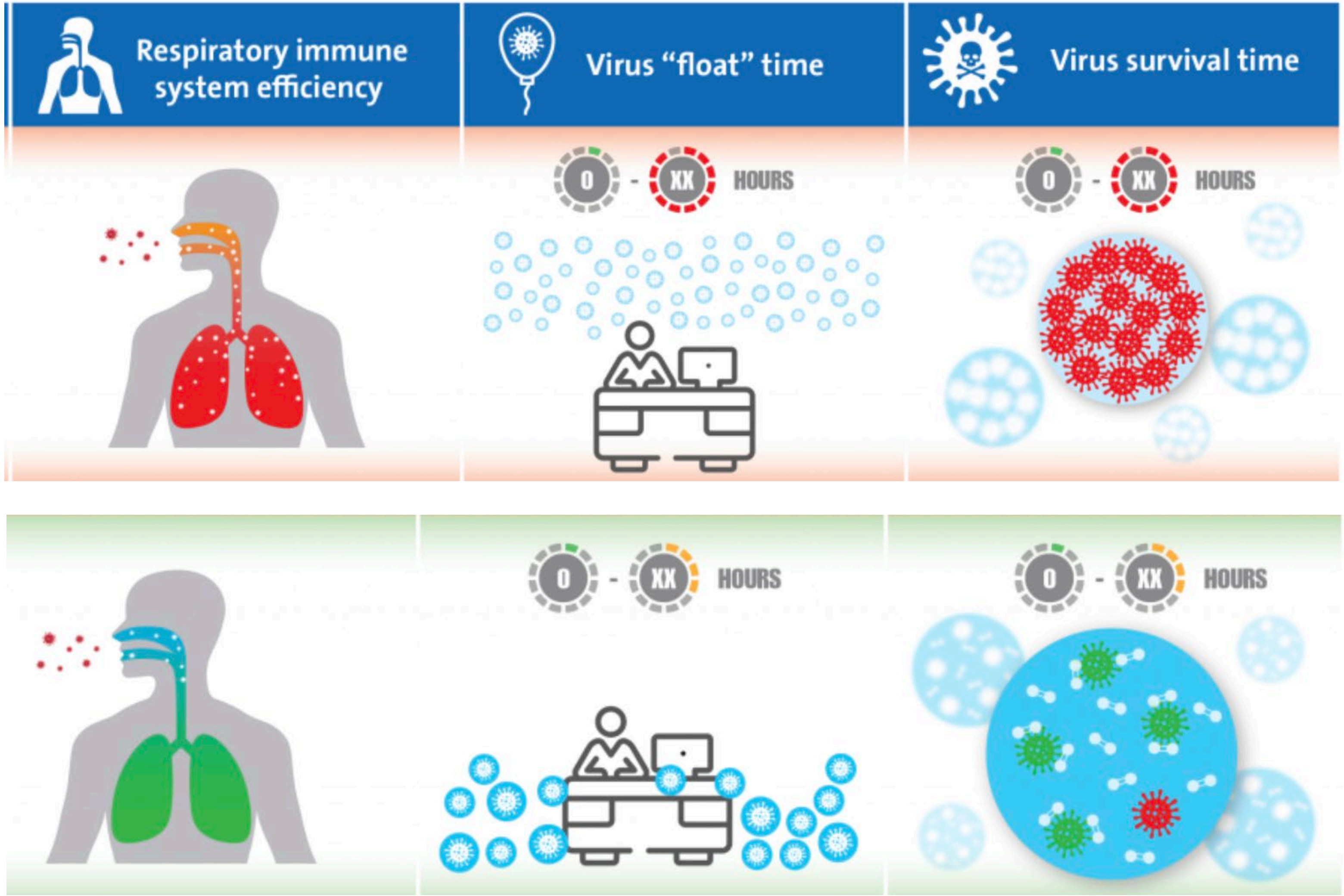
2. Airborne particles travel farther and persist in the breathing zone for longer when indoor humidity is low.

3. Many viruses and bacteria in exhaled bioaerosols are more infectious when indoor humidity is low.

Three Dimensions of RH 40–60% Protection

RH < 40%

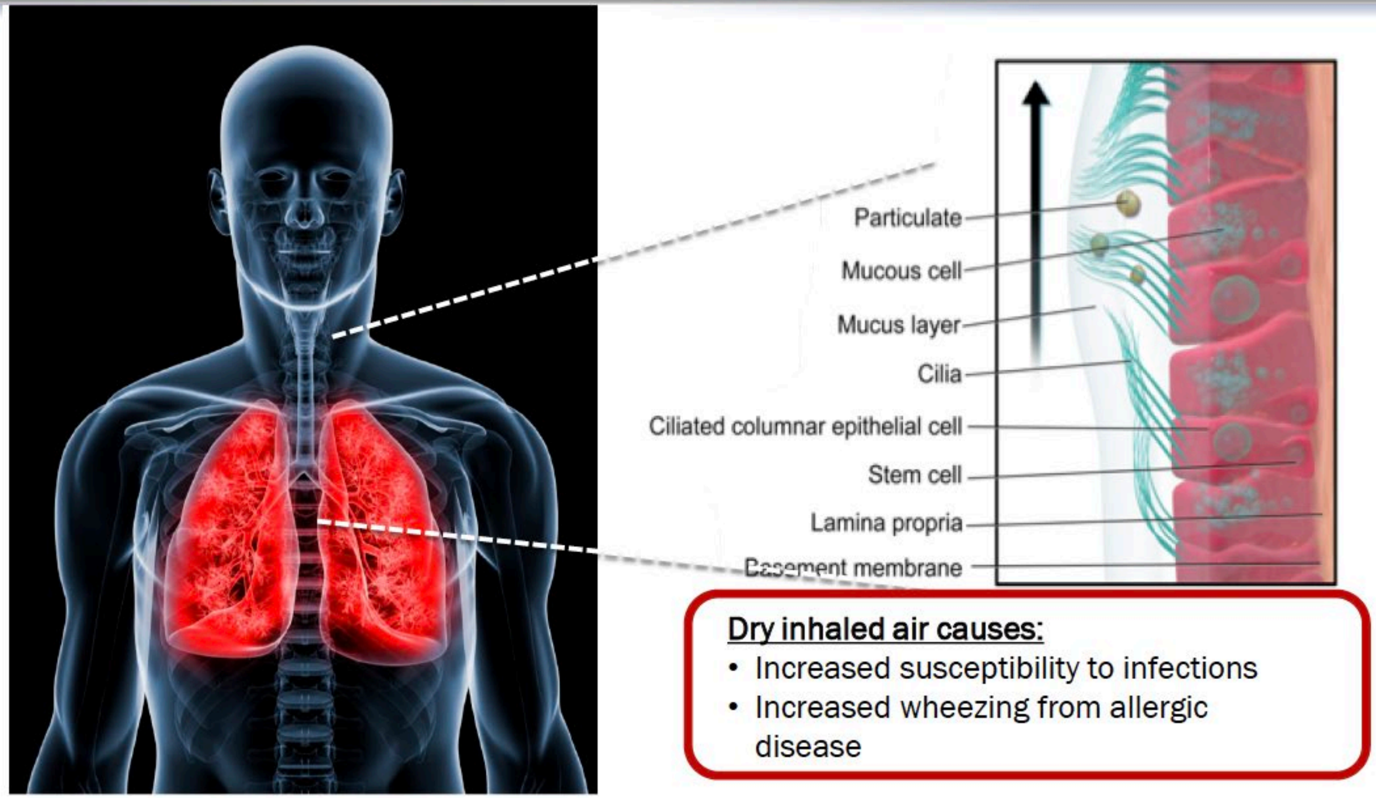
RH 40% – 60%



Graphics courtesy of Stephanie Taylor, MD

Health Effects – Low Humidity

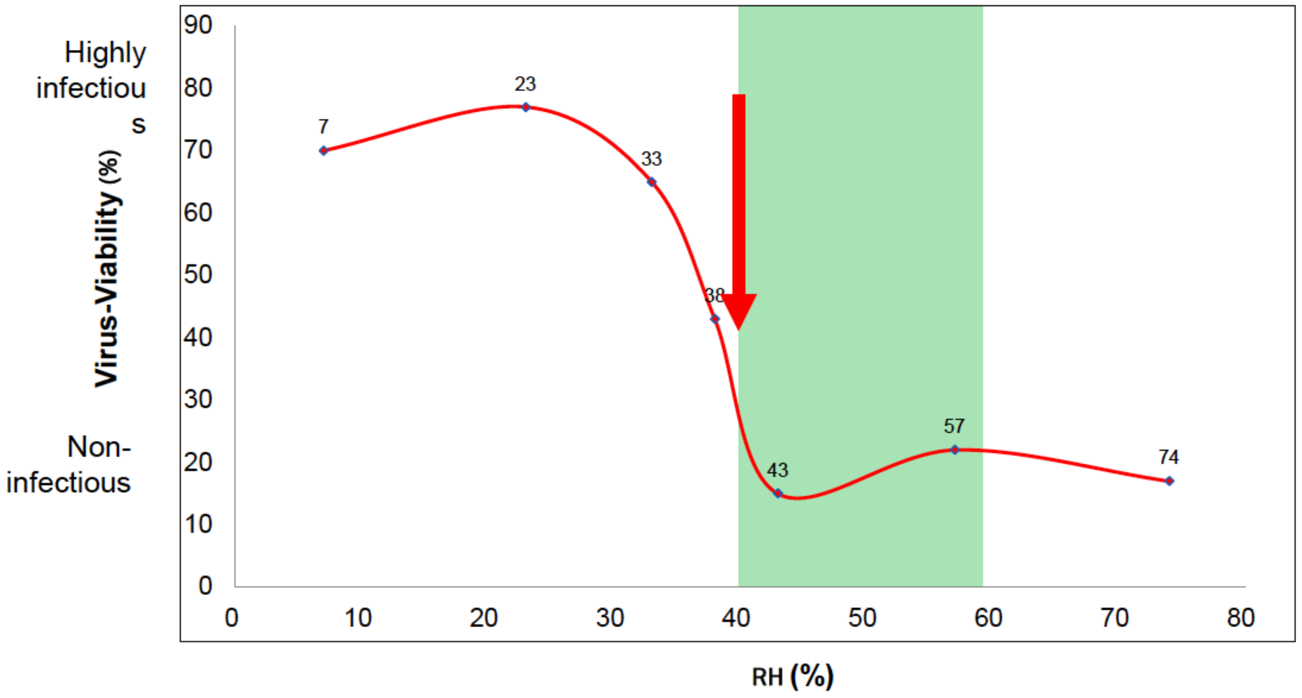
Dry air impairs our respiratory system defenses



Graphics courtesy of Stephanie Taylor, MD

Health Effects – Low Humidity

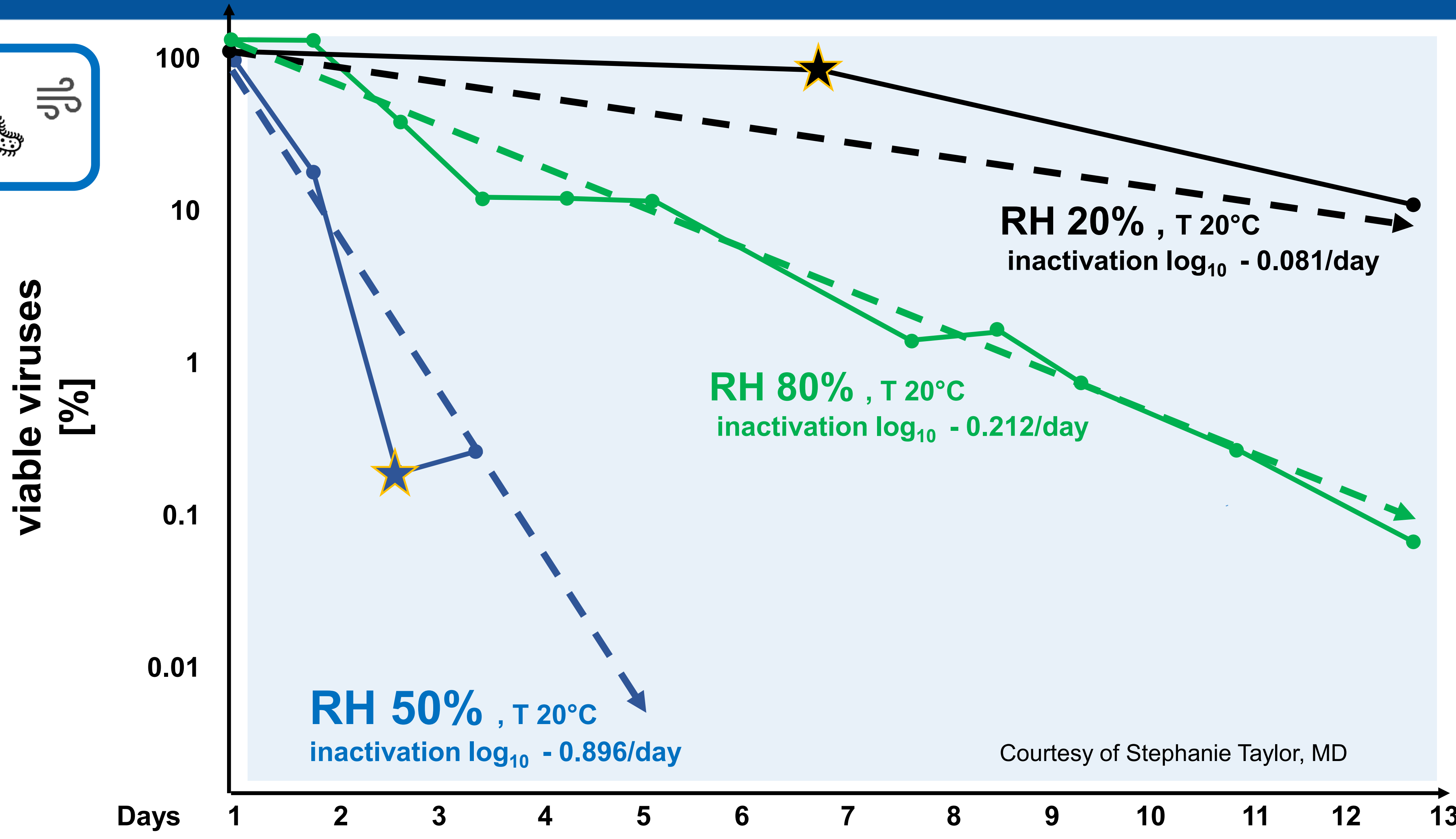
Influenza A virus is more infectious when RH is below 40%



Noti 2007

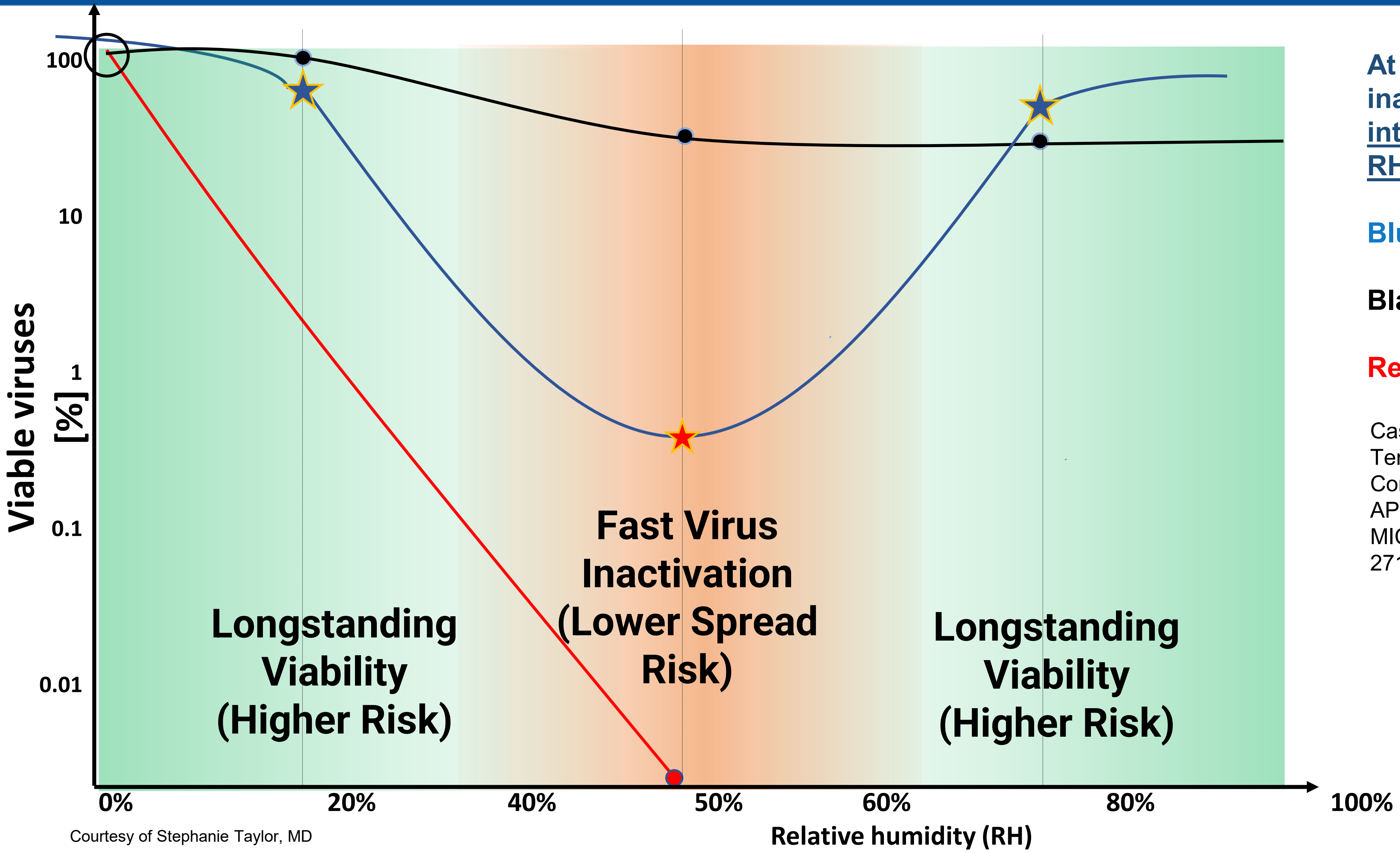
Graphics courtesy of Stephanie Taylor, MD

Humidification to 50% RH & Impact on Covid Infection Risk



Casanova LM et al, Effects of Air Temperature and Relative Humidity on Coronavirus Survival on Surfaces, APPLIED AND ENVIRONMENTAL MICROBIOLOGY, May 2010, p. 2712–2717

Speed of Inactivation of SARS COV-1



Courtesy of Stephanie Taylor, MD

At all temperatures the virus inactivation rate was fastest in intermediate humidity of 50% RH

Blue line = 68° F

Black line = 39° F

Red line = 104° F

Casanova LM et al, Effects of Air Temperature and Relative Humidity on Coronavirus Survival on Surfaces, APPLIED AND ENVIRONMENTAL MICROBIOLOGY, May 2010, p. 2712–2717

Case Controlled Study in a Pre-school

Humidification Decreased Influenza A Illness in Children

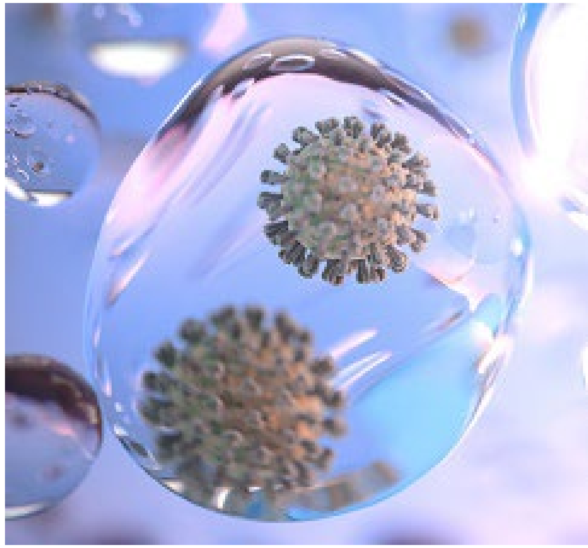
- January 25 – March 11 (32 days)
- Half of the classrooms were humidified, the other half were not

RH of Classrooms	% Airborne Particles Carrying Virus (PCR)	Virulence of Airborne Virus	# Children Absent Due to Influenza Illness
20%	49%	75%	22
45%	19%	35%	9

Reiman JM, Das B, Sindberg GM, Urban MD, Hammerlund MEM, Lee HB, et al. (2018) Humidity as a non-pharmaceutical intervention for influenza A. PLoS ONE 13(9): e0204337. https:// doi.org/10.1371/journal.pone.0204337Graphic courtesy of Stephanie Taylor, MD

Microbes Inside of Exhaled Droplets at RH > 40 & RH < 40%

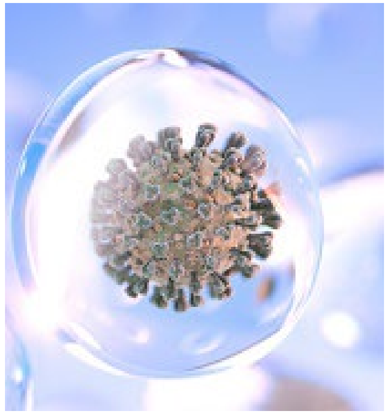
Exiting airways with RH 100%



100 µm

Graphics courtesy of Stephanie Taylor, MD

Indoor RH over 40%



50 µm

Pathogens are inactivated by mid-range salt concentrations (reducing risk for transmission)

Indoor RH below 40%

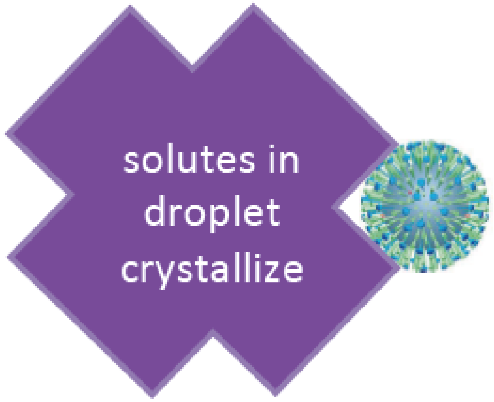
3.9 µm

Pathogens are preserved by high salt concentrations (creating higher risk for transmission)

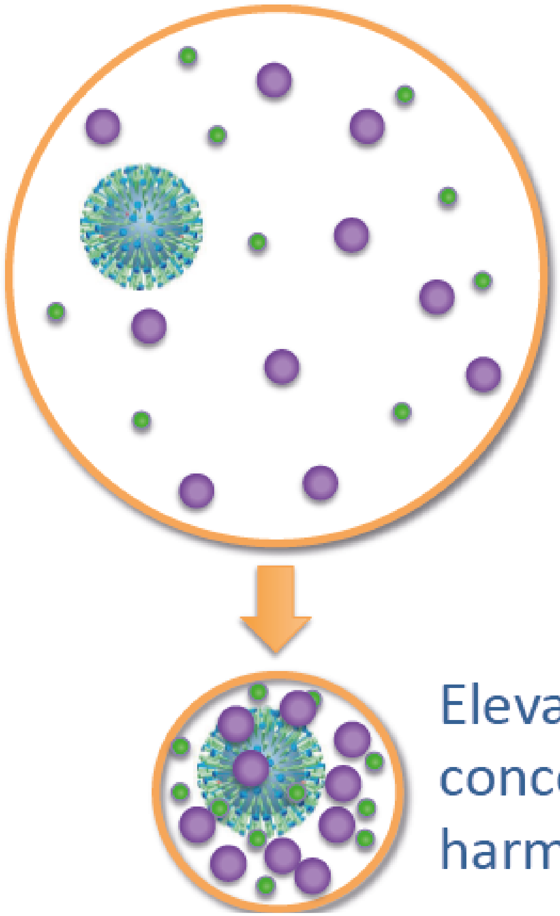
Viral Infectivity and RH

RH < 40%

Efflorescence occurs ⇒ solutes cannot harm virus ⇒ viability is maintained



RH 40–60 %



Elevated solute concentrations may harm virus

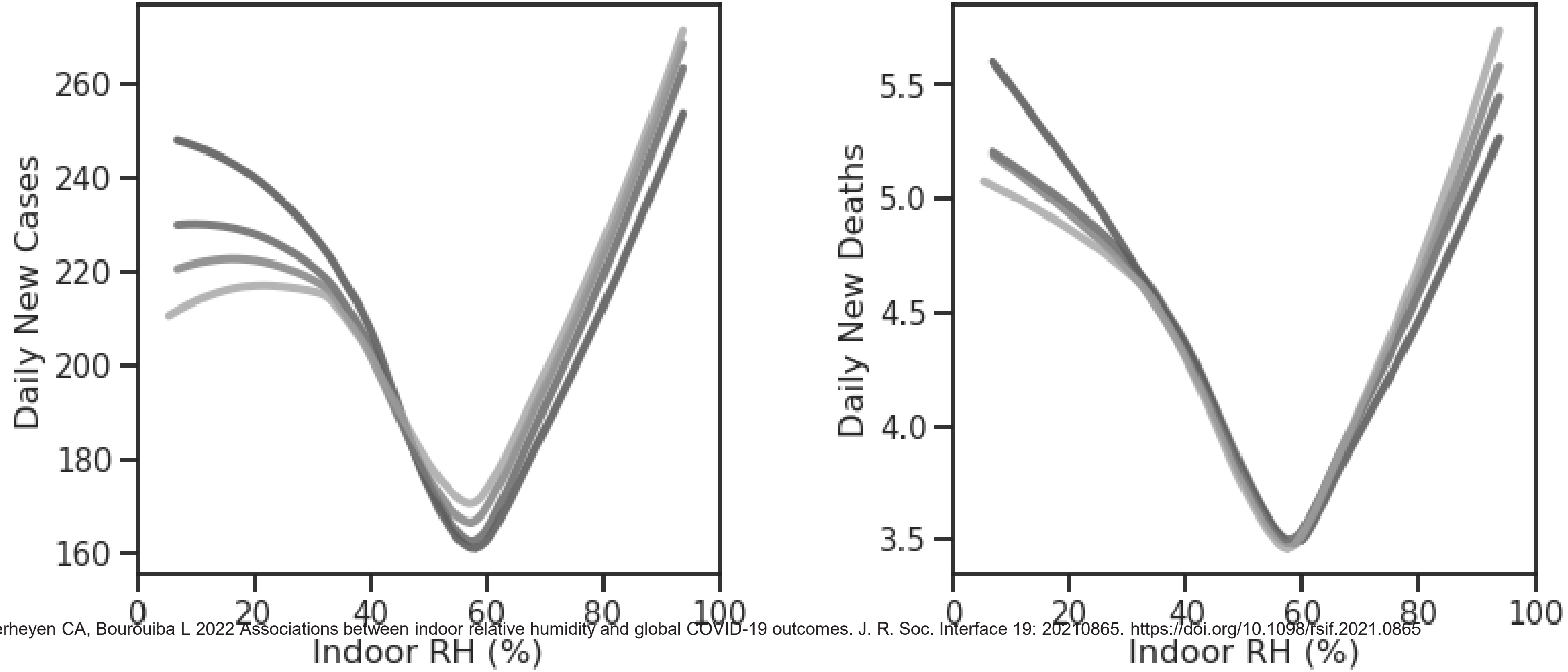
RH > 60%

Minimal evaporation ⇒ physiological conditions are maintained in droplet ⇒ viability is maintained

Yang W, Marr LC, Mechanisms by Which Ambient Humidity May Affect Viruses in Aerosols, Applied and Environmental Microbiology, p.6781-6788, October 2012, Vol. 78, Nr. 19

Graphics courtesy of Stephanie Taylor, MD

Covid-19 Cases and Deaths Were Lowest When Indoor RH was 40–60%



Verheyen CA, Bourouiba L 2022 Associations between indoor relative humidity and global COVID-19 outcomes. J. R. Soc. Interface 19: 20210865. https://doi.org/10.1098/rsif.2021.0865

Overall, the data pointed toward a consistent and robust pattern: COVID-19 outcomes are less severe at intermediate indoor RH levels (between 40% and 60%) and more severe at extreme indoor RH levels. This association is found to be robust to variation in - geographical region, outdoor weather conditions, and government responses, as well as to variations in the underlying methodology.

Perception, (*Page 1 of 2*)

People respond to IEQ (indoor environmental quality)

- Sight,
- Sound,
- Thermal sensations,
- Odors

- Often the interactions between the senses affect reporting of indoor air quality
- High temperature and humidity and lack of air movement often lead to IAQ complaints

Imperceivable Health Threats

- Radon
- CO
- Airborne Pathogens

View information on other IEQ Topics, including acoustics and lighting, on the ASHRAE IEQ Resource page.

Perception, *(Page 2 of 2)*

Most Odors – Not Harmful

Indoor Air Quality Management

I. What is IAQ?
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Introduction – IAQ Concerns

Considerable public interest in the quality of the indoor environment began in the 1970s, owing to the appearance of building-related subclinical health symptoms — also known as Sick Building Syndrome (SBS) symptoms (e.g., headache, shortness of breath, fatigue, eye and throat irritation) and outbreaks of several acute incidents, such as carbon monoxide poisoning (Wright, 2002) and Legionnaires' disease (Fraser et al. 1977). These were often the direct result of policies for conserving energy in buildings implemented during the 1970s energy crisis, such as tightening the building envelope to reduce uncontrolled outdoor air infiltration without using mechanical outdoor air ventilation, which reduced the amount of outdoor air supplied indoors. As a result, modern buildings are often built to be more airtight compared to older structures (Murray and Burmaster, 1995; Jones, 1999).

As a result, buildings more readily produce and accumulate indoor air pollutants than ever before. A number of studies have shown that the concentration of many air pollutants is higher indoors than outdoors, sometimes reaching two orders of magnitude higher (Wallace, 2000; Weisel et al 2005), and generally ranging from 2 to 5 times higher (US EPA, 2024a). Therefore, most human daily air pollutant exposure, even to air pollutants of outdoor origin, occurs indoors (Kim et al. 2005; Liu et al. 2007; Nazaroff 2018).

Awareness of IAQ and Health

Modern health concerns related to air pollutants exposure in buildings have been exacerbated owing to several additional factors. First, the amount of time that people in developed regions spend indoors has been continuously increasing and often exceeds 90% (Klepeis et al. 2001). Additionally, owing to advances in construction technology and widespread development of the chemical industry, there is an increasing influx of synthetic chemicals into indoor environments (Weschler, 2009; Salthammer 2020).

As a result, buildings more readily produce and accumulate indoor air pollutants than ever before. Concentrations can exceed health-based standards for acute and chronic exposures (Logue et al. 2011). Air pollutant exposure indoors not only impacts health, but also impacts overall human well-being, work performance, and learning (Wargocki et al. 2002; Seppänen et al. 2005) with enormous economic implications (Fisk et al. 2011).

Therefore, most human daily air pollutant exposure, even to air pollutants of outdoor origin, occurs indoors (Kim et al. 2005; Liu et al. 2007; Nazaroff 2018), and those concentrations can exceed health-based standards for acute and chronic exposures (Logue et al. 2011). Air pollutant exposure indoors not only impacts health, but also impacts overall human well-being, work performance, and learning (Wargocki et al. 2002; Seppänen et al. 2005) with enormous economic implications (Fisk et al. 2011).

Basic Principles of Managing IAQ

Indoor contaminants may come from outside or from sources in the building, which may include processes, equipment, activities, people, materials; they can also be the result of chemical transformations involving reactions with reactive species such as ozone or hydroxyl radicals. There are four core principles for achieving good IAQ.

1) Manage IAQ. Measure to verify that efforts to limit indoor air pollutant concentrations are working, and the indoor environment minimizes risks associated with health, comfort, work performance, learning, and disturbed sleep of building occupants.

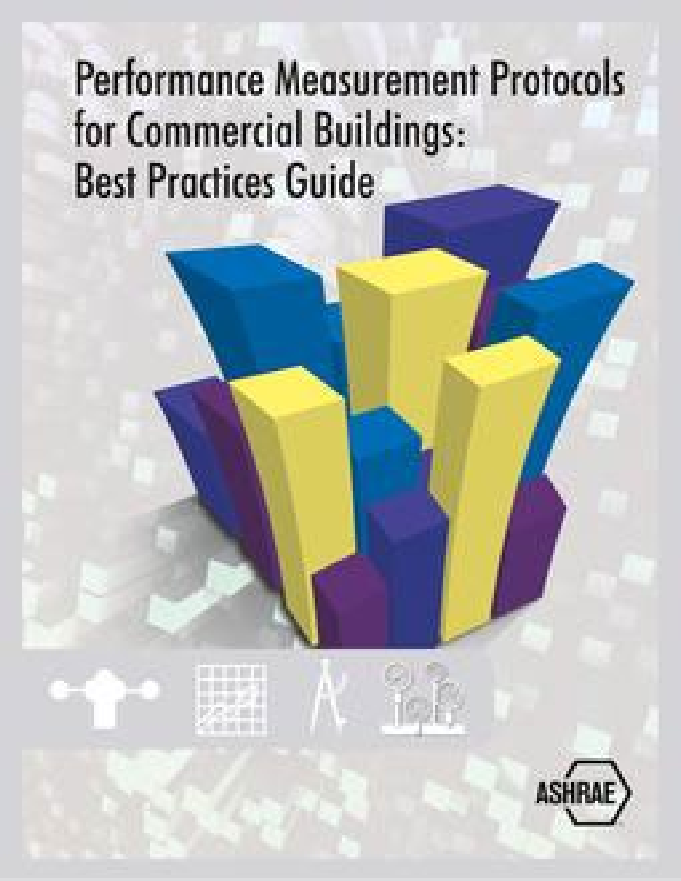
2) ACTION - Control indoor humidity to avoid occupant health problems and moisture damage to building materials;

3) ACTION - The primary method for controlling high levels of pollutants indoors is to minimize indoor emissions by eliminating or reducing sources and the risk for chemical transformations and reactions. This includes local exhaust ventilation, filtration and air cleaning, isolation, or other capture techniques. Ventilate with outdoor air to dilute and extract contaminants, with verification that outdoor air does not transport pollutants from outdoors.

4) ACTION – Improve filtration and air distribution.

ASHRAE Resources - Fundamental

ASHRAE Resources – Operations and Maintenance



ASHRAE Resources – External Events

GUIDELINE

ASHRAE

ASHRAE Guideline 44-2024

Protecting Building Occupants from Smoke During Wildfire and Prescribed Burn Events

Approved by ASHRAE on November 13, 2024.

ASHRAE® Guidelines are scheduled to be updated on a five-year cycle; the date following the Guideline number is the year of ASHRAE approval. The latest edition of an ASHRAE Guideline may be purchased on the ASHRAE website (www.ashrae.org) or from ASHRAE Customer Service, 180 Technology Parkway, Peachtree Corners, GA 30092. E-mail: orders@ashrae.org. Fax: 678-539-2129. Telephone: 404-636-8400 (worldwide) or toll free 1-800-527-4723 (for orders in US and Canada). For reprint permission, go to www.ashrae.org/permissions.

 ISSN 1049-894X

PDF includes hyperlinks for convenient navigation. Click on a reference to a section, table, figure, or equation to jump to its location. Return to the previous page via the bookmark menu.

STANDARD

ASHRAE

ASHRAE Standard 241-2023

Control of Infectious Aerosols

Approved by the ASHRAE Standards Committee on June 24, 2023.

This Standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the Standard. Instructions for how to submit a change can be found on the ASHRAE® website (www.ashrae.org/continuous-maintenance).

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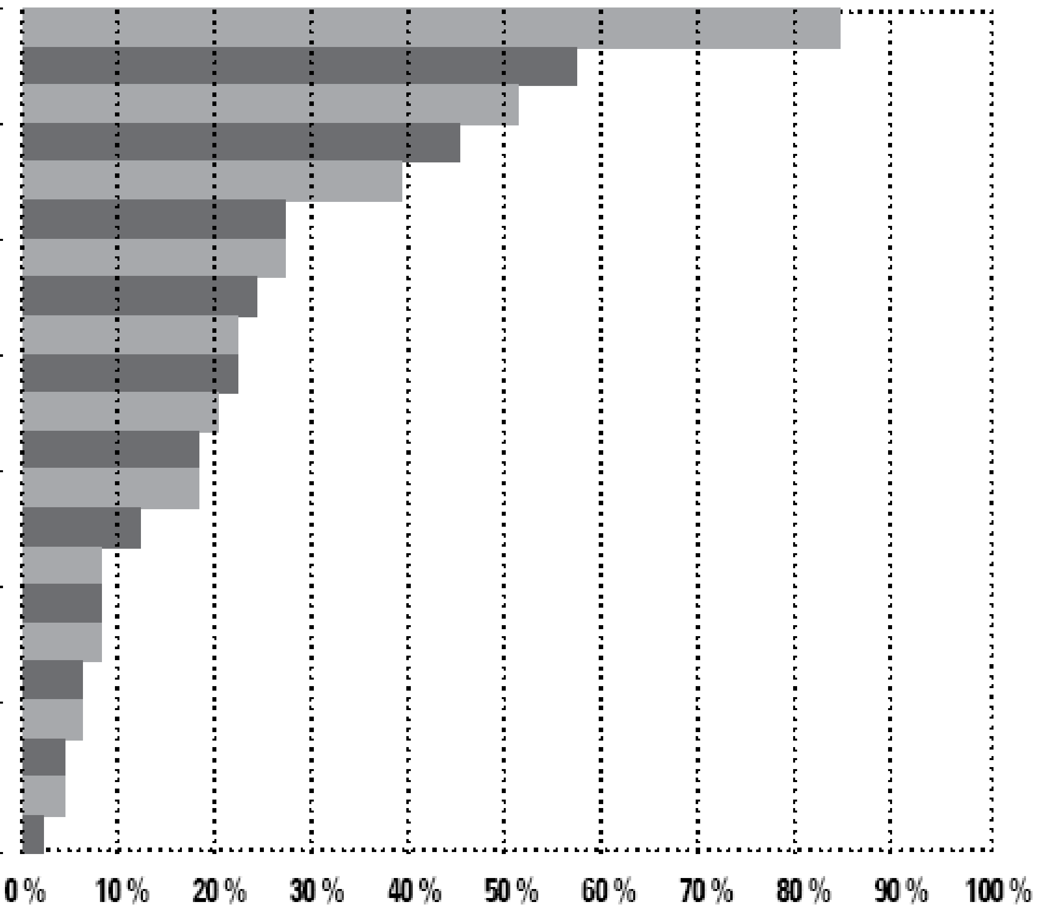
 ISSN 1041-2336B

This standard includes links to online supporting files.

Building Factors Associated with IAQ Problems from 49 NIOSH School Reports

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



Adapted from Angell and Daisey 1997

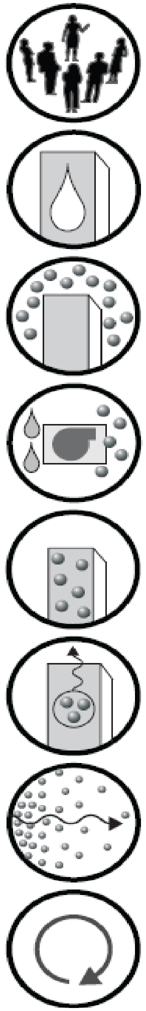
Key Problems Causing Building-Related Symptom Complaints

In decreasing order of importance:

- Excessive building moisture
- Inadequate amount or quality of outdoor air
- Surface dust
- Gases and odors
- Inadequate thermal control
- Inadequate attention by management to preventing adverse effects of IEQ on occupants vs. minimizing immediate costs

Mendell, *et al*. 2006

Indoor Air Quality Guide: Best Practices for Design, Construction, and Commissioning



Objective 1 Manage the Process to Achieve Good IAQ

Objective 2 Control Moisture in Building Assemblies

Objective 3 Limit Entry of Outdoor Contaminants

Objective 5 Control Moisture and Contaminants Related to Mechanical Systems

Objective 5 Limit Contaminants from Indoor Sources

Objective 6 Contain and Exhaust Contaminants from Building Equipment and Activities

Objective 7 Reduce Contaminant Concentrations through Ventilation and Air Cleaning

Objective 8 Apply More Advanced Ventilation Approaches

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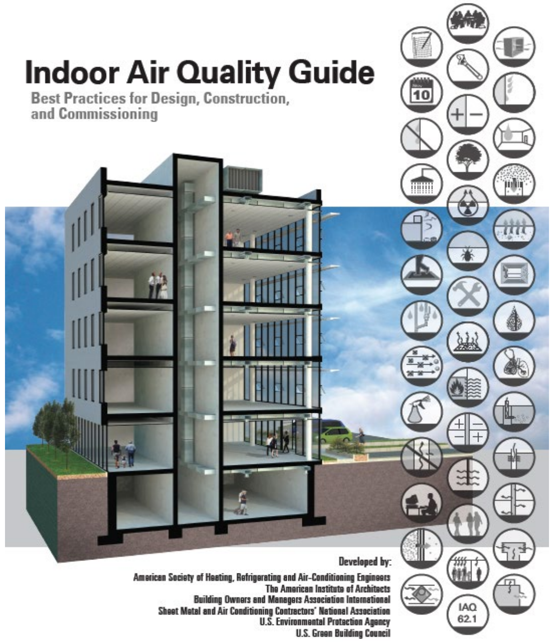
Key Points Regarding Environmental Monitoring of IAQ

From IAQ Guide – Appendix A - Environmental Monitoring

- Never measure anything unless the purpose of environmental monitoring has been clearly established and you know what you are going to do with the results. The specific target pollutants that will be measured and the reference concentrations that will be used for interpreting the results need to be defined before the monitoring and must fulfill the intended purpose for the monitoring effort.
- Short-term, localized measurements represent the conditions only at the place and time the sample is collected and cannot be assumed to represent the building more generally. Monitoring needs to cover a range of times and building operational and use conditions to enable a meaningful characterization of IAQ.
- Airborne concentrations of indoor-source pollutants are strongly dependent on concurrent outdoor air ventilation rates. Only by simultaneously measuring ventilation can concentration results be interpreted correctly, particularly variations over time.
- While it would be ideal to have a simple and easily used metric to quickly and inexpensively establish the acceptability of the IAQ, no such metric exists due to the wide range of pollutants in indoor air and the lack of knowledge regarding human responses to most pollutants and pollutant mixtures.



FREE DOWNLOAD

Detailed information can be found in Appendix A of the *Indoor Air Quality Guide*. The Guide is available for free download at ashrae.org/IAQGuide.

Measuring IAQ Constituents, *(Page 1 of 2)*

- At present, no single organization develops acceptable concentration limits for all substances in indoor air, nor are limits available for all potential design compounds or particles. However, cognizant authorities, such as the United States Environmental Protection Agency (U.S. EPA), California EPA, and the Committee for Health-Related Evaluation of Building Products publish concentration limits for compounds, many of which may be present in the indoor environment.
- As suggested by ASHRAE Standard 62.1, there is no quantitative definition of acceptable IAQ that can necessarily be met by measuring one or more contaminants (ASHRAE, 2022a). With thousands of gases, particles, and microbiological contaminants that can be in the air, direct measurement of most of these constituents is impractical and expensive. There is a lack of epidemiological or toxicological information regarding their impact on occupants within buildings, whether present individually or in various combinations.
- Information on International guidelines and standards is available in Siddique, A, et al., (2023) *Beyond the outdoors: indoor air quality guidelines and standards – challenges, inequalities and the path forward* https://doi.org/10.1515/reveh-2023-0150

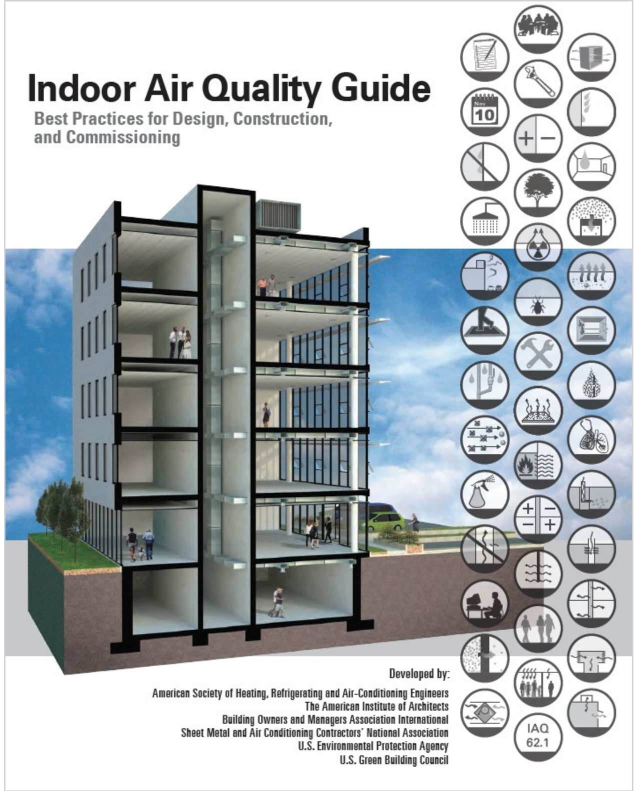
Measuring IAQ Constituents, *(Page 2 of 2)*

- Measurements can be continuous, time-integrated, or targeted.
- Continuous measurements are recommended, not just when a specific problem is identified.
- Targeted measurements involve spot-checks in specific building areas where issues are suspected or indicated by occupant complaints.
- Depending on the type of indoor air pollutant, time-integrated measurements may be conducted once or periodically. Besides direct IAQ measurements, it is crucial to consider factors affecting both the physical and perceived aspects of IAQ.

Temperature and Humidity

- Temperature and humidity should be monitored in occupied spaces.
- Air temperature is used for controlling thermostats.
- Humidity should provide feedback to humidification controls.
- In some cases, surface temperatures should also be measured for controlling humidification systems and energy optimization systems.
- Measurements should be recorded for management and evaluation.
- Temperature and humidity are components of **thermal comfort**.

Visit the Thermal Comfort topic page for more information.



Key Points

- Setting fixed minimum outdoor air (OA) damper position and other indirect methods are inaccurate.
- Direct methods can be accurate if applied properly.
- Providing enough OA at the intake may not be sufficient.
- Verify OA flow through commissioning.
- Provide documentation and training.

Detailed information, diagrams and strategies regarding outdoor air delivery can be found in Objective 7.2 within the *Indoor Air Quality Guide*. The Guide is available for free download at ashrae.org/IAQGuide.

Continuously Monitor and Control OA Delivery, *(Page 2 of 10)*

Use of fixed minimum damper position

- Still the most common method.
- Not accurate
    - Pct damper position ≠ pct OA
    - Damper position not repeatable due to mechanical play & wear
    - DP across opening varies with wind, etc.
- Careful balancing, Cx and periodic RCx warranted if used.
- Only recommended for small constant volume systems such as PTACs.

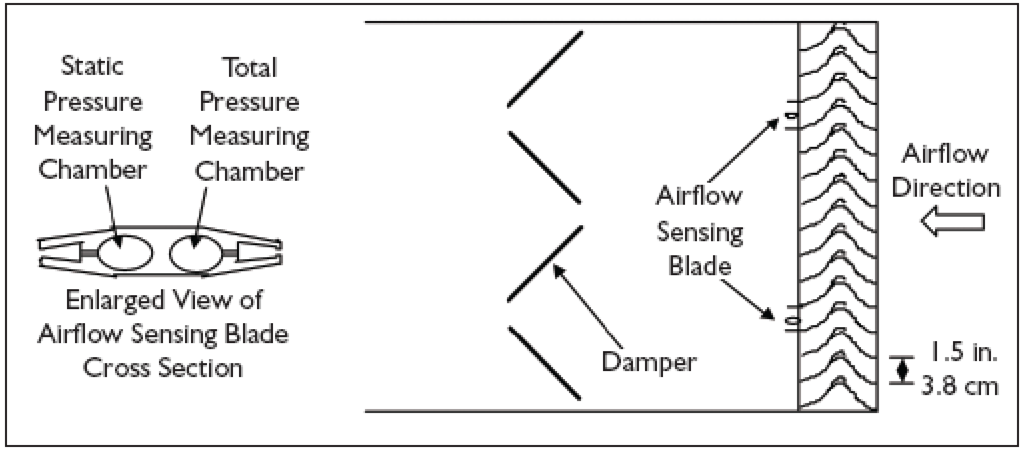
Continuously Monitor and Control OA Delivery, *(Page 3 of 10)*

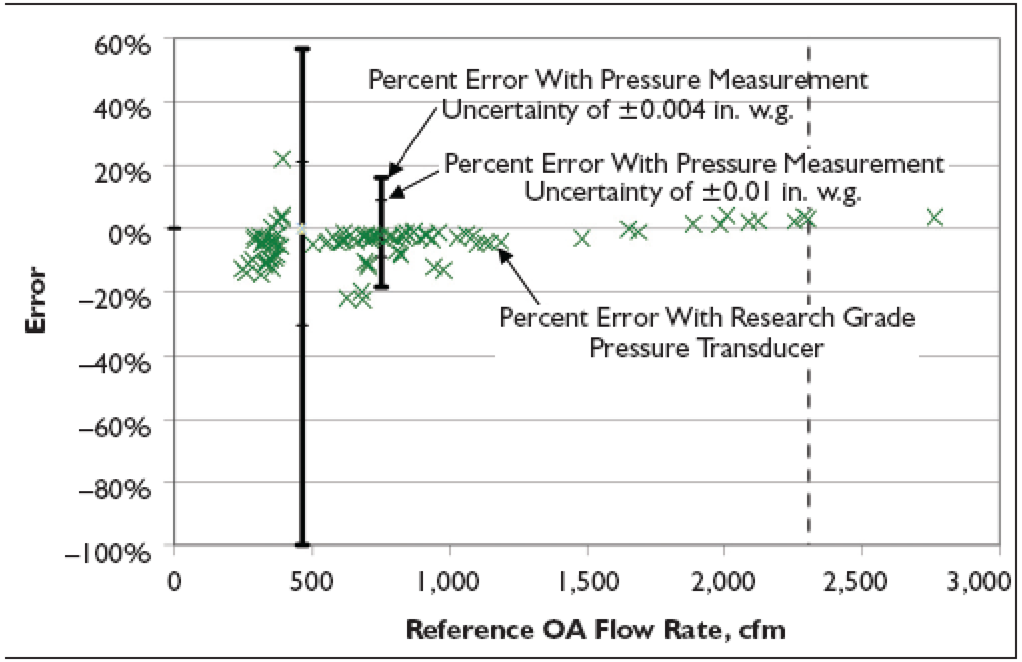
Direct Measurement

- Long, straight duct runs optimal but rarely possible.
    - 7-½ hydraulic diameters upstream of AFMS, 3 hydraulic diameters downstream
- Louver velocities are kept low to minimize entrainment of rain & snow (400-1000 fpm).
- Louvers often sized for max flow with economizer operation.
- Velocity pressure low at max flow and very low at minimum OA.
- Use separate minimum OA duct or non-pressure based air flow measurement technology.

Continuously Monitor and Control OA Delivery, *(Page 4 of 10)*

Direct measurement accuracy example 1: Airflow sensing blades downstream of louver blades

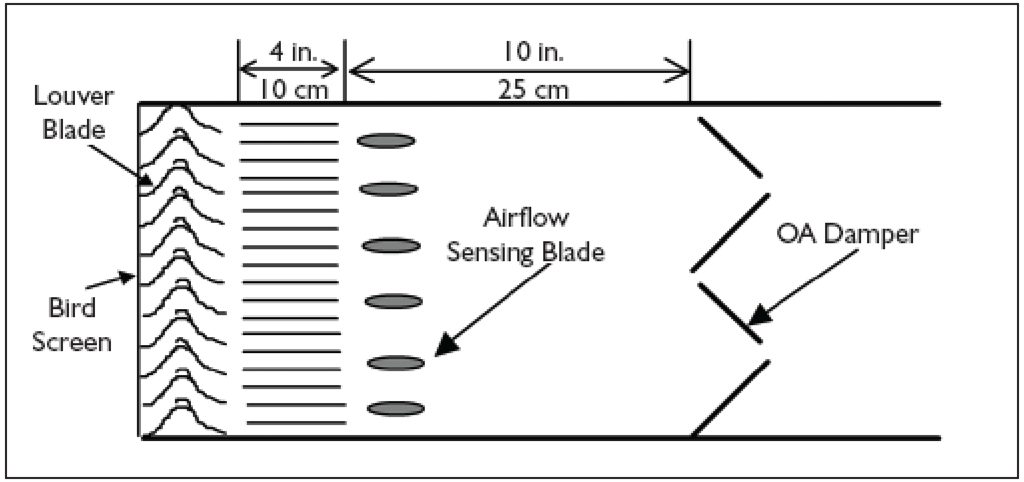


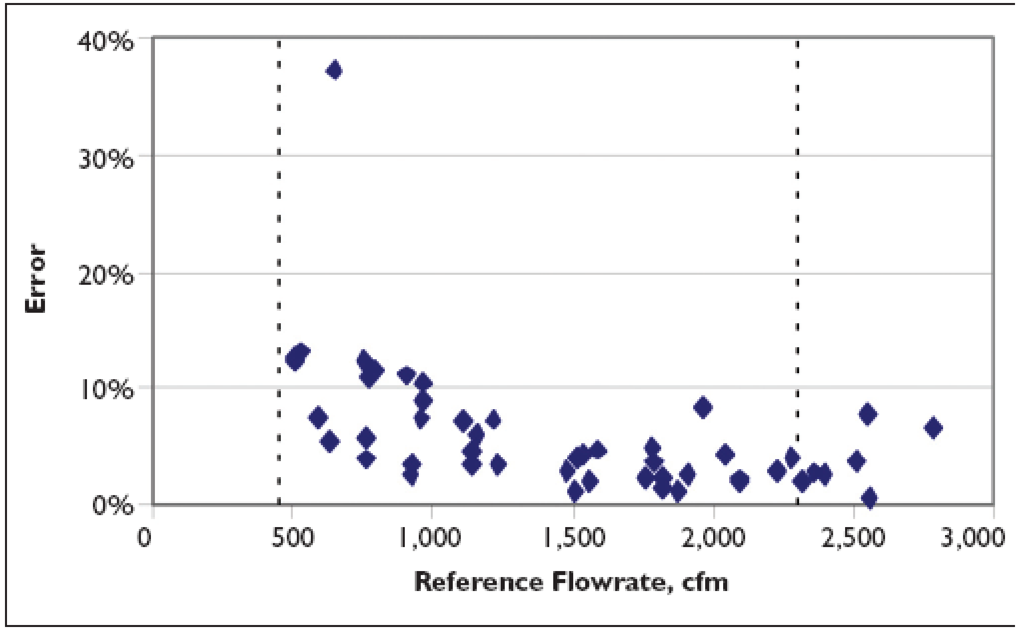


Fisk *et al. ASHRAE Journal* August 2006

Continuously Monitor and Control OA Delivery, (*Page 5 of 10*)

Direct measurement accuracy example 2: Honeycomb airflow straightener upstream of airflow sensing blades & straight duct section

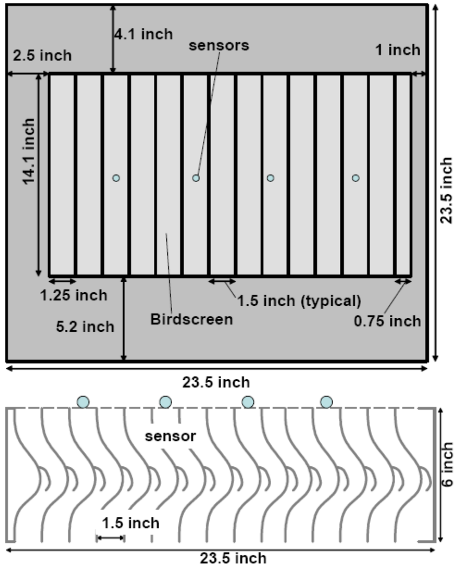


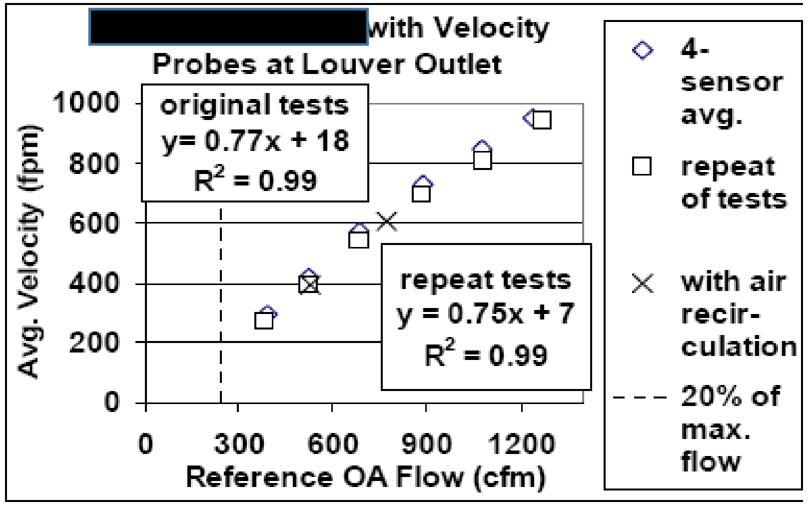


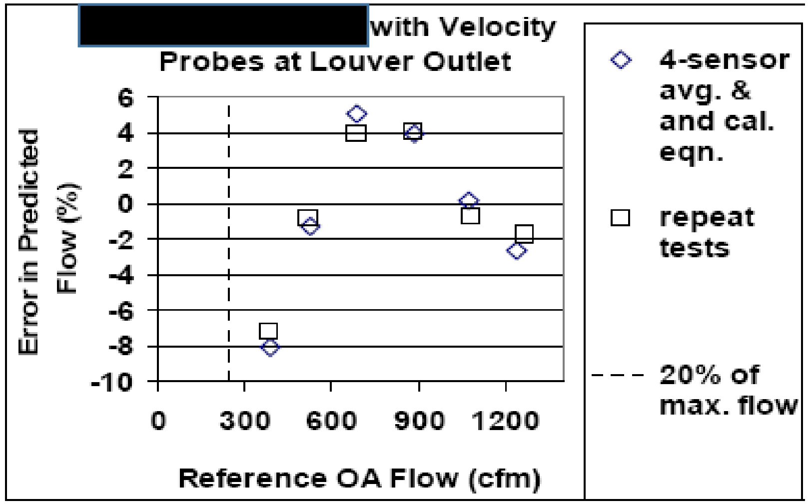
Fisk, *et al. ASHRAE Journal,* August 2006

Continuously Monitor and Control OA Delivery, *(Page 6 of 10)*

Direct measurement accuracy example 3:
Electronic air velocity probes between blades or on outlet face



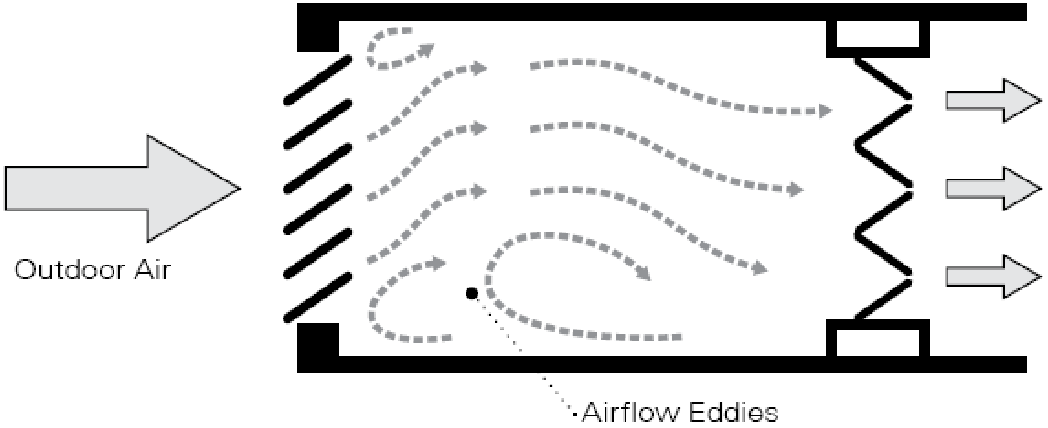




Fisk, William J, Douglas P Sullivan *Measuring Outdoor Air Intake Rates Using Electronic Velocity Sensors at Louvers and Downstream of Airflow Straighteners, 2008, https://indoor.lbl.gov/publications/measuring-outdoor-air-intake-rates*

Continuously Monitor and Control OA Delivery, *(Page 7 of 10)*

Sensor location



Fisk, William J, Douglas P Sullivan *Measuring Outdoor Air Intake Rates Using Electronic Velocity Sensors at Louvers and Downstream of Airflow Straighteners, 2008, https://indoor.lbl.gov/publications/measuring-outdoor-air-intake-rates*

Sensors installed between fixed louvers or on their outlet face may see higher, more uniform velocities and fewer eddies than sensors placed between louvers and dampers even with flow straightening device

Continuously Monitor and Control OA Delivery, *(Page 8 of 10)*

Indirect methods – generally inaccurate not recommended Action: upgrade to accurate method

- Plenum pressure control
- Supply air flow plus CO_2 concentration balance
- Supply air flow plus temp-based energy balance
- Supply flow minus return flow
- Return fan tracking supply fan (VFDs)
- Fixed minimum damper position

Continuously Monitor and Control OA Delivery *(Page 9 of 10)*

System considerations

- Continuous monitoring at OA intake alone does not ensure proper OA delivery to breathing zone in each space
  - Poor mixing in mixed air chamber
  - Poor delivery in space

Continuously Monitor and control OA Delivery, *(Page 10 of 10)*

- ✓ Verify minimum OA flows during Commissioning and occupancy.
- ✓ Provide easy access to sensors.
- ✓ Provide hardware and software that can sense sensor and equipment malfunctions.
- ✓ Document design criteria and occupancy assumptions.
- ✓ Train staff re: O&M needs.

Visit the Commissioning topics page for more information.

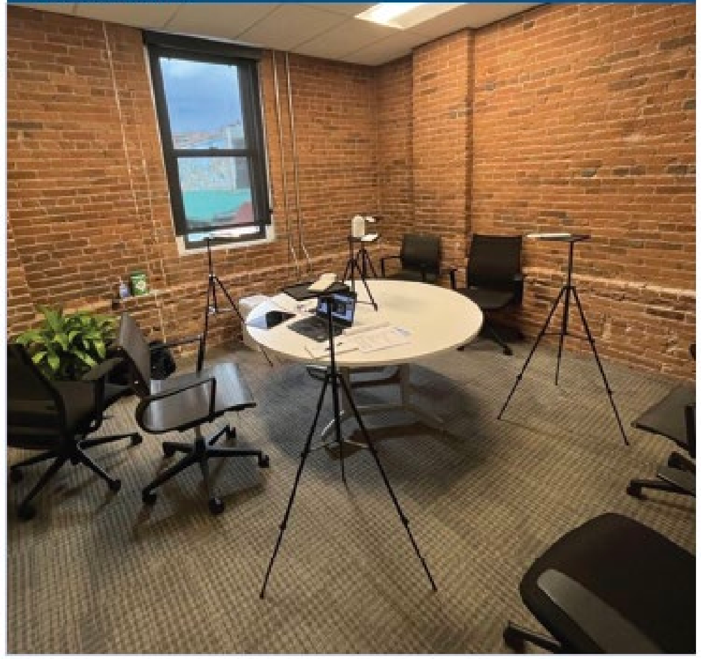
$PM_{2.5}$ —A measure for fine particles

- $PM_{2.5}$ should be controlled in most spaces by using recommended MERV13 filters in the HVAC equipment.
- When measured at least 90% of each sensor's dataset in occupiable spaces for $PM_{2.5}$, including intervals with missing data, should meet the recent EPA's threshold of 9 µg/m^3.
- $PM_{2.5}$ is a measure for fine particles in the (Disability-Adjusted Life Years) DALY evaluation. Health Effects Particles and Chemicals.

Addressing Particulate Matter

- Another method of addressing particulate matter especially as infectious aerosols is to measure particle counts.
- Methodology is currently published in ASHRAE Standard 241-2023 *Control of Infectious Aerosols*.
- Standard 241-2023 specifies equivalent clean airflow rate (ECAi) values per person based on occupancy.
- Equivalent rates can be verified using the methodology in Standard 241-2023 Appendix C.
- The distribution of the particle sizes must be accounted for in testing and in any comparison to mass measures such as EPA's threshold.

FIGURE 1 To directly measure the ECAi of a space, a quadrant configuration of four optical aerosol detectors is set up around an aerosol generator (on the table). A single test covers a maximum of 900 ft^2 (84 m^2). An inert salt aerosol tracer is released, and concentration change is monitored over time across key aerosol particle size ranges.



Kottapalli, K., Zaatari, M., Jackson, M., and Molyneux, S., "Aerosol Tracer Testing Comes of Age in ASHRAE Standard 241", *ASHRAE Journal*, September 2024

Formaldehyde

- Formaldehyde is difficult to measure. Limits in 62.1-2022 IAQP are:

Table 6-5 Design Compounds, PM2.5, and Their Design Limits

Compound or PM2.5	Cognizant Authority	Design Limit
Formaldehyde	Cal EPA 8-hour CREL (2004)	33 µg/m³

- Test methods include:

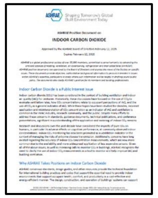
Table 7-1 Allowed Laboratory Test Methods

Compound	Allowed Test Methods
Formaldehyde, acetaldehyde and acetone	ISO 16000-3; EPA TO-11; EPA IP-6; ASTM D5197

- Use low emitting materials and avoid air "cleaners" that modify chemistry and may produce formaldehyde as a byproduct

Indoor CO_2

- Indoor CO_2 concentrations are not overall indicators of IAQ, but they can be a useful tool if users understand how they relate to IAQ and the important limitations of their use.
- Differences between indoor and outdoor CO_2 concentrations can be used to evaluate outdoor ventilation rates and air distribution using established tracer gas measurement methods, but accurate ventilation measurements require the validity of several assumptions and accurate input values.
- Existing evidence for direct impacts of CO_2 on health, well-being, learning outcomes, sleep patterns, and work performance at commonly observed indoor concentrations is inconsistent.
- Sensor performance, location, and calibration are all critical for drawing meaningful inferences from measured indoor CO_2 concentrations.



See ASHRAE's Position Document on Indoor CO_2 for more details.

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CO_2 and Demand Control Ventilation (DCV), *(Page 1 of 2)*

- Using CO_2 to control outdoor air ventilation rates, called Demand Control Ventilation (DCV), has become increasingly popular to achieve energy savings in buildings that have varying occupancy rates.
- DCV is also a mandatory requirement for densely occupied spaces in ASHRAE Standard 90.1, but the standard provides no details how to implement DCV nor does it specifically mention CO_2.
- This addendum adds differential CO_2 concentration limits above ambient to Table 6-1 specifically for use with CO_2 DCV systems.
- Ambient concentration can be determined with ambient CO_2 sensors but is allowed to be assumed to be 400 ppm.
- these CO_2 values are actually limits that the control system must always maintain space concentration to be at or below.
- DCV logic must increase ventilation proportional to zone CO_2 concentration increases above ambient. Because the people- and area-based ventilation rates are additive, the control logic cannot wait until zone CO_2 concentration nears the maximum limit before increasing ventilation.

Download *Addendum ab to ASHRAE 62.1-2022* for further details.

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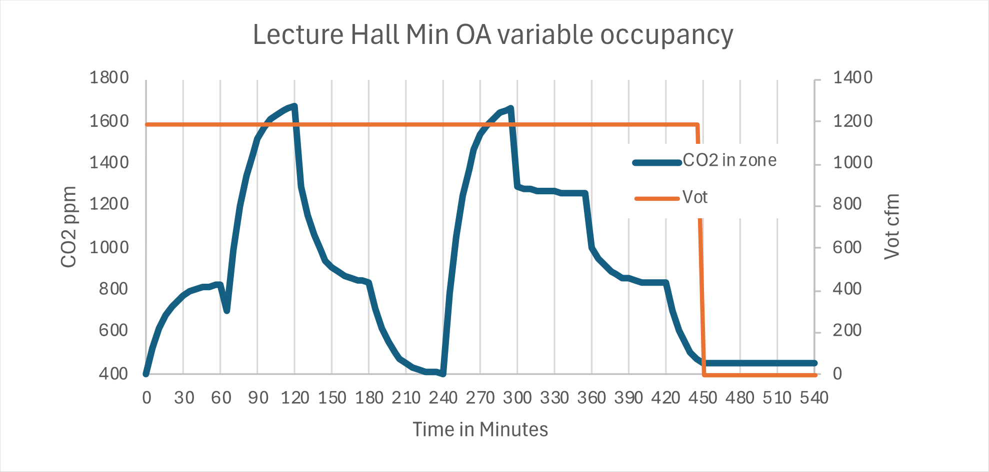
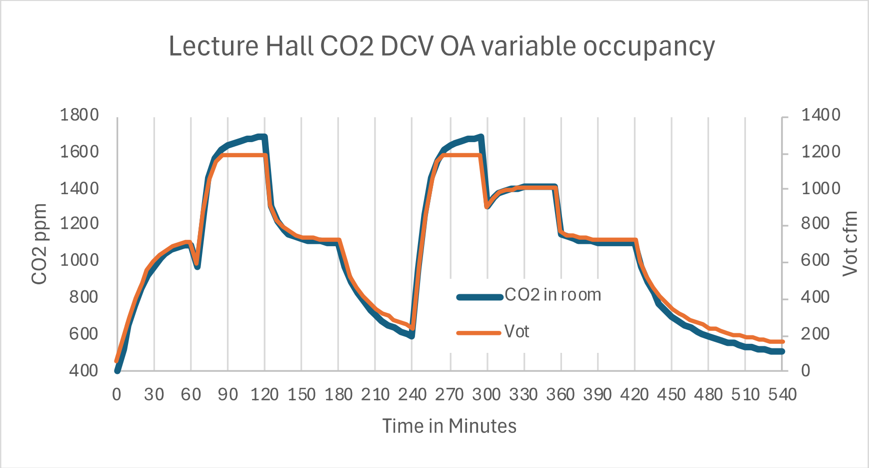
CO_2 and Demand Control Ventilation (DCV), *(Page 2 of 2)*

- Example: Lecture hall in University with and without CO_2 DCV
- Proper operations using minimum OA with Variable Occupancy (different class sizes). No DCV vs w/CO_2 DCV using proportional control





- Conclusions: CO_2 levels fluctuate with time and will vary between 400 ppm and 1700 ppm.
  The only way to track is with continuous monitoring and recording. Grab samples have little meaning.

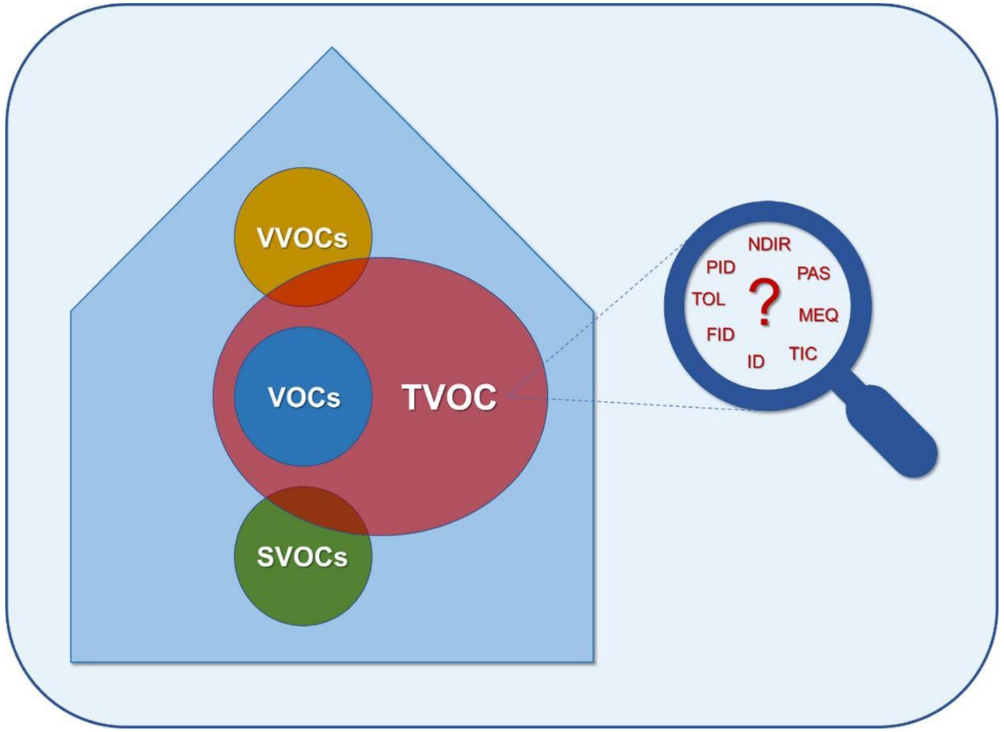
Charts courtesy of Hoy Bohannon.

Other Contaminants

- Ozone should be managed through source control for indoor sources and filtration for ozone in the outdoor air as required by ASHRAE Standard 62.1-2022.
- CO and NOx are associated with combustion and should be measured and monitored when combustion is in or near the building.
- If sensors provided also measure total volatile organic compounds (TVOC), it should only be used in a relative, not absolute, sense because no standard definition of TVOC exists. If certain occupied spaces have significantly higher TVOC levels compared to others, or if TVOC measurements fluctuate, this should prompt further diagnostics.
- Other chemicals may be present, and other standards may be applicable in industrial spaces.

Total Volatile Organic Compounds (TVOC)

- Some organizations and government agencies have established IAQ metrics and measures that include TVOC.
- If measuring TVOC, the technical basis for the methods and relevance to the building should be understood.
- "*It was recognized early that TVOC is not a toxicologically based parameter and is therefore only suitable for a limited number of screening purposes. Consequently, TVOC cannot be used in connection with health-related and odor-related issues. Nevertheless, such references are repeatedly made, which has led to controversial scientific discussions and even court decisions in Germany about the correct and improper use of TVOC.*"



Tunga Salthammer,TVOC - Revisited, Environment International, Volume 167, 2022, 107440, ISSN 0160-4120, https://doi.org/10.1016/j.envint.2022.107440.
(https://www.sciencedirect.com/science/article/pii/S0160412022003671)

Occupant Surveys

Evaluate Occupant Experiences: Subjective Through Surveys, *(Page 1 of 3)*

Occupant ratings of IAQ acceptability and satisfaction:

- Help to identify IAQ problems in buildings.
- Can focus attention on conditions where IAQ is considered unacceptable, allowing for correlation with environmental measurements to detect potential causes of dissatisfaction.
- Review IAQ complaints log and similar reports of continuing or episodic concerns, previous occupant satisfaction surveys, and/or IAQ audits as well as related environmental, health, and safety surveys.
- Review of previous field observations can identify need for more frequent assessments.
- Allow benchmarking against peer buildings.

Evaluate Occupant Experiences: Subjective Through Surveys, *(Page 2 of 3)*

Conduct occupant surveys in a completed and substantially occupied building using existing surveys, such as the CBE (2024) or BUS (2024).

Anonymous surveys with neutrally framed questions provide the best responses. When conducting an evaluation of adapted occupants, respondents should record their perception of zone air quality after 30 minutes of residency in the occupied zone. Ideally, occupants in each regularly occupied zone of a building should be surveyed.

The survey should encompass questions related to acceptability and satisfaction with indoor air quality. The survey questions may also include perceptions of fresh air, stuffiness, the presence and intensity of odors, their pleasantness, etc. An example of the acceptability question could be "*Do you perceive the air quality in your environment to be acceptable or unacceptable?*". An example of a satisfaction question could be "*How satisfied are you with the air quality in your building?*" The satisfaction ratings can be evaluated on a 7-point Likert scale; from –3 (very dissatisfied) to +3 (very satisfied), where zero denotes neutral state (neither satisfied nor dissatisfied).

Evaluate Occupant Experiences: Subjective Through Surveys, *(Page 3 of 3)*

Occupant surveys can be executed through web-based, paper-based, or interview-based methods. Web-based surveys have gained popularity due to their ability to significantly reduce administration costs, and to expedite the data collection and analysis process. All surveys should aim for a representative sample size and a high response rate across the occupied spaces. A minimum 30% response rate from those surveyed is desirable assuming substantial occupancy. A 40% response rate to a general survey of all occupants is generally considered sufficient for evaluating occupancy satisfaction in buildings with substantial occupancy.

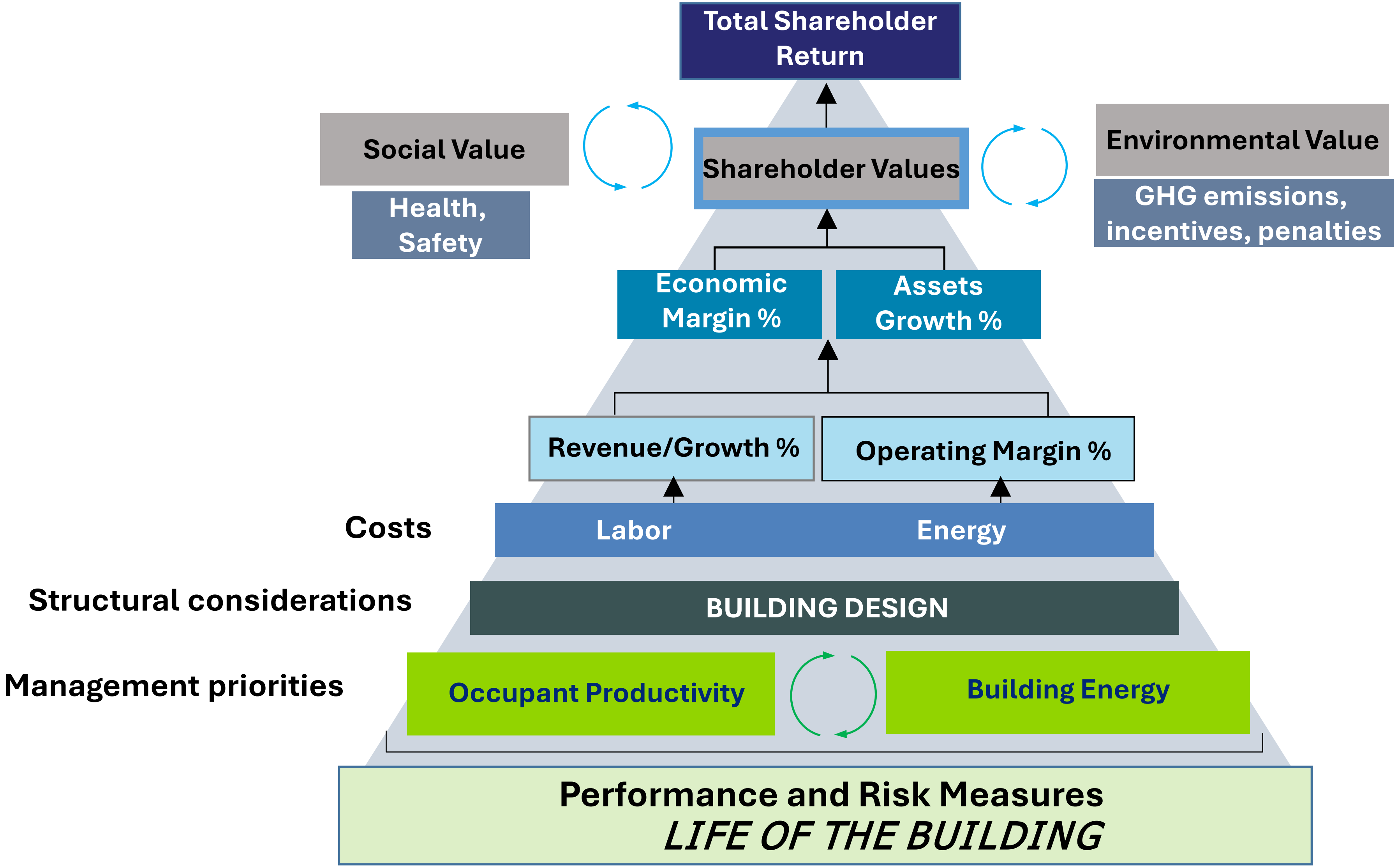
The occupant survey conducted at this level focuses on ratings of acceptability and satisfaction, specifically assessing the IAQ response of building occupants over a designated period (e.g., 6 or 12 months). In the case of a new building, the first IAQ survey may be conducted approximately six months after occupancy – late enough to avoid assessing the effects of commissioning but early enough to identify and address any long-term building issues that may have escaped detection during commissioning.

If the results are communicated to building occupants, it should be done on an aggregated basis, such that no individual occupants can be identified.

MANAGEMENT

- Reporting and data ownership
- Evaluate return on investments

For Each Building Type, Identify The Stakeholders Who Most Experience the Cost/Benefit of Healthy Occupants



Courtesy of Stephanie Taylor, MD

Segment	Senior Living Communities: Director of Facilities; Infection Prevention; Nursing Staff; Sales & Marketing; CFO, Investors
Value Proposition	Keep your residents and staff safe, healthy, and productive using science-backed strategies to optimize indoor air quality (IAQ) for health

Challenges

Costs and reimbursement penalties for Healthcare-associated infections (HAIs)	Patient / family satisfaction, and resident retention	Resident attraction, competitive pressures	Staff satisfaction / retention	Liability for patient health and safety	Lack of consistency of service across building portfolio	Decarbonization / net zero commitments	Operating margins / ROI	Staff health, safety, absenteeism, medical insurance copayments (for self-insured)	Government regulations, facility closures for failed inspections, poor quality rankings

Value Pillars

Value Drivers

Enables

Deliver healthier environments of care rooted in medicine

IAQ health score introduces occupant considerations into facility management

- Fewer incidences of airborne infectious diseases
- Reduced cognitive decline, falls, anxiety, and psychosis in residents
- Faster recovery times from falls and other injuries
- Greater staff retention & productivity, reduced absenteeism, acquisition of premium clinical staff
- Better visualization and management of indoor and outdoor air quality metrics that impact human health
- Improved resident satisfaction surveys that drive higher CMS reimbursement

Reduce healthcare-associated infections (HAIs)

Robust IAQ data and integrated analysis leads to effective prevention and intervention measures

- HAIs result from inadequate control of pathogen transmission, patient health vulnerabilities, and environmental reservoirs of infectious microbes; improving IAQ reduces the risk of transmission via air
- Ability to charge higher rates (seen as premium care provider above competitors)
- Reduce isolation and quarantine direct costs and staffing requirements
- Achieve higher operating margins as expenses from HAI management are reduced
- Provide discounted insurance premiums for optimized Environment of Care

Benchmark facility performance across portfolio

Alignment on value and science behind IAQ score from top to bottom

- IAQ scores stand as a health performance indicator (HPI)
- IAQ score thresholds can be adjusted based on occupant vulnerabilities from age and medical conditions (e.g. lung, heart, cognitive impairments)
- Centralization and standardization of facility management and HPIs

Meet your decarbonization AND patient health / safety goals

Informed decisions lead to appropriate energy use to optimize IAQ

- Analyzing impact of IAQ on health provides optimized target for energy spent
- Comparing the health impact of indoor and outdoor air quality provides a data-based methodology for optimum economizing
- Potential for utility rebates (depending on state/locality)

Courtesy of Stephanie Taylor, MD

Reporting and Data Ownership, *(Page 1 of 2)*

- The target audience for the IAQ measurement methods depends on the purpose of the measurement: benchmarking, IAQ audits, responding to complaints, retro-commissioning, capital planning, new building commissioning, controls and operation, financial audits, sustainability reporting, tenant attraction (e.g., employee recruitment and retention), big data analysis or research.

- For each of these use cases, there are different users of the data, including: tenants/occupants, building owners/owner's reps., architects, consulting engineers/facility managers, building raters, government agencies/legal counsel, building service companies, manufacturers/product suppliers, commissioning specialists and researchers.

Reporting and Data Ownership, *(Page 2 of 2)*

- The data collected is normally owned by the building owner who is responsible for deciding whether to release the data associated with the performance evaluation.

- Publishing or sharing such data without the express consent of the building owner subjects the distributor of the data to legal liability.

- When poor IAQ poses serious health issues, ethical considerations suggest that occupants have a right to know about conditions that may affect their health because transparency is critical to ensure the safety and well-being of occupants.

- Building owners and managers must consider how to communicate these findings and take prompt corrective actions. This can sometimes create a tension between maintaining confidentiality and the need for disclosure to protect public health. Balancing these interests requires careful judgment and, where appropriate, consultation with legal and health professionals to determine the best course of action.

Ethical Considerations Affecting Data Transparency

- When poor building performance poses serious health issues, transparency is critical to ensure the safety and well-being of occupants. Building owners and managers must consider how to communicate these findings and take prompt corrective actions.

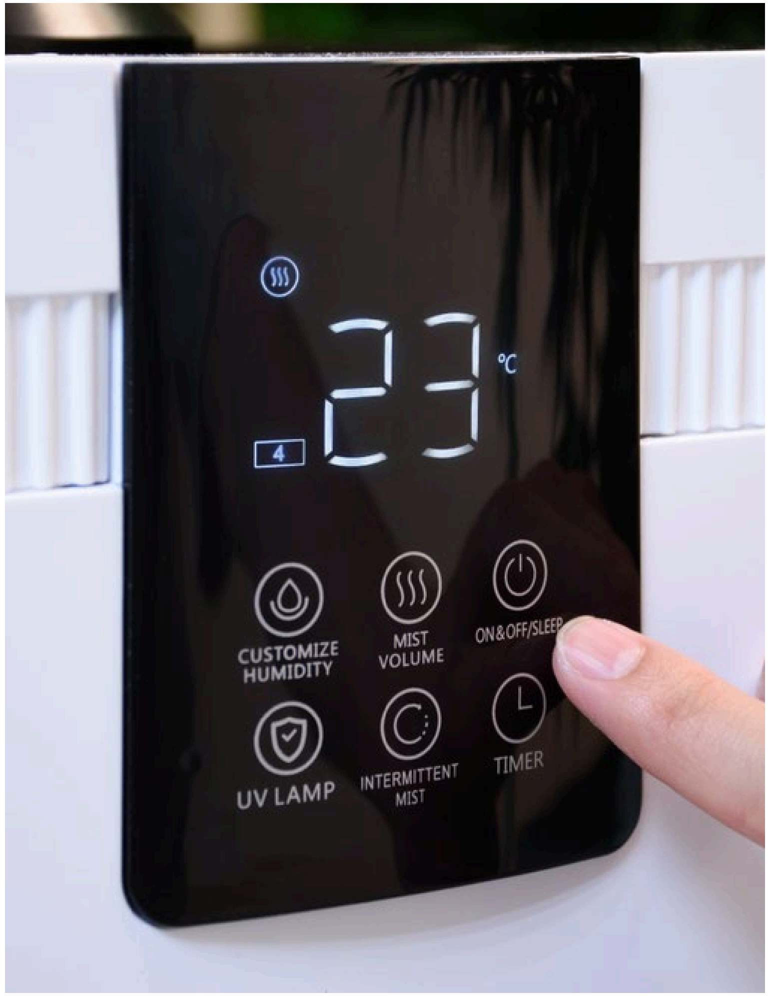
- Ethical considerations suggest that occupants have a right to know about conditions that may affect their health. This can sometimes create a tension between maintaining confidentiality and the need for disclosure to protect public health. Balancing these interests requires careful judgment and, where appropriate, consultation with legal and health professionals to determine the best course of action.

ACTION - Humidity

A) Control Humidity

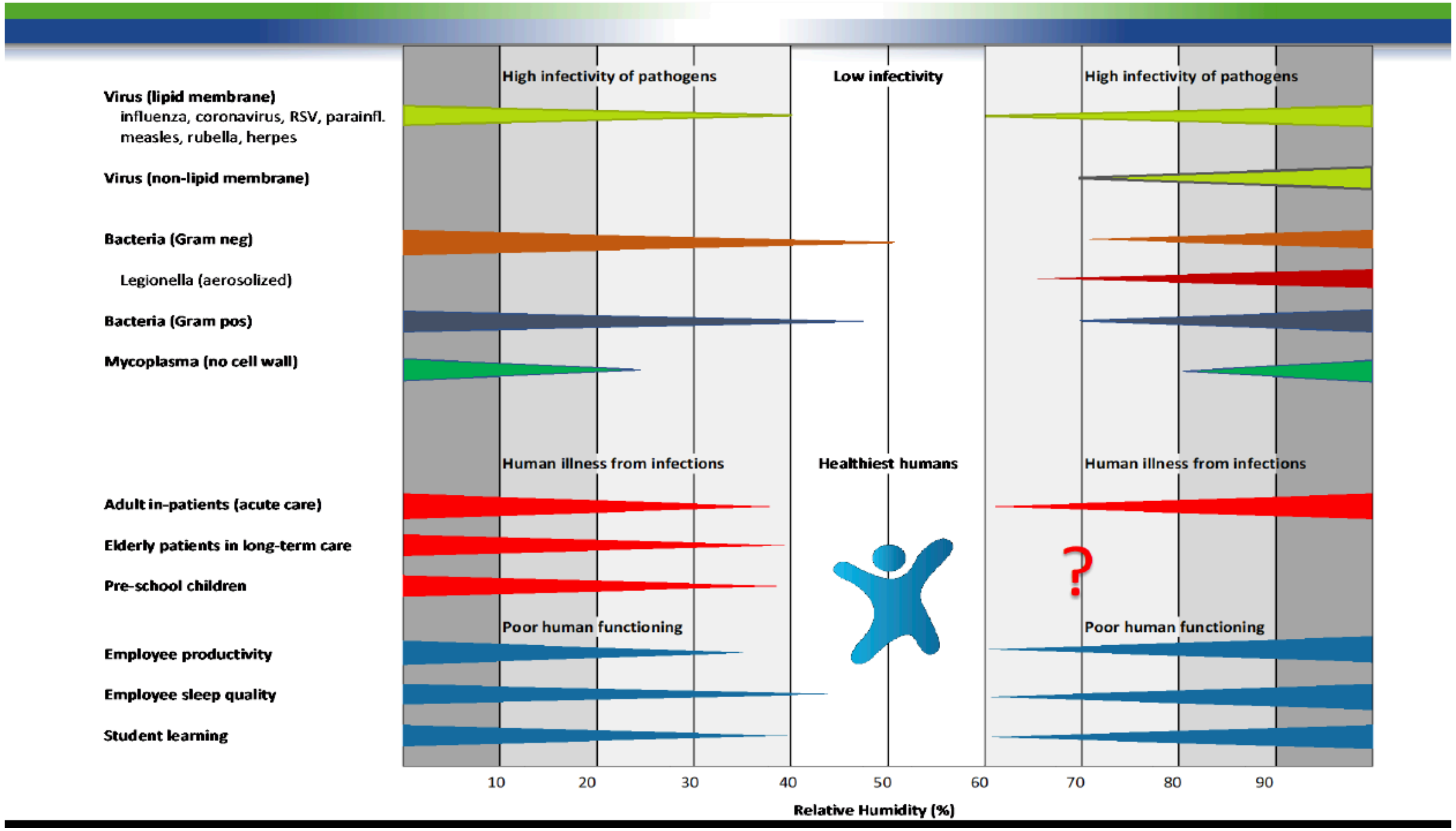
B) Control contaminant concentration through operation of ventilation and air cleaning systems.

C) Improve effectiveness of filtration and air distribution.



Humidity Control – What We Knew Last Century Still Holds

35 years later….. Taylor Chart 2019



Courtesy of Stephanie Taylor, MD

Humidity Control

- Control Moisture from Building Assemblies
- Control Moisture and Contaminants from Mechanical Systems
- High Humidity
- Low Humidity
- Building Pressurization

Control Moisture in Building Assemblies

The following objectives are outlined in the IAQ Guide:

2.1 - Limit penetration of liquid water

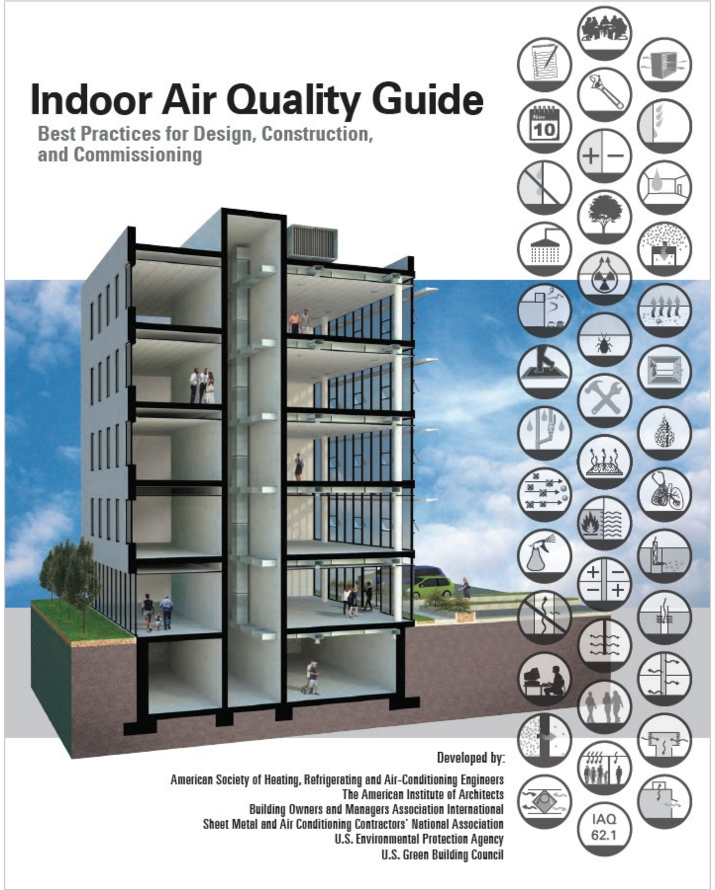
2.2 - Limit condensation of water vapor within the building enclosure

2.3 - Maintain proper building pressurization

2.4 - Control indoor humidity

2.5 - Select suitable materials/equipment/assemblies for areas that are unavoidably wet

2.6 - Consider impacts of landscaping and indoor plants



FREE DOWNLOAD

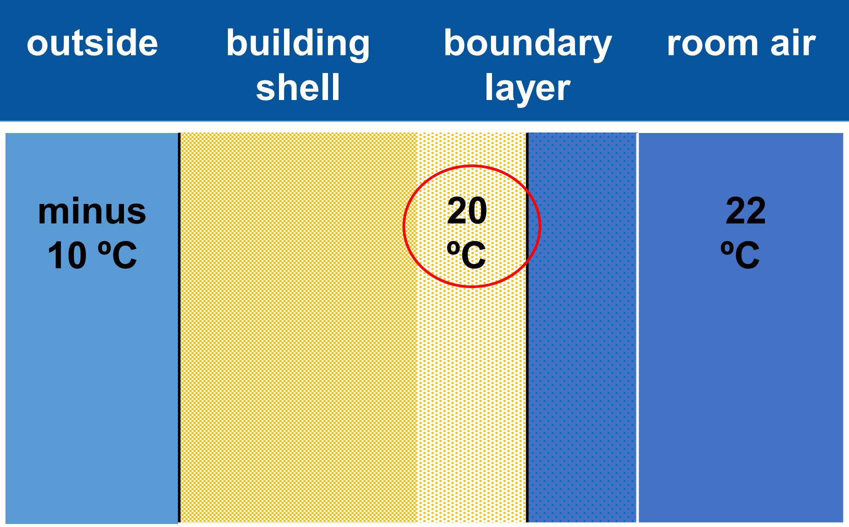
Detailed information, diagrams and strategies regarding moisture control can be found in Objective 2 within the *Indoor Air Quality Guide*.
The Guide is available for free download at ashrae.org/IAQGuide.

Limit Penetration of Liquid Water

Key Points

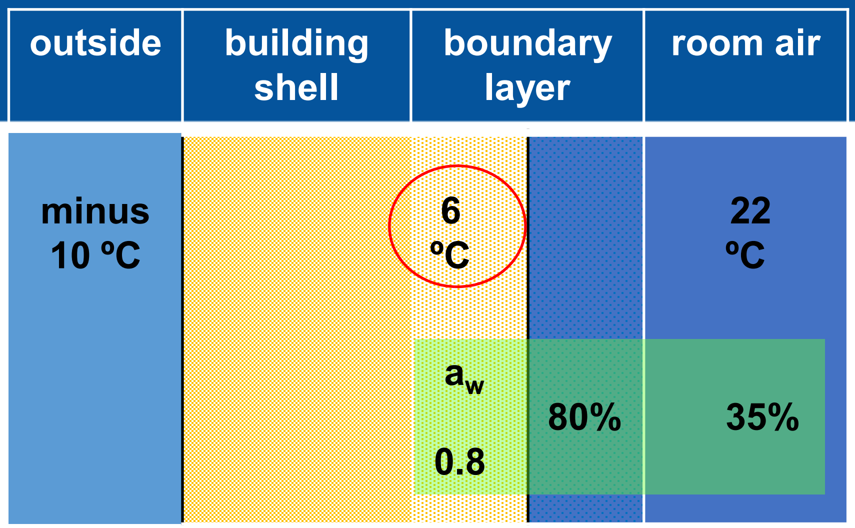
- **Design**
  - Continuous drainage plane
  - Capillary breaks
  - Site drainage
  - Contract documents
- **Quality control**
  - Pen test
  - Submittals/shop drawings
  - Water penetration testing
  - Construction observation

Good insulation properties



R-value = 0.25 W/m²K

Bad insulation properties



R-value = 2.0 W/m²K

With identical air temperatures for outside and inside air, the difference reveals in the inner surface temperature of the wall.

Wall condensation on the wall only starts when RH **> 95 percent.**

Wall condensation starts with RH > **35 percent**.

Courtesy of Stephanie Taylor, MD

Control Moisture and Contaminants Related to Mechanical Systems

The following objectives are outlined in the IAQ Guide:

4.1 - Control moisture and dirt in air handling systems

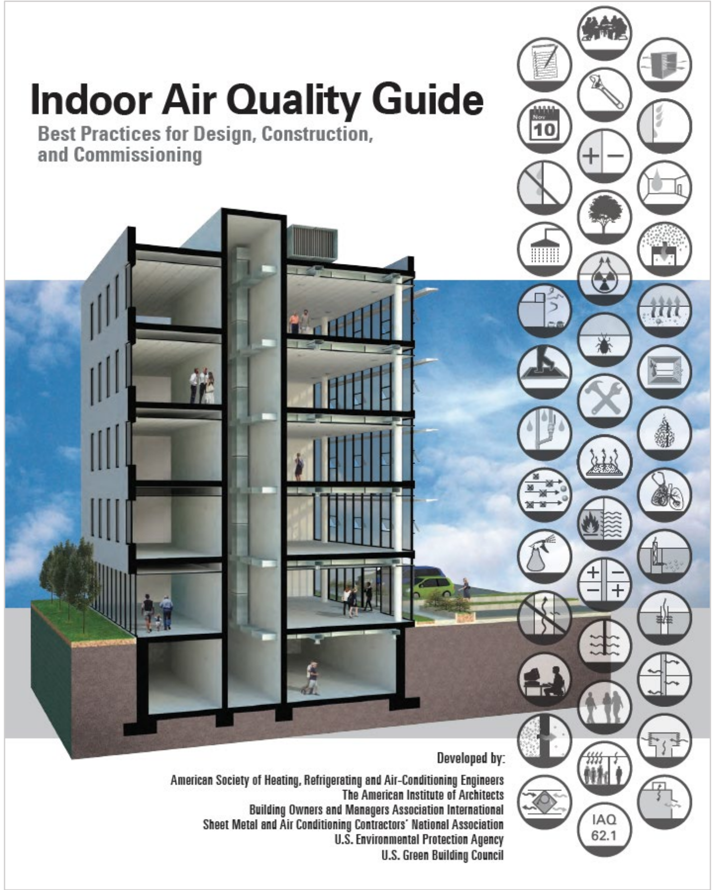
4.2 - Control moisture associated with piping, plumbing fixtures and ductwork

4.3 - Facilitate access for inspection, cleaning and maintenance

4.4 Control *Legionella* in water systems

FREE DOWNLOAD

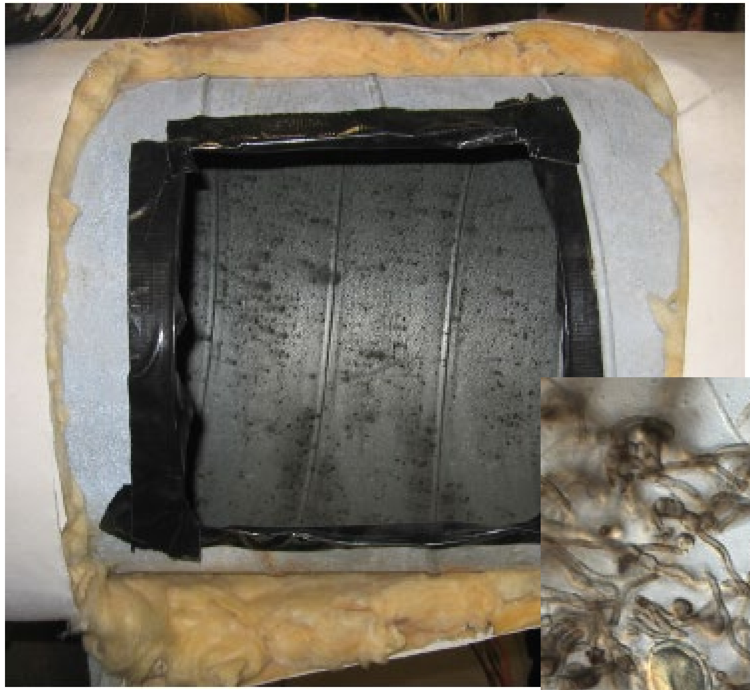
Detailed information, diagrams and strategies regarding moisture control can be found in Objective 4 within the *Indoor Air Quality Guide*.
The Guide is available for free download at ashrae.org/IAQGuide.



Control Moisture and Dirt in Air Handling Systems, *(Page 1 of 6)*

A Few Key Points

- ✓ Moisture + dirt (food) = critters
- ✓ Minimize entry of moisture and dirt at air intakes and areaways
- ✓ Use higher efficiency filtration to keep systems clean; keep filters dry
- ✓ Make sure drain pans drain
- ✓ Minimize condensate carryover
- ✓ Provide smooth, cleanable surfaces
- ✓ Select humidifiers to avoid carryover of microbes in water droplets
- ✓ Minimize rain and snow intrusion
- ✓ Recognize that below-grade and grade level OA intakes are most susceptible to entry of leaves, pesticides, fertilizers, etc.
- ✓ If below-grade or grade level intakes are used, provide easy access for cleaning
- ✓ Provide smooth, corrosion-resistant, cleanable OA intakes



Photos courtesy Phil Morey, *Indoor Air Quality Guide*

~400x

4.1

Control Moisture and Dirt in Air Handling Systems, *(Page 2 of 6)*

Filtration

- Dust = food for microbes.
- Standard 62.1-2022 - MERV 8 upstream of coils.
- High efficiency filtration helps keep food out of wet biological niches in HVAC systems (MERV 11 good, MERV 13 better).
- Locate filters where they will stay dry, and provide for periodic inspections (O&M) to ensure they stay dry.

This image shows a dirty coil not protected by adequate filtration.

Photo courtesy Center for Energy & Environment

Control Moisture and Dirt in Air Handling Systems, *(Page 3 of 6)*

Trap depth

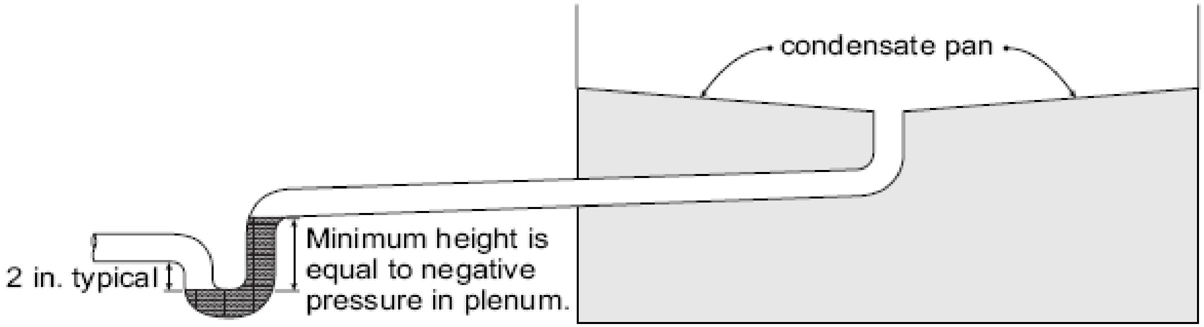


Figure 5-T—

ANSI/ASHRAE Standard 62.1-2007 User's Manual

Make sure drain pans drain

- Slope 0.125 in./ft; make sure AHUs with integral pan are level so pan slopes as intended
- Drain hole at lowest point flush with bottom.
- P-trap deep enough to maintain seal and allow water to drain under maximum negative pressure created by fan.
- Verify proper drainage through commissioning.
- Train operators to locate, properly inspect (slimy?) and physically clean pans.

Control Moisture and Dirt in Air Handling Systems, *(Page 4 of 6)*

Drain Pans Example

- Drain pan inspected due to building- related symptoms and illnesses in area served
- Poor access (10 fasteners)
- Outlet not flush w/bottom
- Biofilm – gelatinous mass of fungi, bacteria and protozoa

Photo courtesy Phil Morey, *Indoor Air Quality Guide*

Control Moisture and Dirt in Air Handling Systems, *(Page 5 of 6)*

Photos courtesy Center for Energy & Environment

Drain Pan Condensate Carryover

- Wide enough to collect water droplets across entire width
- Extend downstream at least half the height of the coil
- Extend as far as necessary to limit carryover to 1.5 ml/m^2 (!) per hour under peak conditions (0.0044 oz/ft^2)
- High face velocity causes carryover: with non-uniform airflow, local face velocity far exceeds average

Control Moisture and Dirt in Air Handling Systems, *(Page 6 of 6)*

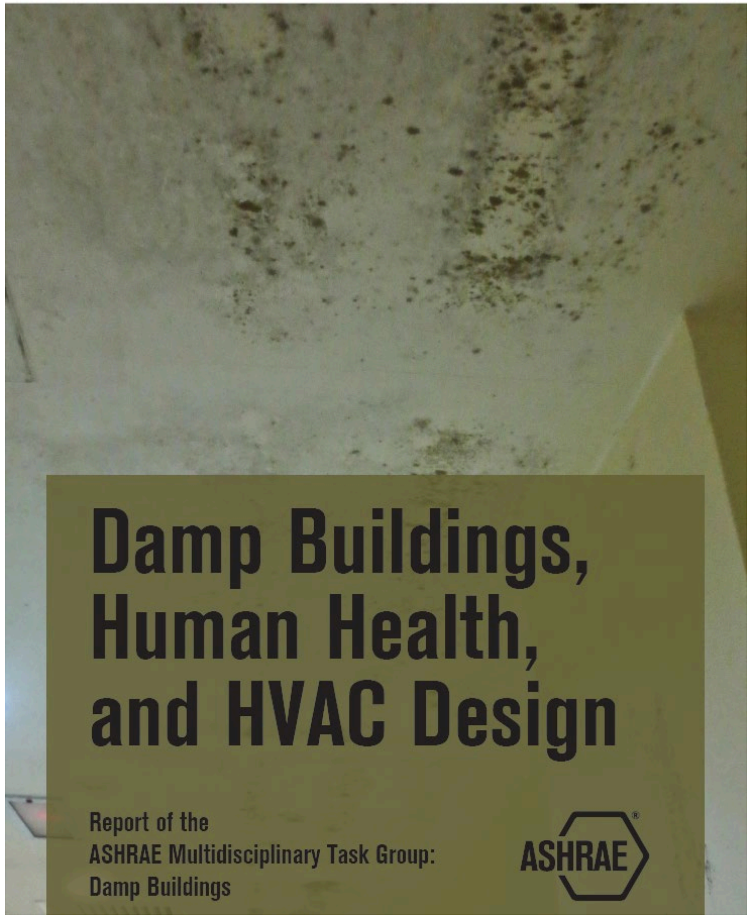
Consider acoustic solutions that don't require porous liners

- Equipment selection, sizing and location
- Proper air distribution design: sizing, velocity, fabrication integrity, diffuser selection
- Double-wall ductwork

Photo courtesy Phil Morey, *Indoor Air Quality Guide*

Critters can grow on smooth but dirty surfaces, but growth is usually greatest on porous or irregular surfaces.

High Humidity, *(Page 1 of 4)*

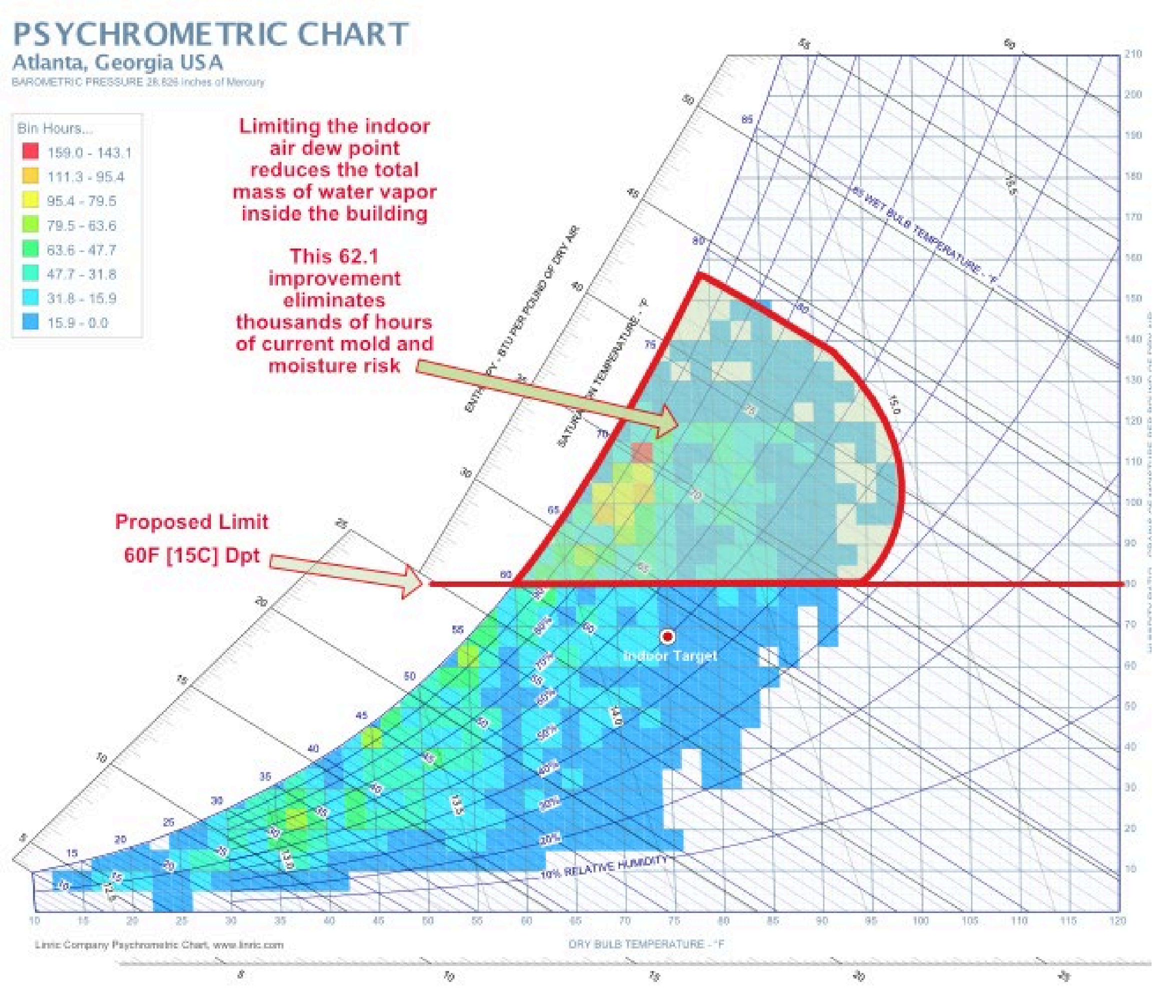


Damp Buildings, Human Health and HVAC Design was prepared by the ASHRAE Multidisciplinary Task Force Group: Damp Buildings. It provides a summary of what is understood within ASHRAE about dampness-related health risks in buildings as well as suggestions for HVAC system designers that can help avoid such risks. As readers understand, knowledge advances over time; this report summarizes the state of understanding of volunteer experts within the Society as of 2019.

FREE DOWNLOAD

This report is available for free download at ashrae.org.

High Humidity, *(Page 2 of 4)*



ANSI/ASHRAE Standard 62.1-2022
MOISTURE Requirements
Section 5.12

Less than 60F dewpoint

High Humidity, *(Page 3 of 4)*

Chilled Beams and Other Chilled Surfaces such as Radiant Ceilings

Operational Considerations (2023 ASHRAE Handbook—*HVAC Applications* p 58.37)

Water supply service to active and passive beams should not be activated until space dew-point temperatures are at or below the chilled water's supply temperature.

Where maintenance of adequate space dew-point temperatures cannot be ensured, some type of condensation detection and mitigation strategy should be used. There are various methods of accomplishing this, including the following:

- Sensors
- Dew-point calculation
- Windows
- Condensate trays

High Humidity, *(Page 4 of 4)*

Chilled Beams or Cooled Ceilings

Raining from Chilled Beams?

What to do?

Chilled beams are usually installed with DOAS (dedicated outdoor air systems). The DOAS should be designed to deal with both the outdoor air and indoor latent (moisture) loads. The chilled beam temperature is below the dewpoint of the air if it has water on the surface. The issue has to do with coordinating the dewpoint of the DOAS supplied air and the latent load with the chilled water temperature within the beam. **The place to start diagnosis is with the control system.**

Humidity Control

Building Interactions

Figure 2.4-E illustrates building interactions. The details that follow the figure explain the effects demonstrated in the diagram.

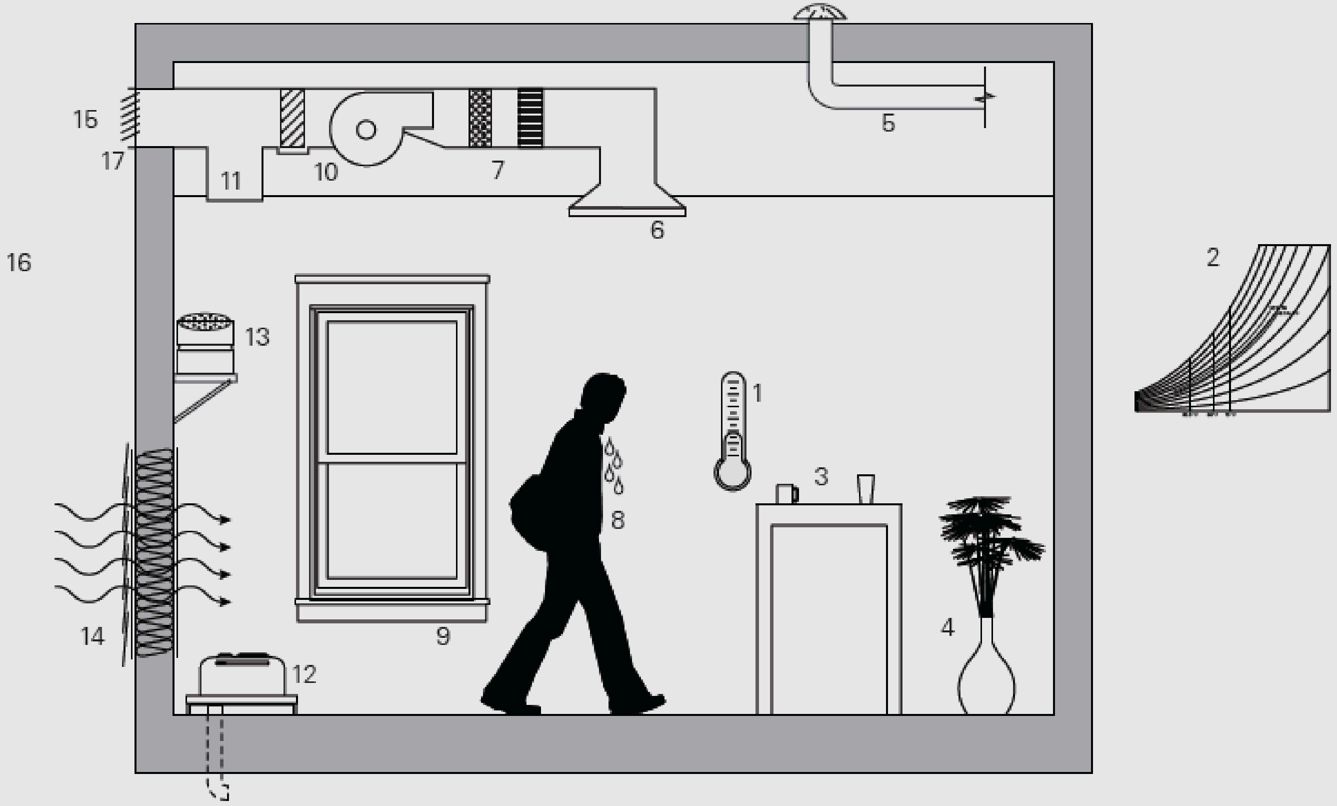


Figure 2.4-E Building Interactions

Humidity control can be complex.

The 17 factors illustrated are discussed in detail on page 304 of the *Indoor Air Quality Guide*, available for free download at ashrae.org/IAQGuide.

Energy Recovery Ventilation

- Energy recovery ventilation can help control humidity.
- Exhaust contaminant transfer must be considered.

Using Energy Recovery System to Control Humidity

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

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

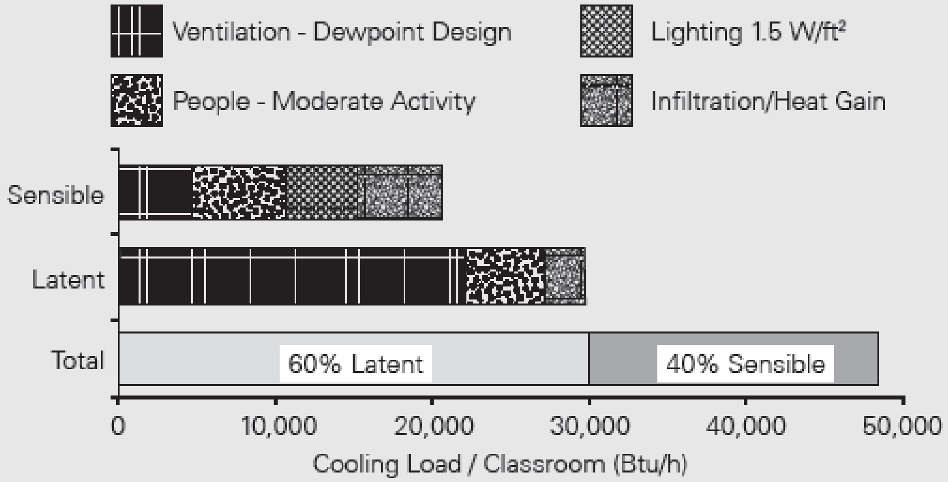


Figure 8.2-A Sensible and Latent Loads for a Typical Classroom in Atlanta

Health Effects – Humidity and Influenza

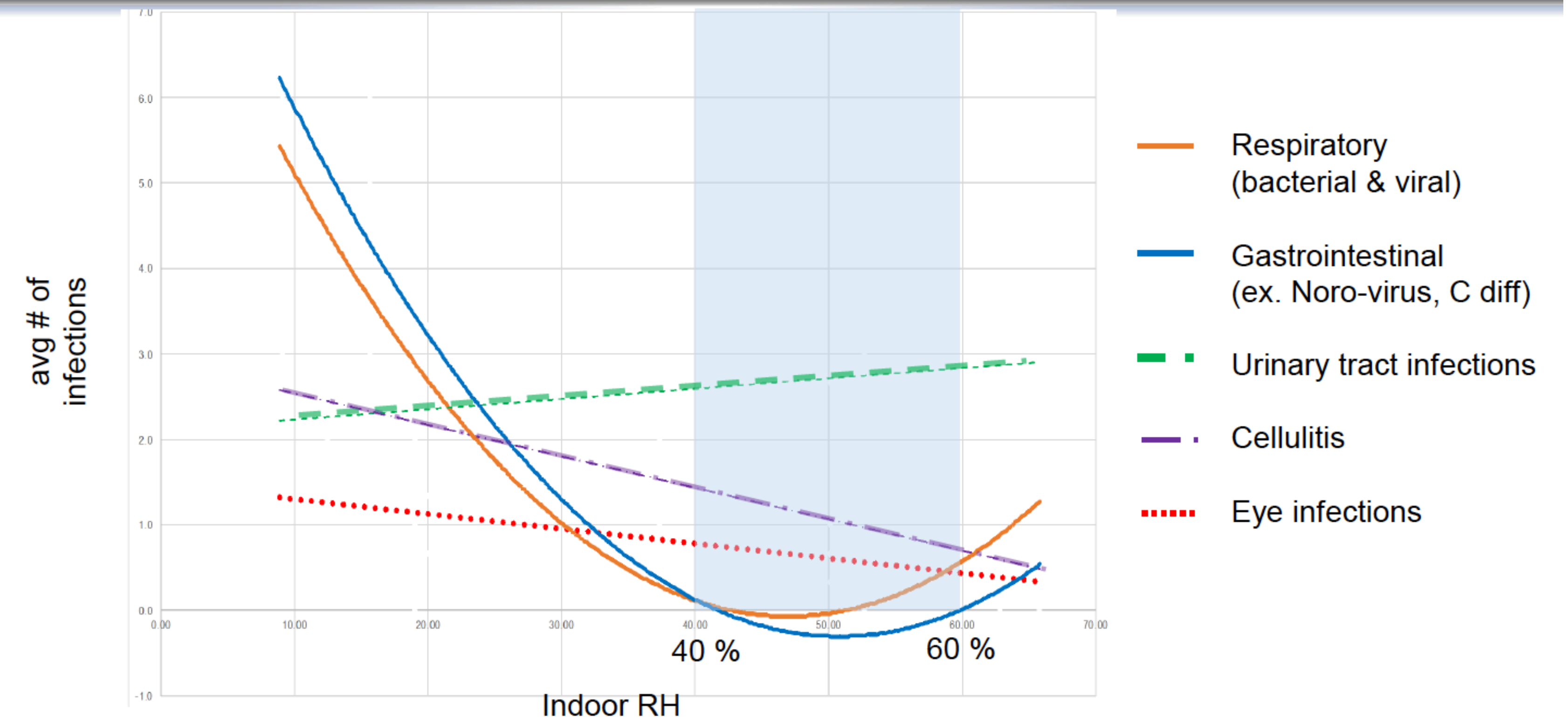
- Six years of data from 5 cities population approx. 100 million
- Temperate and Subtropical climates
- Compared outdoor and indoor RH and AH (absolute humidity)
- Indoor RH compares to Relative Risk

Low Humidity

- Add Moisture through humidification.
- Potable or better water quality.
- If there is a reservoir, vigilance is required to prevent microbial growth.
- Control of humidifier (indoor air dewpoint) must be coordinated with sensing of the lowest indoor surface temperature to prevent condensation.

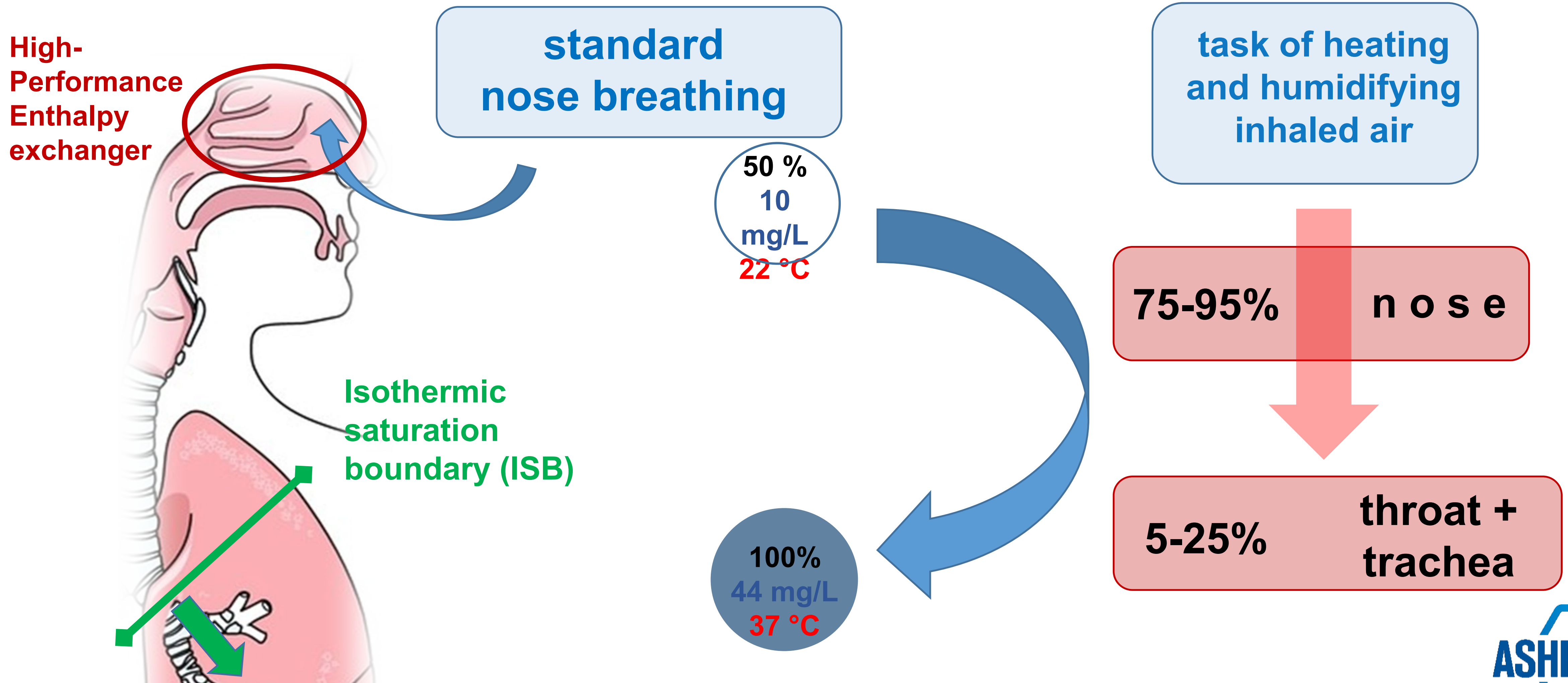
Health Effects – Low Humidity in Long Term Care

Respiratory & GI infection rates were lowest when indoor RH = 40-60%



Courtesy of Stephanie Taylor, MD

Inhaled air must reach 100% saturation by the time it reaches the lungs. When inhaled air is dry, water vapor is drawn from surrounding airway tissues, causing harm.



Source: William R, Relationship between the humidity and temperature of inspired gas and the function of the airway mucosa, Critical Care Medicine, 1996

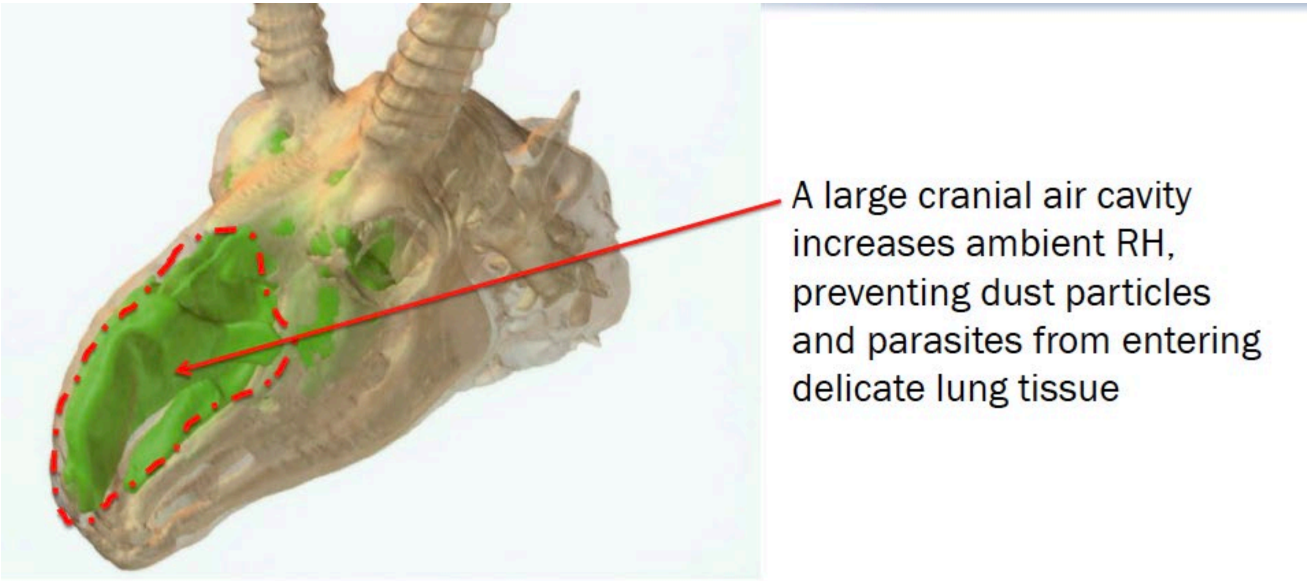
Courtesy of Stephanie Taylor, MD

How necessary is humidification of inhaled air?

Avoiding dry air inhalation is **essential** for respiratory health! This is shown by the adaption of mammalian skulls to accommodate air warming, humidification and filtering prior to inhalation.

Example: First cousin antelopes that migrated to different climates demonstrate skull adaptations.

skull of the grassland Saiga antelope



the African desert first cousin

Courtesy of Stephanie Taylor, MD

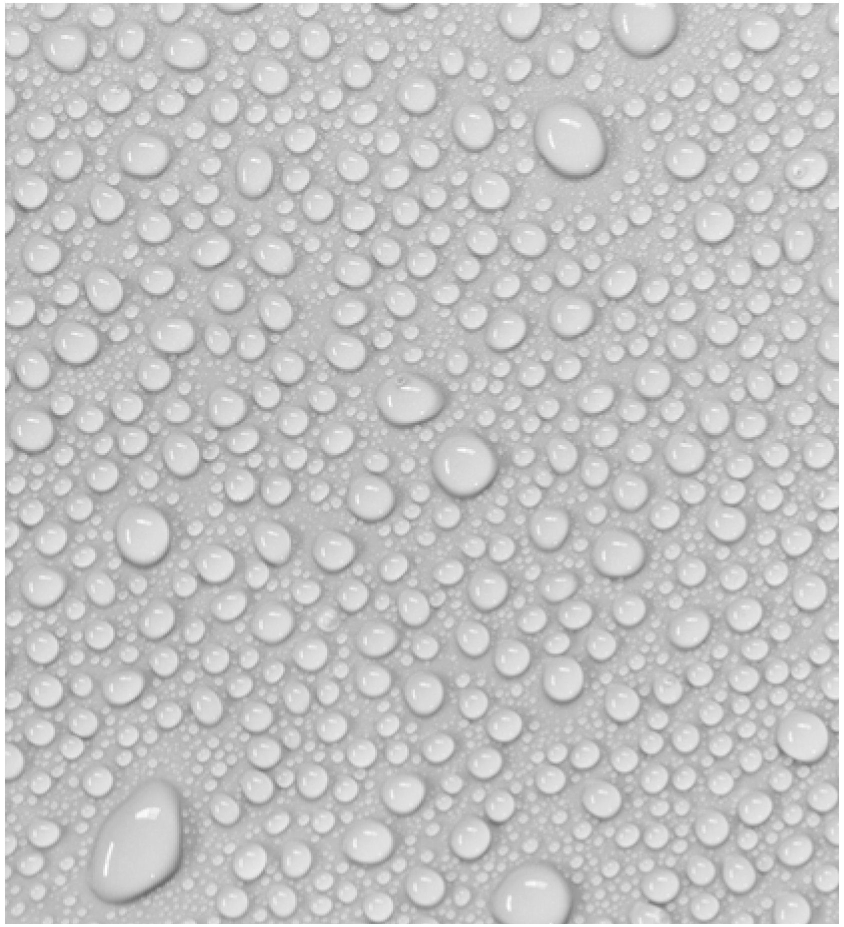
Human Noses and Sinuses Similarly Morphed to Condition Inhaled Air

- The geometry of nasal airways differ across populations, indicating natural selection in the evolution of nose shape in humans.
- Inhaled air must reach 90% of the temperature and humidity levels required for gas exchange before reaching the trachea, tasking the nasal cavity and sinuses as the major conditioning apparatus in humans.
- Nasal width and length correlates with ambient temperature and humidity.
- The geometry of the nasal airways influences the velocity of inspired air and therefore the degree of contact with tissues that specialize in warming, humidification, and filtration of air before it reaches the lungs.
- Wider noses are more common in warm-humid climates.
- Long and narrow noses are more common in cold-dry climates, allowing greater contact between the air and mucosal tissue that warms and humidifies.
- Cold, dry climate populations have a longer nasal cavity, giving more space to warm incoming air to body temperature and humidify to nearly 100% saturation, required for gas exchange. Microscopic hairs lining the airways, the cilia, help to keep out particles and pathogens that may irritate or infect the lungs. The cilia work more efficiently when incoming air is moist.

Courtesy of Stephanie Taylor, MD

Control Moisture

Humidifiers



- Water droplets aerosolized from sumps are heavily colonized.
- Aerosolize molecules, not droplets.
- Use potable water. (Note: boiler water contains corrosion inhibiters.)
- Use smooth, cleanable surfaces within the moisture-absorbing distance.

Building Pressurization

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

Indoor Air Quality Guide, p. 282

2.3

FREE DOWNLOAD

Detailed information, diagrams and strategies regarding building pressurization can be found in Strategy 2.3 within the *Indoor Air Quality Guide*.
The Guide is available for free download at ashrae.org/IAQGuide.

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Maintain Proper Building Pressurization, *(Page 1 of 2)*

Air movement *can transport hundreds of times more moisture than diffusion*

*Applications needing **positive** pressurization:*

- mechanically cooled buildings in hot humid climates,
- low-temperature buildings or spaces; e.g., refrigerated warehouses, ice arenas and
- buildings in areas with poor outdoor air quality.

*Applications needing **negative** or **neutral** pressure:*

- humidified buildings or spaces in cold climates; e.g., natatoriums, indoor gardens, kitchens, hospitals, museums, musical instrument storage and
- other buildings in cold climates.

Maintain Proper Building Pressurization, *(Page 2 of 2)*

Driving forces for infiltration, exfiltration

- Stack effect
- Wind effect
  - In on the windward side, out on the leeward side
- Mechanical effect
  - Exhaust-only ventilation
  - Return plenums
  - Supply plenums (UFAD)
  - Intentionally depressurized (labs) or pressurized (OR’s) areas
  - Balancing problems

ACTION - Contaminants

A) Control Humidity

B) **Control contaminant concentration through operation of ventilation and air cleaning systems.**

C) Improve effectiveness of filtration and air distribution

Hierarchy of recommendations

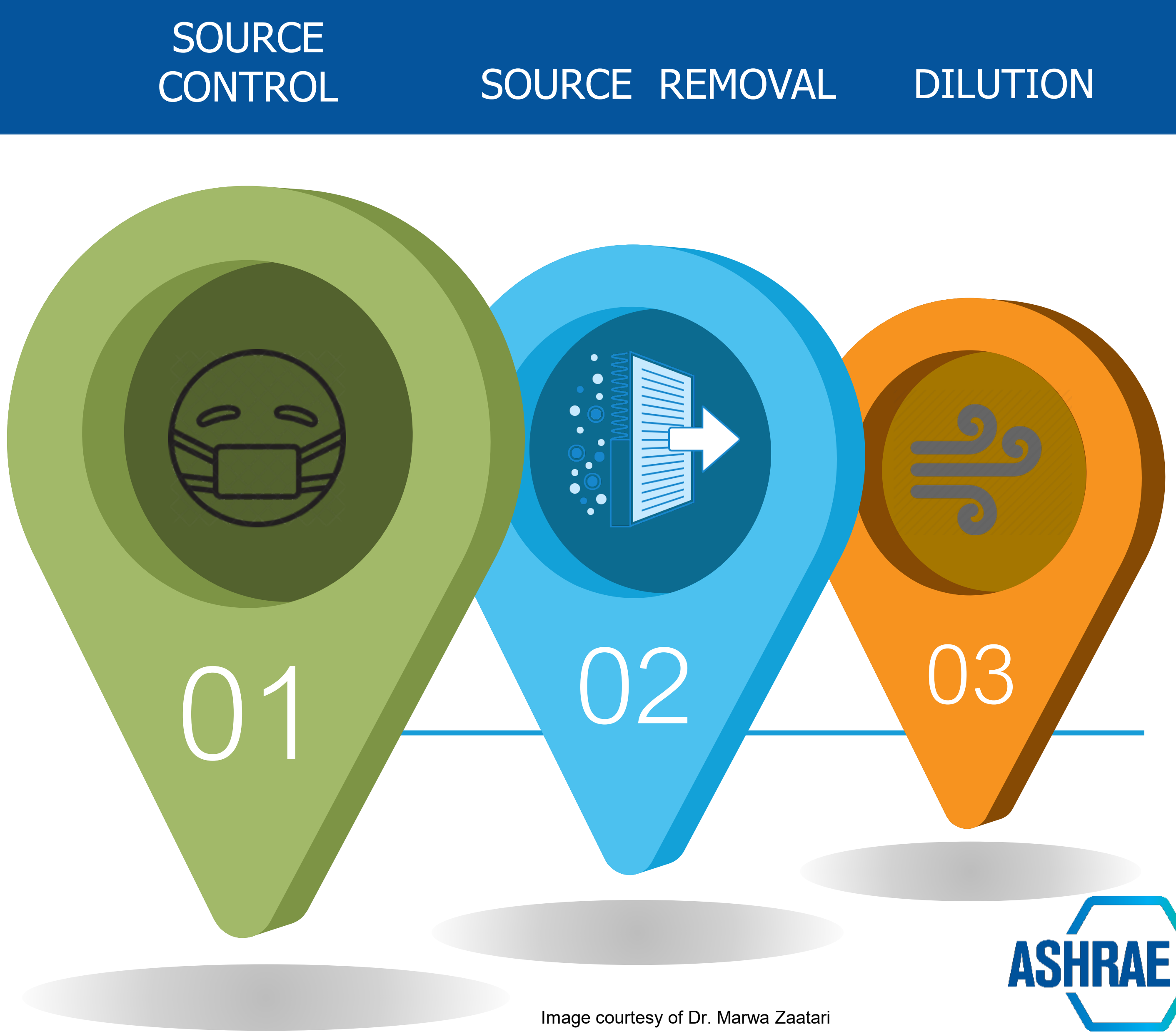


Image courtesy of Dr. Marwa Zaatari

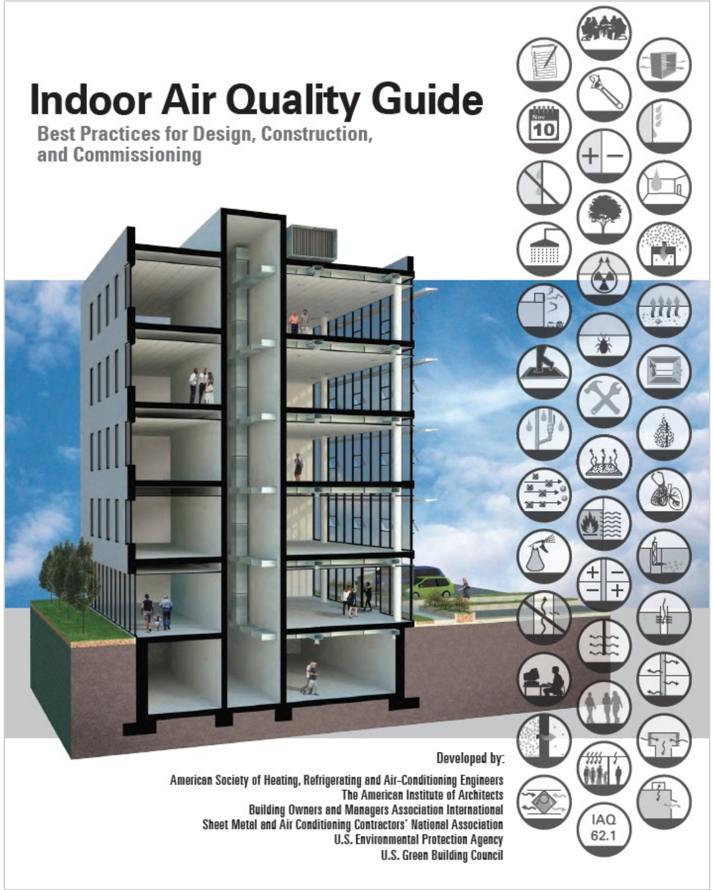
Control Contaminant Concentration

- Don't bring contaminants into the building
  - Control Indoor Sources
  - Outdoor Air Pollution
  - Mechanical Systems as Sources
- Provide adequate ventilation
- Provide contaminant removal by capture or exhaust
- Operate and Maintain Systems

Limit Contaminants From Indoor Sources

Objective 5 in the *Indoor Air Quality Guide*—Limit Contaminants from Indoor Sources

- Select appropriate materials (5.1)
- Limit the impact of emissions (5.2)
- Minimize IAQ impacts associated with cleaning and maintenance (5.3)



FREE DOWNLOAD

Detailed information, diagrams and strategies regarding limiting contaminants from indoor sources can be found Objective 5 within the *Indoor Air Quality Guide*.
The Guide is available for free download at ashrae.org/IAQGuide.

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Control Indoor Contaminant Sources Through Appropriate Material Selection, *(Page 1 of 2)*

Contaminant Emissions: Basic Concepts

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

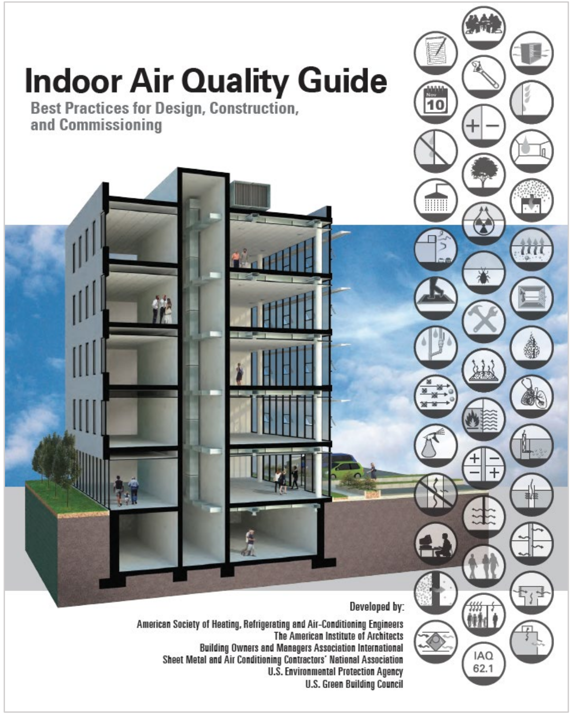
Emissions Data: Available Information

- Manufacturer-Supplied Information: MSDS sheets
- Labels: Content-Based
- Labels: Emissions-Based
- Emissions Databases

Control Indoor Contaminant Sources Through Appropriate Material Selection, *(Page 2 of 2)*

Priority Materials/Finishes/Furnishings

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



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Detailed information, including labels, test methods and specifications on materials can be found in Strategy 5.1 within the *Indoor Air Quality Guide*.
The Guide is available for free download at **ashrae.org/IAQGuide**.

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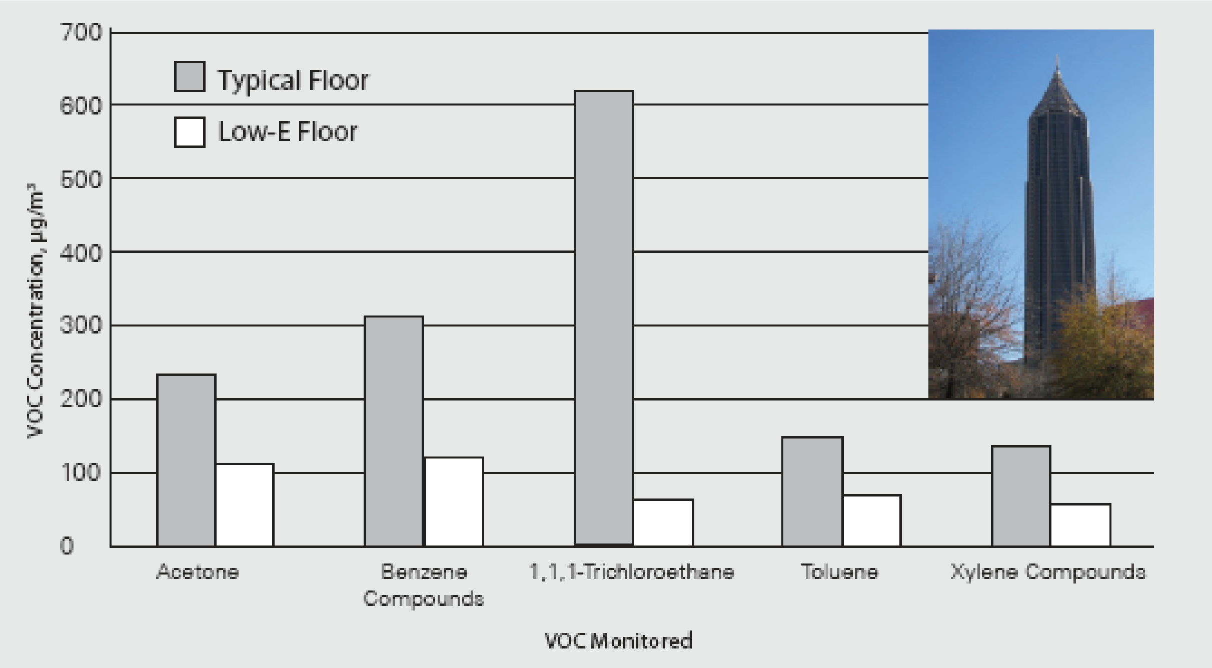
Select Low-Chemical-Emission Materials for Reduced Contaminant Levels

Employ Strategies to Limit the Impact of Emissions

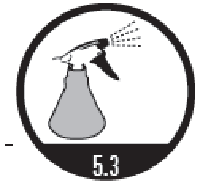
- Control of Emissions through Use of VOC Barriers
- Material Conditioning and In-Place Curing
- Local Exhaust of Unavoidable Sources
- Staged Entry of Materials
- Delayed Occupancy
- Reasons to Avoid Use of Building Bake-Out
- Building Flush-Out
- Ventilation Rates and HVAC Schedules
- Indoor Environmental Conditions
- Filtration and Air Cleaning



Indoor Air Quality Guide, Image courtesy of H.E. Burroughs

Minimize IAQ Impacts Associated with Cleaning and Maintenance

- Select Durable Materials and Finishes that are Simple to Clean and Maintain
- Recommend Cleaning Products with Minimal Emissions
- Provide Appropriate Storage for Cleaning Products
- Recommend Cleaning Protocols that will have Minimal IAQ Impact



Objective 3. Limit Entry of Outdoor Contaminants

- Evaluate regional and local outdoor air quality (3.1)
- Locate OA intakes to minimize introduction of contaminants (3.2)
- Control entry and radon (3.3) and intrusion of vapors from subsurface contaminants (3.4)
- Provide effective track-off systems (3.5)
- Design and build to exclude pests (3.6)

FREE DOWNLOAD

Detailed information on outdoor contaminants can be found in Objective 3.1 within the *Indoor Air Quality Guide*. The Guide is available for free download at ashrae.org/IAQGuide.

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Assess Outdoor Air Quality, *(Page 1 of 2)*

- Determine whether the building is in an EPA non-attainment zone, per NAAQS (US EPA 2024c) and U.S. Weather Service data.
- Obtain and document NAAQS data. For instance, the National Aeronautics and Space Administration (NASA) maintains Tropospheric Emissions: Monitoring of Pollution (TEMPO) that will measure air pollution hourly for all North America starting late 2023 (TEMPO, 2024). For sites outside the United States, use applicable national or state standards for OA quality.
- If the building is in a non-attainment area, verify that appropriate filters for ozone and particulates are in place for outdoor air (OA) intakes, per the requirements in ASHRAE Standard 62.1 (ASHRAE 2022a).

Assess Outdoor Air Quality, (*Page 2 of 2*)

The quality of outdoor air (OA) at the site should be determined using local air quality data sourced from nearby ambient monitoring stations with data on outdoor levels of ozone, particulate matter ($PM_{2.5}$ and PM_{10}), carbon monoxide, sulfur dioxide, and nitrogen dioxide at intervals of at least once per hour from a data-gathering station located within 4 kilometers (2.5 miles) of the building—the closer, the better. These six criteria pollutants are regulated by the EPA's NAAQS and are used to calculate the Air Quality Index (AQI). Daily particulate concentrations and maximum 1-hour, or 8-hour values for other pollutants, reported within a 24-h period, are used to determine AQI. A similar local measurement and reporting approach can be implemented by a government or private entity, following EPA-developed protocols (US EPA, 2023). This data should be documented to supplement the NAAQS data for the site obtained at Level 1.

If the monitored buildings are in areas inadequately covered by existing local weather stations—such as urban heat islands or locales with significant local air pollution sources—it is advisable to conduct targeted measurements of the six criteria pollutants. These six pollutants alone may not capture all local pollutants of concern, so an observational survey of the building site and its surroundings should be conducted to identify additional local air pollutants. The EPA provides guidelines on optimal locations for local air monitoring stations (US EPA, 2024b), and Section 4 of ASHRAE Standard 62.1 (2022a) outlines procedures for this. If measurements indicate poor air quality (e.g., unacceptable AQI), ensure that proper filters for ozone and particulates are installed on OA intakes, as required by ASHRAE Standard 62.1 (2022a).

Investigate Regional and Local Outdoor Air Quality

The U.S. EPA Green Book provides information about National Ambient Air Quality Standards (NAAQS):

- **NAAQS particles**
  - PM10
  - PM2.5
  - Lead

- **NAAQS gases**
  - Ozone (O_3)
  - Nitrogen dioxide (NO_2)
  - Sulfur dioxide (SO_2)
  - Carbon monoxide (CO)

Requirements to Clean Outdoor Air in ASHRAE Standard 62.1-2022

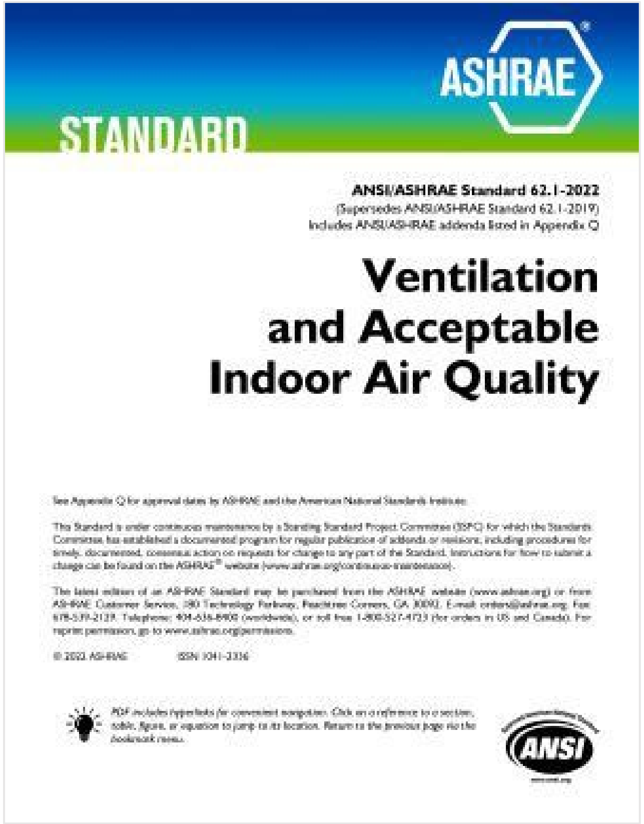
For non-attainment areas in the US and areas in other countries that exceed air quality standards, filtration is required for:

- PM_{10},
- $PM_{2.5}$, and
- Ozone

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

Required by ANSI/ASHRAE 62.1-2022

Local Outdoor Air Quality Survey	Date: Time:
a) Area surveyed	(Brief description of site)
b) Nearby facilities	(Brief description type of facilities—industrial, commercial, hospitality, etc.)
c) Odors or irritants	(List and describe)
d) Visible plumes	(List and describe)



Locate Outdoor Air intakes to Minimize Introduction of Contaminants

Key Points

- Codes and standards are minimums – more is better
- ANSI/ASHRAE 62.1-2022 generally requires greater distances and covers more sources than codes
- Consider implications for OA intake locations when selecting HVAC system types

Control *Legionella* in Water Systems

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

Learn more about *Legionella* on the Water topic page.

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Locate OA Intakes to Minimize Introduction of Contaminants, *(Page 1 of 4)*

Codes and standards are minimums

Example – Cooling Tower Exhaust

- IMC: 5 ft above or 20 ft away
- ANSI/ASHRAE Standard 62.1-2007: 25 ft stretched string distance
- 18,000 cases of Legionnaire's disease in the U.S. annually; 4000-5000 fatalities
- *Legionella* also causes Pontiac fever
- Documented cases of *Legionella* traveling hundreds of feet

Locate OA Intakes to Minimize Introduction of Contaminants, *(Page 2 of 4)*

Example:

Cooling tower exhaust within 20 ft of OA intake. Shroud added to protect intake.

Photos courtesy Leon Alevantis

Locate OA Intakes to Minimize Introduction of Contaminants, *(Page 3 of 4)*

Example:

OA intake downwind of and close to toilet exhaust

OA intake downwind of and close to toilet exhaust

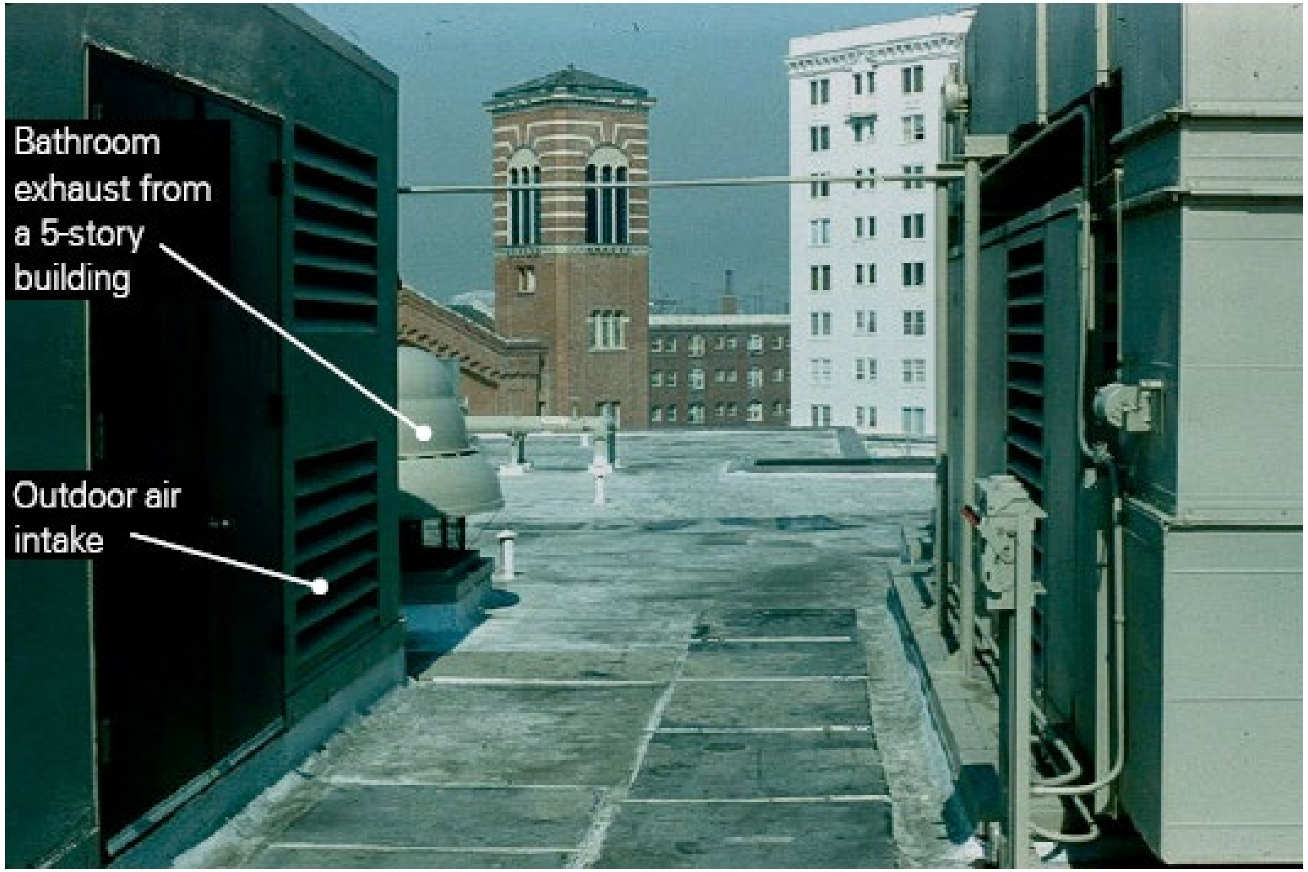

Photo courtesy Hal Levin, *Indoor Air Quality Guide*

Locate OA Intakes to Minimize Introduction of Contaminants, *(Page 4 of 4)*

Consider OA intake locations in system selection

Systems with OA intakes close to the ground may get clogged (!) and encourage introduction of dirt (food for microbes), mold, pesticides, herbicides, fertilizers, vehicle exhaust, etc.

Facilitate Access to HVAC Systems for Inspection, Cleaning and Maintenance

Access In Design Documents

- Locations that Facilitate Access
- Minimum Clearance Distances
- Critical AHU Components
- Air Distribution System
- System Balancing and Monitoring Access
- Terminal Equipment
- Electrical Code Access Criteria
- Access Door/Panel/View Port Requirements

Access During Construction

- Coordination with Trades
- Review of Submittals
- Field Changes
- Monitoring Installations

Unanticipated Access Requirements

- Compliance with SMACNA HVAC Duct Construction Standards
- Repeated Access

Restricted Above-Ceiling Access Compromises Maintenance

Figure 4.3-A Access Door to Systems

Figure 4.3-B Above-Ceiling System

Figure 4.3-C System Location Limits Access

Figure 4.3-D All System Components not Readily Accessible

Photographs courtesy of Jim Hall, *Indoor Air Quality Guide*

Reduce Contaminants Thru Ventilation, Filtration and Air Cleaning

Strategy 7.1 – Provide Appropriate Outdoor Air Quantities for Each Room or Zone

Strategy 7.2 – Continuously Monitor and Control Outdoor Air Delivery

Strategy 7.3 – Effectively Distribute Ventilation Air to the Breathing Zone

Strategy 7.4 – Effectively Distribute Ventilation Air to Multiple Spaces

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

Strategy 7.6 – Provide Comfort Conditions that Enhance Occupant Satisfaction

FREE DOWNLOAD

Detailed information on reducing contaminant concentrations can be found in Objective 7 within the *Indoor Air Quality Guide*.
The Guide is available for free download at ashrae.org/IAQGuide.

Objective 7

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Control Contaminant Concentration – Ventilation

- Ventilation Rates
- Air Distribution
- Exhaust
- Indoor Pressure
- Operations and Maintenance

Determine Ventilation Compliance, *(Page 1 of 2)*

- Compliance with ASHRAE Standard 62.1 does not ensure good IAQ, but the components and requirements are foundational for proper HVAC operation and control, a precursor for acceptable IAQ conditions. The most relevant measurements of indoor and outdoor parameters that affect human health are contaminant concentration levels. Outdoor air ventilation is a driving factor for the control of a broad suite of indoor-generated air contaminants. However, it does not reveal the resultant indoor concentrations. Ventilation is more readily measured than most pollutant levels, though measuring ventilation is still very challenging in many buildings and nearly impossible in some, such as naturally ventilated or mixed-mode buildings with multiple spaces.
- Compliance with the ventilation rate requirements prescribed by ASHRAE Standard 62.1 (2022a) is the minimum performance target of interest. Characterization of IAQ performance should include an assessment of outdoor air ventilation rates and other requirements in ASHRAE Standard 62.1. Compliance can be ensured through measurement of outside airflow rates, measurement of ventilation air distribution in all ventilated (or conditioned) zones of the building. Measured outdoor airflow rates should meet the minimum specified in ASHRAE Standard 62.1.

Determine Ventilation Compliance, *(Page 2 of 2)*

- ✓ On an annual basis, measure outdoor airflow rates at each fan system intake under design conditions. Measured outdoor airflow rates should meet the minimum specified in ASHRAE Standard 62.1.
- ✓ Measure ventilation rates at the OA intake to each HVAC fan system using a pitot tube traverse or flow meter. This rate should be measured annually at design airflow conditions.
- ✓ For variable-air-volume (VAV) systems, controls should be set to the design minimum. Direct measurements should be made.
- ✓ OA measurement techniques and expected accuracies are discussed in Fisk *et al.* (2005).

Provide Appropriate Outdoor Air Quantities for Each Room or Zone

People-Related and Space-Related Ventilation Requirements

- Calculating Minimum Ventilation Rates for Each Zone Using the Ventilation Rate Procedure in ASHRAE *Standard 62.1-2022*
- Occupancy Category
- Boundaries for Zones and Corresponding Areas

Adjusting Outdoor Airflow Rates

- Considering Increased Outdoor Airflow
- Temporarily Decreasing Outdoor Airflow Rates
- Advanced Ventilation Design

Ventilation for Existing Buildings, *(Page 1 of 2)*

Published in 2019

What:

- Simplified rate table for Existing Buildings
- Addition of Informative Appendix G: *Simplified Ventilation Rate Calculation for Multiple-Zone Recirculating Systems Serving only Specified Occupancy Categories in Existing Buildings*

Why:

- ASHRAE 62.1 frequently cited for evaluating existing buildings
  - Examples include: LEED-EBOM, Energy Star, and ASHRAE Building EQ
- Existing buildings with multiple zone systems are often renovated
- Multiple zone systems require calculation of System Ventilation Efficiency (E_v)
- Calculating E_v for existing buildings is often difficult, if not impossible
  - E_v is a function of the supply airflows at the zone level
  - Mechanical drawings not up to date or available.
- With VAV systems, the minimum settings of the VAV boxes may not be known

Ventilation for Existing Buildings (appendix G), *(Page 2 of 2)*

Occupancy Category	Occupancy Minimum Airflow			
	Outdoor Air Rate R_s		Minimum Primary Supply Air Rate R_{pz}	
Educational Facilities	cfm/ft^2	$L/s \cdot m^2$	cfm/ft^2	$L/s \cdot m^2$
Classrooms (ages 5-8)	0.65	0.33	1.12	0.56
Classrooms (age 9 plus)	0.82	0.41	1.41	0.71
Computer lab	0.65	0.33	1.12	0.56
Media center	0.65	0.33	1.12	0.56
Music/theater/dance	0.72	0.36	1.24	0.62
Multi-use assembly	1.42	0.71	2.45	1.22
General				
Conference/meeting	0.44	0.22	0.76	0.38
Corridors	0.11	0.06	0.19	0.10
Office Buildings				
Breakrooms	0.65	0.33	1.12	0.56
Main entry lobbies	0.19	0.10	0.33	0.16
Occupiable storage rooms for dry materials	0.12	0.06	0.21	0.10
Office space	0.15	0.08	0.26	0.13
Reception areas	0.37	0.19	0.64	0.32
Telephone/data entry	0.63	0.32	1.09	0.54
Public Assembly Spaces				
Libraries	0.30	0.15	0.52	0.26

Ventilation and Performance

- Shendell, *et al*. 2004: student absences were 10% to 20% higher than for classrooms where the difference in CO_2 was below 1000 ppm
- Wargocki and Wyon 2006

Learn more at the
Key Economic and Justification Factors topic page.

Design for Varying Operating Conditions According to Standard 62.1-2022

Where it is known that peak occupancy will be of short duration and/or ventilation will be varied or interrupted for a short period of time, the design may be based on the average conditions over a time period *T* determined by Equation 6-11a or 6-11b:

$$T = 3v/V_{bz} \qquad \text{(I-P) (6-11a)}$$

where

T = averaging time period, (min)

v = the volume of the zone for which averaging is being applied, (ft^3)

V_{bz} = the breathing zone outdoor airflow calculated using Equation 6-1 and the design value of the zone population P_z, (cfm)

Effectively Distribute Ventilation Air to the Breathing Zone

- Zone Air Distribution Effectiveness
- The Effect of Ducted Systems on Air Delivery
  - Ducted
  - Non-Ducted

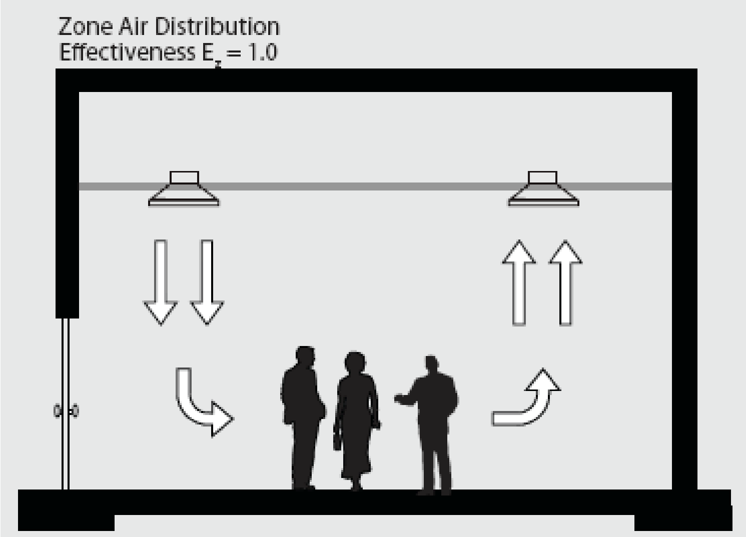


Figure 7.3-A Cold Air Falls and is Well Mixed

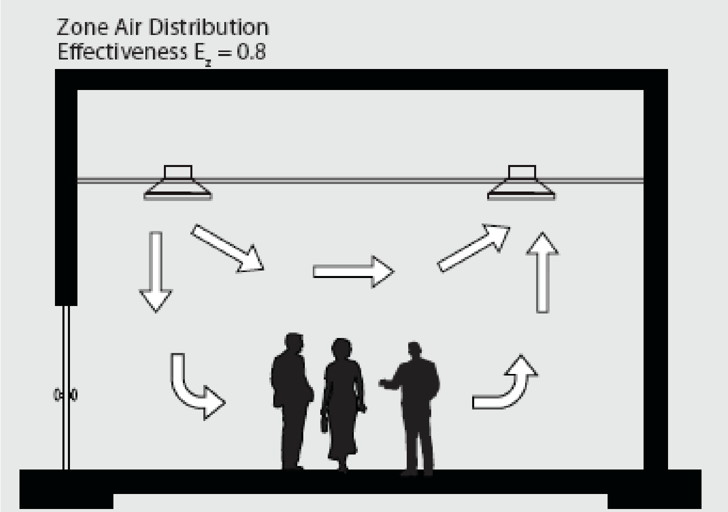


Figure 7.3-B Some Hot Air Stays at the Ceiling so Only 80% of the Air Gets to the Breathing Zone

Effectively Distribute Ventilation Air to Multiple Spaces

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

Continuously Monitor and Control Outdoor Air Delivery

- Direct Measurement of Airflow
  - Straight Ducts
  - HVAC Systems with Economizers
  - Small Packaged HVAC Systems
  - Placement of Airflow Sensors
  - Accuracy and Calibration of Airflow Sensors
- Indirect Methods of Measuring Minimum Outdoor Air
  - Plenum Pressure Control
  - The CO_2 or Temperature Method
- Design Issues for Commissioning, Operation and Maintenance

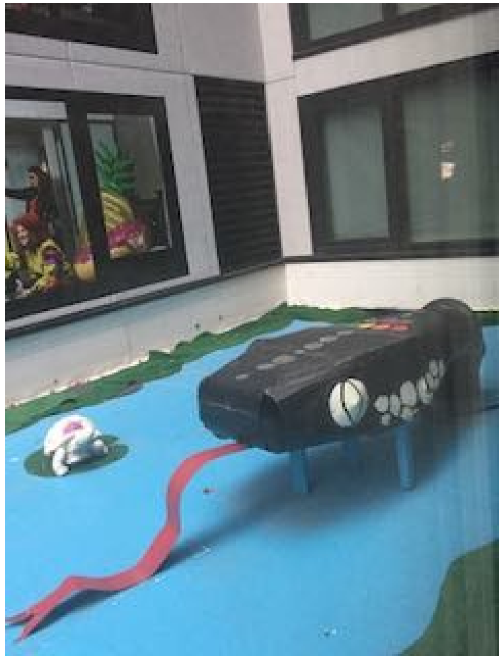
Extraction or Exhaust Systems

- Chimney
- Kitchen Exhaust
- Bathroom Exhaust
- Process Exhaust
- Laboratory Exhaust

Exhaust Fans

Images courtesy of Hoy Bohannon

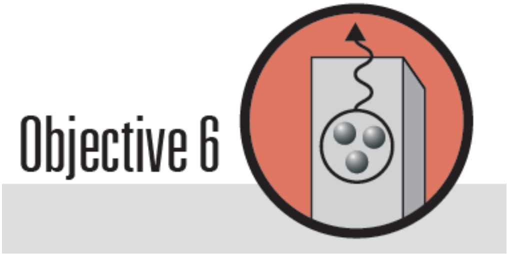
Exhaust Discharge



Images courtesy of Hoy Bohannon

If hazardous, picture 1 is a problem.
2. Lab rooftop.
When artists reconfigure as in picture 3, then it may not work very well.

Capture and Exhaust Contaminants from Building Equipment and Activities



Strategy 6.1 – Properly Vent Combustion Equipment

Strategy 6.2 – Provide Local Capture and Exhaust for Point Sources of Contaminants

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

Strategy 6.4 – Maintain Proper Pressure Relationships Between Spaces

FREE DOWNLOAD

Detailed information on capturing and exhausting contaminants can be found in Objective 6 within the *Indoor Air Quality Guide*.
The Guide is available for free download at ashrae.org/IAQGuide.

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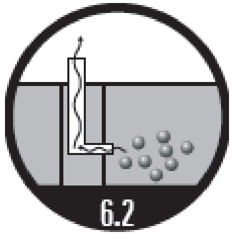
Properly Vent Combustion Equipment

- ✓ Capture and Exhaust of Combustion Products
  - ✓ Chimneys (Nonmechanical, Natural Exhaust)
  - ✓ Induced Draft (Powered, Negative-Pressure Exhaust)
  - ✓ Forced Draft (Powered, Positive-Pressure Exhaust)
- ✓ Design and Installation
- ✓ Outdoor Air for Combustion
- ✓ Proper Operation and Maintenance of Equipment

Learn more on the Commissioning topic page.

Provide Local Capture and Exhaust for Point Sources of Contaminants



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

Lack of Exhaust—Indoor Swimming Pool

Figure 6.2-A Corridor to Indoor Swimming Pool

Photograph courtesy of H.E. Burroughs , from the *Indoor Air Quality Guide.*

1. Pool treatment chemicals not exhausted from space
2. Lack of exhaust contributes to condensation on the fenestration
3. Main hotel building impacted by chemical contaminants and odors

Prevent Exhaust Leakage to Occupied Areas

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

- Effectively Sealing Ductwork to Limit Potential for Duct Leakage
- Providing a Proper Outdoor Discharge Position and Configuration
- Maintaining Exhaust Ducts in Plenum Spaces under Negative Pressure

Improper Separation Between Exhaust and Intake Airstreams

Figure 6.3-A Location of Exhaust Fan

Photo courtesy of Hal Levin, from the *Indoor Air Quality Guide*

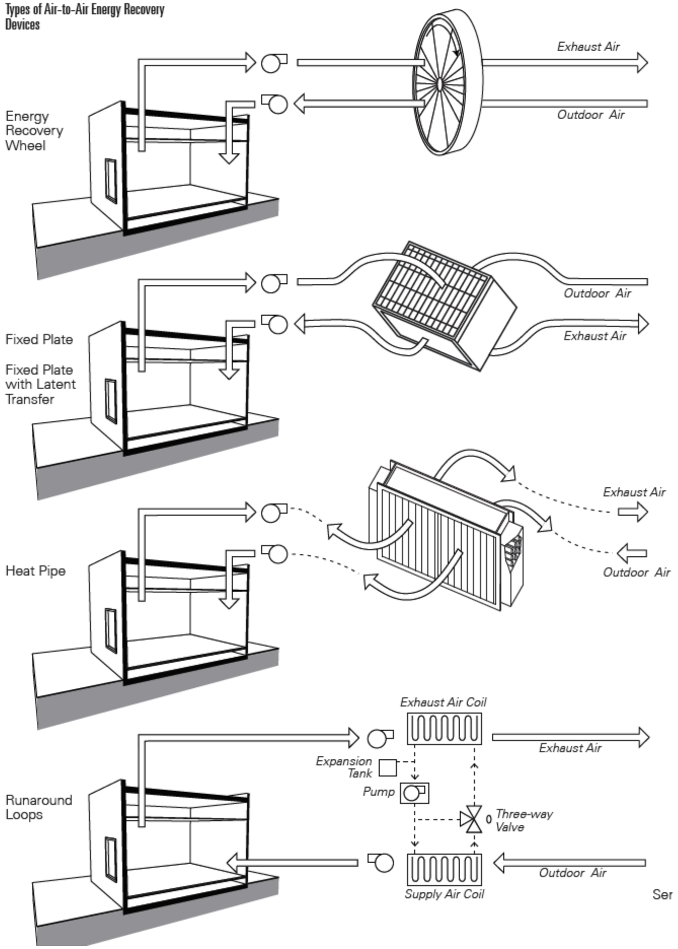
- **Issue**: Toilet exhaust fan shown with dome on top in close proximity to and upwind of the air intake for one of the largest air-handling systems
- **Post-Construction Solution**: Installation of sheet metal surround to raise the height of the air discharge above the height of the intake louver

Exhaust Returning Through Cross Connected ERV

- Energy recovery is mandated by energy codes in many commercial applications
- Some Energy Recovery Ventilators provide the possibility for exhausted (dirty) air to be transferred to the outdoor air (clean) intake airstream
- Heat pipes and runaround loops generally separate the exhaust and outdoor airstreams

FREE DOWNLOAD

See a larger version of the diagram on p. 145 of the *Indoor Air Quality Guide*, available for free download at ashrae.org/IAQGuide.



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Recent Energy Recovery Research, *(Page 1 of 2)*

- ECTR (Exhaust Contaminant Transfer Ratio) quantifies the transfer of gaseous contaminants due to all the mechanisms, while EATR quantifies transfer due to carryover and leakage.
- Must be accounted for in calculations.

FREE DOWNLOAD

ASHRAE Members can download this Research Project Report free as a benefit of membership in the ASHRAE Technology Portal.

ASHRAE Research Project Report

1780-RP

TEST METHOD TO EVALUATE CROSS-CONTAMINATION OF GASEOUS CONTAMINANTS WITHIN TOTAL ENERGY RECOVERY WHEELS

Approval: June 2023

Objective 3: *Evaluation of the test method*

The proposed test method was evaluated by testing eleven gaseous contaminants in two energy wheels, one coated with silica gel (SG) and one with molecular sieve (MS), under a range of design and operating conditions. The method worked well for all gas tested and all design and operating conditions. For both wheels and all design and operating conditions, ammonia had the highest transfer (ECTR ≈ 70 - 80%) and carbon dioxide had the lowest transfer (ECTR ≈ 2 - 10%).

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Recent Energy Recovery Research, *(Page 2 of 2)*

- For applications with potential chemical exhaust request ECTR (not EATR) from the manufacturer.
- For example, in an animal housing facility (vivarium, veterinary office, shelter, kennel) ammonia is a significant emission.
- If 70% of the exhausted ammonia is returned to the space, this must be considered in the design of the system.

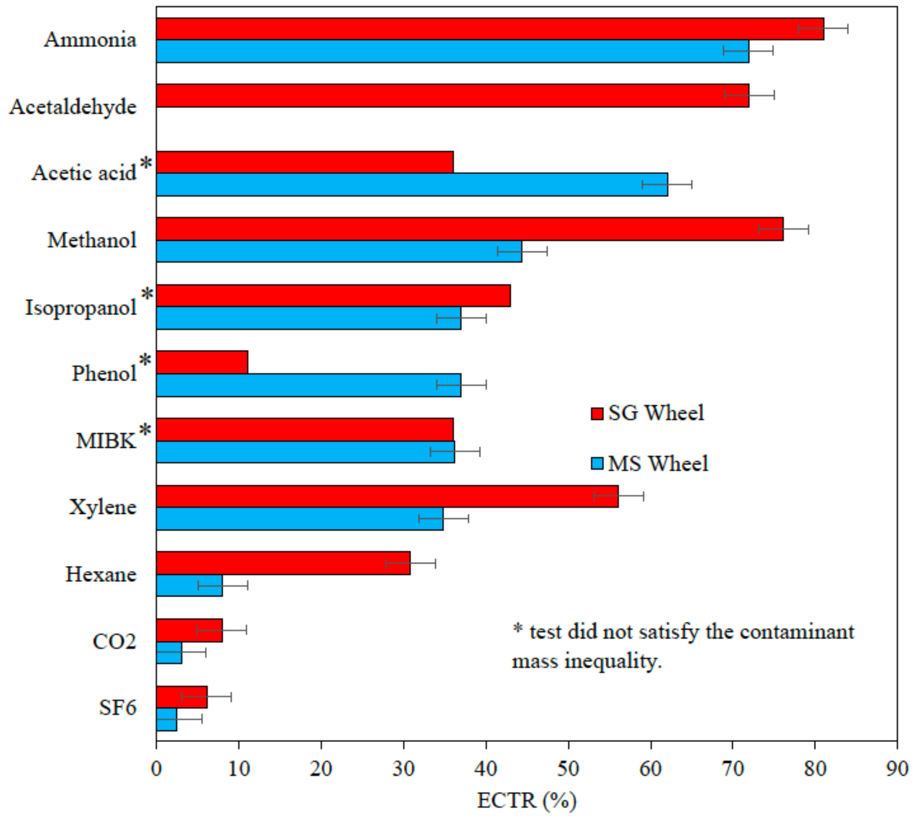


Figure 4.3. Exhaust contaminant transfer ratio (ECTR) of eleven different contaminants for molecular sieve and silica gel coated wheels at room conditions. Detailed operating conditions are listed in Table 4.1.

ASHRAE Research Report 1780, Test Method To Evaluate Cross-Contamination Of Gaseous Contaminants Within Total Energy Recovery Wheels, p. 47. June 2023.

Maintain Proper Pressure Relationships Between Spaces

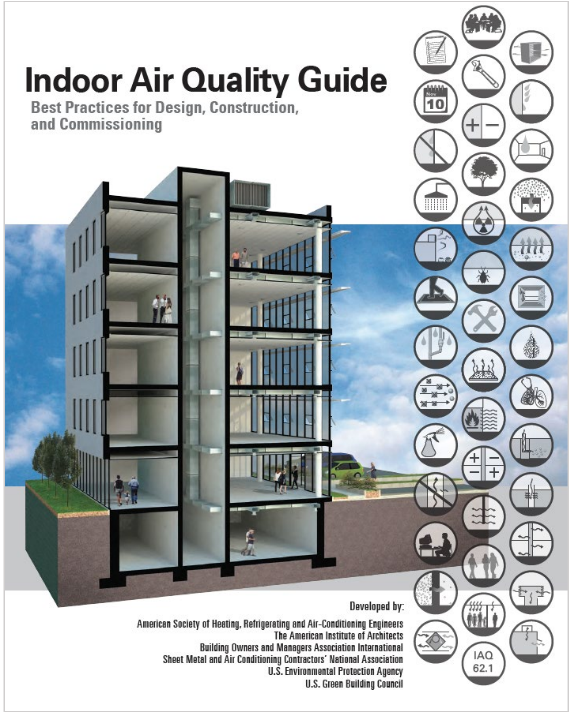
- Space Usage
  - Common Space Types
- Space Layout
- Space Envelope
- Compartmentalization
- HVAC System
  - Airflow Rate Considerations
  - Airflow Monitoring and Control
  - Return Air Plenums
  - Duct Leakage
  - Airflow Measurement
- Verification

Noxious Spa Odors Invade a Hotel

Figure 6.4-B Ill-Fitting Double Glass Doors

- **Issue**: Exercise room and spa located in a separate structure with noticeable odors halfway down the building wing.
- **Cause**: Ill-fitting doors in conjunction with breakfast/ kitchen area exhaust system negatively depressurizing the hotel corridor.
- **Additional Issue**: High humidity odorous airstream enters conditioned space of the guest rooms.

Facilitate Effective Operation and Maintenance for IAQ, *(Page 1 of 2)*



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Detailed information on facilitating effective operation and maintenance can be found in Strategy 1.5 within the *Indoor Air Quality Guide*.
The Guide is available for free download at ashrae.org/IAQGuide.

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Facilitate Effective Operation and Maintenance for IAQ, *(Page 2 of 2)*

Key Points:

- Considering O&M Capabilities in System Selection
- Involving O&M Staff in Planning, Design, Construction and Commissioning
- Providing O&M Documentation that Facilitates Delivery of the Design Intent
    - Owner's Project Requirements and Basis of Design
    - Record Documents
    - Commissioning Report
    - Operations Manual
    - Training Manual
    - Maintenance Manual
    - Format of O&M Documentation
- Providing O&M Training to Support Delivery of the Design Intent
- Prioritizing O&M for IAQ

Site Inspection of Building and Mechanical Systems

- Review facility operational documentation, building and tenant descriptions, as-built drawings, and information on the facility construction. Document the occupancy types and operations for each space type within the facility. Review building plans, including HVAC designs. Note any remodeling and HVAC projects in progress or completed since occupancy, recommissioning, or the last occupant acceptability and satisfaction survey.
- Perform site inspection to assess the design, installation, and operation of building systems affecting IAQ. Table 8-1 of ASHRAE Standard 62.1 (2022) provides a detailed summary of inspection tasks for ventilation system equipment and components. The *Indoor Air Quality Guide* (2009) outlines control measures for moisture and contaminants related to mechanical systems. Including IAQ complaint logs from building occupants for review is also recommended. It is also recommended referring to the EPA BASE protocol presented in the publication *Data on Indoor Air Quality in Public and Commercial Buildings* (US EPA 2006). Also, Appendix B and TAB V of the EPA publication *Building Air Quality Guide: A Guide for Building Owners and Facility Managers* (US EPA 1991), should be consulted to determine the parameters of the building and site inspection.

Document Ventilation Design Intent

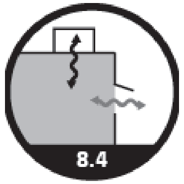
Including the Ventilation Design Intent in Project Drawings Facilitates Proper Building Operation

- Portion of the design intent documentation
- Putting tables n the plans helps to ensure that the ventilation system design intent is available to O&M staff

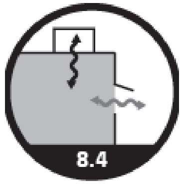
Other Concentration Control

- Natural Ventilation
- Indoor Air Quality Procedure
- Other Technology

Detailed information on capturing and exhausting contaminants can be found in Objective 6 within the *Indoor Air Quality Guide*.
The Guide is available for free download at ashrae.org/IAQGuide.



Natural Ventilation, *(Page 1 of 4)*

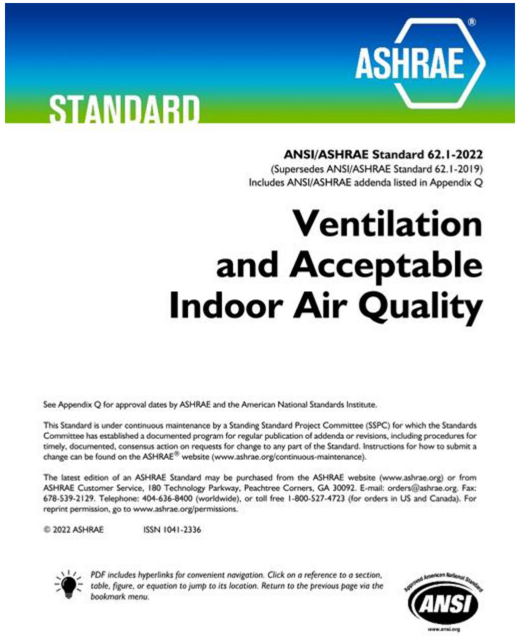


- Natural ventilation relies on outdoor air with no fans (mechanical).
- Most climate zones require some heating and cooling so additional mechanical ventilation is required during those hours.
- In the psychrometric chart at right, natural ventilation provides ventilation and comfort 31% of the hours.

Natural Ventilation, *(Page 2 of 4)*

Procedures According to ASHRAE Standard 62.1-2022

- **6.4 Natural Ventilation Procedure.** Natural ventilation systems shall comply with the requirements of either Section 6.4.1 or Section 6.4.2. Designers shall provide interior air barriers, insulation, or other means that separate naturally-ventilated spaces from mechanically-cooled spaces, to prevent high dew point outdoor air from coming into contact with mechanically cooled surfaces.
- **6.4.1 Prescriptive Compliance Path.** Any zone designed for natural ventilation shall include a mechanical ventilation system designed in accordance with Section 6.2, Section 6.3, or both.
- **Exceptions:**
- 1. Zones in buildings that have all of the following:
- a. natural ventilation openings that comply with the requirements of Section 6.4.1,
- b. controls that prevent the natural ventilation openings from being closed during periods of expected occupancy or natural ventilation openings that are permanently open,
- 2. Zones that are not served by heating or cooling equipment.


STANDARD

ANSI/ASHRAE Standard 62.1-2022
(Supersedes ANSI/ASHRAE Standard 62.1-2019)
Includes ANSI/ASHRAE addenda listed in Appendix Q

Ventilation and Acceptable Indoor Air Quality

See Appendix Q for approval dates by ASHRAE and the American National Standards Institute.

This Standard is under continuous maintenance by a Standing Standard Project Committee (SSPC) for which the Standards Committee has established a documented program for regular publication of addenda or revisions, including procedures for timely, documented, consensus action on requests for change to any part of the Standard. Instructions for how to submit a change can be found on the ASHRAE® website (www.ashrae.org/continuous-maintenance).

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Natural Ventilation, *(Page 3 of 4)*

- **6.4.3 Control and Accessibility.** The means to open required openings shall be readily accessible to building occupants whenever the space is occupied. Controls shall be designed to properly coordinate operation of the natural and mechanical ventilation systems.
- **6.4.4 Documentation.** Where the Natural Ventilation Procedure is used, the designer shall document the values and calculations that demonstrate conformance with the compliance path and the controls systems and sequences required for operation of the natural ventilation system including coordination with mechanical ventilation systems. Where the Prescriptive Compliance Path is used for buildings located in an area where the national standard for one or more contaminants is exceeded, any design assumptions and calculations related to the impact on indoor air quality shall be included in the design documents.

Natural Ventilation, *(Page 4 of 4)*

Older Buildings that rely on natural ventilation through windows may have little to no ventilation.

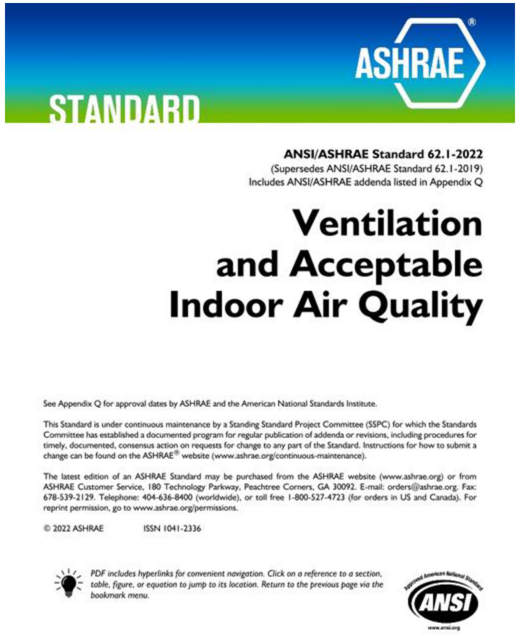
Indoor Air Quality Procedure (IAQP)

- The IAQP is an alternative to the VRP used to determine the design rate of outdoor airflow to maintain concentrations of design compounds (DCs) and PM2.5 in the indoor environment to be less than design limits (DLs), based on indoor and outdoor sources, air cleaning, and other variables.
- These outdoor air requirements shall be calculated with mass-balance equations.
- Verification of occupant satisfaction and indoor DC concentrations shall be performed after the building is completed.

Design Approach—Requirements

Procedures According to ASHRAE Standard 62.1-2022

- **6.3.3 Design Approach.** Zone and system outdoor airflow rates shall be the larger of those determined in accordance with Sections 6.3.3.1 and 6.3.3.2, based on emission rates, concentration limits, and other relevant design parameters.
- **6.3.3.1 Mass-Balance Analysis.** Using a steady-state or dynamic mass-balance analysis, the minimum outdoor airflow rates required to achieve the concentration limits specified in Section 6.3.2 shall be determined for each DC, mixture of DCs, and PM2.5 within each zone served by the system.


STANDARD

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ANSI/ASHRAE Standard 62.1-2022
(Supersedes ANSI/ASHRAE Standard 62.1-2019)
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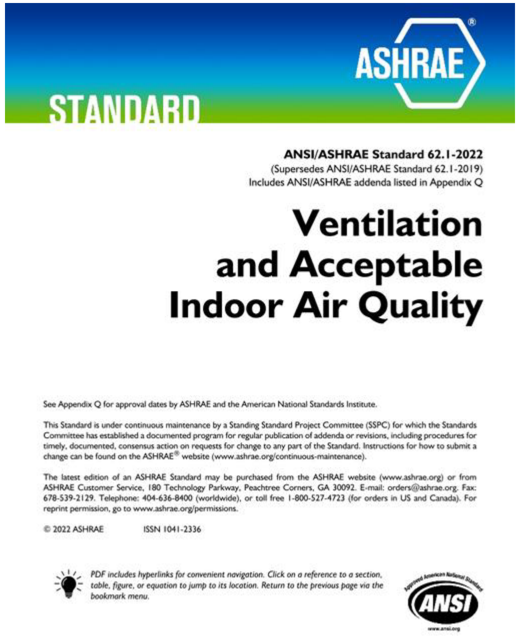
Subjective Evaluation Requirements

Requirements According to ASHRAE Standard 62.1-2022

6.3.3.2 Perceived Indoor Air Quality:

Zone outdoor airflow rates shall be sufficient to ensure that 80% or more of the people exposed do not express dissatisfaction with the quality of the air when tested as required in Section 7.3.2.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Approved American National Standard ANSI www.ansi.org

6.3.4 Air Cleaning

Where particulate matter or gas-phase air cleaning is included in the design, the removal efficiencies shall be specified as follows. Particulate matter filters shall report an efficiency reporting value (MERV) in accordance with ASHRAE Standard 52.2 or reporting in accordance with ISO 16890. Gas-phase air cleaners shall report an efficiency test for all compounds included in the design in accordance with any of the following:

a. ASHRAE Standard 145.2,

b. ISO 10121-2,

c. Testing by methods in Section 6.1.2,10.4, and 10.5 and reported as required in ASHRAE Standard 145.2, Section 11,

d. Testing to a national consensus standard approved by the authority having jurisdiction,

e. For technologies not covered by any of the above, tests developed to demonstrate the removal efficiency shall be performed by a third party.

IAQP - Verification Required

Measurement:

- In the breathing zone and conducted during normal working hours, maximum obtainable occupancy.
- The HVAC system in normal operation with lowest outdoor air intake setting expected during the year.
- The number of measurement points shall be specified according to the table below.

Total Occupied Floor Area, ft^2 (m^2)	Number of Measurements
≤25,000 (2500)	1
>25,000 (2500) and ≤50,000 (5000)	2
>50,000 (5000) and ≤100,000 (10,000)	4
>100,000 (10,000)	6

Table from ASHRAE Standard 62.1-2022 Table 7.3

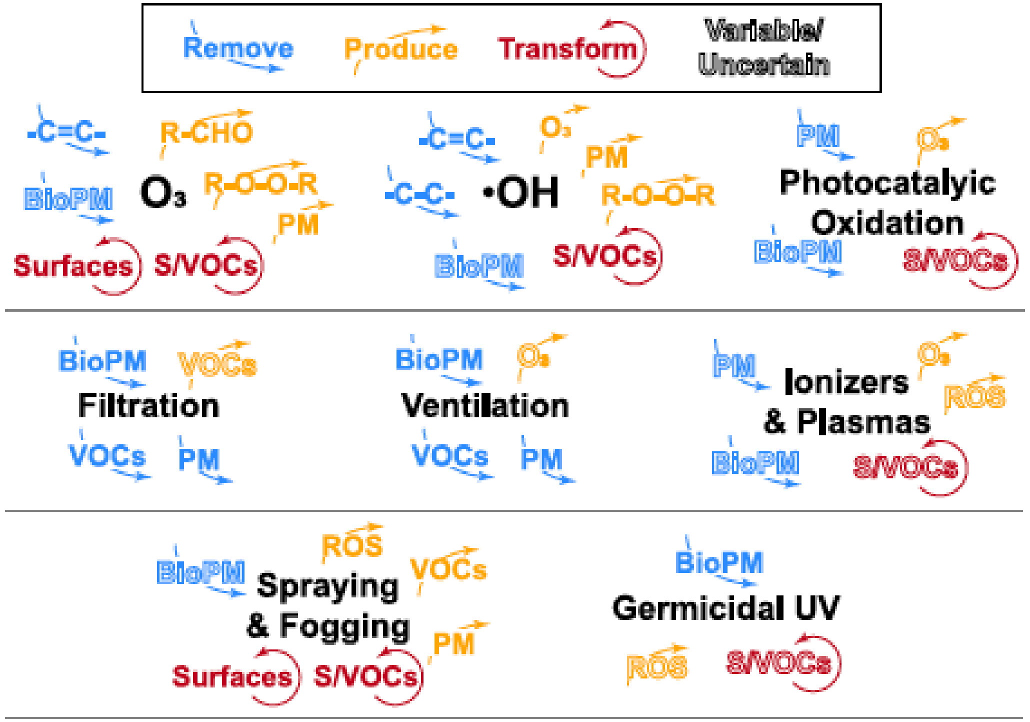
Indoor Air Quality Procedure—Resource

Performance based design approach for compliance with ASHRAE 62.1-2022

[Learn more or purchase in the ASHRAE Bookstore.]

Unintended Consequences of Air Cleaning Chemistry

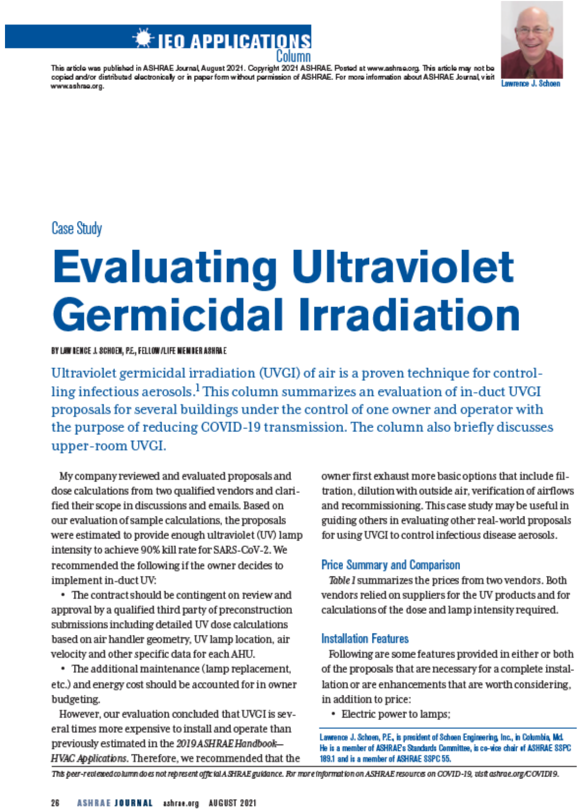
Qualitative summary of chemical effects of select air cleaning and disinfection technologies. BioPM refers to biological PM, S/VOC refers to semi volatile and volatile organic compounds, -C=C- refers to alkenes, -C-C- refers to alkanes, R-CHO refers to aldehydes, and R-O-O-R refers to peroxides. All other abbreviations are defined in the text. Icons with outlined lettering denote effects that are not well studied, highly variable across studies, variable with device operational settings, or remain scientifically uncertain.



Unintended Consequences of Air Cleaning Chemistry, Douglas B. Collins and Delphine K. Farmer, *Environmental Science & Technology* **2021** *55* (18), 12172-12179, Figure 1.
DOI: 10.1021/acs.est.1c02582

Ultraviolet Germicidal Irradiation (UVGI)

- UVGI is useful and effective in upper room installations where airborne infections are known such as tuberculosis isolation rooms.
- UVGI can reduce the frequency of cleaning for cooling coils. It does not replace filtration.
- UVGI for deactivating aerosols in general spaces should be evaluated for cost effectiveness.
- *Evaluating Ultraviolet Germicidal Irradiation*, by Lawrence J. Schoen, P.E., Fellow/Life Member, ASHRAE, *ASHRAE Journal* August 2021, p.26-30.
- UV will affect the local microbiome. It cannot discriminate between commensals and pathogens.



IEQ APPLICATIONS Column

Lawrence J. Schoen

Case Study

Evaluating Ultraviolet Germicidal Irradiation

BY LAWRENCE J. SCHOEN, P.E., FELLOW/LIFE MEMBER ASHRAE

Ultraviolet germicidal irradiation (UVGI) of air is a proven technique for controlling infectious aerosols.[1] This column summarizes an evaluation of in-duct UVGI proposals for several buildings under the control of one owner and operator with the purpose of reducing COVID-19 transmission. The column also briefly discusses upper-room UVGI.

My company reviewed and evaluated proposals and dose calculations from two qualified vendors and clarified their scope in discussions and emails. Based on our evaluation of sample calculations, the proposals were estimated to provide enough ultraviolet (UV) lamp intensity to achieve 90% kill rate for SARS-CoV-2. We recommended the following if the owner decides to implement in-duct UV:

- The contract should be contingent on review and approval by a qualified third party of preconstruction submissions including detailed UV dose calculations based on air handler geometry, UV lamp location, air velocity and other specific data for each AHU.
- The additional maintenance (lamp replacement, etc.) and energy cost should be accounted for in owner budgeting.

However, our evaluation concluded that UVGI is several times more expensive to install and operate than previously estimated in the *2019 ASHRAE Handbook—HVAC Applications*. Therefore, we recommended that the owner first exhaust more basic options that include filtration, dilution with outside air, verification of airflows and recommissioning. This case study may be useful in guiding others in evaluating other real-world proposals for using UVGI to control infectious disease aerosols.

Price Summary and Comparison

Table 1 summarizes the prices from two vendors. Both vendors relied on suppliers for the UV products and for calculations of the dose and lamp intensity required.

Installation Features

Following are some features provided in either or both of the proposals that are necessary for a complete installation or are enhancements that are worth considering, in addition to price:

- Electric power to lamps;

Lawrence J. Schoen, P.E., is president of Schoen Engineering, Inc., in Columbia, Md. He is a member of ASHRAE's Standards Committee, is co-vice chair of ASHRAE SSPC 189.1 and is a member of ASHRAE SSPC 55.

This peer-reviewed column does not represent official ASHRAE guidance. For more information on ASHRAE resources on COVID-19, visit ashrae.org/COVID19.

Ions

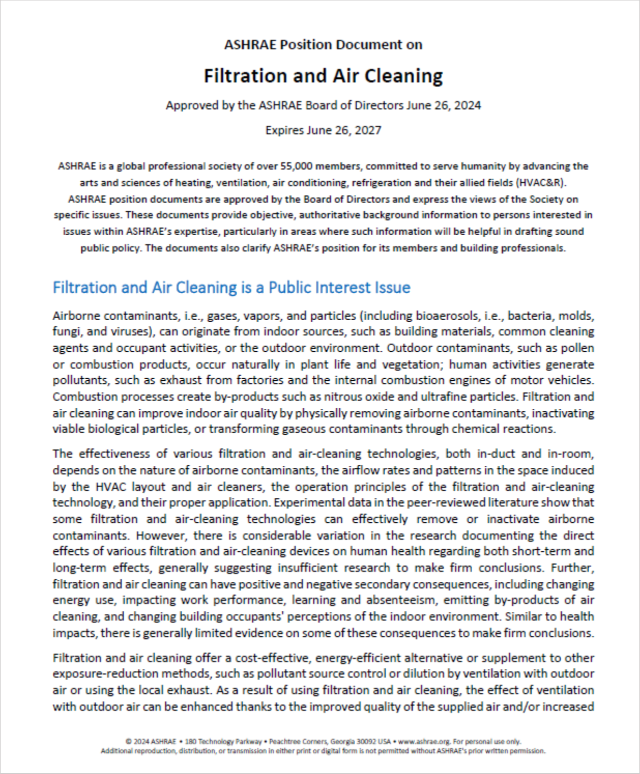
The proposition is that releasing ions will transform the chemistry and biology of the room.

A Mathematical Exercise in Exponents:

- Assume your workspace is 12’ x 10’ with an 8’ ceiling. About 1000 ft^3 (cubic feet) = 10^3
- Each cubic foot of air (gas) contains approximately Avogadro’s number of molecules 6×10^{23} per 23 liters (at STP) x 28 liter/ft^3. (6 / 23) x 28 = 7
- Your workspace contains more than 7×10^{26} molecules. ($7 \times 10^{23} \times 10^3$) Assume 10^{26}.
- Assume an ionizer releases and maintains one million ions 10^6 in the workspace = 1000 ions/ft^3
- You have one ion per 10^{20} molecules in the room.
- What are the chances each ion first encounters a bad actor molecule? (1 per 100,000,000,000,000,000,000)
- You breathe about 0.2 ft^3/minute x 1000 ions/ft^3 = about 200 ions per minute.
- What effect might those 96,000 ions (200 ions/minute x 8 hours) intended to transform chemistry and biology have on your respiratory system during each workday?

Ions and Emerging Technologies—ASHRAE Position, *(Page 1 of 2)*

- *ASHRAE Position Document on Filtration and Air Cleaning* (6/26/24)
- Filtration and air cleaning effectively improve air quality when used properly.
- Caution should be exercised when using filtration and air-cleaning technologies and strategies that may be ineffective or unsafe.
- Filtration and air-cleaning devices that produce compounds to remove or inactivate target pollutant(s) either at the device, in a duct, or in space should only be used if proven safe.
- Filtration and air cleaning performance should be based on nationally or internationally recognized and published standardized tests from ASHRAE and other independent organizations or agencies. A detailed explanation of alternative tests and their correspondence to standardized tests should accompany performance testing results when such tests do not exist.



ASHRAE Position Document on

Filtration and Air Cleaning

Approved by the ASHRAE Board of Directors June 26, 2024

Expires June 26, 2027

ASHRAE is a global professional society of over 55,000 members, committed to serve humanity by advancing the arts and sciences of heating, ventilation, air conditioning, refrigeration and their allied fields (HVAC&R). ASHRAE position documents are approved by the Board of Directors and express the views of the Society on specific issues. These documents provide objective, authoritative background information to persons interested in issues within ASHRAE's expertise, particularly in areas where such information will be helpful in drafting sound public policy. The documents also clarify ASHRAE's position for its members and building professionals.

Filtration and Air Cleaning is a Public Interest Issue

Airborne contaminants, i.e., gases, vapors, and particles (including bioaerosols, i.e., bacteria, molds, fungi, and viruses), can originate from indoor sources, such as building materials, common cleaning agents and occupant activities, or the outdoor environment. Outdoor contaminants, such as pollen or combustion products, occur naturally in plant life and vegetation; human activities generate pollutants, such as exhaust from factories and the internal combustion engines of motor vehicles. Combustion processes create by-products such as nitrous oxide and ultrafine particles. Filtration and air cleaning can improve indoor air quality by physically removing airborne contaminants, inactivating viable biological particles, or transforming gaseous contaminants through chemical reactions.

The effectiveness of various filtration and air-cleaning technologies, both in-duct and in-room, depends on the nature of airborne contaminants, the airflow rates and patterns in the space induced by the HVAC layout and air cleaners, the operation principles of the filtration and air-cleaning technology, and their proper application. Experimental data in the peer-reviewed literature show that some filtration and air-cleaning technologies can effectively remove or inactivate airborne contaminants. However, there is considerable variation in the research documenting the direct effects of various filtration and air-cleaning devices on human health regarding both short-term and long-term effects, generally suggesting insufficient research to make firm conclusions. Further, filtration and air cleaning can have positive and negative secondary consequences, including changing energy use, impacting work performance, learning and absenteeism, emitting by-products of air cleaning, and changing building occupants' perceptions of the indoor environment. Similar to health impacts, there is generally limited evidence on some of these consequences to make firm conclusions.

Filtration and air cleaning offer a cost-effective, energy-efficient alternative or supplement to other exposure-reduction methods, such as pollutant source control or dilution by ventilation with outdoor air or using the local exhaust. As a result of using filtration and air cleaning, the effect of ventilation with outdoor air can be enhanced thanks to the improved quality of the supplied air and/or increased

Ions and Emerging Technologies—ASHRAE Position, *(Page 2 of 2)*

- In-situ effectiveness and safety of filtration and air-cleaning technologies are a strong function of air distribution, maintenance, aging, degradation impacts, component face air velocities, system airflow rates, installation, space volume and other application and contextual factors. Accordingly, filtration and air-cleaning effectiveness and safety in a specific application should not be assumed equivalent to performance determined using controlled laboratory tests under specific conditions.
- All electrically powered filtration and air-cleaning devices should only be used when tested and labeled for ozone emission in accordance with Underwriters Laboratory (UL) 2998 or an equivalent international standardized test to avoid hazards associated with ozone.
- Secondary consequences over the lifetime of filtration and air cleaning devices and under all conditions of use should be considered, including, among others, maintenance implications, harmful by-products or other compounds added to the air, energy implications, odors, noise, material degradation and other aging issues, including reduced air-cleaning performance.
- Efficiency tests, reduction of target contaminant concentrations, or other performance data of filtration and air-cleaning devices alone should not be used to make claims of direct health impacts.

Additive Technologies and Odor

- There is ample anecdotal evidence that additive technologies change people's perception of odors.
- These technologies include ozone, ions, scented candles, sprays, wicking, incense and similar things.
- These all add chemicals (some reactive) to the air or transform chemicals in the air.
- Any of these could have adverse health effects especially the chemically reactive technologies.
- A recommended response is to find the source of the odor and either eliminate it or control it with ventilation or absorptive methods.

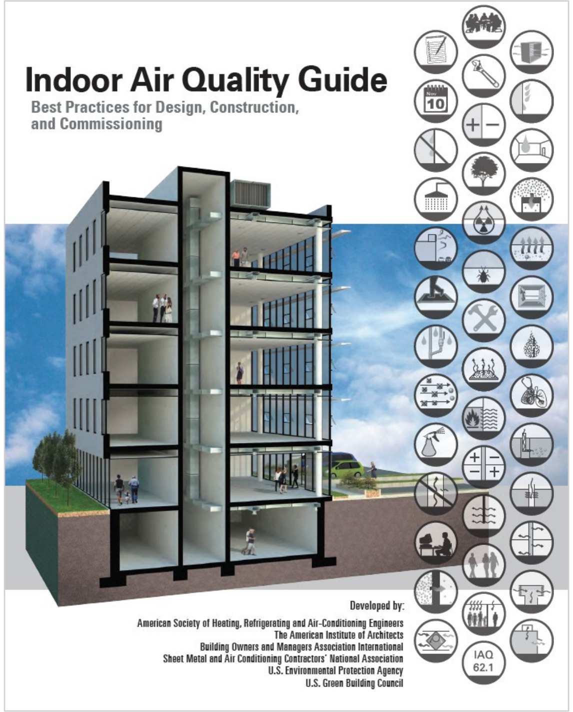
ACTION – Improve Filtration and Air Distribution

A. Control Humidity
B. Control contaminant concentration through operation of ventilation and air cleaning systems.
C. Improve effectiveness of filtration and air distribution

Effective Filtration and Air Distribution

FREE DOWNLOAD

Detailed information can be found in Strategy 7.5, Provide Particle Filtration and Gas-Phase Air Cleaning Consistent with Project IAQ Objectives, within the *Indoor Air Quality Guide*. The Guide is available for free download at ashrae.org/IAQGuide.



Filtration Aligned with IAQ Goals

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

FAC Equipment Selection and Specification Guidance

- Selection Guidance: Particulate Filters
- Selection Guidance: Gas-Phase Air Cleaners
- Air Capture and Seal
- FAC System Location
- Using the IAQ Procedure
- Design Process Protocol

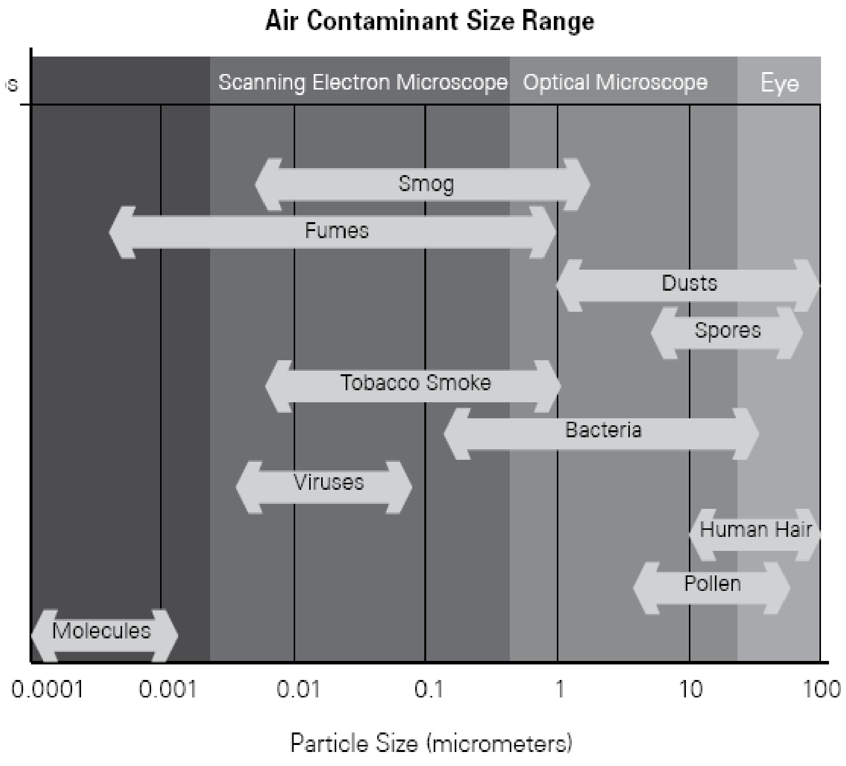
Performance Evaluation and Considerations of FAC Alternatives

- Particulate Filter Efficiency Evaluation—MERV
- Gas-Phase Air Cleaner Efficiency Evaluation

Maximizing the Value and Performance of FAC

- Life-Cycle Analysis
- How to Maximize the Life Cycle and Performance of FAC

Sizes of contaminant particles



Adapted from NIOSH 2003

Particle Settling in Still Air

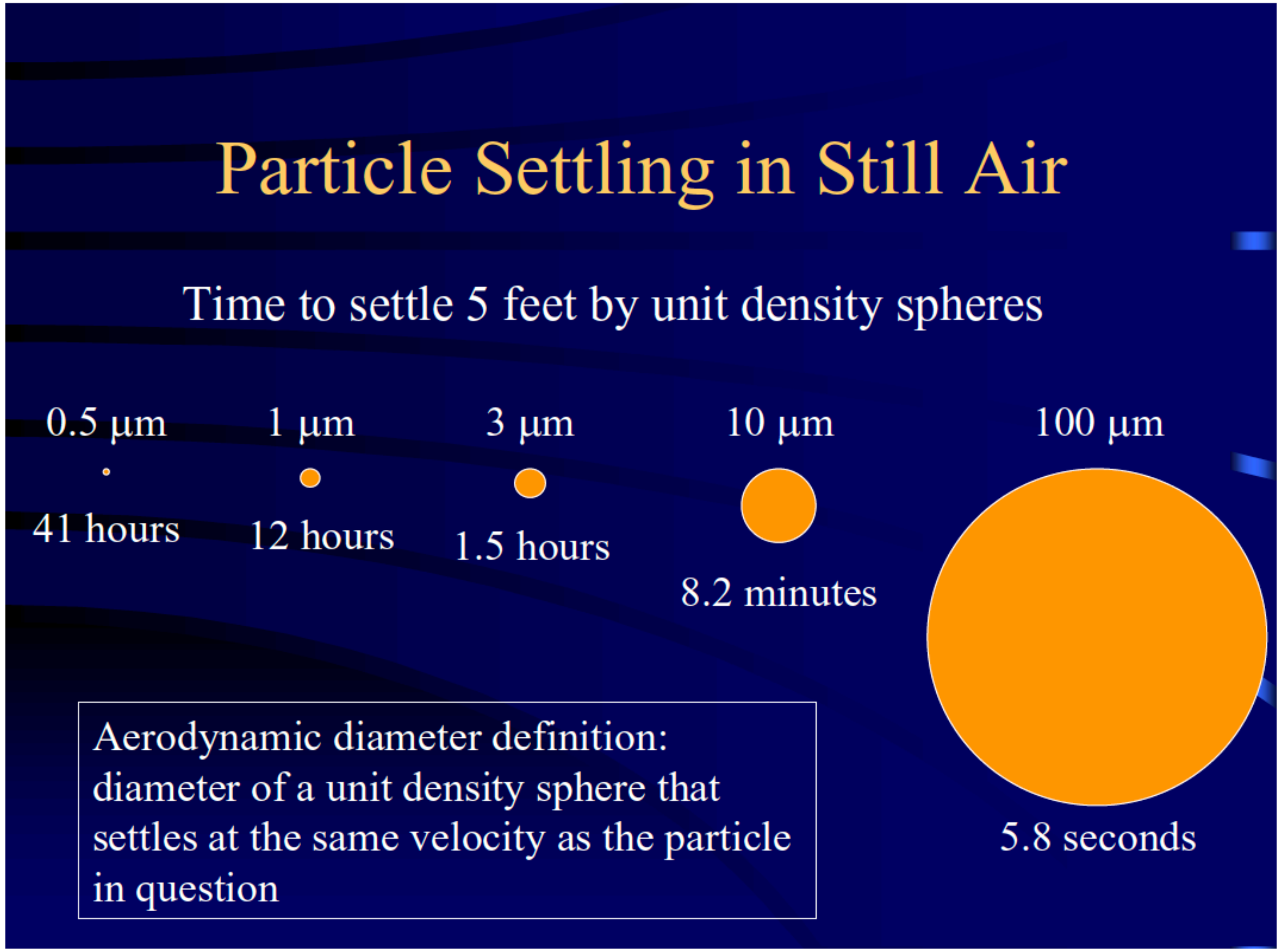
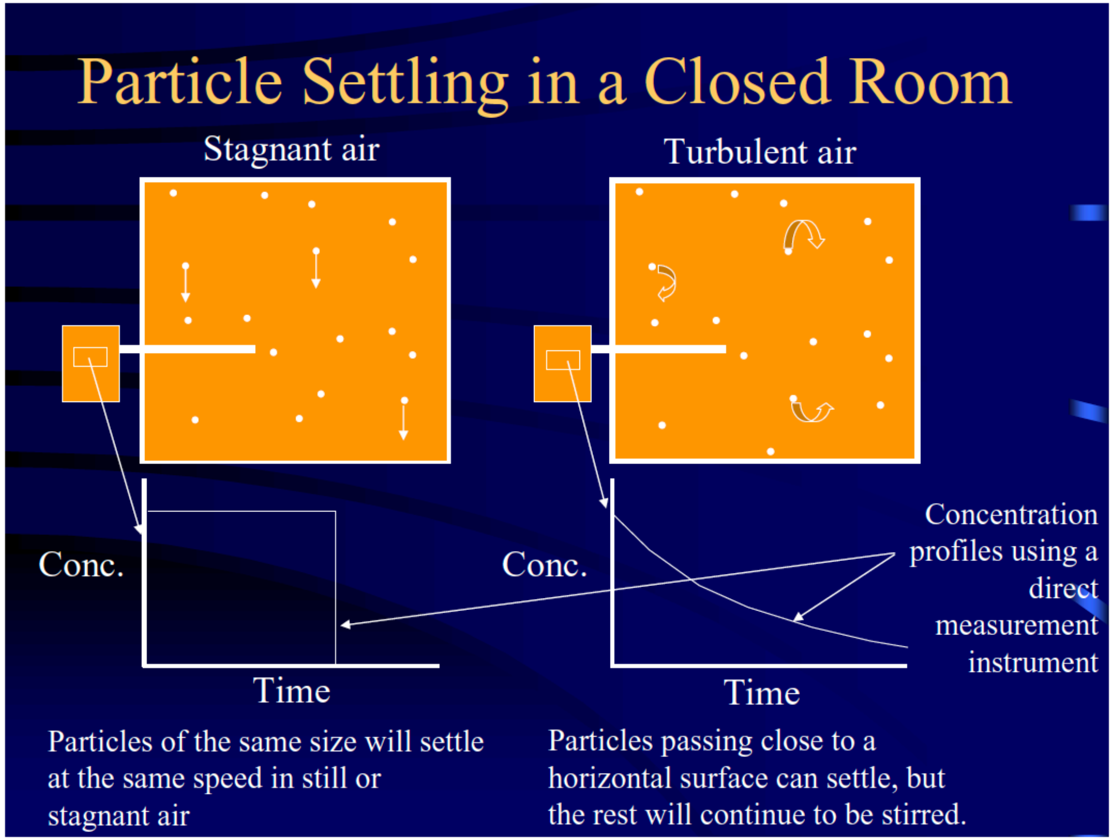
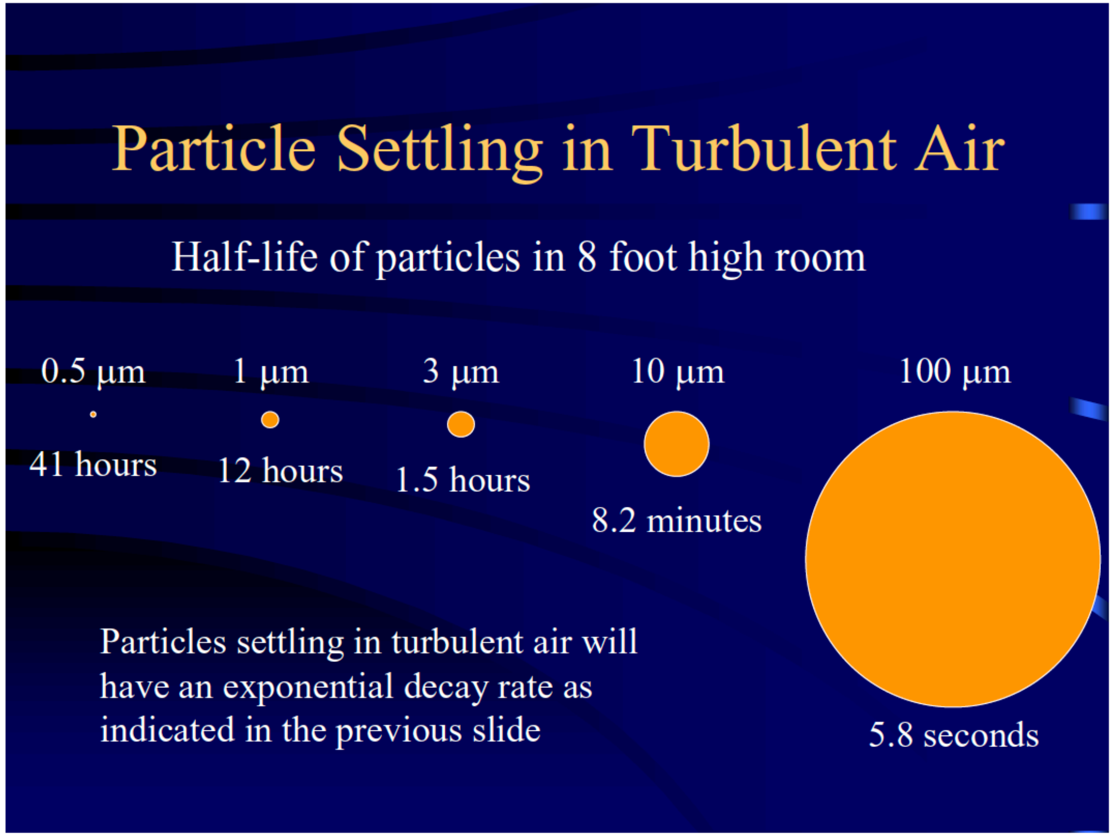


Image from Generation and Behavior of Airborne Particles (Aerosols) p. 12 by Paul Baron, Division of Applied Technology NIOSH https://www.cdc.gov/niosh/docket/archive/pdfs/NIOSH-219/0219-092310-baron.pdf

Particle Settling in a Closed Room and in Turbulent Air





Images from Generation and Behavior of Airborne Particles (Aerosols) p. 13, 14 by Paul Baron, Division of Applied Technology NIOSH https://www.cdc.gov/niosh/docket/archive/pdfs/NIOSH-219/0219-092310-baron.pdf

MERV Ratings

Table 3 Cross-Reference and Application Guidelines

Standard 52.2 MERV	Arrestance Value	Example Range of Contaminants Controlled	Example Applications	Sample Air Cleaner Type(s)
E-1 Range				
MERV 16 MERV 15 MERV 14 MERV 13	N/A N/A N/A N/A	0.3 to 1.0 μm size range: bacteria, smoke (ETS), paint pigments, face powder, some virus, droplet nuclei, insecticide dusts, soldering fumes	Day surgery, general surgery, hospital general ventilation, turbo equipment, compressors, welding/soldering air cleaners, prefilters to HEPAs, LEED for existing (EB) and new (NC) commercial buildings, smoking lounges	Box-style wet-laid or lofted fiberglass, box-style synthetic media, minipleated synthetic or fiberglass paper, depths from 2 to 12 in. Pocket filters of fiberglass or synthetic media 12 to 36 in.
E-2 Range				
MERV 12 MERV 11 MERV 10 MERV 9	N/A N/A N/A N/A	1.0 to 3.0 μm size range: milled flour, lead dust, combustion soot, *Legionella*, coal dust, some bacteria, process grinding dust	Food processing facilities, air separation plants, commercial buildings, better residential, industrial air cleaning, prefiltration to higher-efficiency filters, schools, gymnasiums	Box-style wet-laid or lofted fiberglass, box-style synthetic media, minipleated synthetic or fiberglass paper, depths from 2 to 12 in. Pocket filters either rigid or flexible in synthetic or fiberglass, depths from 12 to 36 in.
E-3 Range				
MERV 8 MERV 7 MERV 6 MERV 5	N/A N/A N/A N/A	3.0 to 10 μm size range: pollens, earth-origin dust, mold spores, cement dust, powdered milk, snuff, hair spray mist	General HVAC filtration, industrial equipment filtration, commercial property, schools, prefilter to high-efficiency filters, paint booth intakes, electrical/phone equipment protection	Wide range of pleated media, ring panels, cubes, pockets in synthetic or fiberglass, disposable panels, depths from 1 to 24 in.
MERV 4 MERV 3 MERV 2 MERV 1	>70% >70% >65% <65%	Arrestance method	Protection from blowing large particle dirt and debris, industrial environment ventilation air	Inertial separators

Table from 2020 ASHRAE Handbook–*HVAC Systems and Equipment* p. 29

Pressure Drop by MERV

- ASHRAE Research Project 1649
- *"…pressure drop is not strongly correlated with MERV"*
- One must research pressure drop when purchasing filter media

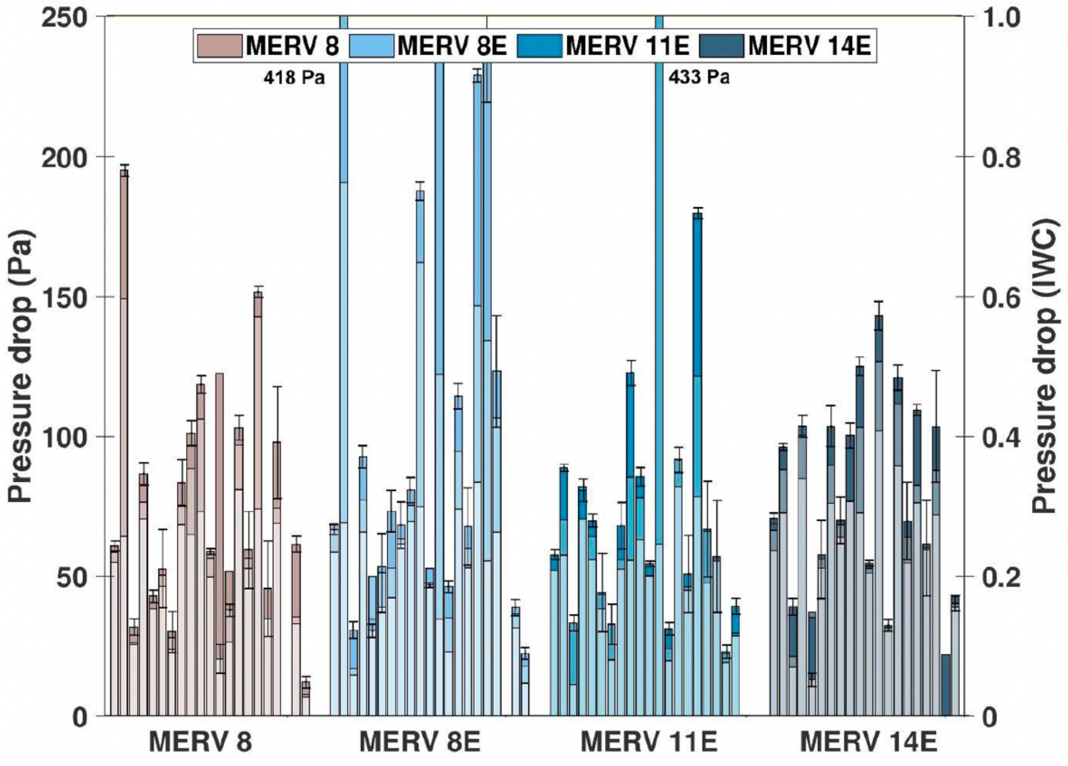


Figure 4.3 Pressure drop of different filters placed in different sites sorted by filter type. On each bar, the lightest color corresponds to the initial pressure drop of a filter, the darker color represents the midlife (6-week) pressure drop of a filter, and the darkest color shows the pressure drop of a 3-month filter.

Example of Filter Failures

Examples of Filter Failures

Figure 7.5-H Fallen Filter with Substantial Visible Gap

This case study highlights examples of filter failures.

The filter shown in Figure 7.5-H, which serves a health-care surgery staff facility, fell because of a poorly sized filter track, resulting in more than 2 in. (50.8 mm) of visible gap. The MERV 14 filter is now behaving as a MERV 8 filter.

The gasketing on the filter access door in Figure 7.5-I has eroded and disappeared. Thus, the door to the filter compartment no longer seals properly.

The corrosion penetration within the air handler shown in Figure 7.5-J allows outdoor air to bypass the filter bank.

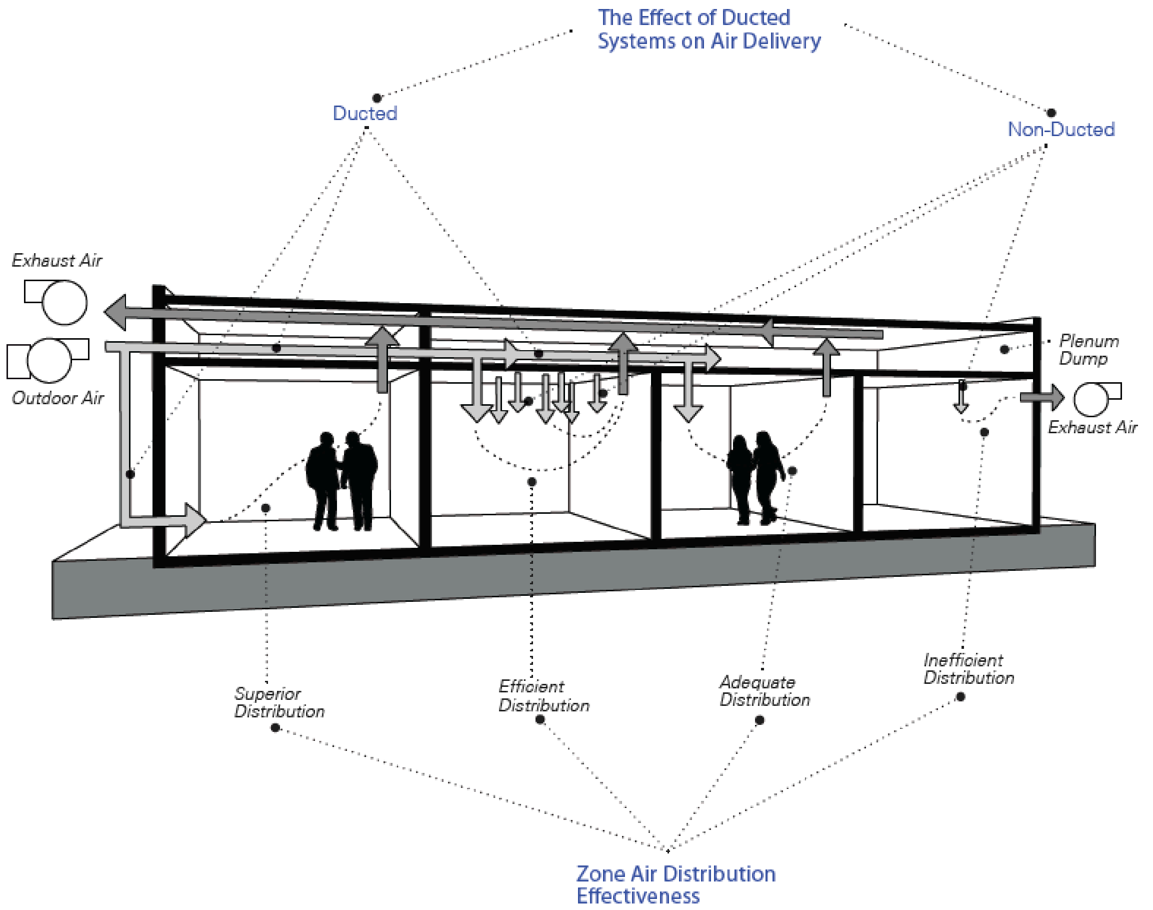
Figure 7.5-I Eroded Gasketing on Filter Access Door

Figure 7.5-J Corrosion Penetration within an Air Handler

Photographs courtesy of H.E. Burroughs.

Images from the *Indoor Air Quality Guide*, courtesy of H.E. Burroughs.

Air Distribution



Indoor Air Quality Guide

Mixing

- Standard 62-1999 stated "*The values in Table 2 define the outdoor air needed in the occupied zone for well mixed conditions.*"
- Most systems designed and installed in the 20th century were intended to be well mixed.
- Many contemporary systems in the 21st century are also intended mix the air.

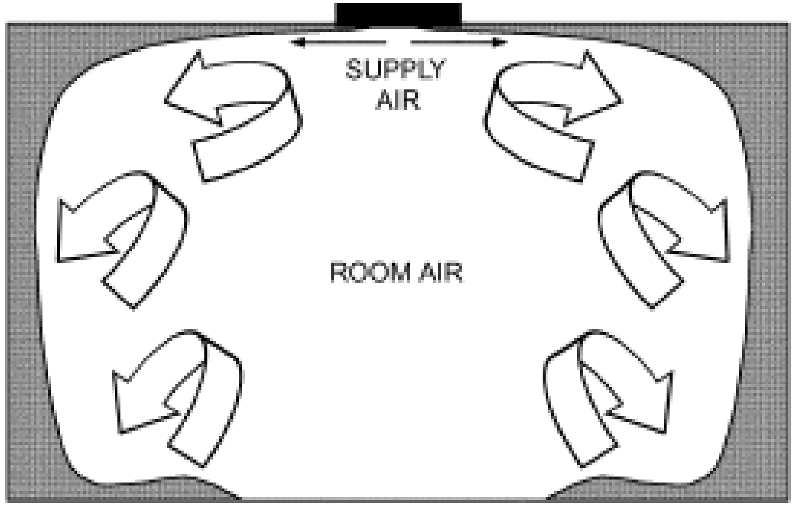


Fig. 5 Air Supplied at Ceiling Induces Room Air into Supply Jet

ASHRAE Handbook 2023—*HVAC Applications* p.58.9

Ventilation Effectiveness

- The purpose of ventilation is to manage the concentrations of potentially harmful contaminants.
- During COVID-19 we learned that the sources of the contaminants were the people in the spaces.
- It is no longer desirable to mix up all the air so that everyone is exposed.
- Some improvements in air distribution are possible and have been available for decades.
- They include stratification and personalized ventilation which are specified in ASHRAE 62.1-2022 as alternatives to mixing.

Stratification

Stratified air distribution uses the thermal plume from occupants to assist in transporting human bioeffluents from the breathing zone to upper unoccupied parts of the room.

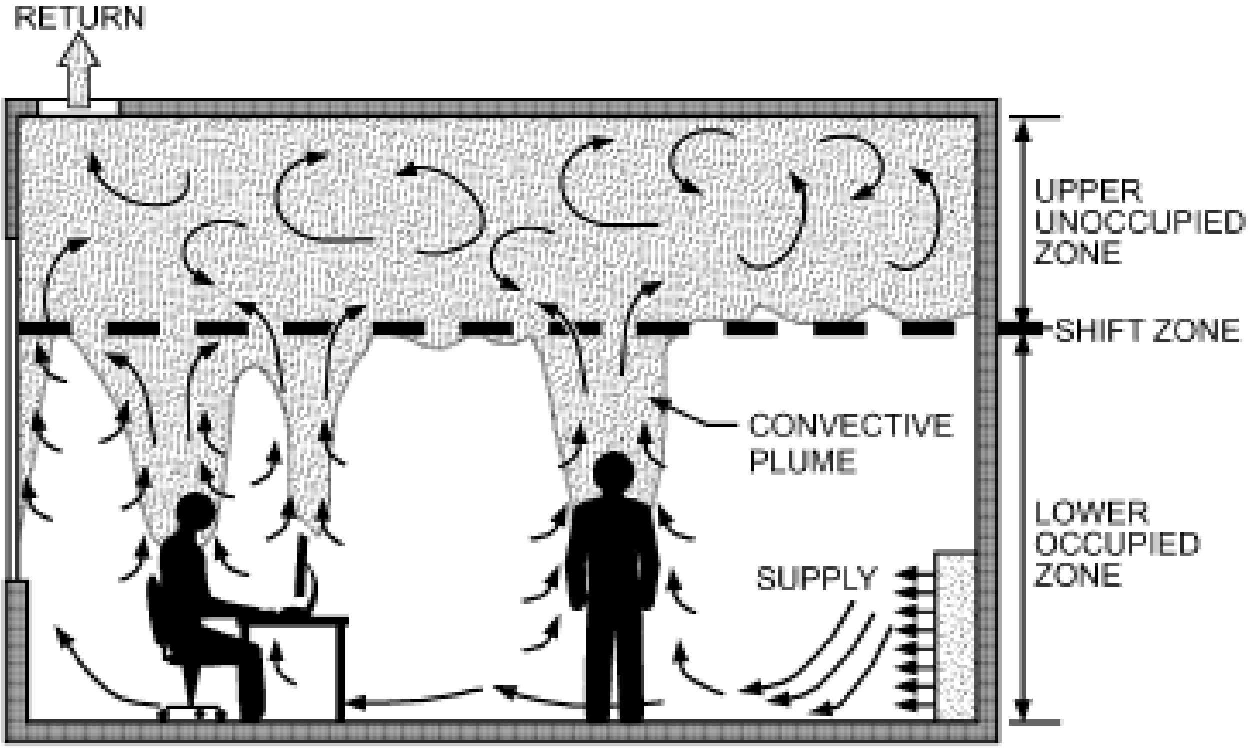
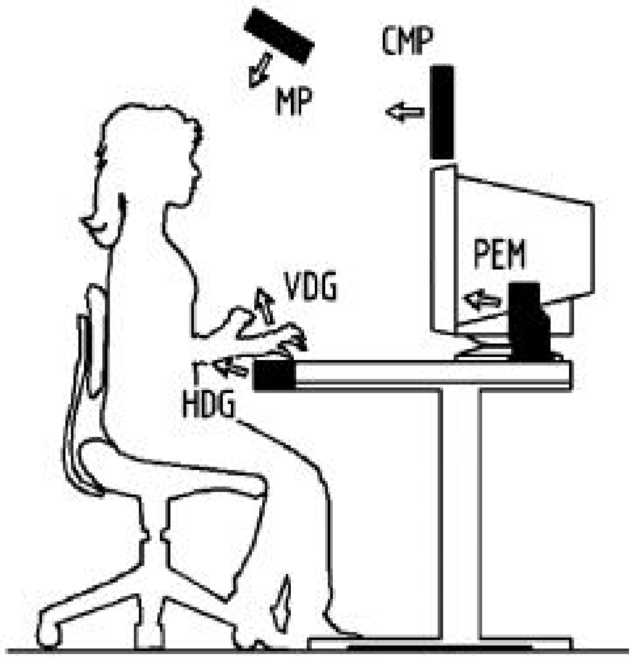


Fig. 6 Displacement Ventilation System Characteristics

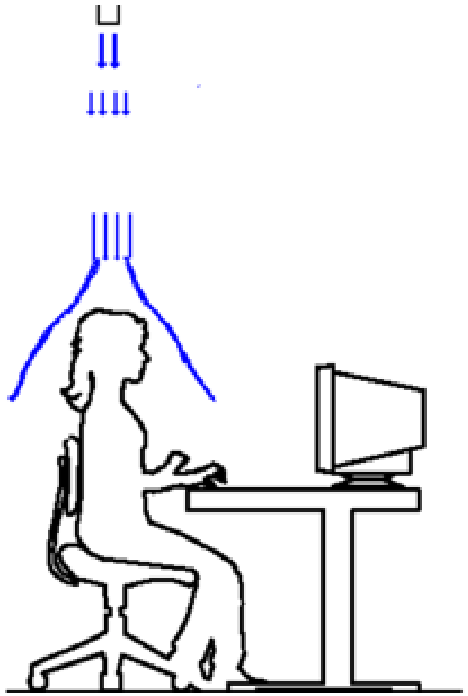
ASHRAE Handbook—*2023 HVAC Applications,* p.58.10

Personalized Ventilation Examples



Courtesy of Dr. Chandra Sekhar

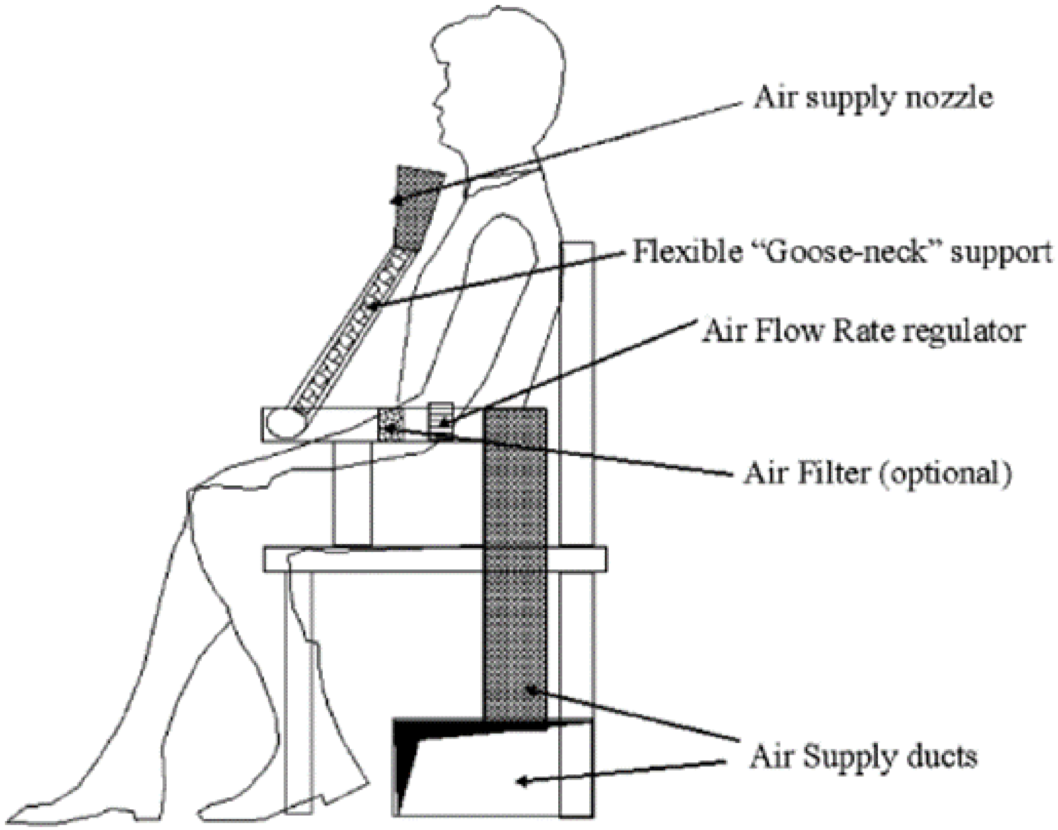
Ceiling mounted



Integrated with the capability of control of airflow interaction in the vicinity of human body to improve the PV in inhaled air.

Personalized Ventilation (PV) Inhaled Air Quality

- PV tended to lower inhaled air temperature by 2-5°C.
- PV can improve ventilation effectiveness at immediate breathing zone by up to 50% more than can be obtained with MV alone. Human response to air quality acceptability was improved by 64%.
- PV temperature and flow rate were found to be more critical than ambient temperature for occupants' PAQ.
- It increased up to 94% portion of clean air into inhaled air and significantly reduced (more than six times) the number of secondarily infected occupants compared to MV.



Courtesy of Dr. Chandra Sekhar

Sandia Study

- A goal of this study was to find cost effective ways to improve the air quality without suffering the long-term increased costs. These improvements would not only protect the health of the community in the current environment, but also reduce the transmission of viruses year-round, including the common cold and flu.
- The results of this study demonstrate that minor modifications to a space that promote through-flow conditions can improve air quality and reduce pathogen concentrations.
- The results and recommended ventilation designs from this study will be generally applicable to minimize risks of airborne transmission for future seasonal flu outbreaks or epidemics.

Figure 1. Photograph (left) and 3-D model (right) of conference room 802/2000.

Information and figure from Studies of Alternative Ventilation Configurations to Mitigate Airborne Exposure Risks in Office Spaces, SAND2021-13511, October 2021, Armenta, Casiano C.; Armijo, Roberto D.; Garcia John M.; Ho, Clifford K.; Naber, Nicole L. https://www.osti.gov/servlets/purl/1827490

Modeling

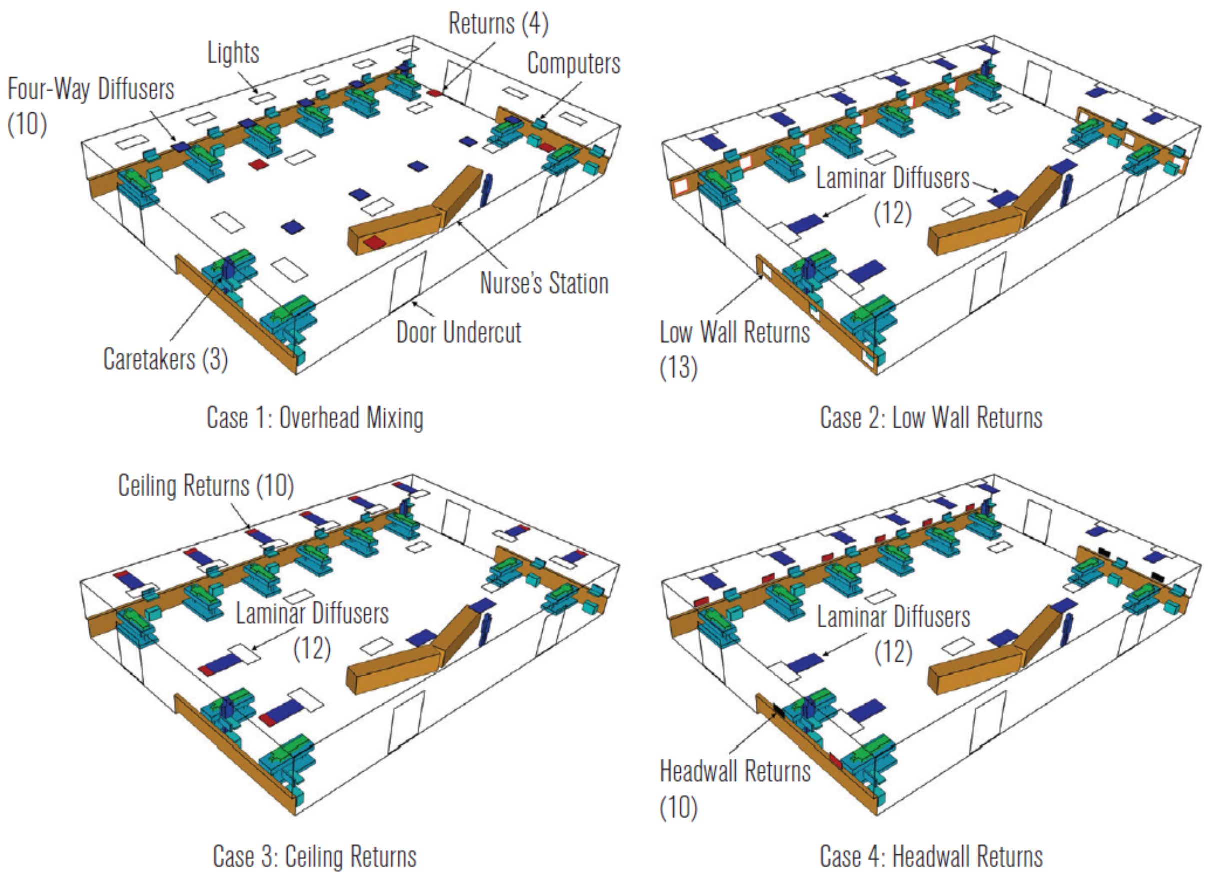
- Standard 62.1-2022 allows for modeling for determining Ez within certain specified parameters.

C2. MODELED AIR DISTRIBUTION SYSTEM

C2.1 Computational Model. The computational fluid dynamics model for calculating zone air distribution effectiveness shall be in accordance with the following subsections.

Modeling Airflow, *(Page 1 of 2)*

FIGURE 1 Schematic diagram of CFD models for four different HVAC layouts.



Optimization of Ventilation Design for the Hospital Post-Anesthesia Care Unit, Khankari, Kishor, Ph.D, Fellow ASHRAE; Garcia, Alberto; Leonid, Turkevich, Ph.D. ; Dunn, Kevin H., CIH; ASHRAE Journal, October 2024 p. 24

Hospital post-anesthesia care units (PACU)

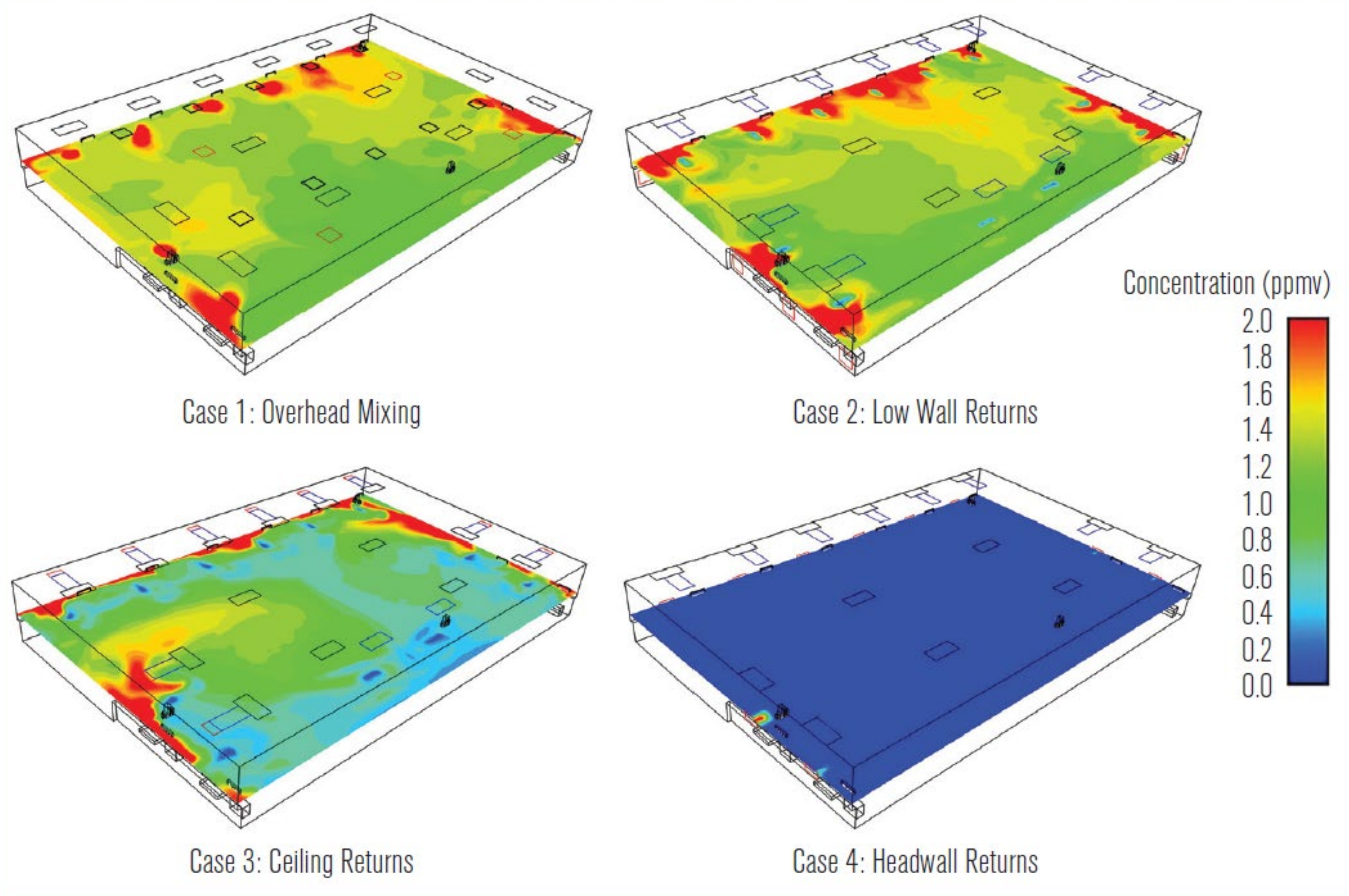
Four ventilation configurations are modeled to the left.

TABLE 1 Description of HVAC layouts analyzed.

CASE	HVAC CONFIGURATIONS ANALYZED
1	Four-way supply diffusers close to the patient beds and returns in the core region – 6 ach
2	Laminar supply diffusers over each bed and low wall returns in the headwall – 6 ach
3	Laminar supply diffusers over each bed and ceiling returns adjacent to the laminar diffuser – 6 ach
4	Laminar supply diffusers over each bed and headwall returns behind the bed – 6 ach
5	Laminar supply diffusers over each bed and headwall returns behind the bed – 4 ach

Modeling Airflow, *(Page 2 of 2)*

FIGURE 3 Distribution of sevoflurane concentration in the breathing plane at a 4 ft (1.2 m) elevation.



Hospital PACU

Substantial variation in Concentration and Exposure between the configurations modeled.

Optimization of Ventilation Design for the Hospital Post-Anesthesia Care Unit, Khankari, Kishor, Ph.D, Fellow ASHRAE; Garcia, Alberto; Leonid, Turkevich, Ph.D. ; Dunn, Kevin H., CIH; ASHRAE Journal, October 2024 p. 28