Improving IAQ for Occupant Health & Performance in Commercial Buildings

Proposing GSA Field Research

1 Improving O&M **KPI for Health**		
2 Improving O&M **KPI for IAQ**	**3** Improving O&M **KPI for HVAC**	**4** Improving O&M **KPI for FM$**
5 **IAQ State of the Room**	**6** **Next Gen Thermostats**	**7** **In-room Filtration**
8 **Imp. Dampers/ Economizers**	**9** **Improved Filters**	**10** **DOAS with Electrification**

GSA Project # 47HAA022Q0184

Center for Building Performance and Diagnostics

Improving IAQ for Occupant Health in Commercial Buildings: 10 Priorities for Field Research Projects for GSA

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Executive Summary

The health impacts of outdoor and indoor air quality began to dominate the dialogue of building owners and managers during the SARS-Covid pandemic, catalyzing design and operational improvements alongside new field research on the costs and benefits of more informed action. As a partner in the White House Clean Air Challenge, and the largest property manager in the US, the US General Services Administration (GSA) committed to identifying and testing the impacts of design and operational improvements for human health and performance. Two GSA-led expert workshops in 2023 offered invaluable insights into the baseline IAQ challenges and applied research that was critically needed. Specific proposals from these two workshops coalesced around three major areas of improvement for IAQ and occupant health: Improve O&M; Improve Clean Air at the Zone/room level; and Improve Clean OA Hardware and Controls at the AHU. A period of four months of background literature review refined the research needed, resulting in ten ventilation research proposals. The draft report "*Improving IAQ for Occupant Health in Commercial Buildings: 10 Priorities for Field Research projects for Commercial Buildings*" was presented to the attendees of both workshops for critical review in March 2024, with this final report issued in May 2024.

Building on the expert identification of critical indoor and outdoor air quality pollutants and contaminants, Chapter 2 summarizes the literature connecting the most identified pollutants to health outcomes, and the emerging thresholds of concern for action. This chapter is not intended to be the definitive textbook on indoor and outdoor pollutants of concern for IAQ. As intended, it identifies gaps in knowledge and areas of uncertainty in the field that would benefit from additional field research.

The expert workshops had extensive discussions about the HVAC conditions of concern for IAQ and Health, discussed in Chapter 3. A pre-workshop survey of experts and two full-day workshops identified critical actions needed at the central AHU and at the zone, room or terminal unit level for delivering indoor air quality (IAQ). Filtration led the set of recommendations, with a commitment to both higher MERV filters for central AHU and the addition of in-room filtration. Increases in air quality monitoring at both the central system and zone/room level was emphasized, with effective control responses from the

BAS system. The importance of operation and maintenance, regularized testing and balancing, and responses to automated fault detection was reinforced. Increased use of outside air and dedicated outside air systems with separate thermal conditioning was championed. Finally, a few additional actions were identified – moving to smaller zone sizes for air and thermal delivery and introducing underfloor air with high returns to reduce mixing air.

The workshops also revealed a consensus that existing ventilation standards are only moderately based on conclusive research, and that evidence-based recommendations for improving ventilation and IAQ are most urgently needed for high occupancy public buildings and schools. While they considered improving health outcomes a high priority, the attendees identified a number of barriers to implementing health upgrades in existing buildings including budgets, lack of expert employees, and competing priorities. Addressing expert recommendations and concerns, this final report was issued in May 2024 with 10 Priorities captured in three overriding areas:

Research to Improve O&M for Indoor Air Quality and Health (Chapter 4)

The expert workshops and a subsequent literature review identified that **significant improvements in operations and maintenance (O&M) are the most critical path to improving indoor air quality (IAQ)**. Until recently, O&M priorities have focused on ensuring thermal comfort, then energy savings, and finally equipment maintenance and longevity, with code-compliant minimum ventilation rates assumed to be adequate for indoor air quality and occupant health. Systemic underfunding of O&M and limited training offerings makes it difficult to add new priorities. The development and testing of key performance indicators (KPI) would catalyze greater O&M Investments and expertise for improving indoor air quality. Four different key performance indicators (KPI) are outlined in Chapter 4 to significantly advance both O&M investments and expertise for IAQ, establishing: 1) Surveys of user satisfaction and health indices by building and zone; 2) Measurements of IAQ indices by building and zone; 3) Solidified industry HVAC condition assessment indices including Fault Detection and Diagnostics (FDD) reporting for IAQ; and 4) Records of Facility Management (FM) investments including budget, manpower, training, turnover, and absenteeism.

> Research #1. Field research in federal buildings should explore the use of user IAQ satisfaction and Wellness surveys by building or even zone, adding additional objective health metrics such as sick days and medical costs, to establish a portfolio-wide KPI index and database for comparing to the impact of building system capital and operational choices, facility management investments, and more, for IAQ and health.

Research #2. Field research in federal buildings should explore the introduction of a set of zone IAQ sensors beyond temperature - such as CO2, PM2.5, and formaldehyde – to provide zone IAQ signatures to establish a portfolio wide KPI for comparing the impact of building system capital and operational choices, facility management investments, and more, for IAQ and health.

Research #3. Maintaining targeted records of central AHU and zone hardware and software conditions, including fault (FDD) and maintenance, could establish a portfolio wide KPI for comparing the impact of building system capital and operational choices, facility management investments, and more for IAQ and health.

Research #4. A facility investment KPI could be developed to record key variables that may influence IAQ and health outcomes: the level of investment in labor and materials per building per year; the area served per full time and part time FM staff; the years of service in that building, turnover and absenteeism; the level of training provided; and the compensation and promotion provided to ensure FM commitment and expertise (green careers). This FM investment KPI can be compared to health outcomes, IAQ measurements and annual maintenance checks and FDD KPIs to support improvements in FM staffing of federal facilities.

Research to Improve Room OA and Equivalent Clean Air (Chapter 5)

Until recently, ventilation standards have focused on the delivery of outside air critical to the breathing needs of occupants in a building and to adequate dilution of pollutants that may be generated indoors. To capture these two tasks, NIH differentiates air exchange efficiency - how efficiently the fresh air is being distributed in the room - from ventilation effectiveness - how efficiently the airborne pollutant is being removed from the room (WHO, 2009). The question for both ventilation efficiency and effectiveness is whether existing HVAC configurations and operations are ensuring adequate OA and air exchange quantities given the distribution paths, diffuser locations, and furniture configurations in conditioned zones. With the recent increases in the transfer of infectious diseases such as SARS-Covid, even more scrutiny is being given for the delivery of outside air and air exchange as well as emerging room filters for removing these and other contaminants of concern. Three significant research areas related to room ventilation efficiency and effectiveness are outlined in Chapter 5, with the first level of background research.

Research #5. Field research in select federal buildings should explore the use of existing distributed continuous CO_2 sensor data to estimate the ventilation OA and equivalent air change rate per zone and per person, adding additional sensors or engaging occupant centric sensors where data is too sparse to establish the baseline OA ventilation and air exchange rate for contaminant removal to establish the 'State of the Room'.

Research #6. Field research in select federal buildings should initiate a next-gen thermostat research intervention that would compare conventional temperature-centric thermostats with temperature sensors (wireless or wired sensor suite) with commensurate improvements to the BAS control of dampers and fans, in side-by-side analyses of IAQ, health and energy outcomes.

Research #7: Field research in select federal buildings should comparatively assess the IAQ, energy and operational benefits of equivalent clean air (ECA or eqOA) delivery with in-room HEPA and UVGI as compared to increased outside air from the central air handler (and possibly operable windows).

Research to Improve Central AHU Outdoor Air, Filtration and Delivery

Three significant research areas related to the efficiency and effectiveness of central air handling units for delivering efficient, effective, and healthy ventilation are outlined in Chapter 6, with the first level of background research.

Research #8. Field research in select federal buildings should evaluate ~~T~~the quantity of filtered outside air can be measurably increased at the central air handler without energy penalty - updating iteratively damper/sensor/actuator, VFD fans, correlated BAS algorithms, airside economizers with updated ranges at high and low temperatures, and economizers with energy recovery.

Research #9. Field research in select federal buildings should evaluate t~~T~~he quality of filtered outside air can be measurably improved at the central air handler through filter material quality, replacement schedule, and location.

Research #10. Field research in select federal buildings should study the ~~The~~ ~~i~~introduction of dedicated outside air (DOAS to the zone or room) with separate thermal conditioning (VRF, radiant, dual duct in either new or retrofit buildings) will improve IAQ for occupants, save energy, ensure thermal comfort, and support mixed mode with natural ventilation wherever possible.

Chapter 1

Introduction

Given that we spend more than 90% of our time indoors, the health impacts of outdoor and indoor air quality continue to demand design and operational improvements alongside field research on the costs and benefits of more informed action. As a partner in the White House Clean Air in Buildings Challenge, and the largest property manager in the US, GSA is committed to identifying and testing the impacts of design and operational improvements for human health and performance.

Under the Clean Air in Buildings Challenge many federal agencies agreed to commit to provide cleaner indoor air across the country. GSA committed to establish its portfolio of approximately 1,600 federally owned facilities as an exemplar of innovation, implementation, and standards for indoor air quality. This includes evaluating how the design and operation of ventilation systems can improve indoor air quality and the health, comfort, and performance of building occupants. GSA's commitments include:

- Extending programs to verify proper ventilation in federally owned buildings
- Partnering with experts and researchers on "real-world research"
- Convening subject matter experts to suggest changes to policy
- Sharing leading practices from research in training resources

In 2022, GSA completed a program to verify ventilation in a set of 62 federally owned buildings representing approximately 20% of its floorspace. From this evaluation, the program found air handling equipment serving over 34% of occupied space was not meeting minimum outdoor air requirements. Additionally, a range of maintenance issues and mechanical repairs were identified and corrected. The program has been extended in 2024 to another 78 buildings representing an additional 20% of floor space though the exact amount is subject to the availability of funding. Findings from this work informed the research activities described in this report.

On May 17, 2023 GSA assembled over 35 experts from diverse professional backgrounds and multiple US regions in a full day expert panel workshop dedicated to identifying HVAC conditions of critical importance of occupant health, and needs for 'Real World Implementation Research'. To ensure focused use of their time, the experts completed pre-workshop questionnaires ranking possible central and zone HVAC conditions of concern for both short term and long term health and performance.

The pre-workshop survey was instrumental in establishing the five breakout sessions to define critical research for improving indoor air in federal buildings for human health and performance.

1. Improve Outdoor Air Hardware/Software and/or Economizers
2. Improve Filters (type, efficiency, and installation and sealing) at AHUs
3. Improve Supply Air / Return Air Fans and System Balancing at AHUs
4. Improve Clean Air Flow Rate & Air Quality Sensors at room/zone/terminal units
5. Improve O&M (i.e. frequency of Commissioning, enabling Automated Fault Detection & Diagnostics, workforce training, or other)

In each of these areas, two subgroups of 5-7 experts brainstormed to develop suggestions for definitive field research on HVAC capital and operational upgrades most likely to improve IAQ for human health and performance – directly leading to the 10 research areas outlined in this report.

A second GSA workshop held with the National Academies NRC Federal Facilities Council on July 27, 2023 added critical depth to the design of 'Enhanced Ventilation for Cleaner Air in Buildings'. The recent release of ASHRAE Standard 241-2023 for an Infection Risk Management Mode (IRMM) to Control Infectious Aerosols was introduced (fig. 3.5), highlighting the importance of engineering 'equivalent Clean Air Flow' that combines centrally filtered outside and return air with locally filtered room air to measurably increase the overall air exchange in occupied spaces whenever there are heightened health concerns in commercial buildings. The expertise gathered by GSA and the Federal Facilities Council spanned from health and safety to general science, air research, facility engineering and facility management, to program management. This workshop added depth and priority to the May 17 recommendations, highlighting a number of additional directions for building intervention and assessments.

The two GSA led workshops offered invaluable insights into the baseline IAQ challenges and actions that could address them as a catalyst for applied research. Specific proposals from these two workshops coalesced around three major areas of improvement which are the basis of the three chapters that follow: Improve O&M; Improve Clean Air at the Zone/room level; and Improve Clean OA Hardware and Controls at the AHU. A period of four months of background literature review enabled the Carnegie Mellon CBPD team to refine the research needs outlined in the two workshops, resulting in the ten ventilation research proposals outlined in the following three chapters. The draft report "*Improving IAQ for Occupant Health in Commercial Buildings: 10 Priorities for Field Research projects for Commercial Buildings*" was presented to the attendees of both workshops for critical review on March 20, 2024. Addressing expert recommendations and concerns, this final report was issued May 2024.

In an additional focus of its real world research, GSA committed to evaluate potential changes in building operations and maintenance policy based on emerging requirements for reducing the risk of infection indoors. To support this, GSA compared the principal sources for emerging requirements, ASHRAE Standard 241 (ASHRAE), CDC Ventilation in Buildings Guidelines (CDC), and EPA Clean Air in Buildings Challenge (EPA) and found significant differences between them. GSA convened a panel of over 30 subject matter experts in the diverse fields of ventilation design, indoor air quality, facility management, and public health to suggest how to harmonize the emerging standards. The experts suggested focusing primarily on ASHRAE and conducting a feasibility study and pilot of the Standard as its application, especially to existing buildings, would be challenging and require evaluation of approaches and technologies not currently in widespread use in the field. GSA decided to pilot the standard beginning in 2024 by adding its scope to a VVP project.

The GSA will share the results of its research findings including the feasibility study and pilot of ASHRAE, and any future recommendations for adjustments to policy, through its involvement in collaborative bodies including the Federal Real Property Council (FRPC), Interagency Sustainability Working Group (ISWG), and efforts with the National Academies of Science, Engineering and Medicine’s Federal Facilities Council (FFC) and Health in Buildings Roundtable (HiBR).

Chapter 2

Indoor and Outdoor Pollutants of Concern and Health Literature

A May 17, 2023 GSA Workshop engaged over 35 experts across the US in ranking both the indoor and outdoor pollutant or contaminants and other air quality indicators of concern for both short term and long term health and performance. Both indoor and outdoor contaminants need to be ranked separately since the building design and operation responses will be different. Outdoor pollutants should be addressed through filtration at the air handling unit and through reducing or minimizing infiltration, while indoor pollutants need to be addressed in the occupied zone first, and then through management of the recirculated air stream. The results of this pre-workshop survey of experts are shown in fig. 2.1, with viruses the leading pollutant for short term health and performance, and particulates the leading pollutant for long term health and performance. The following sections will expand on the research related to why these may be critical pollutants/ contaminants/ indicators of concern and summarize some of the known thresholds of concern. This chapter compiles research that can contribute to a future definitive textbook on IAQ pollutants of concern and the thresholds critical for action, that needs to be written by the health and standards community.

Contaminants of Concern for Short-Term Impact ***Contaminants of Concern for Long-term Impact***

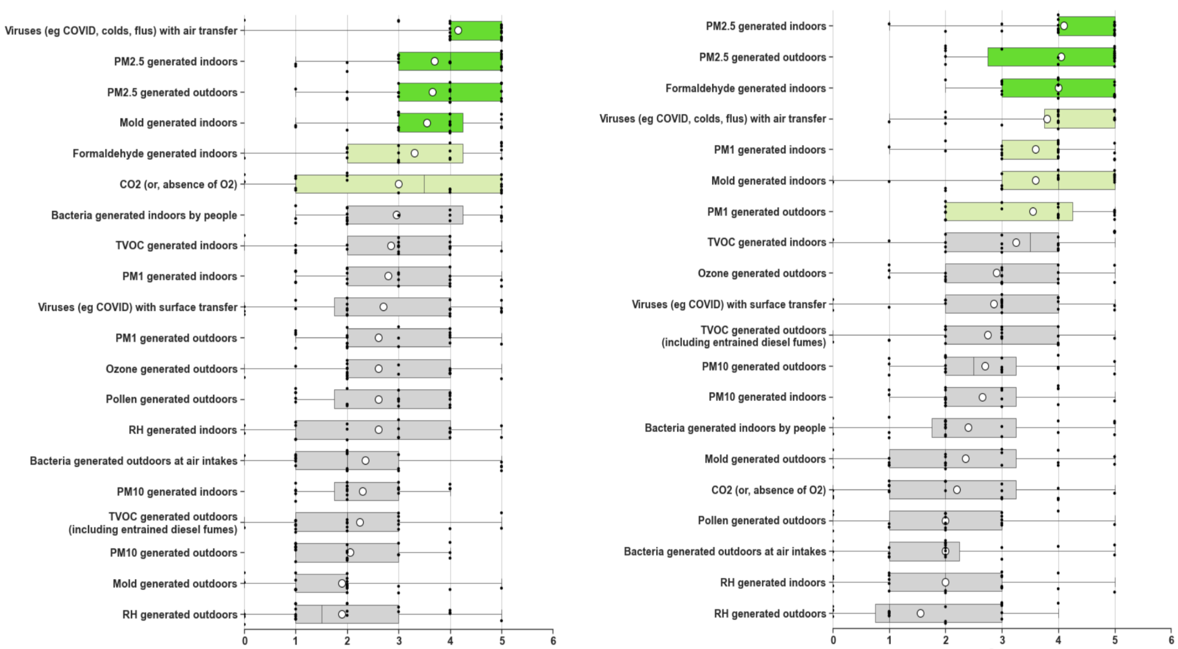


*fig. 2.1 Expert Prioritization of Pollutants with **Short-Term Impact** (left) and **Long-term Impact** (right) on Human Health & Performance in Offices.*

2.1 Particulates generated outdoors and indoors (PM10, PM2.5 – fine, PM1 and below – superfine)

Particulates are both a direct pollutant of concern for human health and a carrier of viruses such as SARS-Cov-2 virus that can cause COVID-19, making them doubly important to control (Comunian et al, 2020). Particulate matter (PM) comprises a blend of solid and liquid particles in the air, encompassing acids, organic chemicals, soot, metals, soil, and dust. Based on its diameter, particulate matter is often distinguished by size, from below PM1.0 (less than 1.0 μm), to PM2.5 (less than 2.5 μm), to PM10 (less than 10 μm) (Yin & Harrison, 2008). **Outdoor particulates** that enter the ventilation system can be elevated due to power plants, diesel engine combustion, construction, wildfires and more. Equally significant, **indoor particulates** can be elevated due to occupant activities, office equipment, room deodorizers. ionizers and more (https://epa.gov/pm-pollution/particulate-matter-pm-basics). While filtration in the central air handler can be very effective at reducing outdoor particulates, either dilution through increased air change rates or room filtration is needed to reduce indoor particulates.

The health effects of PM include increased risk of heart or lung disease, non-fatal heart attacks, irregular heartbeat, and aggravated asthma (Environmental Protection Agency, 2021). Ehrlich et al. pointed out the causal effect between exposure to PM2.5 and PM1.0 particles and respiratory infection, impairment of blood vessels, and alterations in heart rate variability, blood clotting, and functioning of the cardiac autonomic nervous system (Ehrlich et al., 2007). Examples of research linking PM concentration and COVID-19 and other health concerns include:

> *In a 2016 intervention study of 89 participants in Taiwan province, Wu et al. identified that a 10-μg/m3 increase in indoor PM2.5 resulted in 1.9% to 2.3% increase in baPWV (Brachial–ankle pulse wave velocity), which indicates higher arterial stiffness levels ($p<0.05$).*

> *In a 2020 metadata analysis of the PM concentration levels and COVID-19 diffusion rates in 17 provinces in Italy, Setti et al. identified a strong positive correlation between a number of infected people with the COVID virus and outdoor PM10 levels above 50 μg/m3 ($p<0.001$).*

> *In a 2021 observational study of 36,085 adults in Swiss, Strassmann et al. identified that per 10μg/m^3 increase in long-term (1-year) exposure to PM2.5 (indoor and outdoor exposures) resulted in pulmonary effects that include a 1.36% decrease in forced expiratory volume within the first second (FEV1, $p<0.001$) and 2% decrease in forced vital capacity (FVC, $p<0.001$).*

In a 2021 prospective observational study among 302 office workers in 6 countries (China, India, Mexico, Thailand, US, UK), Laurent et al identified that an IQR (IQR= 8.8 μg m−3) increase in PM2.5 level was associated with an reduction in measures of productivity including 0.82% longer Stroop response time, a 6.18% increase in Stroop interference time, a 0.7% decrease in Stroop throughput, and a 1.51% decrease in ADD throughput.

In a 2023 before and after office study with 55 subjects in Beijing, Zhou et al. identified that the implementation of ozone-free Hyper-HEPA purifiers (Atem Desk Air Purifier, IQAir®, Switzerland) reduced PM2.5 levels by 74.9% (at 3.7μg/m3) resulting in an 11.2% improvement in reaction time (RT) for estimation skills ($p < 0.001$), a 7.5% improvement in RT for recognition skills ($p < 0.05$), and a 4.6% improvement in RT for divided attention for attention-related evaluation, as well as 7.6% improvement in a short term memory for a memory-related evaluation ($p<0.05$), as compared to a space without air purifiers (PM 2.5 at 18 μg/m3).

The thresholds of concern are being debated worldwide, with critical modifications reflecting regional limitations on controlling particulate matter. To capture this global debate, a scale with good, better, and best indoor thresholds from different organizations is shown for PM2.5 and PM10. It is critical to note that these are not thresholds of definitive harm, but indoor thresholds at which action is recommended. Notably, in more polluted areas, these thresholds may differ, as highlighted in standards like WELL.

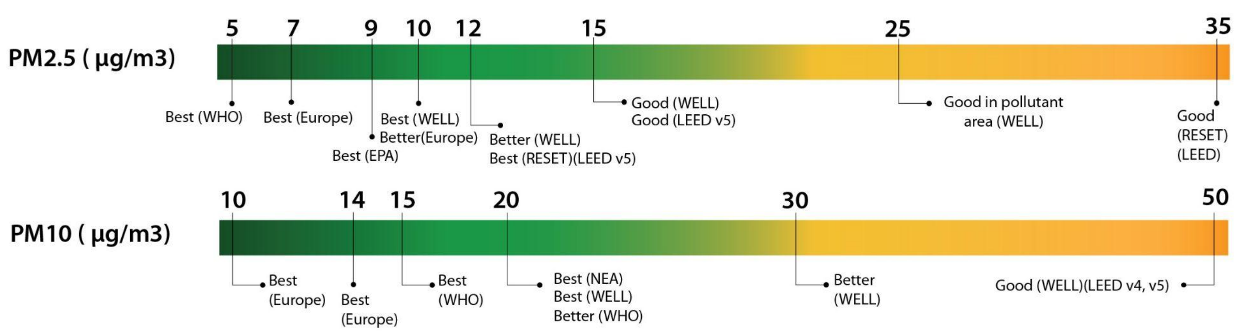


fig. 2.2 Thresholds of concern for Indoor PM2.5 and PM10.

2.2 Carbon Dioxide (CO_2)

CO2 is both a pollutant and an indicator of inadequate ventilation for dilution of a host of other indoor pollutant sources. CO2 is a colorless, odorless, and tasteless gas, slightly toxic when inhaled, and is ubiquitous in the atmosphere. With a concentration of approximately 400 ppm outdoors, CO2 is elevated indoors predominantly due to occupant breathing (Huang et al., 2021) and has been used as a surrogate marker to assess indoor air quality and the effectiveness of ventilation systems (ASHRAE_ indoorcarbondioxide_2022). As a pollutant source, CO2 must reach relatively high levels to cause significant human health impacts. OSHA has established a Permissible Exposure Limit (PEL) for CO2 of 5,000 parts per million (ppm) (0.5% CO2 in air) averaged over an 8-hour workday (time-weighted average or TWA) (FSIS, 2020). However, as a marker for adequate ventilation, CO2 over 1000 ppm is often considered problematic (Satish et al, 2012). In the era of infectious disease including COVID and flus, maximum thresholds of CO2, as one of the few measured IAQ variables in occupied spaces, have become important to understanding occupancy densities and ventilation rates.

In a “Position Document on Indoor Carbon Dioxide” (ASHRAE2022), ASHRAE cautions:

- Indoor CO2 concentrations do not provide an overall indication of IAQ, but they can be a useful tool in IAQ assessments if users understand the limitations in these applications.
- Existing evidence for direct impacts of CO2 on health, well-being, learning outcomes, and work performance at commonly observed indoor concentrations is inconsistent, and therefore does not currently justify changes to ventilation and IAQ standards, regulations, or guidelines.
- The use of indoor CO2 measurements to assess and control the risk of airborne disease transmission must account for the definition of acceptable risk, the type of space and its occupancy, and differences in CO2 and infectious aerosol emissions and their subsequent fate and transport.
- Differences between indoor and outdoor CO2 concentrations can be used to evaluate ventilation rates and air distribution using established tracer gas measurement methods, but accurate results require the validity of several assumptions and accurate input values.
- Sensor accuracy, location, and calibration are all critical for drawing meaningful inferences from measured indoor CO2 concentrations.
- Air-cleaning technologies that remove only CO2 will not necessarily improve overall IAQ and can interfere with systems using CO2 for ventilation control or IAQ monitoring.

As identified in this ASHRAE document, the importance of controlling CO2 (and associated bio-effluents) from occupant densities continues to be a subject of research relative to human health, cognitive performance, and occupant satisfaction in the workplace. A number of these studies included controlled comparisons of performance or health in different CO2 conditions that could be markers for multiple IAQ concerns:

In a 2003 multi-school study, Daisy et al. found significant associations of mucous membrane and lower respiratory Sick Building Syndrome (SBS) symptoms correlated with CO2 concentrations above 700 ppm.

In a ten-year field study (2003 to 2014) of IEQ measurements and user satisfaction survey responses at 1600 workstations in 64 buildings dating, Park et al. (2019) identified statistically significant improvements in occupant satisfaction with indoor air quality when indoor CO2 is below 600 ppm.

In 2019 on-site chamber measurement study in India, Shriram et al. identified that CO2 concentration over 2000 and 3000 ppm led to reduced Forced Expiratory Volume 1 (0.4–1 L) and Forced Vital Capacity (0.2–1.1 L) values, leading to restrictive behavior of the lungs.

In a 2020 meta-data analysis from 20 studies across more than 760 schools in various international locations, including Denmark, Costa Rica, Chile and the US, Wargocki et al identified that reducing CO2 concentrations from 2100 ppm to 900 ppm could enhance the speed of performing psychological tests and school tasks by approximately 12% and reduce errors by about 2%. (classrooms > 2000, t= 1996-2015, $p < 0.001$).

A few research projects independently studied CO2 as a contaminant:

In a 2012 controlled lab study, Kajtár et al. identified that subjects relocated to a closed space seeded with over 3000 ppm of CO2 exhibited 5% reduced capacity to concentrate and 15% reduced mid-frequency heart rate variability MF-HRV ($p<0.05$) after 2-3 hours, as compared to their normal work settings with 600 ppm CO2. Additionally, the blood pressure increased 5.5 Hgmm and 50% of the spectral power of the high-frequency heart rate variability (HF-HRV) when CO2 increased from 600 ppm to 5000 ppm ($p<0.05$).

In a 2016 field experimental study with 24 participants in an office building in Syracuse, Allen et al identified that a 400-ppm increase in CO2, seeded into the supply air, was associated with a 21% decrease in participant's cognitive scores, and a 500-µg/m3 increase in TVOCs was associated with a 13% decrease in cognitive scores ($p < 0.0001$).

In the same 2016 before and after study, MacNaughton et al. identified that an 1000 ppm increase in CO2 (from 400 ppm to 1400 ppm) resulted in a 2 bpm increase in heart rate ($p<0.001$) and a 43% average increase in self-reported health symptoms, including wheezing, sneezing, tension, dizziness, and headaches. ($p=0.019$)

In a 2021 lab experiment, Lee et al. identified that artificially adding pure CO2 to raise indoor CO2 levels of 500 ppm to 1000 ppm resulted in significant reductions in memory-related task performance ($n=30$, $p<0.05$).

However, other studies suggest that other bio-effluents from occupants are causing health and cognitive challenges, not specifically the CO2 levels:

In a 2016 controlled experiment, Zhang et al. identified that adding pure CO_2 into the air, up to 3000 ppm, did not significantly affect health symptoms or cognitive performance. However, exposures to bio effluents alongside CO_2 at 3000 ppm increased reported headache, fatigue, sleepiness, and difficulty in thinking clearly, and reduced the speed of addition, the response time in a redirection task, and the number of correct links made in the cue-utilization test. ($n=25$, $t=255$ min (each exposure), $p<0.05$)

In a follow-up 2016 study, Zhang et al again identified that adding CO_2 into the air stream up to 5000 ppm (from a 500 ppm baseline), had no significant impact on perceived air quality, most physiological responses, or cognitive and office task performance, in healthy young adults during a 2.5-hour exposure, except for two outcomes - increases in end-tidal CO_2 ($ETCO_2$) and reports of nose dryness ($n=10$, $t=2.5h$ (each exposure), $p<0.05$).

While elevated CO2 levels may not have a known impact on human health, they serve as indicators of increased levels of bio-effluents from building occupants which do have human health and cognitive impacts. CO2 levels also serve as early indicators of inadequate ventilation rates.

When elevated levels of CO2 are used as an indicator of bio-effluents and ventilation air delivery challenges, the thresholds of concern are captured in the scalar below with acceptable, better and best indoor thresholds for CO2 from a number of worldwide standards (WELL v2, RESET Air v2.0, NAAQS).

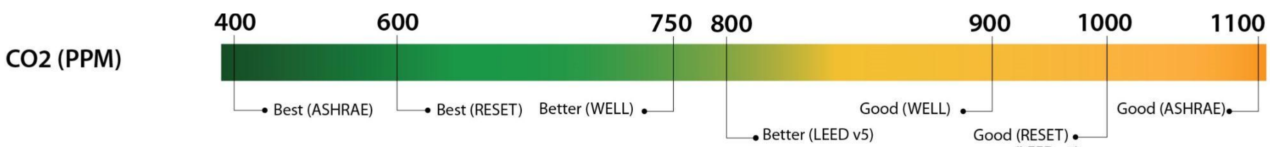


fig. 2.3 Thresholds of concern for CO2 as an indicator of bio-effluents and ventilation air delivery for occupant health and performance.

It is critical to note that these are not thresholds of definitive harm, but indoor thresholds at which action is recommended. Relative to direct toxicity concerns from CO2, the following scalar captures the USDA Environmental Safety and Health Group (ESHG) thresholds for providing a safe and healthful work environment for Food Safety and Inspection Service employees (FSIS, 2020).

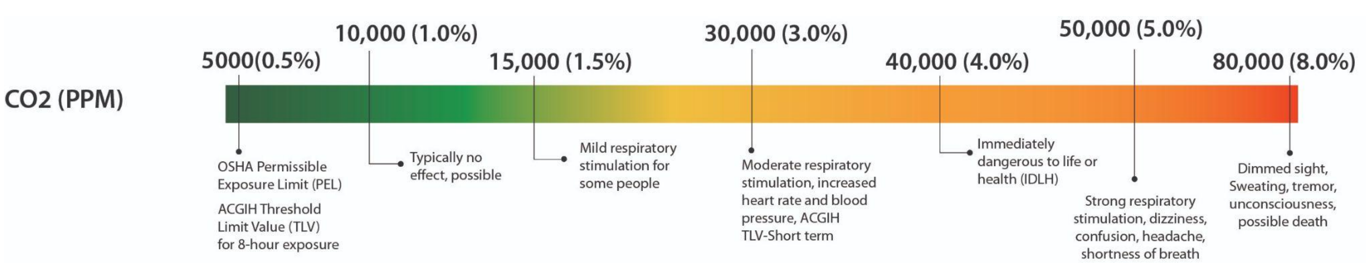


Fig 2.4 Thresholds of concern for CO2 as a pollutant source for health (FSIS 2020)

The WELL standard criteria for indoor CO2 setpoints and thresholds is based on an international set of standards and guidelines, summarized in Table 2.1.

Table 2.1 WELL standard ranking criteria for indoor CO_2 thresholds and setpoints.

	Mechanically ventilated spaces	**Naturally ventilated spaces**	**Naturally ventilated spaces in areas with elevated particulate matter**	**Ventilation monitoring**
Adequate	Standards: ASHRAE 62.1 ASHRAE 62.2 EN 16798-1 AS 1668.2 CIBSE Guide A	a) **Standards**: ASHRAE 62.1 CIBSE AM10 AS 1668.4 b) (**Operable windows not used** in ventilation calculations may be user operated) c) **Outdoor air**: PM 2.5 < 15 $\mu g/m^3$ PM10<30 $\mu g/m^3$	d) **Standards**: ASHRAE 62.1 CIBSE AM10 AS 1668.4 e) (**Operable windows not used** in ventilation calculations may be user operated) f) **Outdoor air**: PM 2.5 < 35 $\mu g/m^3$ PM10 < 70 $\mu g/m^3$	Carbon dioxide < 900 ppm Or CO2 < 500 ppm above outdoor levels
Enhanced (Part 1: Increase outdoor air supply)	a) Exceed outdoor air supply: GOOD: 30% EXCELLENT: 60% b) Demand control ventilation: Good: CO2 < 900 ppm Excellent: CO2 < 750 ppm	Implement and engineered natural ventilation system that is sufficient to keep CO2 levels in the breathing zone of all regularly occupied spaces below the specified thresholds at the maximum intended occupancies: Good: CO2 < 900 ppm Excellent: CO2 < 750 ppm		Carbon dioxide < 750 ppm Or CO2 < 350 ppm above outdoor levels
Enhanced (part 2: Improve ventilation effectiveness)	a) Displacement Ventilation System in at least 90% of regularly occupied spaces based on standards (ASHRAE , REHVA) b) For at least 50% of workstations, the following requirements are met: • Outdoor air is supplied in the breathing zone, with an airspeed of no greater than 50 fpm at the occupant's head. • The return air diffuser is located at least 90 ft above the floor.			

2.3 Ventilation Rate (OA cfm) as compared to Equivalent Clean Air (ECA or eqOA)

Worldwide minimum ventilation standards are designed to ensure that a critical amount of filtered outside air (OA) reaches the occupied space for the breathing needs of the occupant and to reduce indoor pollutants of concern. As shown in this 2019 chart from Nielsen, the minimum required quantity of outside air has cycled from 10 to 15 to 50 in cubic feet per minute per person and down again over the years, in SI units from 5 to 25 to 11 to 28 liters/second/person (figure 2.3). Some of these variations reflect the need for more than breathing air to ventilation to dilute other contaminants.

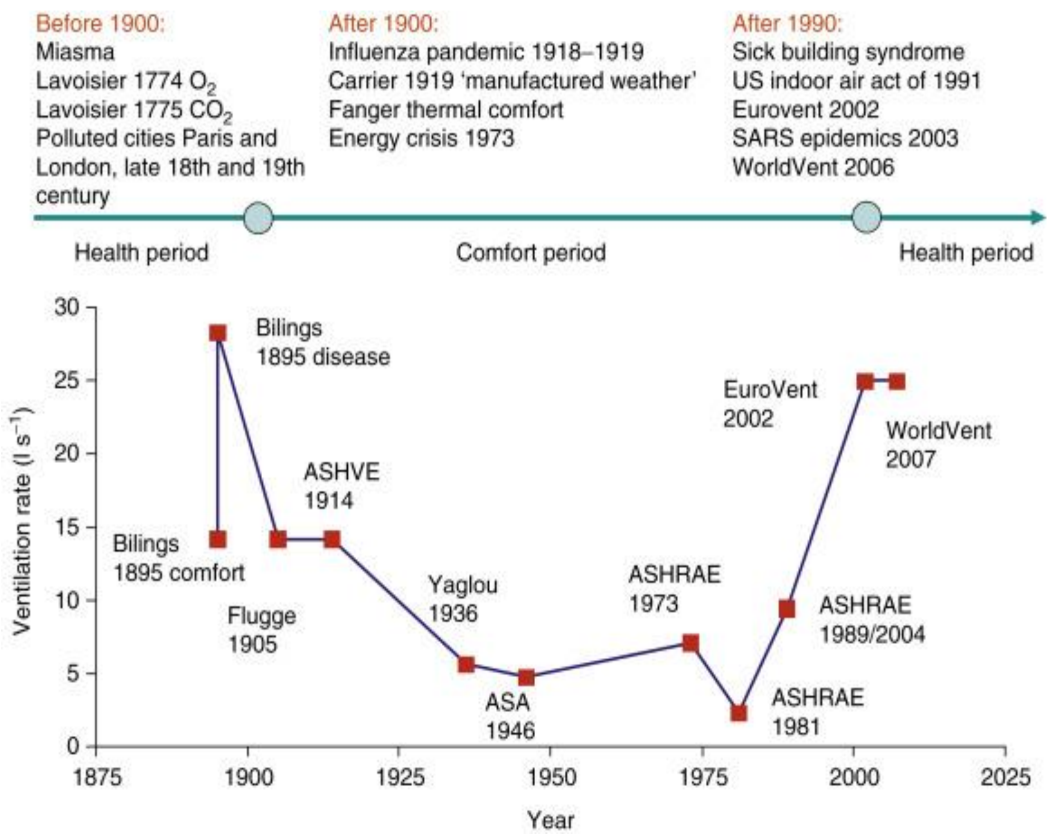


fig. 2.5 Representative minimum OA ventilation rates for offices over time, as recommended by ventilation standards or scientific studies (Nielsen et al 2019).

Before 1900, research focused on fresh air as a critical path to controlling airborne diseases from bacteria and viruses. Between 1900 and 2000, thermal comfort and energy efficiency began to reduce outdoor ventilation rates to the minimum requirements for breathing, with air change rates from filtered recirculated air providing dilution for indoor pollutants. Growing concern about indoor pollutants led to the historic shift in the 1980's to increase minimum outdoor ventilation rates.

In 1936, Yaglou et al concluded that a minimum ventilation rate of 10 cubic feet per minute per person (5 l/s/person) could reduce the odor from human bioeffluents to acceptable levels, while 15 cubic feet per minute per person (7.5 liters per second) was recommended for effective bioeffluent odor control, with higher rates needed under certain conditions (Yaglou et al 1936).

In a 2002 meta analysis of 105 papers, Wargocki et al identified that outside air OA ventilation rates above 50 cfm/person (25 l/s/person) is associated with a reduction in SBS symptoms and increased productivity outcomes (Wargocki et al 2002).

In a 2010 meta analysis of 27 papers, Sundell et al identified that rates lower than 50 cfm/person ventilation rates (25 l/s per person) are linked with increases in the prevalence of respiratory symptoms and asthma in both homes and offices.

A number of studies offer controlled comparisons of performance or health impacts at different outside air ventilation rates, often with corresponding CO2 conditions:

In a 2012 lab experiment at LBNL in Berkeley, California, Satish et al. identified that reducing CO2 levels from 1000 ppm to 600 ppm by increasing the outdoor air ventilation rate from 7.1 to 11.8L/s per person resulted in an average increase of 19% improvement in decision making performance. ($p<0.05$)

In a 2016 crossover experimental study in primary schools, Petersen et al. identified that raising outdoor air supply from an average of 3.6-14.0 cfm per person (1.7 to 6.6 l/s per person) led to a corresponding decrease from 1500 to 900 ppm CO2 concentrations, and enhanced children's performance across various tasks including addition, number comparison, grammatical reasoning, and reading comprehension ($p<0.1$).

In a 2017 office building study in Finland, Maula identified that occupants working in settings with outdoor air flow rate of 59.8 cfm per person (28.2 l/s person) and corresponding CO2 concentrations of 540 ppm had lower fatigue and slightly improved information search performance as compared to occupants in settings with outdoor air flow rate of 2.3 l/s person and corresponding CO2 concentrations of 2260 ppm, over a 4-hour period.

In a 2022 simulation study of a medium-sized office building across 19 Climate Zones and 8 scenarios of outdoor air delivery, Pang et al identified that infection risk can be significantly reduced by increasing the outdoor air fraction from 30% up to 100% depending on the ratio of infected individuals, with 0.3% infected having risks less than 2% at 30% outside air, while 10% infected the risk jumps to 40% unless OA in increased significantly. [Zhihong Pang, 2023]

The most recent ASHRAE 62.1-2022 requires the outdoor air flow in the breathing zone (V_{bz}) of the occupiable space or spaces in a ventilation zone shall be not less than the value determined by the equation:

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

where
R_p = Outdoor airflow rate required per person (L/s•person)
R_a = Outdoor airflow rate required per unit area (L/s•m^2)
A_z = Zone floor area, the net occupiable floor area of the ventilation zone, m^2
P_z = Zone population, the number of people in the ventilation zone during use

For office spaces, the R_p is set to 2.5 L/s•person and the R_a is set to 0.3 L/s•m^2. A default occupant density of 5 person per 100 m^2 results in an 8.5 L/s per person or 18 cfm/person of outside air.

Emerging standards embrace the potential of increased air change rates and in-room contaminant filtration as an alternative to increasing outside air ventilation rates to delimit the energy and carbon costs. While OA rates are critical for supporting occupant breathing needs, room air change rates typically exceed minimum outside air requirements to provide for thermal conditioning. In recent years, the critical need for extracting and filtering pollutants generated indoors, ranging from chemicals to viruses and bacteria, has led to higher requirements for zone air change rates (ACH) that can be achieved through a combination of outside air delivery in cfm (OA l/s) and locally filtered 'clean air'. Defined as equivalent clean air (ECA or eqOA) or equivalent ACH (eqACH or eACH), the air change rates are shifting from 2-3 ACH to 5 and more, identified as critical increases for human health. The ECA or eACH reflects the power of local filtration and remediation with HEPA and UVGI to achieve equivalent air change rates per hour in lieu of increased outside air from the AHU.

The thresholds of concern for OA cfm and ECH are being debated world-wide. Two scalars with acceptable, better and best thresholds are drawn from a number of worldwide standards.

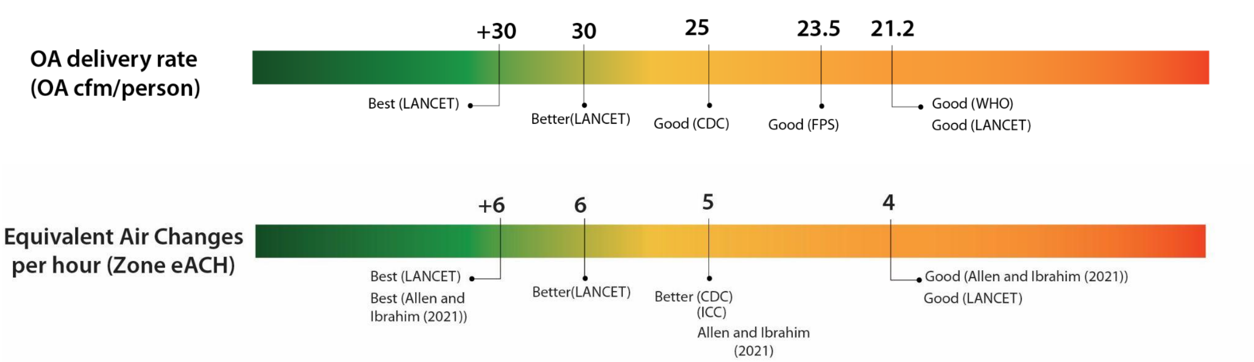


fig. 2.6 Thresholds of concern for OA cfm and eACH.

While there is growing evidence that increased OA ventilation rates alongside well filtered return air help to reduce the spread of infectious disease (ASHRAE, 2023), further research is needed to understand the importance of increased outside air (OA) delivery within this ventilation rate.

2.4 Mold

According to the Centers for Disease Control and Prevention, more than 75,000 hospitalizations and nearly 9 million outpatient visits occur every year due to fungal diseases, with an estimated 7200 deaths from fungal diseases in 2021 (CDC, 2023, WHO, 2009).

While not all molds are health risks, there are four main types of visible mold in buildings (EPA, 2024):

- Alternia - the most common and primary cause of allergic reactions
- Aspergillus - classified as toxic mold affecting the immune system and lungs
- Cladosporium - can grow at any temperature (including cold storage), often linked with asthma attacks.
- Penicillium - a type of toxic mold though its mycotoxins were used to develop antibiotic penicillin.

The health risks of dampness and mold in workplaces is serious, with numerous studies revealing that dampness and mold are related to ocular, nasal, throat and dermal symptoms.

> *In a 2007 field study of residential homes from 8 European cities, Shenassa et al identified that dampness or mold in homes was associated with depression-like symptoms (odds ratio =1.34 - 1.44 for minimal, moderate, and extensive exposure, respectively, compared with no exposure). This association was independently mediated by perception of control over one's home (OR = 1.34 - 1.40; global p = .069) and by a physical health index (OR = 1.32, 1.37, and 1.15; global p = 0.104).*
>
> *In a 2011 field study of residential homes, Karvala et al. identified that a total of 62 patients (13%) reported having developed new-onset asthma from prolonged exposure to damp and moldy workplaces. The continued exposure to indoor dampness in the same or the new work environment was reported by 18.8% of asthmatics and 11.4% of the non-asthmatics.*

In a 2021 field study of a school building in Johor Bahru, Malaysia, Fu et al identified that higher indoor relative humidity and visible dampness or mold in classrooms were associated with a higher concentration of potential risk bacteria and a lower concentration of potential protective bacteria ($p < 0.01$). About 51% of students reported SBS symptoms with the prevalence of ocular, nasal, throat, and dermal symptoms.

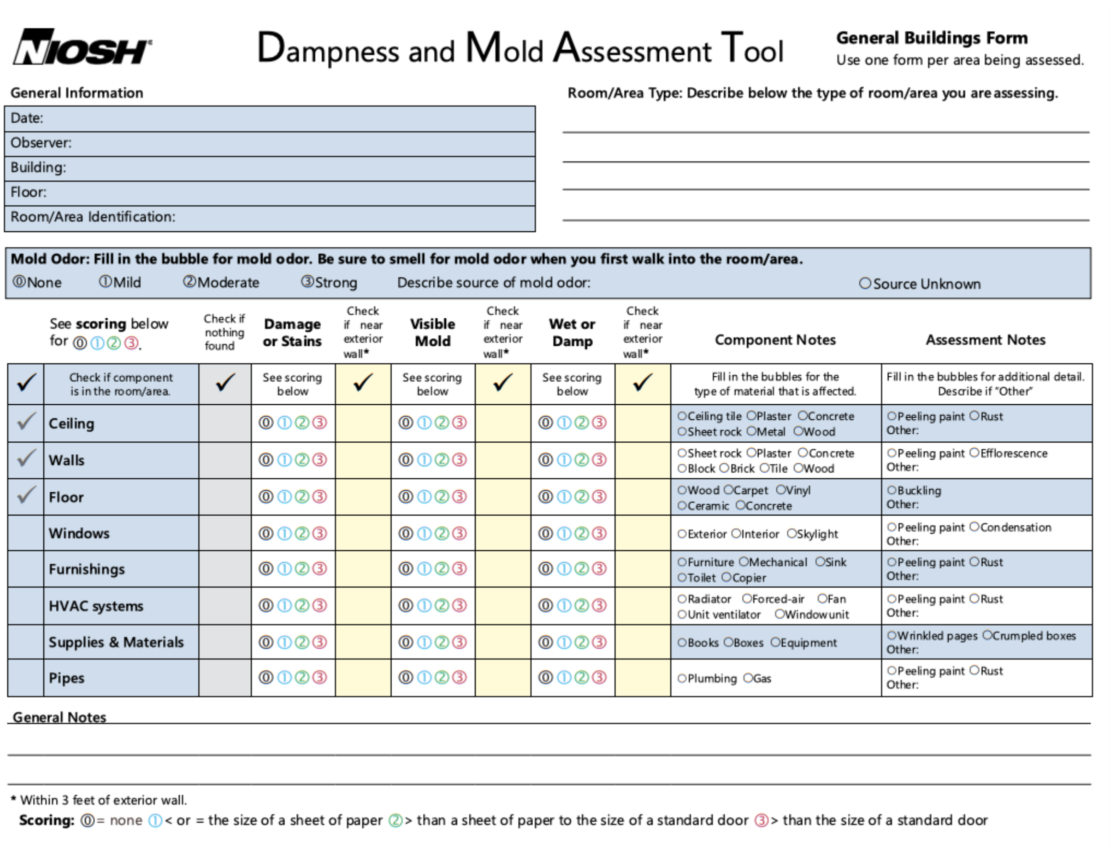
There are no simplified thresholds for mold given that the spore count and culture based sampling procedures each produce different units, and require sophisticated field and lab instruments, as outlined in Table 2.2 (adapted from AIHA FAQs About Spore Trap Air Sampling for Mold for Direct Microscopical Examination, 2020). Both direct examination and culturing methods usually entail the collection and comparison of indoor and outdoor samples (Cox et al., 2020). Depending on the environmental conditions at the location, the investigator is typically seeking to ascertain whether there are any notably higher indoor fungal levels that deviate from or are unusual compared to the outdoor microbial population.

Table 2.2 Sampling Methods for Fungi/Mold.

Sampling Method	Identification	Units	Process
Direct Microscopical Examination (Non Viable Spore Count Method)	Mold/Fungi	Spores per cubic meter of air (spores/m3)	Samples are collected using an inertial impactor with air sampling cassettes. The results are analyzed and reported as spore count along with each spore type's number and relative percentage. [AIHA, 2020]. Tape-lift Sampling/ Bulk sampling/ Swab/ Filter Cassette is done when visible mold is present.
Culture-Based Analysis (Viable Culturable Method)	Mold/Fungi, Bacteria	Colony forming units per cubic meter of air (CFU/m3)	Air samples are collected using inertial impaction devices. Once collected on the impaction surface, the sample is cultivated in a lab setting. Fungal colonies that grow on the provided medium are then tallied and distinguished using conventional microbiological techniques. The turnaround time to test for cultural fungal air samples is around 7-14 days. [AIHA, 2020]

Given the complexity and cost of physical sampling for mold, simplified methods to identify areas of concern have turned to humans as sensors. Mold, visible dampness, and records of water damage can be visibly identified by building occupants and facilities managers. The NIOSH dampness and mold assessment questionnaire (fig.

2.5) provides robust input for identifying mold concerns in buildings, evaluating ceilings, walls, floors, furnishings and HVAC and plumbing systems (Dampness and Mold Assessment Tool General Buildings https://www.cdc.gov/niosh/docs/2019-115/pdfs/2019-115.pdf).



NIOSH Dampness and Mold Assessment Tool

General Buildings Form
Use one form per area being assessed.

General Information

Date:
Observer:
Building:
Floor:
Room/Area Identification:

Room/Area Type: Describe below the type of room/area you are assessing.

Mold Odor: Fill in the bubble for mold odor. Be sure to smell for mold odor when you first walk into the room/area.
⓪None ①Mild ②Moderate ③Strong Describe source of mold odor: ○Source Unknown

See **scoring** below for ⓪①②③.		Check if nothing found	**Damage or Stains**	Check if near exterior wall*	**Visible Mold**	Check if near exterior wall*	**Wet or Damp**	Check if near exterior wall*	**Component Notes**	**Assessment Notes**
✓	Check if component is in the room/area.	✓	See scoring below	✓	See scoring below	✓	See scoring below	✓	Fill in the bubbles for the type of material that is affected.	Fill in the bubbles for additional detail. Describe if "Other"
✓	**Ceiling**		⓪①②③		⓪①②③		⓪①②③		○Ceiling tile ○Plaster ○Concrete ○Sheet rock ○Metal ○Wood	○Peeling paint ○Rust Other:
✓	**Walls**		⓪①②③		⓪①②③		⓪①②③		○Sheet rock ○Plaster ○Concrete ○Block ○Brick ○Tile ○Wood	○Peeling paint ○Efflorescence Other:
✓	**Floor**		⓪①②③		⓪①②③		⓪①②③		○Wood ○Carpet ○Vinyl ○Ceramic ○Concrete	○Buckling Other:
	Windows		⓪①②③		⓪①②③		⓪①②③		○Exterior ○Interior ○Skylight	○Peeling paint ○Condensation Other:
	Furnishings		⓪①②③		⓪①②③		⓪①②③		○Furniture ○Mechanical ○Sink ○Toilet ○Copier	○Peeling paint ○Rust Other:
	HVAC systems		⓪①②③		⓪①②③		⓪①②③		○Radiator ○Forced-air ○Fan ○Unit ventilator ○Window unit	○Peeling paint ○Rust Other:
	Supplies & Materials		⓪①②③		⓪①②③		⓪①②③		○Books ○Boxes ○Equipment	○Wrinkled pages ○Crumpled boxes Other:
	Pipes		⓪①②③		⓪①②③		⓪①②③		○Plumbing ○Gas	○Peeling paint ○Rust Other:

General Notes

* Within 3 feet of exterior wall.
Scoring: ⓪= none ①< or = the size of a sheet of paper ②> than a sheet of paper to the size of a standard door ③> than the size of a standard door

fig 2.7 Example of Dampness and Mold Assessment Tool by NIOSH.

In indoor environments, the presence of mold contamination can be readily perceived by occupants, in contrast to the less noticeable bacterial and viral contaminants. Observable indicators include moldy or musty odors, damp surfaces, signs of previous water damage, and visible mold growth. These observations necessitate immediate intervention. The NIOSH questionnaire introduces an urgency factor based on the area of the mold, dampness, or past water damage with 1-3 levels of urgency:

1. The combined area of damage is the size of a standard sheet of paper (8½ inches X 11 inches) or smaller.
2. The combined area of damage is greater than the size of a standard sheet of paper (8 1/2" x 11") and less than the size of a standard interior door (32" x 80").
3. The combined area of damage is greater than the size of a standard interior door

The organizations that have guidance related to mold response are listed in Table 2.3.

Table 2.3 Guidance related to mold response by various organizations and agencies.

Organization / Agency	Guidelines (Links)
American Industrial Hygiene Association (AIHA)	• Mold and Dampness in the Built Environment • FAQs About Spore Trap Air Sampling for Mold for Direct Microscopical Examination
Centers for Disease Control and Prevention	• Mold After a Disaster • Homeowner's and Renter's Guide to Mold Cleanup After Disasters
Federal Emergency Management Agency	• Dealing with Mold & Mildew in Your Flood-Damaged Home
Canadian Centre for Occupational Health and Safety	• OSH Answer Fact Sheets: Indoor Air Quality – Moulds and Fungi
U.S. Environmental Protection Agency	• A Brief Guide to Mold, Moisture, and Your Home
National Institute for Occupational Safety and Health	• NIOSH Recommendations for the Cleaning and Remediation of Flood-Contaminated HVAC Systems: A Guide for Building Owners and Managers
U.S. Occupational Safety and Health Administration	• Fungi Hazards and Flood Cleanup

2.5 Pathogenic Viruses & Bacteria in the air and on surfaces

Viruses and Bacteria that can travel from person to person by direct contact, on surfaces, and in air transfer (as bio-aerosols often with the assistance of particulates) and are the primary contributor to shared colds, flus, allergies and most recently SARS/Covid-19.

Bioaerosols are very small airborne particles (ranging from 0.001 to 100 μm) that originate biologically from plants/animals and can contain living organisms. Pathogenic and non-pathogenic dead or alive microorganisms (e.g., viruses, bacteria, as well as fungi) may exist in bioaerosols and are easily transferred because of their small size and light weight. In recent years, exposure to bioaerosols in both occupational and residential environments has drawn much attention considering their probable impacts on human health. (Kim et al 2018).

> *In a 2021 field study of a kindergarten school in Gliwice, Poland, Ewa et al identified the use of indoor HEPA filter air purifiers with an 18% decrease in bacterial aerosol concentration along with a 20% decrease in respirable fraction (particle size < 3.3 μm) of bacteria enhancing improved indoor air quality. (n = 24, p<0.005)*

In a 2022 epidemiological health study of college residences, classrooms, and laboratories in New Delhi, India, Kumar et al identified that culture-based sampling of bacterial and fungal aerosol concentrations ranging between 300–4150 CFU/m3 increased reported headaches (28%) and allergies (20%) in the winter season.

Establishing thresholds of concern for virus and bacterial concentrations is nontrivial since there is no single sampling or analytical method appropriate for all indoor bioaerosols. Bioaerosol behavior is strongly coupled to particle size (Nazaroff, 2016), and thus sample collection is dependent on the size selectivity of the sampler. Each study will have a specific type of sampling equipment, the number and location of samples, the volume of air to be sampled, and if culturing, type of culture medium, and incubation conditions. Quality control decisions are also method-specific such as the determination of an acceptable sample and procedures of identification, counting, and data analysis. The sampling always pairs indoor and outdoor measurements, often with bioaerosol and particle concentrations measured using 5-min (indoor) and 10-min (outdoor) sampling periods with filter cassette sampling systems (Godwin, 2006). The instrumental set-ups for virus sampling are further described by Kim et al (2018), excerpted in Table 2.4.

Table 2.4. Example Virus Bioaerosol Sampling Methods (Kim et al 2018).

Reverse transcription, quantitative, polymerase chain reaction (RtT-qPCR)	RT-qPCR indicates the presence or absence of viral DNA.	PCR-based analysis cannot differentiate between viable and non-viable viruses. To determine the virus concentration Tissue Culture (TCID50) method is used. It calculates the viral concentration by measuring the quantity of samples required to initiate an infection in a cell culture.
Tissue Culture Method (TCID50)	For TCID50, plaque-forming units per milliliter (PFU/mL) are used and can be converted to PFU/m3 by using sampled air volume and virus extraction volume.	During plaque assays, cells within dishes are exposed to a virus, which then multiplies and spreads to neighboring cells, resulting in the formation of a plaque or a region of cell mortality. The rule of thumb is that the PFU/mL concentration is 70% of the TCID50 concentration. [Evan L., 2021]
Sampling from **Surface Swabs** or **Air Sampling with Filtration Pigment** for Bioaerosols		Surface swab sampling typically covers a small area (about 25 cm2) using a damp nasal swab. [Mainelis G., 2020] Air Sampling of Bioaerosols: The cut-off diameter, or d50, is where 50% collection efficiency is reached for aerodynamic particles. As particles grow in size, density, and speed, their Stokes number rises. Using impactors with successively smaller nozzles increases air speeds and captures smaller particles, forming a multi-stage impactor. [Mainelis G., 2020]

Establishing the thresholds of concern for bioaerosols (inclusive of bacteria, viruses, and fungi) are still emerging. To capture this global debate, a single scalar with acceptable, better and best indoor thresholds is shown with a number of worldwide standards indicated from acceptable to better to best. The units and thresholds are based on the CFU or colony formulation unit of virus or bacteria aerosolized in an m3 of air.

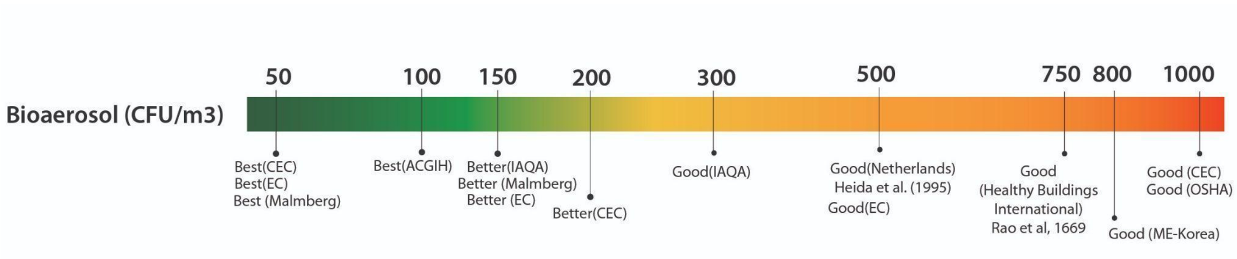


fig. 2.8 Thresholds of concern for bioaerosols.

Again, it is critical to note that these are not thresholds of definitive harm, but indoor thresholds at which action is recommended. A summary of quantitative standards and guidelines for bioaerosols in air by governmental and private organizations from Kim et al (2018) are included in Table 2.5.

Table 2.5 Standards and guidelines for bioaerosols (Kim et al 2018).

Organization	Guideline	Remarks	Reference
American Conference of Governmental Industrial Hygienists (ACGIH)	< 100 CFU/m3	Low	Macher et al. (1995)
	100–1000 CFU/m3	Intermediate	
	> 1000 CFU/m3	High	
American Industrial Hygiene Association (AIHA)	There is no safe level of an uncontained **pathogenic organism**		
Commission of the European Communities (CEC)	For homes		
	< 50 CFU/m3	Very low	
	< 200 CFU/m3	Low	
	< 103 CFU/m3	Intermediate	
	< 104 CFU/m3	High	
	> 104 CFU/m3	Very high	
Healthy Buildings International	< 750 CFU/m3	Total airborne **bacteria** and fungi is OK if species are not infective or allergenic	Rao et al. (1996)
Indoor Air Quality Association (IAQ)	< 300 CFU/m3	Common **fungi** is OK	IAQA (1995)
	< 150 CFU/m3	Mixed fungi other than pathogenic orexigenic is OK	
IAQ in office buildings: a technical guide	> 50 CFU/m3	One species should be investigated	Malmberg (1991)
	< 150 C CFU/m3	If mixture of species is OK	

Organization	Guideline	Remarks	Reference
The Netherlands research methods in biological indoor air pollution	> 104 CFU/m3	Total fungi is a threat to health	Heida et al. (1995)
	> 500 CFU/m3	One species of potentially pathogenic nature is a threat to health	
Occupational Safety and Health Administration (OSHA)	> 1000 CFU/m3	Indicates contamination	OSHA (1994)
	> 106 fungi/g of dust	Indicates contamination	
Environment Canada (EC)	Pathogenic and toxigenic fungi	Unacceptable in indoor air	EC (1989)
	> 50 CFU/m3	One species should be investigated	
	< 150 CFU/m3	OK if mixture of species	
	< 500 CFU/m3	OK if Cladosporium or other common phylloplane	
Ministry of environment (ME), Republic of Korea	< 800 CFU/m3	OK	Ministry of Environment, Republic of Korea (2010)

2.6 VOCs including Formaldehyde (when indoors>outdoors)

Volatile Organic Compounds (VOCs) are of critical concern for human health and are often captured with comprehensive metrics such as TVOC (total) or SVOC (select) in an attempt to measure the full set of compounds of concern to human health. The WELL Standard sets thresholds for 7 VOC's of concern:

Acetaldehyde:	140 μg/m^3 or lower
Acrylonitrile:	5 μg/m^3 or lower
Caprolactam:	2.2 μg/m^3 or lower
Benzene:	3 μg/m^3 or lower
Formaldehyde:	9 μg/m^3 or lower
Naphthalene:	9 μg/m^3 or lower
Toluene:	300 μg/m^3 or lower

In 2023, Morantes et al build on the 2012 work of Logue et alto estimate the chronic health impact of residential indoor air contaminants - both particulate and gas phased contaminants - to introduce the disability adjusted life years (DALY) effects to help in prioritizing contaminants and their thresholds.

One of the most common and concerning of these indoor VOCs is Formaldehyde (CH2O) - a colorless gas with a pungent irritating odor at levels five time higher than the acceptable limit (Golden, 2011). Salthammer et al. summarized the sources of formaldehyde to include: construction materials (mineral wool, wood), insulation, furniture, combustion of automobile engines, cleaning products, etc. (Salthammar 2010). Identified as a human carcinogen by the World Health Organization (WHO in IARC, 2006) its hazard has been widely acknowledged.

The importance of minimizing the exposure of building occupants to formaldehyde and other VOC's cannot be overstated. For example, the research reveals that formaldehyde has an association with a series of health issues, such as irritation, itch, cough, tears, runny nose, chest pains, breath wheezing, and, more seriously, lifetime cancer risk (LCR) (Cruz et al., 2020, Jafari et al., 2015). Other research connects TVOC levels to productivity:

> *In a 2016 controlled experiment in a controlled office environment at the Carrier TIEQ Laboratory, Allen et al identified that a low **TVOC** concentration office (<50 ug/m3) resulted in a 61% increase in **cognitive scores** as compared to a high TVOC concentration office (506–666 μg/m3). (n=24 x 6 days, p<0.0001)*

There is substantive debate about the use of TVOC as a metric given the mix of pollutants it is tracking. In the words of Salthammer "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." (Salthammer, 2022).

While the thresholds of concern for TVOC and Formaldehyde are being debated world-wide, two scalars with acceptable, better and best indoor thresholds are shown from a number of worldwide standards. It is critical to note that these are not thresholds of definitive harm, but indoor thresholds at which action is recommended.

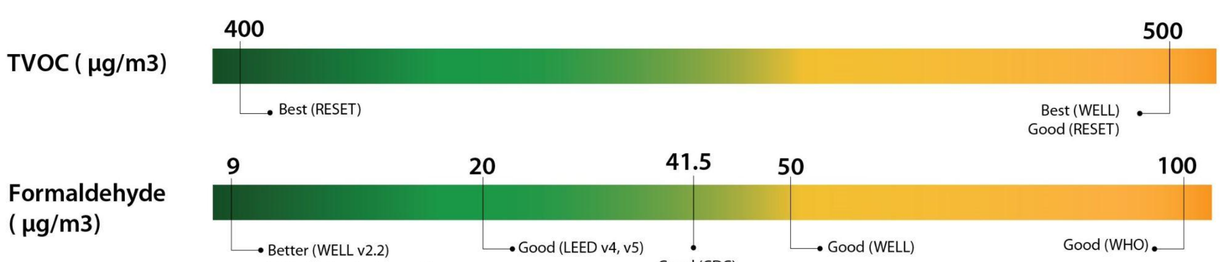


fig. 2.9 Thresholds of concern for TVOC and formaldehyde.

2.7 Ozone generated outdoors

Ozone (O3) is a barely visible gas with a mild smell that is a key component of smog forming outdoors through complex reactions between ozone and chemicals emitted from vehicles, industrial plants, consumer products and other sources. In metropolitan areas of California, outdoor ozone concentrations frequently exceed existing health-protective standards in the summertime.

Relative to outdoor ozone, research has shown evidence of ozone's adverse respiratory effects including lung inflammation, airway narrowing, lung function decrements, lung permeability, and epithelial injury (Uysal et al., 2003; Nuvolone et al., 2018). Ozone can damage the tissues of the respiratory tract, causing inflammation and irritation, and result in symptoms such as coughing, chest tightness and worsening of asthma symptoms. In addition, ozone causes substantial damage to crops, forests and native plants. In 2005, after an extensive review of the scientific literature, CARB approved an eight-hour standard for ambient outdoor ozone of 0.070 ppm and retained the one-hour 0.09 ppm standard previously established in 1987. Evidence from the reviewed studies indicates that significant harmful health effects could occur among both adults and children if exposed to levels above these standards. On October 1, 2015, the U.S. EPA lowered the national eight-hour outdoor ozone standard from 0.075 ppm to 0.070 ppm.

Indoor devices such as printers, photocopiers, and air cleaners can produce ozone, and outdoor ozone can enter the occupied space through infiltration and mechanical air intakes (Salonen et al., 2018). Ozone reacts with surfaces as it penetrates the indoor environment, but usually at lower levels indoors than outdoors. The California Air Resources Board warns that in addition to outdoor ozone, indoor equipment such as photocopiers, laser printers and certain air purifiers can emit ozone indoors as well. Air purifiers that purposely emit ozone, called ozone generators, should not be used in occupied spaces as they can emit unsafe levels of ozone. (https://ww2.arb.ca.gov/resources/ozone-and-health)

The thresholds of concern for indoor ozone are emerging with different units than the outdoor standards. these are not thresholds of definitive harm, but indoor thresholds at which action is recommended. A single scalar capturing good and better levels from five international standards reveals:

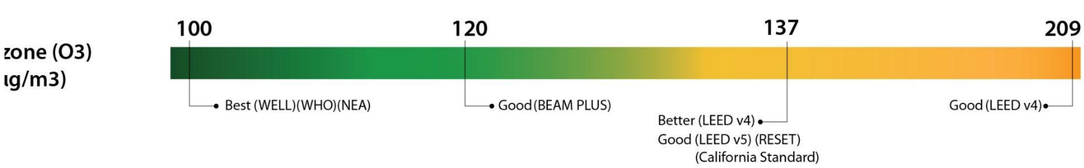


fig. 2.10 Thresholds of concern for indoor ozone.

2.8 Carbon Monoxide (CO) and Nitrous Dioxide (NO2)

Inorganic gasses are also a concern for human health. Carbon Monoxide (CO) is toxic to humans and is typically generated by combustion. If inadequately ventilated at the source, CO can be fatal.

Carbon Monoxide (CO) is a colorless, tasteless, odorless, but toxic gas. Similar to particulate matter (PM), there are both indoor and outdoor sources of CO, predominantly related to combustion: fossil fuel burners, fireplaces, industries, motors, etc. (Chowdhury et al., 2013). Indoors, CO is associated with a broad spectrum of health concerns, including headaches, nausea, dizziness, and fatigue, and high exposures to CO can even lead to coma and death. Research has also shown that exhaled CO is associated with an elevated risk of ischemic cardio-cerebral-vascular diseases (CCVD) and various chronic respiratory symptoms, including cough, sputum production, and chronic allergy. (Zeidan et al., 2014; Bernstein et al., 2008).

At the same time, Nitrogen Dioxide (NO2) is another bi-product of combustion with adverse health effects, including decreased pulmonary function and bronchoconstriction (Berglund et al., 1993). NO2 can be more dangerous to asthmatics, children, and seniors (Dunlea et al., 2007).

The thresholds of concern for indoor CO and NO2 are being debated with two scalars identifying acceptable, better and best indoor thresholds from a number of worldwide standards. It is critical to note that these are not thresholds of definitive harm, but indoor thresholds at which action is recommended.

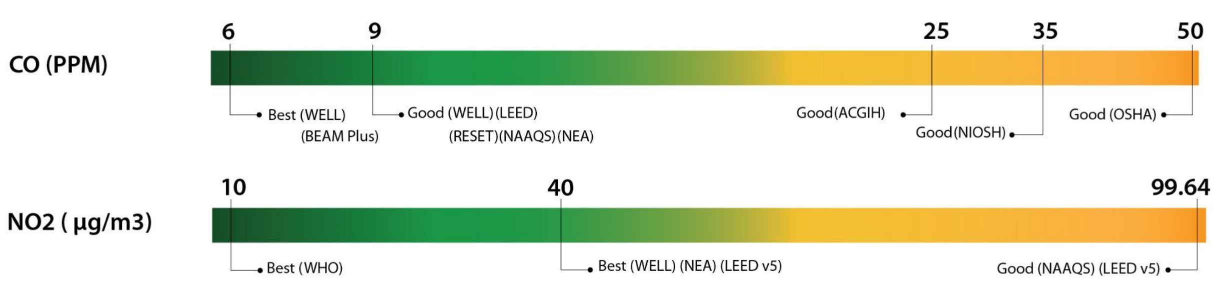


fig. 2.11 Thresholds of concern for indoor CO and NO2.

A Definitive Textbook on IAQ Contaminants/ Pollutants of Concern Needed

This chapter is meant as background to the ten research priorities that follow, not as the definitive textbook on IAQ pollutants of concern and the thresholds critical for action. The future IAQ Contaminants of Concern textbook will require significantly more controlled and longitudinal research and critically needs to be written by the health and standards community.

One challenge is to interpret and integrate across studies based on widely different methodologies to to set overarching standards. A second challenge will be prioritizing contaminants of concern. Morantes et al, uses DALY to establish comparable harm from residential indoor air contaminants (Morantes et al, 2024). DALYs are generated by toxicological and epidemiological hazards and may not be the only or best health outcomes for prioritization. A third challenge will be establishing the thresholds for action and the acceptable time periods for exposure, especially as they relate to the wide diversity of environmentally sensitive populations.

A recent article in Science by 40 leading air quality experts “Mandating Indoor Air Quality for Public Buildings” begins to address these challenges (Morantes et al., 2024). It is critical for the health and standards community - CDC, NIST, AIHA, EPA, ASHRAE and others - to join the international community in writing the definitive textbook on IAQ contaminants of concern, and to set new standards to ensure that indoor environments are designed and managed for occupant health and wellbeing.

Chapter 2 Pollutant & Health References

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Chapter 3

HVAC Conditions of Concern for IAQ and Health

In a seminal 2020 paper “How can airborne transmission of COVID-19 indoors be minimized?” published in Environment International, a group of 36 international air quality and health experts outlined critical actions needed in buildings to reduce infectious disease transfer until effective treatments or vaccines were available, summarized in figure 3.1 (Morawska et al, 2020):

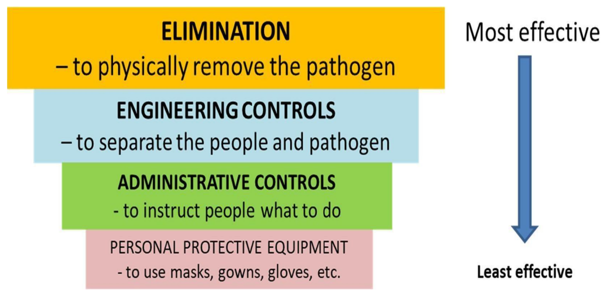

fig. 3.1 Traditional infection control pyramid (adapted from CDC, 2015).

This article outlines five critical actions: “Until effective pharmacological treatments or vaccines are available to reduce the effective reproductive number to less than 1.0 and stop the ongoing COVID-19 pandemic, enhanced ventilation may be a key element in limiting the spread of the SARS-CoV-2 virus”. Five key ventilation-associated actions are needed:

(1) To remind and highlight to building managers and hospital administrators and infection control teams that engineering controls are effective to control and reduce the risks of airborne infection – and SARS-CoV-2 has the potential and is likely to be causing some infections by this route.

(2) To increase the existing ventilation rates (outdoor air change rate) and enhance ventilation effectiveness - using existing systems.

(3) To eliminate any air-recirculation within the ventilation system so as to just supply fresh (outdoor) air.

(4) To supplement existing ventilation with portable air cleaners (with mechanical filtration systems to capture the airborne microdroplets), where there are areas of known air stagnation (which are not well-ventilated with the existing system), or isolate high patient exhaled airborne viral loads (e.g., on COVID-19 cohort patient bays or

wards). Adequate replacement of the filters in the air cleaners and their maintenance is crucial.

(5) To avoid overcrowding, e.g., pupils sitting at every other desk in school classrooms, or customers at every other table in restaurants, or every other seat in public transport, cinemas, etc.”

While there is ample evidence that vaccines, masking and social distancing are leading priorities for reducing the risk of infectious disease transfer, the engineering, operation and maintenance of HVAC systems still play a significant role for reducing virus and bacterial infection transfer and for diluting other contaminants of concern in the workplace (fig. 3.2) (Melikov, 2020).

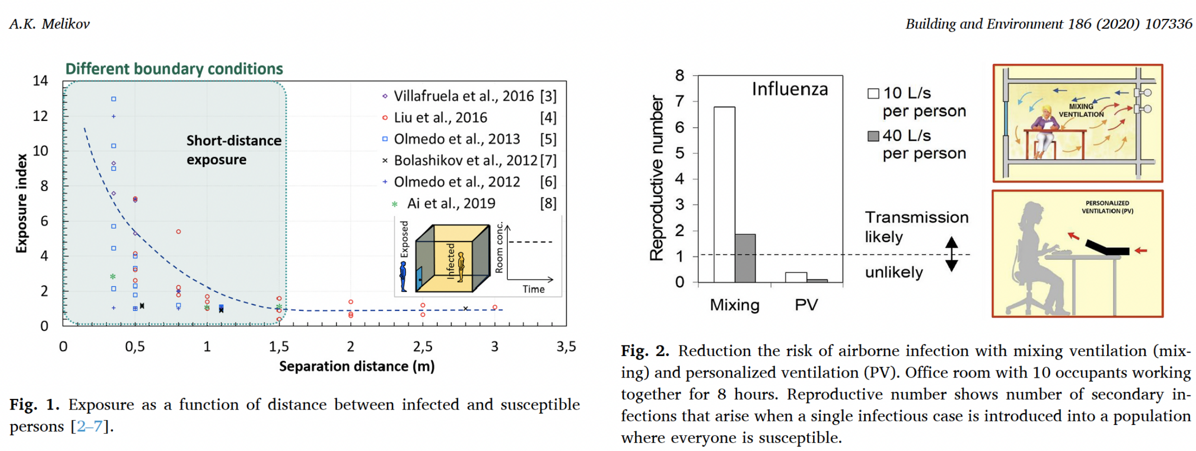

figure 3.2 beyond the benefits of social distancing,
HVAC design plays a critical role in reducing infectious disease transfer

Given that we spend more than 90% of our time indoors, the health impacts of outdoor and indoor air quality continue to demand design and operational improvements alongside field research on the costs and benefits of more informed action. As a partner in the White House Clean Air Challenge, and the largest property manager in the US, GSA is committed to identifying and testing the impacts of design and operational improvements for human health and performance.

On May 17, 2023 GSA assembled over 35 experts from diverse professional backgrounds and multiple US regions in a full day expert panel workshop dedicated to identifying HVAC conditions of critical importance of occupant health, and needs for ‘Real World Implementation Research’. To ensure focused use of their time, the experts completed pre-workshop questionnaires ranking possible central and zone HVAC conditions of concern for both short term and long term health and performance.

The results of this pre-workshop survey of experts are shown in fig. 3.3 and 3.4, with filter quality and condition the leading intervention at the central AHU, and maintenance and commissioning the leading intervention at the terminal unit or zone.

Maintaining and Updating the Central AHU

The leading concerns for delivering indoor air quality (IAQ) at the central AHU level may lead with filter upgrades and filter maintenance but extend to a host of critical capital and operational improvements that are needed for IAQ and health (fig. 3.3).

Prioritizing HVAC Interventions at the Central AHU

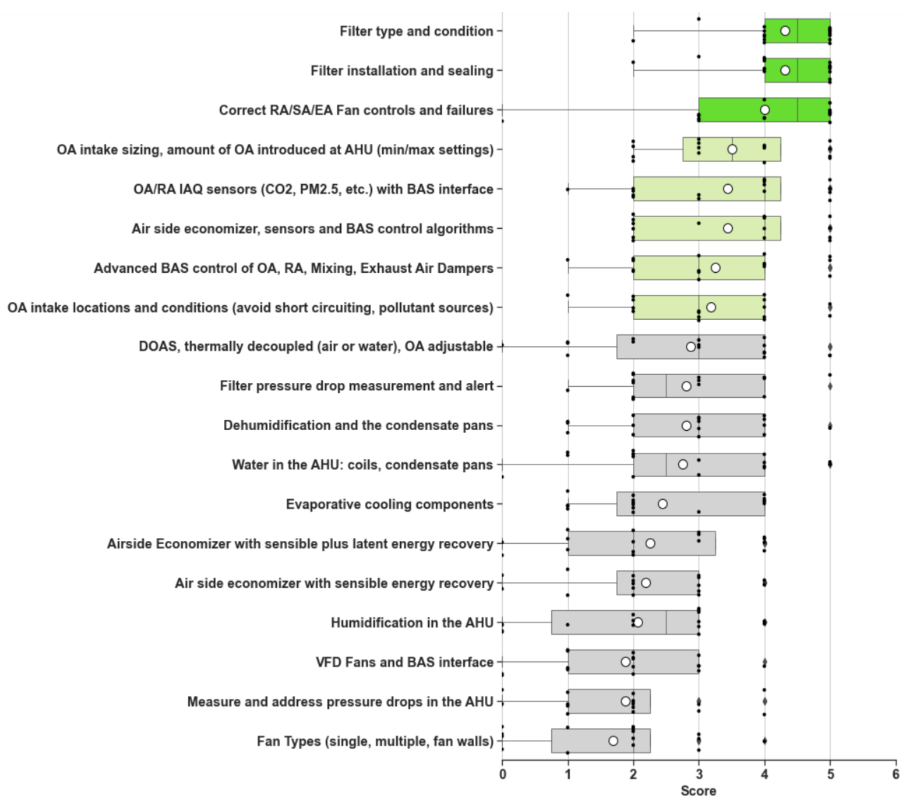

fig. 3.3 Leading concerns for delivering indoor air quality (IAQ) at the central AHU level.

Critically, the assurance of adequate outside air intake through functioning sensors, actuators and dampers is needed at each major control point – coordinating the outside air damper, the return air damper, the mixing damper, the exhaust damper and the zone supply air damper – to ensure that minimum outside air is delivered to each zone. OA intake locations and conditions must be designed and maintained without short circuiting or rooftop contaminants.

Beyond OA minimums, there are significant health benefits and energy savings to be achieved by air-side economizers driven by enthalpy differential sensors and advanced BAS systems. A shift to dedicated outside air systems (DOAS) with energy recovery combined with separate thermal conditioning in future HVAC systems would eliminate the substantial recirculated air challenges of conventional HVAC. Given that 30-50 air handling units may be needed for a large federal office building, the greatest challenge to ensuring healthy air for each zone served may be the shortage of O&M dollars and manpower to undertake the continuous commissioning that is critically needed.

Maintaining and Updating the Zone Delivery of Quality Air

The leading concerns for delivering indoor air quality (IAQ) at the zone, room or terminal unit level leads with the need for enhanced maintenance and continuous commissioning, supported by a more rigorous set of sensors for automated fault detection. Increased 'clean' air change rates, especially in periods of high infection risk, will be critical, achieved through a combination of increased in outside air, better filtration of mixed outside and return air, and the introduction of zone or room filtration with HEPA and UVGI filters (fig. 3.4).

Prioritizing HVAC Interventions at the Terminal Unit

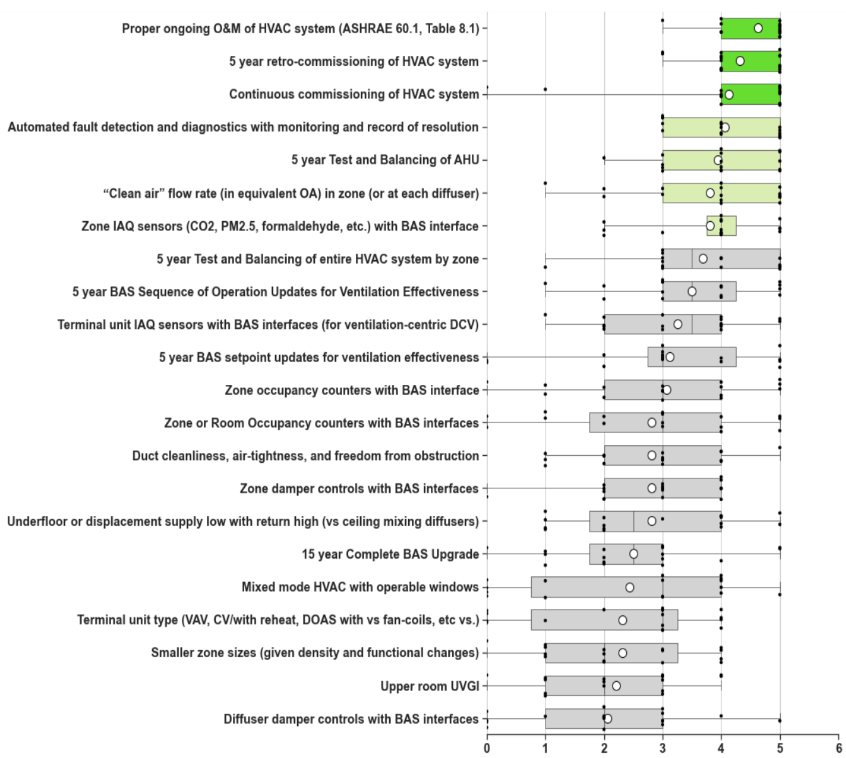

fig. 3.4 Leading concerns for delivering indoor air quality (IAQ) at the central AHU level and at the zone, room or terminal unit level.

Five Overriding HVAC Actions for Improving Ventilation in Existing Buildings

One quote from the expert workshop was repeated by many:
'Nothing is more important than maintenance/commissioning to ensure operation as intended. Good control of indoor PM is critical and proper installation of filters is critical to indoor PM control.'

The pre-workshop survey was instrumental in establishing the five breakout sessions to define critical research for improving indoor air in federal buildings for human health and performance.

1. Improve Outdoor Air Hardware/Software and/or Economizers
2. Improve Filters (type, efficiency, and installation and sealing) at AHUs
3. Improve Supply Air / Return Air Fans and System Balancing at AHUs
4. Improve Clean Air Flow Rate & Air Quality Sensors at room/zone/terminal units
5. Improve O&M (i.e. frequency of Commissioning, enabling Automated Fault Detection & Diagnostics, workforce training, or other)

A subgroup of 5-7 experts brainstormed to develop suggestions for definitive field research on HVAC capital and operational upgrades most likely to improve IAQ for human health and performance. They were asked to:

- Write a hypothesis that outlines an HVAC upgrade the group considers to be critical to IEQ for human health and performance (limit discussion to ideas that are of practical application in existing buildings based on technology available today).
- Identify the type of experiment and outcome measures that might be definitive in proving gains in IAQ as well as gains in human health and performance, and tools that could be used to quantify these. Suggest both IAQ and human health measures.
- Outline a methodology
- Hypothesize the impact of the research for the commercial building portfolio and why this experiment should be prioritized above others.
- Repeat and develop outlines for additional experiments for this topic or the hypothesis developed, as time permits.

A second GSA workshop held with the National Academy's NRC Federal Facilities Council on July 27 focused on 'Enhanced Ventilation for Cleaner Air in Buildings'. The recent release of ASHRAE Standard 241-2023 for an Infection Risk Management Mode

(IRMM) to Control Infectious Aerosols was introduced at the workshop (ASHRAE, 2023), highlighting the importance of engineering 'equivalent Clean Air Flow' that combines centrally filtered outside and return air with locally filtered room air to measurably increase the overall air exchange in occupied spaces whenever there are heightened health concerns in commercial buildings (fig. 3.5).

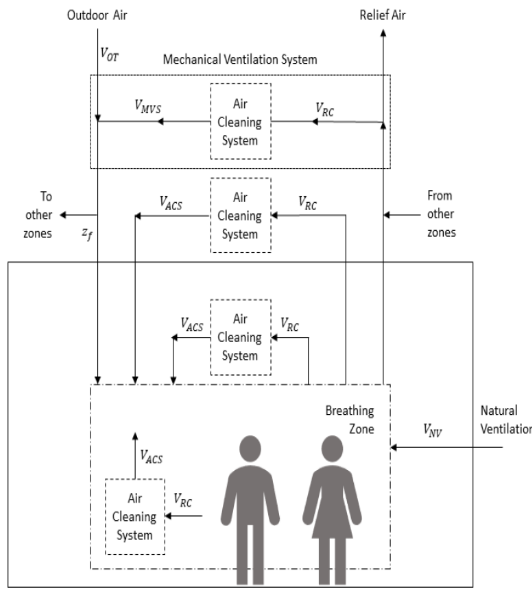

Figure 6-1 Sources of outdoor and clean air (for V_{RC}, see Section 7).

fig. 3.5 Sources of outdoor and clean air (for VRC, see Section 7) (ASHRAE, 2023).

The expertise gathered by GSA and the Federal Facilities Council spanned from health and safety to general science, air research, facility engineering and facility management, to program management. This workshop added depth and priority to the May 17 recommendations, highlighting a number of additional directions for building intervention and assessments (fig. 3.6).

Again, filtration led the set of recommendations, with a commitment to both higher MERV filters for central AHU and the addition of in-room filtration. Increases in air quality monitoring at both the central system and zone/room level was emphasized, with effective control responses from the BAS system. The importance of operation and maintenance, regularized testing and balancing, and responses to automated fault detection was reinforced. Increased use of outside air and dedicated outside air systems with separate thermal conditioning was championed. Finally, a few additional actions were identified – moving to smaller zone sizes for air and thermal delivery, and the use of underfloor air with high returns to reduce mixing air.

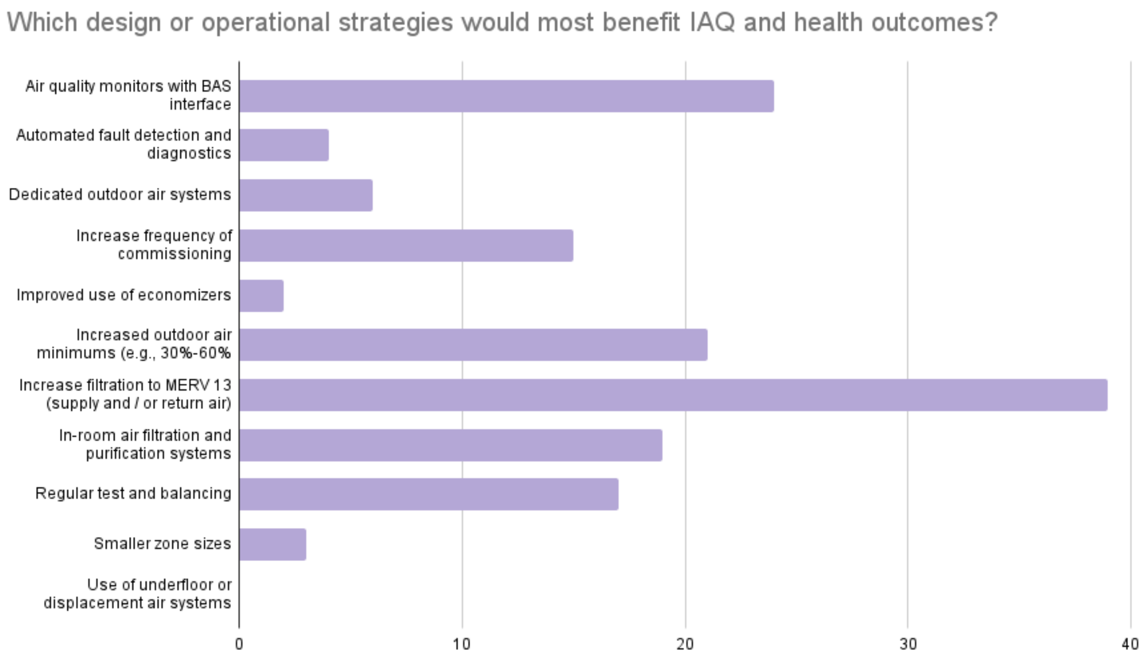

fig. 3.6 Design or operational strategies that would most benefit IAQ and health outcomes.

The FFC workshop also revealed a consensus that existing ventilation standards are only moderately based on conclusive research (63%), and that evidence-based recommendations for improving ventilation and IAQ are most urgently needed for high occupancy public buildings and schools. While they considered improving health outcomes a high priority (75%), the attendees identified a number of barriers to implementing health upgrades in existing buildings including budgets, lack of expert employees, and competing priorities.

The two GSA led workshops offered invaluable insights into the baseline IAQ challenges and actions that could address them as a catalyst for applied research. Specific proposals from these two workshops coalesced around three major areas of improvement which are the basis of the three chapters that follow: Improve O&M; Improve Clean Air at the Zone/room level; and Improve Clean OA Hardware and Controls at the AHU (following figure 3.7).

Proposed Intervention & Analyses: Improve O&M

Key O&M issues that impact indoor air quality include:

- No standard for sensing and assessing IAQ at room / zone level
- No standard health surveys to engage occupants as IAQ sensors
- Long-term under-funding of facility maintenance (<1.5% of current plant value)

Hypotheses: Reporting on a set of building KPI's would improve O&M and improve IAQ

1. KPI for resolution of specific faults that may be tied to IAQ in Fault Detection and Diagnostics.
2. IAQ performance KPI against thresholds at the building, AHU or zone level (eg CO2, PM)
3. KPI of user health indices surveyed at the building or zone level (eg SBS, infections)
4. Facility Management KPI indices (i.e. budget, manpower, staff training, turnover)

Proposed Intervention & Analyses: Improve clean air at room/zone/terminal unit

Key issues impact delivery of clean air at the Zone/Room level:

- The adequacy of in-room air delivery is not monitored.
- Changes in space uses and layouts and HVAC hardware are not synchronized.
- The density of occupants in spaces is highly volatile, especially since Covid.

Hypothesis: Adjusting controls and equipment would improve conditions at the zone/room level

1. Compare ventilation effectiveness strategies (diffuser types/locations including UFAD, displacement, controls)
2. Expand zone 'thermostat' controllers to include IAQ and occupancy sensors
3. Introduce in-room air cleaning for equivalent OA (i.e. portable HEPA, ceiling UVGI)

Proposed Intervention & Analyses: Improve OA Hardware/Controls at AHU

Key issues impacting delivery of clean air from the Central AHU:

- AHU outside air (OA) and mixing hardware and software is prone to failure.
- Adjusting for changes in seasons, use-type, occupant density need FM training .
- Economizers have mixed success and metrics of performance.

Hypothesis: Improving designs for delivering OA at AHU will improve clean air at zone

1. Increase quantity of OA along with technologies to avoid energy penalty (new damper/sensor/actuator, VFD fans and BAS assemblies, economizer, ERV)
2. Improve filter materials, replacement schedule, and locations
3. Introduce DOAS with separate VRF for thermal conditioning

A period of four months of background literature review enabled the CMU CBPD team to refine the research needs outlined in the two workshops in the three key outcome areas, resulting in the ten ventilation research proposals outlined in the following chapters.

The draft report "*Improving IAQ for Occupant Health in Commercial Buildings: 10 Priorities for Field Research projects for GSA*" was presented to the attendees of both workshops for critical review on March 20, 2024. Addressing expert recommendations and concerns, this final report was issued in May 2024 with the 10 Priorities captured in three overriding areas: Research to Improve O&M for IAQ and Health; Research for Improving Room OA and eqOA; and Research for Improving Central AHU Outdoor Air Quantity, Filtration and Delivery.

Chapter 3 References on HVAC Conditions of Concern

American Society of Heating, Refrigerating and Air-Conditioning Engineers. (2023). ASHRAE 241-2023, Control of Infectious Aerosols.

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Chapter 4

Key Performance Indicators (KPIs) for Improving O&M for IAQ

The GSA May 17, 2023 expert workshop identified that improvements in operations and maintenance (O&M) are the most critical actions for improving indoor air quality in large commercial buildings. They also identified a number of challenges that limit the prioritization of indoor air quality or ventilation effectiveness for property and facility managers:

- **O&M priorities** have focused on ensuring thermal comfort, then energy savings, and finally equipment maintenance and longevity, with code-compliant minimum ventilation rates assumed to be adequate for indoor air quality and occupant health.

- There are **no standards for sensing and assessing IAQ** in building zones or workstations over time **and no standard health surveys to engage occupants as IAQ sensors**. While consensus is building for CO2, PM2.5 and an index of VOC sensing with ASHRAE, RESET and WELL thresholds of acceptability, the cost, reliability and data base for widespread sensors is daunting.

- There is also **long-term under-funding of facility maintenance, including capital and operating budgets and staffing** (NAS records less than 1.5% of current plant value), with crises overtaking routine maintenance, and staffing reductions, outsourcing, and turnover an ongoing challenge to maintenance and IAQ.

The research that may be critical to addressing these challenges is the development and testing of key performance indicators (KPI) for catalyzing greater O&M Investments and expertise for improving indoor air quality. Four different key performance indicators are outlined in this chapter, with the hypothesis that **new building KPI's could significantly advance both O&M investments and expertise for IAQ:**

1. Surveys of user satisfaction and health indices by building or zone
2. Measurements of IAQ indices by building or zone
3. Solidified industry HVAC condition assessment indices incl. FDD reporting for IAQ
4. Records of FM investments - budget, manpower, training, turnover, absenteeism.
5. Robust, accessible databases and data analytics

4.1 Surveys of user satisfaction and health (KPI 1)

Wellness/ SBS, IAQ Satisfaction, and Health Key Performance indicators

Research #1. Field research in federal buildings should explore the use of user IAQ satisfaction and Wellness surveys by building or even zone, adding additional objective health metrics such as sick days and medical costs, to establish a portfolio wide KPI index and database for comparing to the impact of building system capital and operational choices, facility management investments, and more, for IAQ and health.

4.1.1 User Satisfaction and Wellness Surveys as Annual KPI

For over fifty years, user satisfaction and SBS questionnaires have been issued to building occupants to identify concerns and prioritize actions for facility investments, in some cases across portfolios of buildings in a number of countries (Gerald Davis_NRC, Loftnes/Aziz_CBPD COPE, Brager_CBE, Woods-Bagot_AUS) .

User satisfaction questionnaires, for example, typically address a full range of indoor environmental quality (IEQ) questions in both long and short questionnaires, with a selected set of questions that might relate to indoor air quality at individual workstations, using the classic seven point scale from -3 to +3 around neutral:

Classic User Satisfaction Surveys for Office Zones or Building IAQ

- Satisfaction with air quality
- Satisfaction with air movement (with subset questions of too drafty, too still)
- Satisfaction with humidity (with subset questions of too dry, too humid)
- Satisfaction with temperature (with subset questions of too cold, too warm).

And yet the outcome of these user satisfaction surveys have not become a standard for seasonal or annual reports of effective facility management, with no portfolio baselines or database for comparison. Some of the largest data bases of user satisfaction responses in North America may be with the Berkeley Center for the Built Environment with over 10,000 responses in 900 buildings, National Research Council Canada with over 779 responses, and with the Carnegie Mellon NEAT database with over 2500 responses in 75 buildings (Graham et al, 2021, Veitch et al, 2007, Park et al 2019). Emerging Requirements for minimum % satisfied with air quality and air movement in LEED and WELL standards may establish a critical baseline for national reporting of user perception of indoor air quality.

GSA, with its large portfolio of commercial buildings could merge user air quality satisfaction KPIs with measured IAQ as a seasonal score for building zones and buildings. Seasonal user satisfaction questionnaires for IAQ with corresponding information about each of the building systems, operations, and office layouts that determine the IAQ - could generate a baseline KPI and database for shifting investments to those systems, operations and layouts that ensure the highest thermal and air quality satisfaction. In appendix A, the COPE2 questionnaire modified from the National Research Council Canada is included as reference.

However, humans are not comprehensive air quality sensors and can often not identify IAQ conditions that might compromise their health, such as increases in infectious aerosols. To this end, user perception of air quality can be significantly advanced through **wellness or SBS surveys** that capture the frequency of health symptoms in the workplace (from eye, to respiratory, to skin to general health conditions), many of which strongly correlate to IAQ conditions (Zhou, 2022).

Classic Wellness or SBS Questions related to Health Condition Frequency

Q1. How frequently do you experience the following conditions at work (daily, weekly, monthly, rarely)?
Q2. Do they go away when you leave work?

Eye/Dermal Symptoms

- Eye dryness
- Eye irritation
- Dry Skin

Respiratory Symptoms

- Runny Nose
- Stuffy Nose
- Dry Throat
- Coughing
- Colds
- Difficulty Breathing

General Symptoms

- Headaches
- Irritability
- Fatigue
- Difficulty Concentrating
- Dizziness/ Nausea

In the past decade, the OFFICAIR project, a European research initiative, developed a method to determine associations between European office environments and the health and comfort of office workers (appendix B). This method, implemented through a checklist and a self-administered questionnaire, includes environmental, physiological, psychological, and social aspects (Bluyssen et al, 2016).

> *In a 2021 survey study of 37 office buildings across eight European countries, Sakellaris et al compared user perception of health of 1299 occupants with 5-days of air sampling and identified that: VOCs and xylenes were associated with headaches, tiredness and skin symptoms; Ethylbenzene with eye irritation and respiratory symptoms; a-pinene with respiratory and heart symptoms; styrene with skin symptoms; aldehydes, acrolein, and formaldehyde with respiratory and general symptoms; and Propionaldehyde with respiratory, general, and heart symptoms. Ozone was associated with almost all symptom groups (Sakellaris 2020).*

Japan has introduced a similar building related symptom questionnaire, with field correlations to IAQ in a portfolio of office buildings with over 3000 office worker responses (appendix C & D). In a 2017 cross-sectional study of self-administered questionnaires among 489 office buildings and 3024 office workers in Japan, Azuma et al identified that dryness of air was an important and significant risk factor associated with BRSs in both winter and summer, alongside noise, dust and dirt, and unpleasant odors (Azuma et al 2017). The Japanese Wellness survey may be the most robust for GSA consideration.

The correlation between responses to SBS or Wellness questions and known indoor air contaminants such as high CO2, TVOCs, PM2.5, Ozone, continues to emerge in the research literature.

> *In a 2022 study of a 10-story office building in Greece, Nezis et al. identified that exposure to black carbon and PM2.5 was associated with increased prevalence of sick building syndrome symptoms including irritation of the eyes, stuffy or runny nose, headache and drowsiness.*
>
> *In a 2015 field study in Taiwan, Lu et al identified that SBS responses from 417 employees in 87 office rooms of 8 high-rise buildings correlated with per 100 ppm increase in dCO2 associated with dry throat (OR= 1.10, 95% CI = (1.00–1.22)), tiredness (OR=1.16, 95% CI = (1.04–1.29)), and dizziness (OR= 1.22, 95% CI = (1.08–1.37)) (fig. 4.1).*

Table 3. Summary in prevalence of participants characteristics and sick building syndrome symptoms among office employees (n =417).

Individual Characteristics	%	Symptoms	%
Female	77.9	**Eye, any**	22.5
Age (≥40 years)	30.0	Eye dryness	18.7
Current smoker	11.3	Eye irritation	5.5
Working time >5 days/week	11.8		
Working time >9 h/day	20.9	**Upper respiratory, any**	15.3
Working stress	14.6	Nose itching	2.4
Lacking of family support	40.3	Runny nose	2.4
Asthma	3.4	Stuffy nose	6.2
Nasosinusitis	7.0	Sneezing	2.4
Atopic rhinitis	29.0	Dry throat	6.7
Migraine	17.0		
Dust allergy	24.5	**Lower respiratory, any**	6.5
Animal allergy	8.6	Difficulties in breathing	6.5
Sensitivity to tobacco smoke	68.3		
Sensitivity to chemicals in air	64.5	**Skin, any**	1.9
Exposure to ETS	15.6	Skin dryness	1.9
Using Sanitizing chemical	29.7		
Carpet in workspace	61.4	**Non-specific, any**	25.4
New furniture	4.6	Tiredness	20.9
New decoration	9.4	Difficulties in concentrating	14.6
Painting recently	5.5	Irritability	12.7
Leaking	10.1	Dizziness	7.2
Speck of molds	7.7		

Table 5. Crude, adjusted prevalence odds ratios and 95% confidence intervals (in parentheses) for sick building syndrome symptom association with per 100 ppb increase in total volatile organic compounds in indoor air (TVOCs) obtained from generalized estimating equations logistic regression models (n = 417).

Sick-Building	TVOCs (per 100 ppm)		
Syndrome Symptom	**Crude**	**Adjusted [a]**	**Adjusted [b]**
Eye, any	1.00 (0.99–1.00)	1.00 (1.00–1.00)	1.00 (0.99–1.00)
Eye dryness	1.00 (1.00–1.01)	1.00 (1.00–1.01)	1.00 (0.99–1.00)
Eye irritation	1.00 (1.00–1.01)	1.01 (1.00–1.01)	**1.01 (1.00–1.02)**
Upper respiratory, any	**1.04 (1.02–1.06)**	**1.06 (1.04–1.07)**	**1.06 (1.05–1.07)**
Nose itching	0.98 (0.92–1.04)	1.00 (0.97–1.03)	1.00 (0.97–1.03)
Runny nose	0.97 (0.90–1.06)	1.00 (0.95–1.05)	1.00 (0.96–1.04)
Stuffy nose	**1.01 (1.00–1.01)**	**1.01 (1.01–1.02)**	**1.01 (1.01–1.02)**
Sneezing	**1.01 (1.00–1.01)**	1.07 (0.86–1.33)	2.63 (0.18–38.7)
Dry throat	1.02 (1.00–1.05)	**1.06 (1.03–1.09)**	**1.06 (1.02–1.09)**
Lower respiratory, any	1.00 (1.00–1.01)	**1.01 (1.00–1.01)**	1.01 (1.00–1.01)
Difficulties in breathing	1.00 (1.00–1.01)	**1.01 (1.00–1.01)**	1.01 (1.00–1.01)
Skin, any	**1.01 (1.01–1.01)**	**1.01 (1.00–1.02)**	**1.01 (1.00–1.02)**
Dryness	**1.01 (1.01–1.01)**	**1.01 (1.00–1.02)**	**1.01 (1.00–1.02)**
Non-specific, any	**1.03 (1.02–1.04)**	**1.03 (1.02–1.05)**	**1.02 (1.01–1.03)**
Tiredness	**1.03 (1.02–1.04)**	**1.02 (1.01–1.04)**	**1.01 (1.01–1.02)**
Difficulties in concentrating	1.00 (1.00–1.01)	1.00 (1.00–1.01)	1.00 (1.00–1.01)
Irritability	**1.03 (1.02–1.03)**	**1.02 (1.01–1.04)**	**1.02 (1.00–1.03)**
Dizziness	**1.01 (1.01–1.01)**	**1.01 (1.00–1.02)**	**1.01 (1.00–1.01)**

fig. 4.1. Building-Related Symptoms among Office Employees Associated with Indoor Carbon Dioxide and TVOC, Chung-Yen Lu, Int. J. Environ. Res. Public Health 2015.

Annual Wellness or SBS questionnaires (as to the frequency of key health conditions and their presence in the office) should be anchored to zones of workstations along with corresponding information about the specific building systems, operations, and office layouts that determine the IAQ for that workstation. An example of the Technical Attributes of Building Systems (TABS) that might determine IAQ in that zone are attached in Appendix E. A Wellness KPI in conjunction with zone TABS could generate an actionable KPI and a database for shifting investments to those systems, operations and layouts that ensure the lowest records of office related health concerns (see summary below). Concerns about privacy and liability need to be addressed by ensuring voluntary involvement and unnamed input into aggregated data bases of workplace zones and buildings.

> *In a 2021 study of two office buildings in Iran, Sarkhosh et al. identified a **70.10% increased prevalence of Sick Building Syndrome** when there was increased microbial and volatile organic compounds (VOC) concentrations. With a Decision Tree Model, the research identified Staph Pathog (Aureus) and Klebsiella pneumoniae occurred in areas with poor airflow and nearby WC, resulting in heavy heads, shortness of breath and skin dryness; the VOC Toluene occurred in areas with a lack of airflow and office equipment and cleaning activities, resulting in feeling exhausted, heavy heads, weakness, blurred vision; the VOC's Ethylbenzene, p-Xylene, and o-Xylene occurred in areas with a lack of airflow resulting in sore throat, periodic headaches, pressure or pain in the chest, weakness, nasal irritation. This reinforces the value of subjective Wellness or SBS questionnaires as markers for potential IAQ contaminants.*

4.1.2 Objective Health metrics as Annual KPI

Beyond user perception of health, there are a range of **objective occupant health KPIs** that could be aggregated in collaboration with HR leaders in commercial office buildings as catalysts for near and long term investment, as previously introduced. Some of these measured health indices can be found in existing data, separated from others that may have cost implications and human subject constraints (measurements that may be available are identified in purple).

Objective Health metrics vs baseline and change over time

1. Absenteeism, records of Sick days
2. Asthma, Allergy, Covid and other Health records (OSHA?),
   for building occupancy, short and long term frequency, including costs.
3. Insurance claims
4. Attraction-retention rates, turnover (and exit interviews)

5. Sweat biomarkers of stress and immune response
6. Blood pressure (as an indicator of PM2.5 impacts on building occupants)
7. Resting Heart Rate and Heart Rate Variability (stress and relaxation response)
8. Physical activity, posture, and sleep quality - wearable health monitors
9. Combinations of the above

Other metrics

1. Complaint numbers (Tsantaki et al, 2022)
   Complaints about perceived Indoor Air Quality linked to SBS:
   Drafty, Stuffy, Dry Air, Unpleasant Odors, Dirty, Static Electricity,
   Temperature too high, too low, too variable, Passive Smoking
2. Fault detection FDD frequency and speed of response relative to air quality
3. Energy cost/benefits

4. Cognitive performance, next day cognition
5. Mood records
6. Inequity measures, Ethical/moral issues for human health

4.2 Zone IAQ Key Performance indicator (KPI 2)

Collecting and Recording Measurements of IAQ Indices by Building and Zone towards identifying concerns and improving IAQ in occupied spaces

Research #2. Field research in federal buildings should explore the introduction of a set of zone IAQ sensors beyond temperature - such as CO2, PM2.5, and formaldehyde – to provide zone IAQ signatures to establish a portfolio wide KPI for comparing the impact of building system capital and operational choices, facility management investments, and more, for IAQ and health.

There is a long-term practice of measuring temperature in every building zone as the controlled variable for HVAC systems to ensure thermal comfort for 80% of the building occupancy and meet ASHRAE comfort standards. In large office buildings, these HVAC zones may serve 1 or as many as 100 occupants, with a federal workplace average of 15 -25 occupants per zone, after removing the executive and conference dedicated zones (NEAT user's manual). At the central air handler, additional sensors are typically in place to assess OA, RA and SA temperature, and possibly humidity, CO2 and PM2.5. These sensors are used to manage the HVAC system but not as yet used as KPIs for the thermal conditions in buildings, much less for the IAQ conditions in buildings. Given the emerging research on IAQ and health, there are at least ten IAQ metrics that could form a KPI for a building, a zone or a workstation:

IAQ metrics vs thresholds (acceptable, better, best)
and their change over time = reduced concentrations of:

1. PM2.5 generated indoors – at workstation, at zone RA, at AHU RA
2. PM2.5 generated outdoors – at OA intake, at AHU SA
   (measure of filter quality especially given wildfires)
3. CO2 and delta CO2 outdoor/indoor as an index of ventilation rate – at zone RA, at AHU RA and SA (not a universal index for IAQ).
4. New metric for OA delivery and ACH in each zone (new sensor suite?)
5. Formaldehyde generated indoors (VOC) at zone RA?
6. Viruses generated indoors – how to measure?
7. Mold generated indoors – Occupant assessments of dampness and mold?
8. Temperature – at workstation, at zone RA, at AHU RA and SA?
9. Relative humidity - at zone RA, at AHU RA and SA?
10. Radon - at zone.

The selection of which contaminants to measure in each zone, what quality of sensors to use, and where to locate them, is non-trivial. A 2021 comparative study of three particulate matter sensors (PM2.5) yielded significantly different results for the same room (Kureshi et al, 2021). A 2021 study on the location of CO2 sensors in a large meeting room identified the need for multiple sensors distributed in relation to occupancy density and return air locations *(*Mou et al, 2021*)*.

The thresholds of concern for many of these contaminants are included in emerging IAQ recommended levels or standards, as shown in chapter 3. Particulate Matter thresholds may need two unique IAQ standards for periods of very high outdoor levels during wildfires or inversions, or internationally in areas with high levels of combustion pollution.

The following page consolidates all of the pollutants of concern that can be measured with on-site sensors with their threshold recommendations along a scale from acceptable to better to best (fig. 4.2). Fungi, Bacteria and Viruses are not included in this set of contaminant thresholds because they typically require laboratory based analyses of air or surface samples.

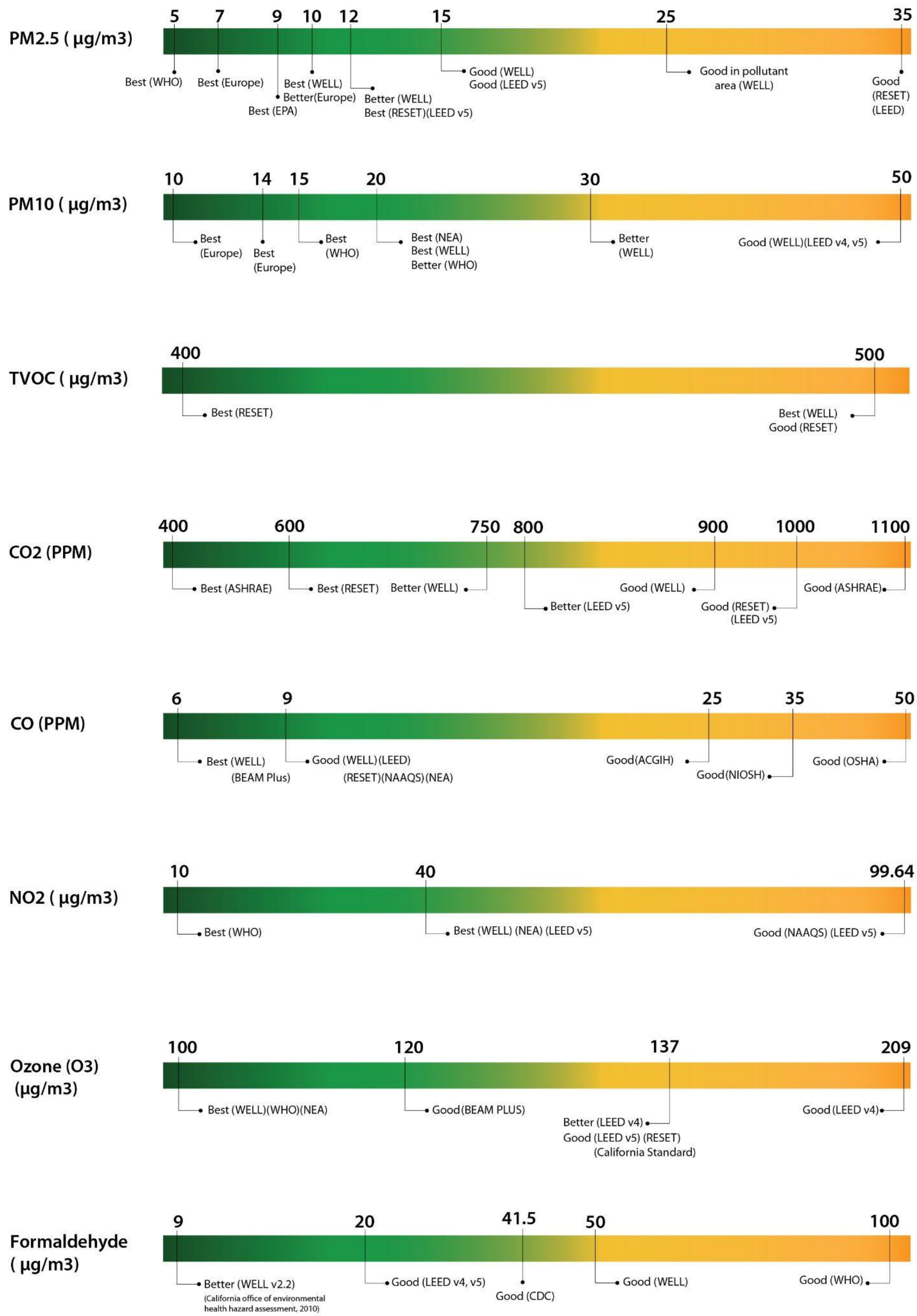


fig. 4.2 Thresholds for IAQ Contaminants of Concern
(note: these are thresholds for action not thresholds of harm)

Purchasing IAQ sensors for every building zone may be a daunting task, especially given the robustness of the range of sensors needed. However, whenever thermostats need to be replaced, there is potential to install a “next gen thermostat” that will provide zone level records of key IAQ variables beyond temperature - at a minimum CO2, and possibly PM2.5, RH and TVOC (see Chapter 7). These records would reveal conditions in each occupied zone over time and provide publishable KPIs for prioritizing facility investments or even space utilization in periods of high infection risk. Similar to temperature sensors, the expanded IAQ zone or room sensors will need to leverage an industry standard middleware to collect data from multiple sensor types and manufacturers, to benchmark against accepted thresholds of concern, and to actuate BAS controls across multiple configurations.

In the meantime, capturing CO2 data from all Zone or Room CO2 sensors (e.g. those that have been installed for DCV in the past decade) would enable the comparison of supply air and zone return air CO2 readings as one measure of ventilation effectiveness. Standard 62.1 had a recent addendum that establishes maximum delta-CO2 concentration vs. ambient that is based on assumed activity level (and other assumptions) and rate per person requirements (ASHRAE, 2022). Additional zone IAQ measurements could be introduced in a sampling of building zones to compare the effectiveness of filtration and to correlate cfm of air delivered with indoor contaminants of concern for occupant health.

> *In a 2015 field study in Taiwan, Lu et al identified that SBS responses from 417 employees in 87 office rooms of 8 high-rise buildings correlated dry throat (OR= 1.10), tiredness (OR=1.16), and dizziness (OR= 1.22) with 100 ppm increase in CO2, with 95% confidence intervals, and an additional set of SBS symptoms with increases in TVOC (fig. 4.3) .*

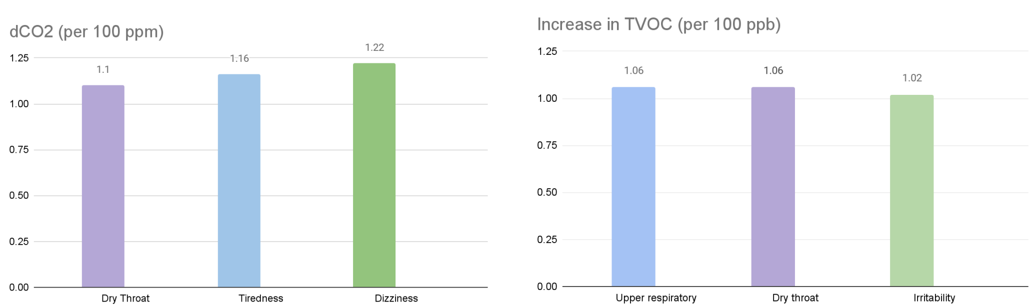


fig. 4.3 Building-Related Symptoms among Office Employees Associated with Indoor Carbon Dioxide and Total Volatile Organic Compounds, Chung-Yen Lu, Int. J. Environ. Res. Public Health 2015.

To illustrate the power of workstation IAQ measurements, the GSA/CBPD NEAT evaluation of 1300 workstations across 62 buildings enabled the *comparison of CO2 and user satisfaction of air quality*. This reveals that setting +1 to +3 satisfaction with air quality (on a -3 to +3 7-point Likert scale) as a goal for air quality satisfaction as it is for thermal satisfaction, would argue for workplaces to reduce CO2 to under 675 ppm rather than 1000 ppm (fig. 4.4). Statistical analysis of these correlations suggest that we should strive to keep indoor CO2 within 200 ppm of outdoor CO2 (now about 420 ppm worldwide). Given that this could triple present OA ventilation rates, it is important to consider economizer and DOAS innovations for energy efficiency during extreme temperature periods.

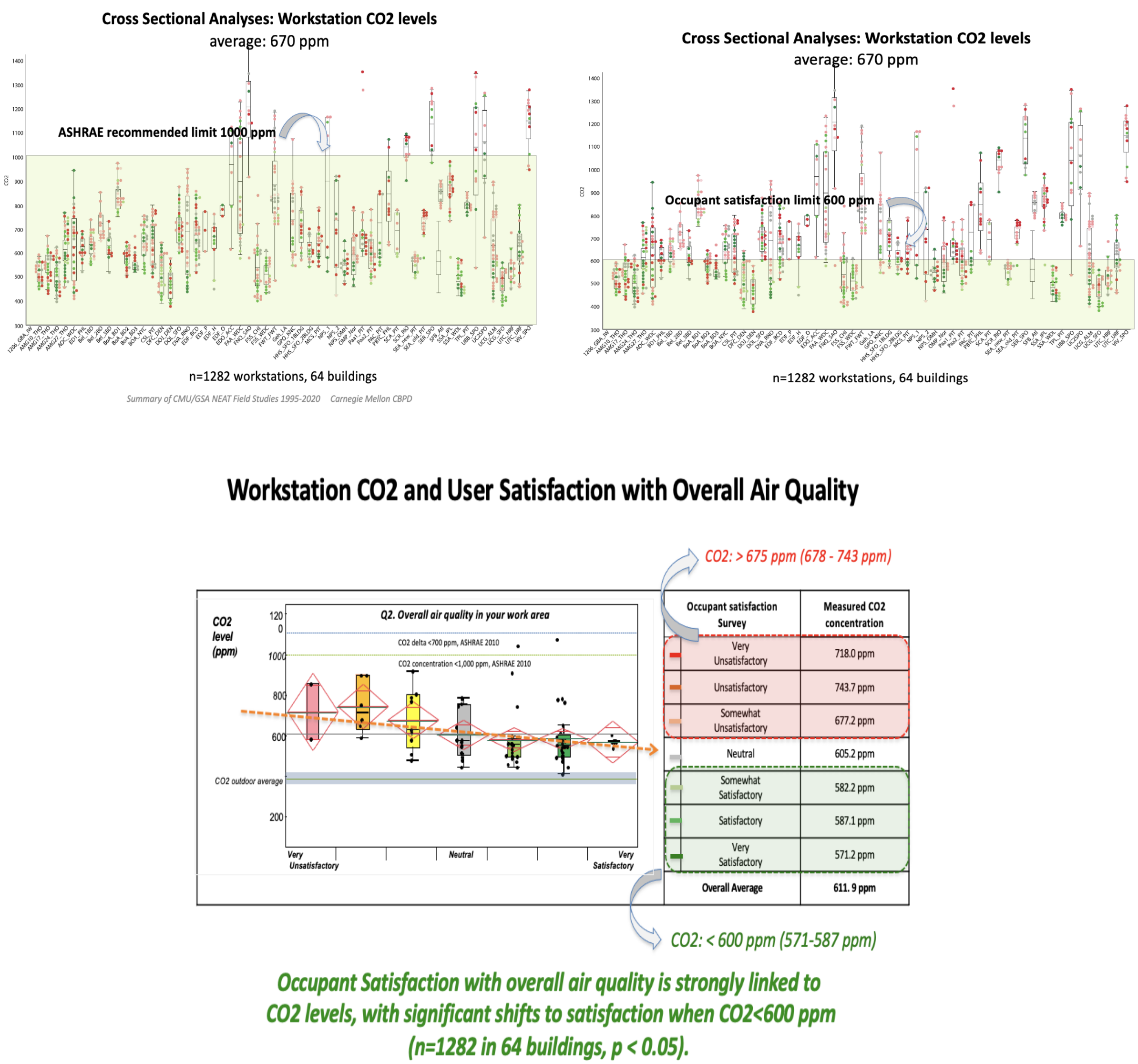


fig. 4.4 Correlations between Air Quality Satisfaction and CO2 conditions provide invaluable insights into thresholds that matter.

Field Measured Building and Zone IAQ Signatures with corresponding information about each of the building systems, operations, and office layouts that determine the IAQ - could generate a baseline KPI and database for shifting investments to those systems, operations and layouts that ensure the highest thermal and air quality satisfaction.

Evaluating for microbial contamination may be the most difficult of the objective IAQ measurements, often relying on air sampling and lab testing or DNA surface swabbing.

Since 2020 and the rise of Covid infections, controlling PM2.5 to minimize the air transport of the virus from person to person has grown in importance. As a result the cross section of zone measurements should also include particulates, at a minimum PM2.5.

Sensors are proliferating in the workplace and at home, tied to HEPA filters or advanced thermostats, and even desktop air quality monitors linked to smart phones and internet capture. Workstation or occupant centric spot and continuous IAQ measurement has to be anticipated in the near future and should be captured as possible to support rapid response to IAQ concerns and the refinement of standards.

4.3 HVAC Condition Key Performance indicator (KPI 3)
Quantifying HVAC condition reporting & FDD indices for IAQ

Research #3. Maintaining targeted records of central AHU and zone hardware and software conditions, including fault (FDD) and maintenance, could establish a portfolio-wide KPI for comparing the impact of building system capital and operational choices, facility management investments, and more for IAQ and health.

4.3.1 Maintenance Tracking KPI as Catalysts for O&M for IAQ

A recent NOVA study of 1700 AHU's in 62 large commercial buildings revealed a number of critical field conditions that may need to be addressed for IAQ and health in buildings (CBPD NOVA, 2023). The distillation of these guidelines into a discrete set of metrics for annual reporting on HVAC condition relative to IAQ might include:

HVAC Condition KPI for Improving IAQ in Large Commercial Buildings
Certify annual completion of condition check at each AHU of:

- Outside air delivery rate per AHU exceeds ASHRAE min (either directly measure the OA at the OA damper, or using Supply Air Rate - Recirculated Air Rate).
- OA, RA, MA, and zone dampers are functioning, and min/max and desired settings with BAS are functioning.
- Airflow sensors functioning and the links to the BAS are normal.
- Duct static pressure limits.
- MERV 13 filter min., replaced every 6 months or based on PT pressure drop.
- Coils and condensate pans are not fouled, moldy, or distorted.
- VFD installed and in good working condition.
- Economizer operation functioning (identify sensors, OA constraints?).
- DCV has been disabled during high health alert periods.
- AHU operating hours expanded from original.
- 5 year commissioning or Testing, Adjusting, and Balancing.

At least seven different guidelines and standards are focused on maintenance requirements for indoor air quality in commercial buildings, with critical updates related to periods of high infection risk:

- **ANSI/ASHRAE Standard 62.1**-2022, Ventilation and Acceptable Indoor Air Quality: Minimum Maintenance Activity and Frequency for Ventilation System Equipment and Associated Components

- **ASHRAE/ACCA 180**-2018 Standard Practice for Inspection and Maintenance of Commercial Building HVAC Systems

- **ASHRAE Standard 241**-2023 Standard for Infection Risk Mode
  Table 9.1 Minimum Maintenance Activity and Frequency for Ventilation System Equipment and Associated Components
  Table 9.2 Building Readiness Plan: Minimum Maintenance Activity and Frequency for Additional Engineering Controls and Associated Components While in Use

- **GSA Public Buildings Maintenance Standards** (January 1, 2022), General Services Administration Public Buildings Service

- **CDC Ventilation Mitigation Strategies** (updated 2023)
  https://www.cdc.gov/coronavirus/2019-ncov/community/ventilation.html

- **NEMI Ventilation Verification for Indoor Air Quality Specification** 2021, National Energy Management Institute
- **EPA Clean Air in Buildings Challenge** https://www.epa.gov/indoor-air-quality-iaq/clean-air-buildings-challenge

From these guidelines and standards, there are a number of critical actions for central air handling units as well as zone hardware and software maintenance that could form the basis of an annual KPI record for commercial buildings. To simplify the range of recommendations, the following matrix tries to capture 15 key HVAC maintenance requirements and frequencies that might influence IAQ (Table 4.1 https://docs.google.com/spreadsheets/d/1wGeKq1nxKH0M4ehL7sfN6EZDqXGTc1wwKfbmG_gMCXc/edit#gid=0).

Table 4.1. Maintenance Requirements/KPI for Ensuring Indoor Air Quality.

Key actions	ASHRAE 62.1	ASHRAE 180	ASHRAE 241	GSA	CDC	NEMA	EPA
Verify the operation of the outdoor air ventilation system and any dynamic minimum outdoor air controls; repair or replace as necessary.	15 cfm/person (8.5 L/s/p) 2 x Annual		ECAi rate: 30 cfm/p (15 L/s/p)			Check	Check
Verify the total quantity of outdoor air delivered by air handlers set to minimum outdoor air mode. If measured minimum airflow rates are less than the design minimum rate documented in the O&M manual, ±10% balancing tolerance, adjust or modify the air handler components to correct the airflow deficiency.	5 years		Every 3 years			Check	Check
Visually inspect outside air intake locations, louvers, screens for cleanliness, dryness and integrity	2 x Annual						
Check for proper damper operation. Clean, lubricate, repair, replace, or adjust as needed to ensure proper operation.	Annually	Annually	4xAnnual		Periodic		

Key actions	ASHRAE 62.1	ASHRAE 180	ASHRAE 241	GSA	CDC	NEMA	EPA
Verify the accuracy of permanently mounted sensors whose primary function is outdoor air delivery and dynamic minimum outdoor air control, such as AHU and DCV flow stations, including CO2 sensors. A sensor failing to meet the accuracy specified shall be recalibrated or replaced as per ASHRAE Standard.	5 years		Every 2 years			Check	Check
Check pressure drop and confirm replacement of filters and air cleaning devices. Confirm that pressure drop does not exceed the maximum pressure drop of the filter or maximum allowable for the fan. Clean or replace filters as necessary.	4xAnnual	4xAnnual	4xAnnual or when replaced	4xAnnual		Check	Check
Check air filter fit and housing seal integrity. Correct as needed.	Annually	Annually	Annually or when replaced	4xAnnual			Check
Check fan belt tension, alignments, wear and tear	2 x Annual						
Check drain pan, drain line, coil, and other areas of moisture accumulation for visible signs of biological growth.	Annually	4xAnnual		Annually		Check	
Check cooling tower water systems and evaporative condensers for microbial growth.	Monthly						
Check BAS control system and devices for evidence **of improper operation of dampers**.	2 x Annual	2 x Annual		Weekly Monthly Quarterly Annually	Periodic		
If present, **Maintain Ultraviolet (UV) germicidal irradiation in AHU** and verify performance and safety per manufacturer's instructions in accordance with ANSI/IESt.	4xAnnual	4xAnnual	4xAnnual or per manufact urer		Per manufa cturer		Check
Verify In-room air cleaners are in appropriate location and operating at the speed assumed in the VECAi calculation. Maintain and verify performance per manufacturer's instructions. Visually inspect intake for debris and clean as necessary.			Monthly		Per manufa cturer instructi ons		Check
Test-And-Balance				5-Year		Check	Check

4.3.2 Tracking Fault Detection KPI as Catalysts for O&M for IAQ

An HVAC Condition KPI should include an annual report on the **frequency and duration of critical HVAC faults (FDD) related to IAQ** from the building automation system (faults, alerts or sparks depending on BAS Industry). Thresholds of concern for excessive *frequency and duration* will need to be developed, but the data is already tracked in BAS systems and could be utilized as a KPI for building HVAC condition relative to IAQ. The FDD indices that may be of greatest concern for IAQ are just emerging in the research literature, but there are obvious clusters of concern around damper controls at both the central AHU and zone level, as well as fan controls, and temperature/CO2 and pressure sensors that control the delivery of outside air from the AHU to each zone (see fig. 4.5 for central AHU sensor suite) (Fisk, 2008; Zhang et al., 2021).

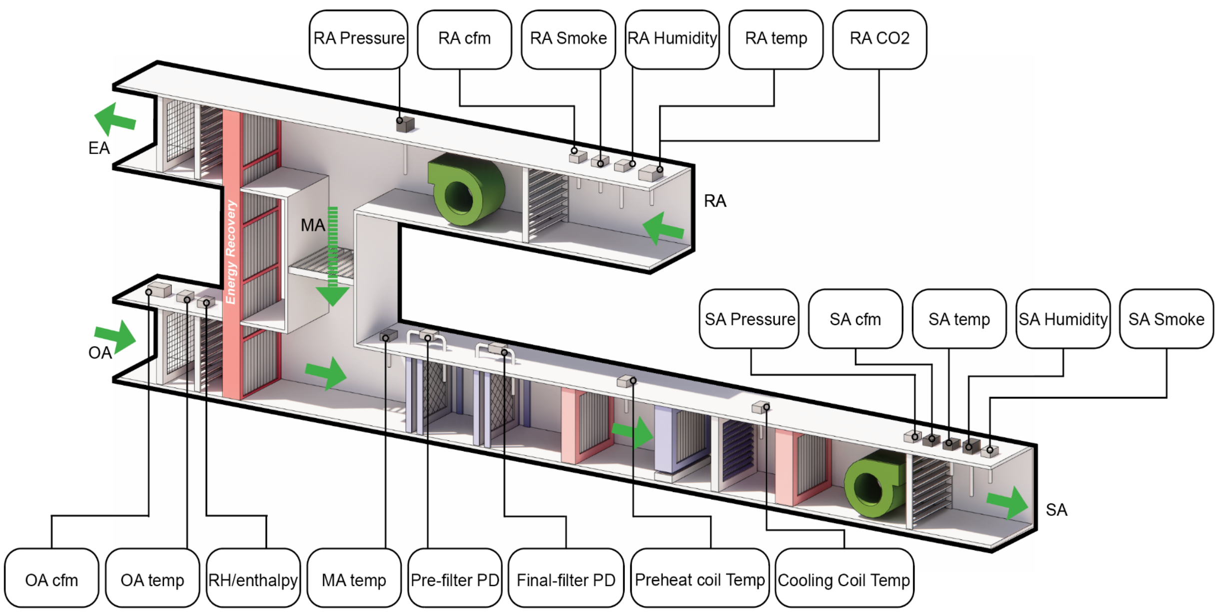


fig. 4.5 Schematic of a typical AHU with common sensor measurements.

Examples of the research findings linking specific faults to specific IAQ and potentially health impacts include:

> *In 2002 simulation and field study of one AHU serving 1200 m2 in an office building, Wang & Chen identified that stuck dampers, failures in OA, SA and RA air flow, BAS linkage, and CO2 sensor faults increased measured return air CO2 concentrations by 40% and energy consumption by 4.8%.*

In a 2006 simulation and field study of one AHU of an office building, Jin & Du identified that temperature sensor faults in the AHU OA and SA airstream of a VAV HVAC system resulted in a 30% increase in TVOCs concentrations in the zone served and a 2.9% increase in energy consumption.

In a 2013 field study of six air pollutants (NO, NO2, PM10, PM2.5, CO and CO2) in an underground building space, Kim et al. identified that the PM10 sensor fault may result in up to 3 times more PM10 than the normal range, with 25% of total occupied time below the standard, as well as increasing energy consumption.

In a 2014 field study of one office building, Qi and Dong and Xiao et al. identified that correcting zone temperature sensor faults, VAV flow sensor faults, VAV damper stuck, VAV flow sensor reading out of range, SA temperature too high/low, VAV terminal under capacity, and extreme high cooling load faults for terminal units and AHUs can potentially reduce energy consumption 20%–30% and improve low air flow rate 10%–40%.

In 2017 data-driven study for three AHU FDD portfolios, including data sources from NIST 6964, ASHRAE projects RP-1020 and RP-1312, Zhao et al. identified that faults with SA flow rate, SA pressure, filter pressure differentials, OA/RA/EA damper control, as well as SA/RA fan faults, had a 40% negative effect on building supply air flow rate and 25%-30% effect on building energy.

In a 2020 field study of a school building's FDD, Taal & Itard identified 19 faults, including CO2 sensor fault, damper, filter, and fan faults contributing to CO2 levels, and proposed new FDD priorities to reduce high CO2 concentration faults in mechanical zones by 6.7%.

In a 2020 data-driven study of a portfolio of buildings, Haleem et al. demonstrated that temperature sensors, airflow measurement, differential pressure transducers, air damper actuators, heating or cooling valves, and variable frequency drive faults in AHUs are highly correlated with IAQ and energy consumption in office buildings. The results showed that resolving faults can reduce up to 10% of zone CO2 concentration with 4.99% energy reduction.

Across ten field research studies linking FDD with ventilation effectiveness and IAQ, ten faults were cited most consistently (table below): OA/SA/Zone damper stuck, Failures in SA flow, OA/SA temperature sensor, Failures in OA flow, Pressure sensor for SA/filter, Failures in RA flow, CO2/Occupancy sensor, VAV flow sensor, and Heating & cooling simultaneously.

Table 4.2 Existing research linking FDD with ventilation effectiveness and IAQ.

Fault names	Wang & Chen, 2002	Jin & Du, 2006	Kim et al., 2013	Qi & Dong and Xiao et al., 2014	Zhao et al., 2017	Taal & Itard, 2020	Haleem et al., 2020	Hosamo et al., 2022	Nojedehi et al., 2023	
OA/SA/Zone Damper stuck										5
Failures in SA flow										4
OA/SA temperature sensor										4
Failures in OA flow										3
Pressure sensor for SA/filter										3
Failures in RA flow										2
CO2/Occupancy sensor										2
VAV flow sensor										2
Heating & cooling simultaneously										2
BAS linkage										1
PM10 sensor										1
Flow sensor out of range										1
SA temperature too high/low										1
Terminal under capacity										1
Extreme high cooling load										1
SA/RA fans										1
Window control sensor										1
Variable frequency drive										1

These researchers identified changes in CO_2, TVOC, PM, RH, thermal comfort and energy that resulted from a range of faults and fault frequencies (FDD reporting).

Table 4.3 Summary of range of faults and fault frequencies.

Author	Study Type	Fault Description	IAQ/Vent.	Thermal	Energy
Wang & Chen, 2002	Field & simulation office study	stuck dampers, failures in OA flow, failures in SA flow, failures in RA flow, BAS linkage, and CO2 sensor	40% increase of RA CO2 concentration by	Not discussed	4.8% Increase of energy penalty
Jin & Du, 2006	Simulation office study	AHU OA, Temperature sensor, OA and SA VAV airstream feeding faults	30% increase in TVOCs concentration	15% increase in relative humidity	2.9% increase in energy waste
Kim et al., 2013	Field underground building	PM10 sensor fault	3 times more PM10 than normal, 25% of occupied time below the standard	Not discussed	Extra energy (didn't mention specific values)
Qi & Dong and Xiao et al., 2014	Field office study	Zone temperature sensor faults, VAV flow sensor faults, VAV damper stuck, VAV flow sensor out of range, SA temperature too high/low, VAV terminal under capacity, extreme high cooling faults	10%–40% increase of low air flow rate issues	Around 14% temperature increase	20%–30% extra energy consumption
Zhao et al., 2017	Portfolio study for ASHRAE projects	SA flow rate, SA pressure, filter pressure differentials, OA/RA/EA damper control and SA/RA fans faults	40% negative effect on SA flow rate	Not discussed	Approximate 25%-30% energy waste
Taal & Itard, 2020	Data-driven field study for a school building	Occupancy sensor, CO2 sensor, pressure sensor, damper stuck, SA pressure, missing data, and window control sensor faults	6.7% increase of CO2 concentration in zone	Not discussed	Extra energy (didn't mention specific values)
Haleem et al., 2020	Portfolio with simulation study	Faults in Temperature sensors, airflow, differential pressure transducers, air damper actuators, heating or cooling valve, and variable frequency drive	10% increase of zone CO2 concentration	25% reduction of PMV/PPM thermal comfort	4.99% increase of energy penalty
Hosamo et al., 2022	Field campus study	Heating and cooling simultaneously	35 PA pressure increase in SA	No significant impacts	40% increase of energy penalty
Nojedehi et al., 2023	18 workstations in office building	Zone airflow and air temperature sensor faults	10% of CO2 concentration increase	29% of thermal discomfort reduction	Not discussed
Li & O'Neill, 2019	DOE's prototype office study	Studied 129 faults and AHU running during unoccupancy is the most significant	Not discussed	Fault causes most thermal comfort penalty	Fault causes most energy penalty

Given this background, FDD records can generate critical KPI to prioritize the buildings and systems of greatest need for attention relative to indoor air quality and health.

The potential to correlate existing FDD data as a KPI with field condition assessments and a number of IAQ outcomes including CO2 and cfm data is a critical area for GSA research, given existing BAS sources on setpoints and IAQ for at least 10 buildings.

The research linking fault corrections to energy and comfort is vast, but often devoid of indoor air costs or benefits. Nonetheless, this body of research reveals that addressing faults will also have measurable energy and comfort benefits. In 2019, Deshmukh et al. identified that fixing stuck and leaky dampers in office buildings resulted in 18% HVAC energy savings, but without indication of air quality benefits (Deshmukh et al. 2019). In 2019, Shea et al. identified that fixing malfunctioning economizer controls can result in 17% fan energy savings (fig. 4.6), again without quantification of air quality benefits (Shea et al. 2019).

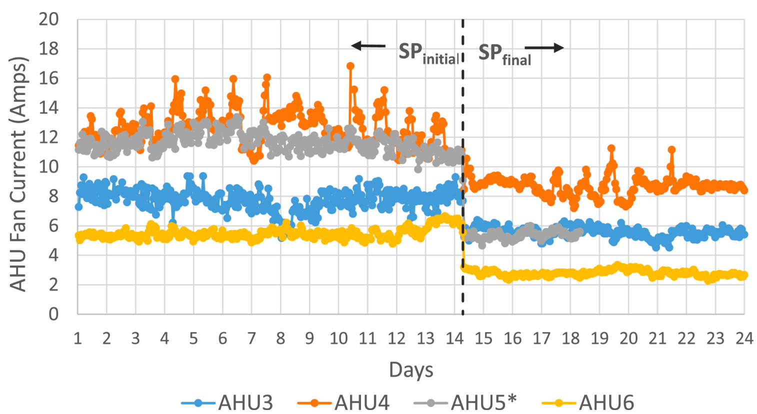


fig. 4.6 Reduction in AHU fans energy with economizer control fixes (Shea et al., 2019).

The availability of GSALink BAS sensor and setpoint data and Spark FDD Records would support the development of a database for decision tree analysis relating cause and effect for IAQ. In combination with TECI energy reports and NOVA reports on the condition of the diversity of AHU in a representation of federal large commercial buildings, it should be possible to identify the most important faults for ensuring a number of measured IAQ variables, such as cfm of OA and %OA/RA mix in the SA, and zone cfm and CO2.

The body of literature and early analyses of these data sets for select buildings has revealed a number of air handling unit faults and zone faults that need to be prioritized for IAQ, summarized in the following 3 page Table 4.4 with linked spreadsheets identifying:

- BAS records related to AHU Faults that could correlate with IAQ
  https://docs.google.com/spreadsheets/d/13-Cl-SysPTMaqmyE3c0-nmfl3fZ3F_cloo8drZTANtk/edit#gid=725740695

- BAS records related to Terminal Unit Faults that could correlate with IAQ
  https://docs.google.com/spreadsheets/d/13-Cl-SysPTMaqmyE3c0-nmfl3fZ3F_cloo8drZTANtk/edit#gid=1964345097.

Central AHU Faults			
Spark Labels		**AHU Faults**	**Possible Issues**
AHU Outdoor Damper Stuck Closed		Find periods when discharge fan is on, outside damper is greater than a threshold and the calculated outside air percentage is lower by more than a percentage. The outside air percentage will be calculated using the return air temperature, mixed air temperature, and outside air temperature sensor. If the mixed air temperature sensor is not available then the discharge air temperature sensor will be used when cooling and heating are both off. If the return air temperature is not available then the zone air temperature sensor will be used. Will not find these periods when the outside air temperature sensor is within a threshold of the return air temperature sensor.(1.5h)	● Outside air damper not operating properly ● Return air damper not operating properly ● Sensors may need calibration ● Mixed air plenum pressure issues; return fan not operating properly, plenum restrictions (intake screens, fire dampers, etc…)
AHU Damper Unstable	OA Damper	Find periods when any damper position jumps by more than a threshold (40%), more than a given amount of times, within a detection period of 2h	● Improper setpoints or deadband ● Incorrect sequence of operation ● Improperly tuned loop
AHU Damper Unstable **AHU Outside Airflow Too Low**	RA Damper MA Damper Exhaust Damper Bypass Damper	Find periods when any damper position jumps by more than a threshold (40%), more than a given amount of times, within a detection period of 2h Find periods when the discharge fan is on and the outside airflow is below the outside airflow setpoint for over a duration (1h) during occupancy.	● Improper setpoints or deadband ● Incorrect sequence of operation ● Improperly tuned loop ● Equipment not programmed properly to maintain minimum outside airflow ● Airflow setpoint not properly set ● Sensors out of calibration ● Outside air damper not operating properly ● Minimum outdoor air damper not operating properly ● Mixed air plenum pressure issues; return fan not operating properly, plenum restrictions (intake screens, fire dampers,
AHU Outside Airflow Unstable		Find periods when the discharge fan is on and the outside airflow bounces above and below the outside airflow setpoint by a deadband (300cfm). Periods are only found when the airflow crosses (above and below) the setpoint by the deadband more than the given amount of crosses in any 2h detection period.	● Improper setpoints or deadband ● Incorrect sequence of operation
AHU Discharge Fan Failure		Find periods when discharge fan is on and duct static pressure is below a threshold (0.2inH2O) for over a duration (0.5h)	● AHU Fan is not working correctly ● Loose belts on fan
AHU Discharge Fan Unstable		Find periods when the discharge fan speed jumps by more than a threshold (40%), more than a given amount of times, within a period of 2h	● Improper setpoints or deadband ● Incorrect sequence of operation

Central AHU Faults continued			
Spark Labels	**AHU Faults**	**Possible Issues**	
AHU Discharge Pressure Setpoint Unreachable	Below the setpoint	Find periods when discharge fan is on and discharge pressure is below the discharge pressure setpoint by a threshold (0.3inH2O) for over a duration (2h)	● AHU Fan is not operating correctly ● Loose belt on fan ● Incorrect setpoint ● Air balancing issue ● Sensor(s) not calibrated ● Fire damper or other duct restrictions
AHU Discharge Pressure Setpoint Unreachable AHU Discharge Pressure Unstable	Below the setpoint	Find periods when discharge fan is on and discharge pressure is below the discharge pressure setpoint by a threshold (0.3inH2O) for over a duration (2h) Find periods when the discharge fan is on and the discharge pressure bounces above and below the discharge pressure setpoint by a deadband (0.2inH2O). Periods are only found when the pressure crosses (above and below) the setpoint by the deadband more than the given amount of crosses in any 2h detection period	● AHU Fan is not operating correctly ● Loose belt on fan ● Incorrect setpoint ● Air balancing issue ● Sensor(s) not calibrated ● Fire damper or other duct restrictions ● Improper setpoints or deadband ● Incorrect sequence of operation
AHU Sensor Failure	OA Temp	Find periods when a sensor does not change by a threshold for a 24-hour period and equipment is running for over a duration.	● Broken sensor ● Wires to sensor are open or closed
AHU Sensor Failure AHU Sensor Out of Range	RA Temp MA Temp OA Air Flow SA Air Flow RA Air Flow SA Pressure Return Air CO2 OA Temp (-30 - 125F)	Find periods when a sensor does not change by a threshold for a 24-hour period and equipment is running for over a duration. Find periods when a sensor goes below or above limits for over a duration (1h).	● Broken sensor ● Wires to sensor are open or closed ● Broken sensor ● Wires to sensor are open or closed ● Equipment running outside of acceptable ranges
AHU Sensor Out of Range	RA Temp (35 - 110F) MA Temp (35 - 145F) OA Air Flow (-10 - 50kcfm) SA Air Flow (-10 - 50k cfm) RA Air Flow (-10 - 50k cfm) SA Pressure Return Air CO2 (300-2,500ppm)	Find periods when a sensor goes below or above limits for over a duration (1h).	● Broken sensor ● Wires to sensor are open or closed ● Equipment running outside of acceptable ranges

Terminal Unit Faults			
Terminal Unit Airflow Setpoint Unreachable	Below the setpoint	Find periods when the discharge airflow cannot get within a threshold (100cfm) of discharge airflow setpoint for over a duration (0.5h), while the AHUs discharge fan is on. Airflow must be above a minimum threshold (75cfm).	● Damper not operating properly ● Improper setpoints or deadband ● Balancing Issue ● AHU discharge fan problem ● Airflow sensor problem
Terminal Unit Airflow Setpoint Unreachable Terminal Unit Airflow Unstable	Below the setpoint	Find periods when the discharge airflow cannot get within a threshold (100cfm) of discharge airflow setpoint for over a duration (0.5h), while the AHUs discharge fan is on. Airflow must be above a minimum threshold (75cfm). Find periods when the discharge airflow bounces above and below the discharge airflow setpoint by a deadband (100c fm). Periods are only found when the discharge airflow crosses (above and below) the setpoint by the deadband more than the given amount of crosses in any 2h detection period, also while the AHUs discharge fan is on.	● Damper not operating properly ● Improper setpoints or deadband ● Balancing Issue ● AHU discharge fan problem ● Airflow sensor problem ● Damper not operating properly ● Improper setpoints or deadband ● Balancing Issue ● AHU discharge fan problem ● Airflow sensor problem
Zone Cooling Damper Malfunction		Find periods when the cooling damper is open above a threshold and the zone damper discharge air temperature is not within a threshold (4F) of the cold deck discharge air temperature for over a duration (1h). The AHU discharge fan must be on	● Cooling/Heating Damper not opening/closing properly ● Temperature sensor calibration issue
Zone Heating Damper Malfunction		Find periods when the heating damper is open above a threshold and the zone damper discharge air temperature is not within a threshold (4F) of the hot deck discharge air temperature for over a duration (1h). The AHU discharge fan must be on during this period.	● Cooling/Heating damper not opening/closing properly ● Temperature sensor calibration issue
Zone Pressure Setpoint Unreachable	Below the setpoint	Find periods when the zone pressure is below or above the zone pressure setpoint by a threshold (0.005inH2O) for over a duration (1h). If the equipment has a discharge fan the fan must also be on.	● Equipment bringing in too much OA ● Equipment not bringing in enough OA ● Exhaust fans not operating properly
Zone Pressure Setpoint Unreachable Terminal Unit Sensor Failure	Below the setpoint Zone Air Flow	Find periods when the zone pressure is below or above the zone pressure setpoint by a threshold (0.005inH2O) for over a duration (1h). If the equipment has a discharge fan the fan must also be on. Find periods when a sensor does not change by a threshold for a 24-hour period and equipment is running for over a duration.	● Equipment bringing in too much OA ● Equipment not bringing in enough OA ● Exhaust fans not operating properly ● Broken sensor ● Wires to sensor are open or closed ● Equipment running outside of acceptable ranges
Terminal Unit Sensor Failure Terminal Unit Sensor Out of Range	Zone Temperature Zone CO2 Zone Air Flow (-10 - 6,000cfm)	Find periods when a sensor does not change by a threshold for a 24-hour period and equipment is running for over a duration. Find periods when a sensor goes below or above limits for over a duration (1h).	● Broken sensor ● Wires to sensor are open or closed ● Equipment running outside of acceptable ranges ● Broken sensor ● Wires to sensor are open or closed ● Equipment running outside of acceptable ranges
Terminal Unit Sensor Out of Range	Zone Temperature (50 - 90F) Zone CO2 (300-2,500ppm)	Find periods when a sensor goes below or above limits for over a duration (1h).	● Broken sensor ● Wires to sensor are open or closed ● Equipment running outside of acceptable ranges

4.4 Record of Annual FM investments as Key Performance indicator (KPI 4)

Research #4. A facility investment KPI could be developed to record key variables that may influence IAQ and health outcomes: the level of investment in labor and materials per building per year; the area served per full time and part time FM staff; the years of service in that building, turnover and absenteeism; the level of training provided; and the compensation and promotion provided to ensure FM commitment and expertise (green careers). This FM investment KPI can be compared to health outcomes, IAQ measurements and annual maintenance checks and FDD KPIs to support improvements in FM staffing of federal facilities.

A preliminary list of data that could be requested for each federal facility includes:

1. Per Square foot budgets for capital and for operations per building and comparisons to current replacement value (CRV)
2. Maintenance budgets per occupant density and hours of occupancy
3. Record of full time vs part time staffers, in-house vs off-site, federal vs contract.
4. Sqft served per full-time on-site staffer (and full-time + part-time mix)
5. Years in the building of full-time staffers
6. Annual Turnover of full-time and part-time staffers
7. Annual Absenteeism of full-time and part-time staffers
8. Record of Promotion, Compensation, Training, of FM Staff

The expert workshop of May 17, 2023 proposed some corollary actions that might be considered to Independently assess expertise, size, consistency, training and funding of FM teams for correlation with IAQ, comfort, energy. The recommendation included independently assessing expertise, size, consistency, training and funding of FM teams for correlation with IAQ, comfort, energy:

phase 1: interview top IEQ performers (based on WELL or similar metrics) to benchmark quality of air delivered to each zone given HVAC configuration and operational records.
phase 2: determine criteria for success to attract, train and retain the best FM teams
phase 3: complete a portfolio wide assessment of FM staffing, structure, and contracting changes to meet high IEQ and energy goals.

It is important to note that large US commercial buildings in both the public and private sector have long records of underfunding. There are remarkably few databases on actual facility management expenditures and manpower, or KPI's that might set minimum thresholds. Three studies have been identified, two from the National Academy of Sciences Federal Facilities Council and one from the Healthcare industry in Israel.

National Academy Studies on Budgeting for Facilities Maintenance and Repair

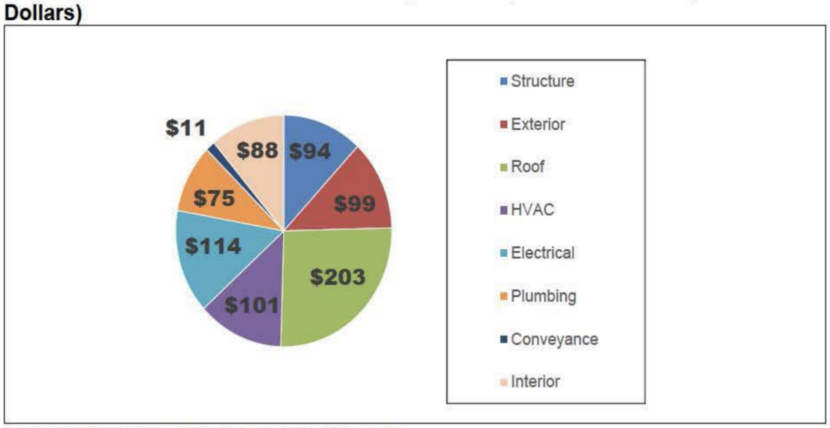
In the 1990 Building Research Board report *Committing to the cost of ownership—Maintenance and repair of public buildings*, the National Research Council identified that a range of 2-4% of **current plant value (CPV)** would be critical for ensuring the operational performance of federal buildings. The Federal Facility Council members of this National Academy study defined the variables that would push for a 4% annual maintenance budget to include: 24 hour operation, complexity of system, age of system, mission critical buildings, and more. The FFC members gathered data from their respective portfolios and identified that existing federal facilities were being maintained at 1.5% of CPV, revealing chronic underinvestment.

The 1990 committee identified that agencies generally are in agreement that M&R budgets *should not include* funds for any activities that are primarily operational (custodial, pest control, security, fire protection) or for any construction work that expands or changes the function of a facility or lengthens its life beyond its original design life. Given the shifts from in-house to contract facility management services, and the use of military recruits for maintenance, they could draw no conclusions about staffing levels required for effective long term maintenance.

In 2005, the National Research Council updated the 1990 study with "Key Performance Indicators for Federal Facilities Portfolios" : Federal Facilities Council Technical Report Number 147. Following these guidelines, the Smithsonian Institution began an annual assessment of facility conditions, color coded and normalized to the NRC guideline. They determined that "facilities requiring routine maintenance and repair may require funding levels of 2 percent of CRV and are coded blue. Facilities in a more deteriorated condition may require investments of 3 percent of CRV and are color coded green. Severely deteriorated facilities may require investments of 5 to 6 percent of CRV and are coded red or lavender. Physical changes then are cost-estimated by systems, summed for a facility, and compared with the color standards to determine color status. Projected or expected funding is matched to repair schedules to project when color status will change in an out year."

In 2014, the Smithsonian Institution identified that investments remained substantially below 2% with deferred maintenance over $800 million dollars stretched across roofs, HVAC, electrical, exterior, structure and interiors (fig. 4.7).

Figure 4: Cost Breakout for the Eight Major Systems in the Smithsonian's Estimated Deferred Maintenance Backlog, as of September 30, 2014 (in Millions of Dollars)



Source: OIG analysis of Smithsonian Facilities data.

fig. 4.7 Roofs, Electrical and HVAC lead the 2014 Smithsonian Deferred Maintenance list.

In the 2023 National Academy report, *Strategies to Renew Federal Facilities* (https://nap.nationalacademies.org/download/26806), the NRC Federal Facilities Council introduces a more detailed facility condition index (FCI). This NRC report references a Lawrence Livermore Lab study of 25 years of facility maintenance data (Shang, Abed, and Farrell, 2019) that targets the importance of a facility condition index (FCI) to not greater than 5 percent (with critical facilities not greater than 9 percent), where FCI is defined as the sum of maintenance requirements for a facility divided by present replacement value (PRV) of that facility. The report concludes that federal facilities need to allocate more than 2.5 percent of present replacement value (PRV) for maintenance to reduce deferred maintenance backlogs, adding the following details:

Implement a Federal Facility Asset Management System

The Office of Management and Budget (OMB), in concert with the Federal Real Property Council, should update OMB Circulars A-11 and A-123 to improve guidance for implementing facility asset management systems by:

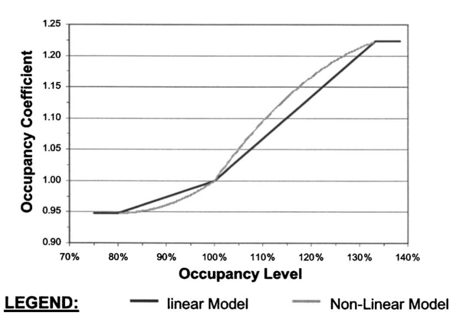
- Requiring federal agencies to use a comprehensive and principle-based facility **asset management system, as defined by International Organization for Standardization 55000**—Asset Management System standards, to implement federal facility renewal strategies;
- Clarifying how **enterprise risk management** and internal controls support implementation of federal facility renewal strategies by improving and clarifying policies contained in OMB Circulars A-11 and A-123;

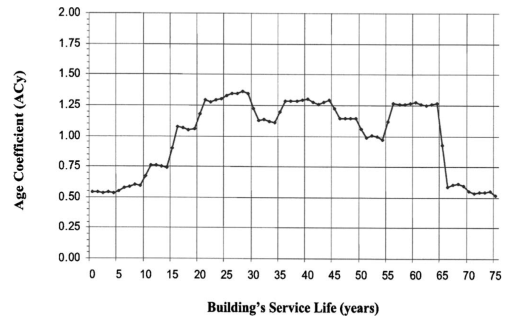
- Clarifying agency **senior real property officer's fiduciary responsibilities** to ensure and assure that the agency is maintaining its facility portfolio efficiently and effectively, and that achievement of this responsibility is reported as part of the agency's OMB Circular A-136—Financial Reporting Requirements;
- Detailing **whole asset life-cycle costs**, whole asset portfolios, and whole benefit analysis support resource-and-investment decisionmaking; and
- **Updating OMB Circular A-11,** Section 83 (Object Classification) to **remove fragmentation** and many-to-many relationships that make it exceedingly difficult to generate and audit integrated real property performance–budget and management balance sheets.

Quantitative precedent: Israel's key performance indicators for strategic healthcare facilities maintenance

In a 2006 case study and statistical analysis of KPIs for the facility management of critical healthcare facilities in a university's hospital in Israel, Sholet et al proposed 11 KPIs and a model to calculate maintenance effectiveness that integrates quantitative performance, manpower, and maintenance indicators. These "Key performance indicators for strategic healthcare facilities maintenance" published in the *Journal of Construction Engineering and Management* in 2006 and 2017 provide valuable metrics for establishing a new Facility Maintenance Investment KPI, outlined in Table 4.5.

Table 4.5. Shohet Hospital Facility Maintenance Investment KPI

	KPI	Description	Formula
1	**Building Area** (case study 120,000 m2)	● Larger area decreases the expense per square meter by giving a wide basis. ● Larger area also increases need for infrastructure increases maintenance cost	
2	**Occupancy Coefficient** (case study 6 patients/ 1000m2) **Occupancy Coefficient = 0.95**	● The standard in Israeli healthcare facilities is 10 patients/1000m2 ● 22% more resources required if occupancy increases to 13.3patient/ 1000m2 ● 5% savings for the low occupancy.	 **Fig. 1.** Occupancy coefficient (for annual maintenance expenditure) for different occupancy levels

3	**Facility Age** **Age coefficient = 1.15** as per 25 years	Peaks seen at the age of 25th, 40th, 60th years which reflect the building's electro-mechanical systems.	 **Fig. 2.** Age coefficient (AC_y) versus building's service life
4	**In House vs Outsourcing FM staff 8.5 employees /1000m2**	On average in Israel 6.5 employees/ 1000m2 in house	
5	**Scope of Outsourcing** - Maintenance Sources Diagram (MSD)	● Outsourcing constitutes an alternative to the implementation of maintenance activities by in-house employees, who require ongoing management. ● Outsourcing can serve as a source for the execution of seasonal preventive maintenance works, as well as rehabilitation, renovation, and replacement works.	
6	**Managerial Span of Control** (MSC) **MSC = 9** Expected = 6	Number of subordinates reporting to a given supervisor. For a typical acute care facility 80,000 m2 with 50 in-house maintenance personnel, the desired span of control at the head of organization level is no greater than six, while at the maintenance manager's level the desired span of control is eight subordinates	
7	**Maintenance Organization Structure**	● KPIs 4 to 6 ● Flexibility in resource allocation	
8	**Building Performance Indicator** (BPI)(Pn) **Pn= 81.4** (good performance) Pn for elevators , and water and sanitation is low	● 60<Pn<70 deteriorating performance ● Pn= 70 marginal performance ● Pn= 80 satisfactory performance ● Pn>80 good condition ● Israel Standards Institutions 2002 ● Weighting of each building system (Wn) in the BPI is accomplished by weighing the contributions of the system's components to the total cost of erection, maintenance, and replacement life cycle costs.	BPI = (Actual Component Condition * Weight of Component Condition) + (Failures Affecting service * Weight of Failures) + (Actual Preventive activities * Weight of Preventive Maintenance) $P_n = C_n^* W(C)_n + F_n^* W(F)_n + \mathrm{PM}_n^* W(\mathrm{pm})_n$
9	**Annual Maintenance Expenditure** (AME) **$35/sq. meter** Nat = $37.2/sq. m	The average annual maintenance expenditure (AMEy) per m2 was assessed as 2.5% of the reinstatement value of a clinic facility which was calculated to be $1,180 per built m2.	
10	**Annual Maintenance Expenditure/ Bed** **$8,100/ patient bed** (national ave. $450/ bed)		

11	**Maintenance Efficiency Indicator (MEI)** **MEI = 0.40** Expected range 0.52>MEI>0.37	• Examine the investment in maintenance in relation to facilities performance • MEI<0.37 indicates lack of resources and/or high efficiency with which the resources are utilized, or both • 0.52>MEI>0.37 reflects a reasonable range of maintenance, in which the lower limit indicates good efficiency while the upper limit indicates low efficiency and/or a high level of resources • MEI>0.52 indicates high inputs relative to the actual performance. Such high indicator values may express high maintenance expenditures, low physical performance, or a combination of these two extreme situations.	**Maintenance Efficiency Indicator = (Annual Maintenance Expenditure / Age Coefficient of year y) * (1 / Building Performance Indicator) * (1 / Occupancy Coefficient) * Prices Index** MEI = (AME/AC) (1/BPI) (1/OC) (Pindex)

Table 2. Expected Categories of KPIs

KPI	Category
Built floor area (m^2)	60,000–100,000
Occupancy (patient beds/1,000 m^2)	$13 \geqslant OC \geqslant 8$
AC_y	$1.36 \geqslant AC_y \geqslant 0.53$
Number of employees per 1,000 m^2	0.64
MSD	MSD ⩾ 60%
MSC	6
Organizational structure	Learning
BPI	BPI ⩾ 80
AME ($/$m^2$)	37.2
AME per patient bed ($/patient bed)	3,750
MEI ($/$m^2$)	$0.52 \geqslant MEI \geqslant 0.37$

Sholet et al completed 24 hospital case studies comparing hospital maintenance investment in Israel. This study identified the threshold of maintenance expenditure and staffing, both in-house and outsourced, summarized in the Maintenance Expenditure Indicator (MEI). MEI was critical to achieving the highest building performance indicator across all building system investments, weighted for performance as shown in figure 4.8 and 4.9. Most hospitals invested substantially less than the $32 dollars per square meter normalized annual maintenance expenditure of the highest performers, and their building performance indicators reflected the lack of investment (Shohet et al., 2006).

Table. Case Study Results for Building Performance Indicator

Building System	Weight (Wn)	BPI (Pn)
Structure	12.4	84
Interior Finish	34.8	79.5
Exterior Envelope	5.3	84.2
Fire Protection	2.2	75.0
Water and Sanitation	7.6	68.8
Elevators	4.1	57.1
Electric Systems	12.7	91.7
Communications	4.6	82
HVAC	13.7	85.0
Medical Gases	2.6	100
BPI	100	81.4

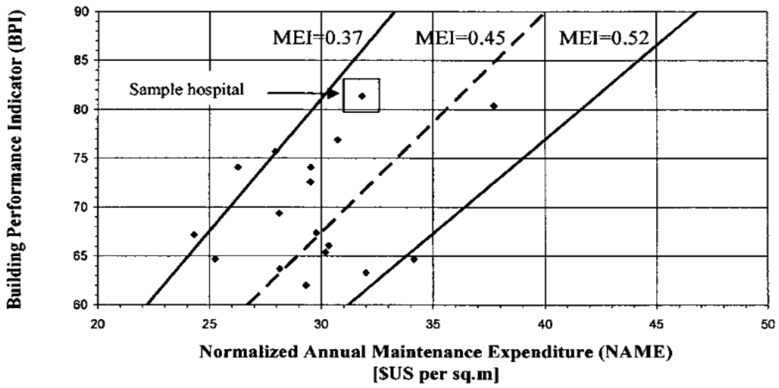


Fig. 3. Building performance indicator of hospital studied compared with population of public acute care hospital facilities in Israel

figure 4.8-4.9 Maintenance Expenditure Indicator scores for 24 hospital case studies

In 2017, Sholet et al additionally evaluated 31 health clinic case studies to compare to the 24 hospital case studies, all in Israel. The comparison revealed that clinical facilities required less maintenance for long term investment and may want to be strategically considered as support for hospitals to establish cost-effective FM and maintenance facility services (Shohet et al., 2017).

Key performance indicators of this comparative study include:

- A combination of 60% outsourcing and 40% in-house labor for maintenance may represent a solid balance in healthcare facilities located in a large urban area under standard service conditions.
- “While hospital facilities necessitate the allocation of double the amount of resources for maintenance and the computed annual expenditure for hospitals required to accomplish full performance is $54 per m2 (3.23% of the reinstatement (replacement) value) compared with $29 per m2 (2.5% of reinstatement (replacement) value) in clinics, accomplishing high performance for hospital built-facilities is complex” (Sholet 2017).

4.5 Building Statistical Correlations between Four New KPIs to catalyze O&M investments for IAQ

Correlations between these new emerging KPIs - SBS, IAQ, maintenance and FM investment - could be evaluated against a number of factors to establish priorities for investment, including:

- Age of building
- size and complexity of building/ building mission
- Age of HVAC system: AHU, BAS, sensor/actuators
- Type of HVAC system
- Presence of economizer and ERV
- Zone sizes (# occupants per thermostat/ damper)

Four Key Performance Indicator (KPI) Proposals

Beginning with a set of test buildings, each of the KPI's - user satisfaction/SBS, zone IAQ, maintenance records, and FM investment - could be tested to ensure that they do not unduly burden the FM team, and that the outcomes have meaning for FM action. The intentions of these KPI's are to improve all of the resources for O&M to ensure greater IAQ and Health in federal buildings, by ensuring:

1. Better IAQ/IEQ consistently at the portfolio level
2. Increased investments in central and zone HVAC (eg updating damper, sensor/actuator, BAS, and economizer with and without ERV determined by climate ASHRAE and LCC)
3. Increased investments and interest in the facilities management profession
4. Increased skills and awareness on the importance of IAQ and IEQ
5. increased investments by large building owners and leasers in FM attraction, retention, numbers, and training with known benefits to energy, IEQ.
6. Reduced O&M costs resulting from better management of facilities
7. Development of new regulations focusing on O&M practices
8. Development of new metrics / KPIs of OM / IAQ / health outcomes that are legible to building owners/occupants / FM including criteria for measuring sensor quality and deployment.

4.6 Next generation BASE study of the federal portfolio, with HVAC records, IEQ field measurements, and IAQ data analytics

The U.S. EPA's Building Assessment Survey and Evaluation (BASE) study and Summary and Analysis Report (EPA, 2001) aimed to assess the status of indoor air quality (IAQ) in 100 randomly selected U.S. buildings. In an updated report, Persily and Gorfain (2008) found that the average outdoor air intake was approximately 49 L/s/person (105 cfm/person), influenced by higher than minimum outdoor air fractions and actual occupancy rates typically at 80% of design condition. When considering scenarios where the minimum outdoor air intake is combined with reduced occupancy levels, the mean ventilation rate is around 11 L/s/person (22 cfm/person), and about 50% of the values failed to satisfy the individual requirements in Standard 62.

Although both mean values exceed the minimum outdoor air requirement of 10L/s/person in ASHRAE 62.1-2001 (and the 8.5 L/s/person in ASHRAE 62.1-2022), roughly 50% of measured minimum outdoor air intake values were less than the 10L/sec/person requirement and 25% were less than 5 L/s/person. During a pandemic that involves infectious airborne disease, the mean measured values would not fulfill the equivalent 15 L/s/person requirement in ASHRAE 241 unless local filtrations and air change equipment was added..

The study also examined HVAC hardware and software, IAQ measurements, as well as occupant perceptions of environmental conditions. The authors identified the difficulty in: quantifying building tightness and using tracer gas measurements for infiltration rates; obtaining reliable outdoor air measurements; accessing HVAC system components; and having appropriate ductwork configurations for zone air delivery.

The BASE study could provide a structure for the Ventilation Verification Project (VVP) that began with 62 buildings and will expand to several hundred federal buildings. The use of consistent, expert field teams to gather data about HVAC system configurations, operational setpoints and fault detection, multi-zone indoor air quality measurements and user perception, as well as corresponding energy demands, can inform the new design and retrofits of commercial building system integration, management, and operations.

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Chapter 4 Appendix A: COPE 'Right Now' Satisfaction Questionnaire

The questionnaire supports the statistical analysis of 'right now' IAQ, satisfaction and the technical attributes of the building systems.

CMU's On-Site User Satisfaction Questionnaire (based on NRC COPE [i])

What building are you in (address or title)? ______________________

What floor? ______________________

How long have you worked here? ______________________

In a typical work week how many hours do you spend here? ______________________

How do you feel about?	Very Dissatisfied	Dissatisfied	Somewhat Dissatisfied	Neutral	Somewhat Satisfied	Satisfied	Very Satisfied
1. Light on the desk for paper-based tasks (reading & writing)	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
2. Overall air quality in your work area	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
2a. Odors in your work area	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
3. Temperature in your work area	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)

Temperature in your work area during:	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
3a. Winter	☐	☐	☐	☐	☐	☐	☐
3b. Spring	☐	☐	☐	☐	☐	☐	☐
3c. Summer	☐	☐	☐	☐	☐	☐	☐
3d. Fall	☐	☐	☐	☐	☐	☐	☐

How do you feel about?	Very Dissatisfied	Dissatisfied	Somewhat Dissatisfied	Neutral	Somewhat Satisfied	Satisfied	Very Satisfied
4. Aesthetic appearance of your work area	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
4a. Cleanliness of your work area	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
5. Level of acoustic privacy for conversations in your work area	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
6. Level of visual privacy within your work area	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
7. Amount of noise from other people's conversations while you are at your workstation	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
8. Size of your personal work area to accommodate your work, materials and visitors	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
9. Amount of background noise from mechanical or office equipment you hear at your workstation	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)
10. Light for computer work	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)

How often do you experience glare:	Always	Morning	Noon	Late Afternoon	Night	Never
11. On your computer screen	☐	☐	☐	☐	☐	☐
12. From electric lighting fixtures	☐	☐	☐	☐	☐	☐
13. From daylight	☐	☐	☐	☐	☐	☐

How do you feel about?	Very Dissatisfied	Dissatisfied	Somewhat Dissatisfied	Neutral	Somewhat Satisfied	Satisfied	Very Satisfied
14. Air movement in your work area	(-3)	(-2)	(-1)	(0)	(1)	(2)	(3)

	Stuffy	Drafty	Both	N/A
If dissatisfied with the air movement, what are the conditions:	☐	☐	☐	☐

How do you feel about?	Very Dissatisfied	Dissatisfied	Somewhat Dissatisfied	Neutral	Somewhat Satisfied	Satisfied	Very Satisfied
15. Your ability to alter physical conditions in your work area	-3	-2	-1	0	1	2	3
16. Your access to a view of outside from where you sit	-3	-2	-1	0	1	2	3
17. Distance between you and other people you work with	-3	-2	-1	0	1	2	3
18. Overall quality of lighting in your work area	-3	-2	-1	0	1	2	3
19. Frequency of distraction from other people	-3	-2	-1	0	1	2	3
20. Degree of enclosure of your work area by walls, screens or furniture	-3	-2	-1	0	1	2	3

Rank of importance (1-7)	Noise	Temperature	Privacy	Air Quality Ventilation	Size of Workspace	Window Access	Lighting
21. Rank from 1st-7th what should be improved to support your effectiveness at work (1st is the most important and 7th is the least important)	___	___	___	___	___	___	___

Please check the appropriate box:

22. Age	20-29	30-39	40-49	50-59	60-69	70+
23. Gender	Female	Male				
24. Highest level of education	High School	Community College	Some University	Bachelor Degree	Graduate Degree	Doctorate
25. Job category	Administrative	Techinical	Professional	Managerial		

How do you feel about?	Strongly Disagree	Disagree	Somewhat Disagree	Neutral	Somewhat Agree	Agree	Strongly Agree
26. My department/agency is a good place to work	-3	-2	-1	0	1	2	3
27. I am satisfied with my job	-3	-2	-1	0	1	2	3
28. The environmental conditions in my work area support my personal productivity	-3	-2	-1	0	1	2	3
29. I am satisfied with the indoor environment in my work area as a whole	-3	-2	-1	0	1	2	3

Please add any comments that you would like to share with us related to your work environment:

____

____

____

____

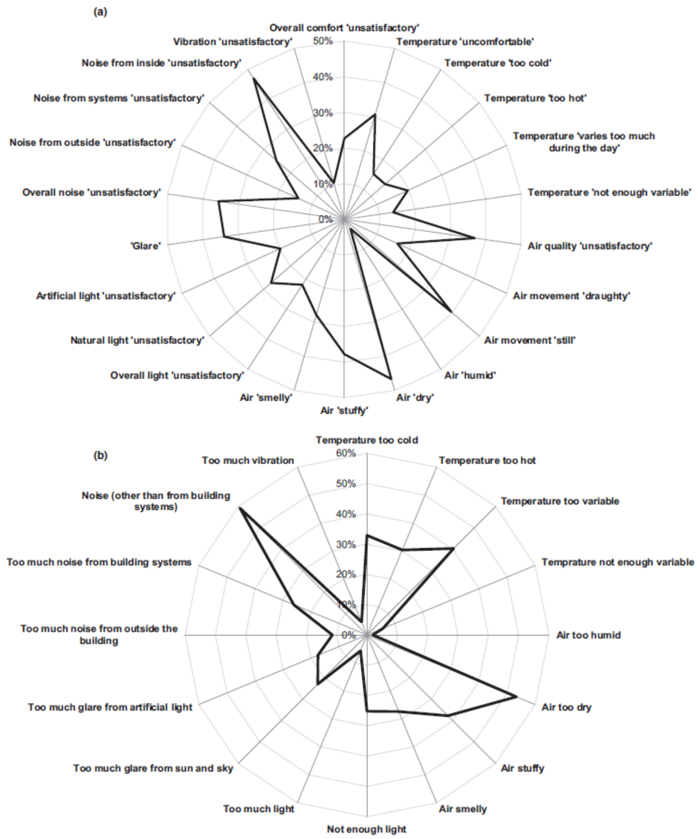
____

[1] Based on the COPE survey of the Institute for Research in Construction, National Research Council Canada, and revised by the Center for Building Performance and Diagnostics at Carnegie Mellon University.

Please fax or mail this completed survey to:
Azizan Aziz, Center for Building Performance and Diagnostics, Carnegie Mellon University,
5000 Forbes Avenue, 410 Margaret Morrison Carnegie Hall, Pittsburgh, PA 15213
Telephone: 412-268-6882 | Fax: 412-268-6129

Chapter 4 Appendix B: EU OfficeAir Satisfaction and SBS Survey Questions

(Bluyssen et al 2016)



Worker's perception of environmental conditions during the past month (a) and reason mentioned by the respondents when the overall comfort is shifted to unsatisfactory side in the scale (less than the middle point) (b) in the OFFICAIR study. Note: Noise from building systems (e.g., heating, ventilation, air conditioning, and plumbing), and noise other than from building systems (e.g., phone calls, colleagues chatting, and photocopiers). (a) values are the percentages of office workers who rated the environmental parameters below the value '4' on a scale from 1 to 7. Perceived environmental conditions were expressed throughout unipolar scales, except for temperature too cold/too hot, temperature varies too much during the day/not enough variable, air movement drafty/still and air humid/dry which were expressed using bipolar scales. (b) the question asked was 'You have rated your overall comfort in the last 4 weeks less than 4, what could be the reason of this?'

Table 5 Correlation between perceived control over the indoor environment and perceived indoor environment conditions and health (Personal Symptom Index, PSI) in the OFFICAIR study

	Overall comfort (1: unsatisfactory – 7: satisfactory)	Temperature (1: uncomfortable – 7: comfortable)	Air movement (1: draughty or still – 7: acceptable)	Air quality (1: stuffy – 7: fresh)	Air quality overall (1: unsatisfactory – 7: satisfactory)	Light overall (1: unsatisfactory – 7: satisfactory)	Noise overall (1: unsatisfactory – 7: satisfactory)	PSI-5
Control over temperature	0.358	0.420	0.163	0.265	0.327	0.269	0.280	−0.223
(1: none at all – 7: full)	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Control over ventilation	0.306	0.309	0.153	0.256	0.307	0.266	0.237	−0.201
(1: none at all – 7: full)	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Control over shading	0.339	0.275	0.105	0.257	0.278	0.341	0.262	−0.198
from the sun	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
(1: none at all – 7: full)								
Control over lighting	0.390	0.331	0.119	0.260	0.315	0.401	0.306	−0.228
(1: none at all – 7: full)	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*
Control over noise	0.373	0.288	0.145	0.257	0.295	0.246	0.408	−0.248
(1: none at all – 7: full)	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*	*<0.001*

Rho and *P*-value of Spearman's rank correlation. *P*-values are in italic.
Personal Symptom Index (PSI-5) defined on five symptoms: dry eyes, blocked or stuffy nose, dry/irritated throat, headache, and lethargy.

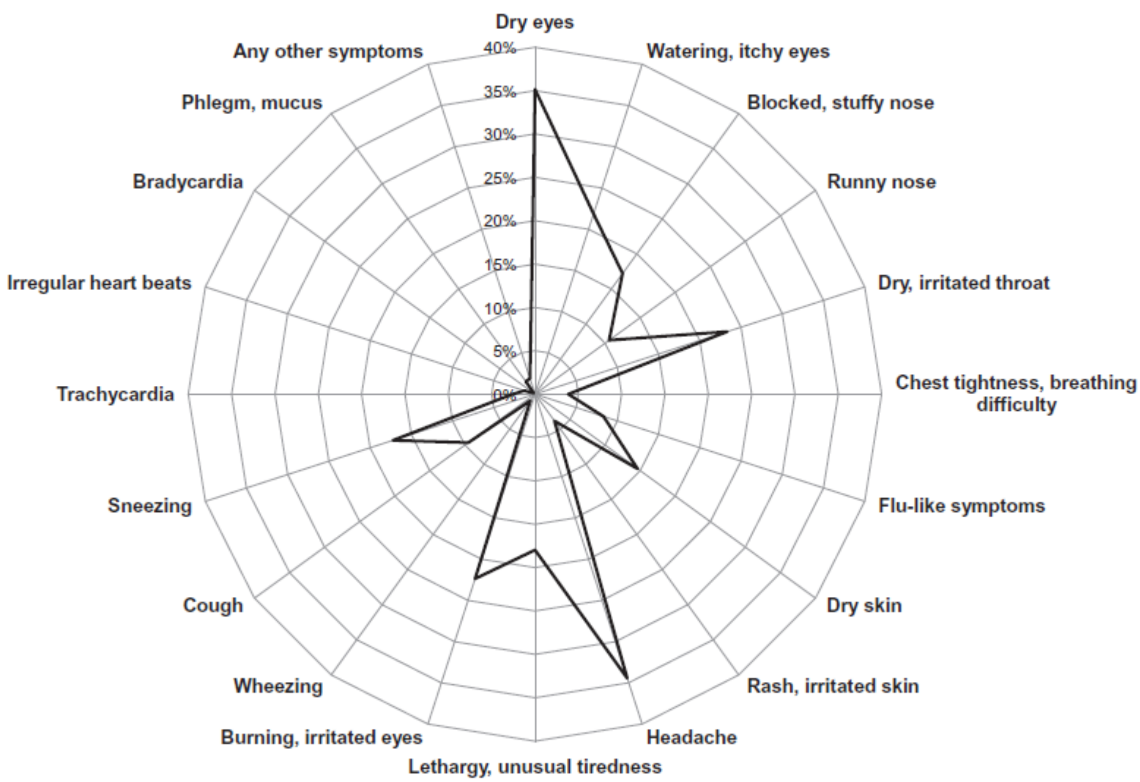


Fig. 4 Prevalence of building-related health symptoms in the OFFICAIR study

Chapter 4 Appendix C: Japanese Stress/ IEQ Questionnaire, Azuma 2017

Table 6 Final models for the association between weekly building-related symptoms and all variables (Model 4)

Variable factors	Eye irritation OR (95% CI)	General symptoms[l] OR (95% CI)	Upper respiratory OR (95% CI)	Skin symptoms[l] OR (95% CI)
	$N = 2330$	$N = 2275$	$N = 2260$	$N = 2436$
Personal				
Gender (female)	1.67 (1.23–2.28)**	1.80 (1.36–2.38)**	2.27 (1.48–3.48)**	3.12 (1.48–6.59)**
Age				
10–19	–	1.96 (0.19–19.71)	–	–
20–29	–	3.24 (1.68–6.23)**	–	–
30–39	–	2.16 (1.16–4.00)*	–	–
40–49	–	1.66 (0.89–3.11)	–	–
50–59	–	1.35 (0.71–2.58)	–	–
≥ 60	–	Ref.	–	–
p for trend	–	<0.001	–	–
Contact lens use	1.59 (1.20–2.10)**	–	1.73 (1.16–2.57)**	–
Pet ownership (Cat)			–	2.86 (1.28–6.43)*
Work environment				
No. of people in office[a]	1.19 (1.03–1.39)*	–	–	–
Work station				
Floor carpet (with)	1.44 (1.07–1.95)*	1.53 (1.15–2.05)**	1.74 (1.10–2.75)*	–
Reflection or glare in vision[b]	1.25 (1.07–1.45)**	1.32 (1.13–1.55)**	–	–
Chair comfort[c]	1.37 (1.13–1.67)**	1.35 (1.11–1.63)**	1.74 (1.34–2.27)**	–
Work with computer	5.51 (1.62–18.73)**	–		
Use of odorous chemicals[d]	1.11 (1.02–1.21)*	–	–	–
Change in workplace[e]				
Painted wall			4.72 (1.57–14.22)**	
Workplace conditions in last 4 weeks[f]				
Too little air movement	–	1.37 (1.21–1.56)**	1.26 (1.05–1.50)*	–
Varying room temperature	1.23 (1.07–1.42)**	–	–	–
Too cold	–	1.45 (1.21–1.73)**	–	–
Air too humid	–	1.20 (1.02–1.43)*	–	–
Air too dry	1.46 (1.24–1.72)**	–	1.76 (1.44–2.14)**	2.71 (2.10–3.51)**
Static electricity	–	–	–	–
Noise	1.29 (1.05–1.59)*	1.54 (1.25–1.88)**	1.41 (1.09–1.82)**	–
Dust and dirt	–	–	1.26 (1.00–1.58)*	–
Tobacco smoke odor	1.21 (1.02–1.43)*	–	–	–
Unpleasant chemical odor	–	–	1.96 (1.24–3.08)**	2.60 (1.63–4.15)**
Unpleasant other odor[g]	1.22 (1.02–1.45)*	1.35 (1.14–1.61)**	–	
Job stressors				
Amount of work[h]	1.34 (1.19–1.51)**	1.38 (1.23–1.55)**	1.25 (1.06–1.46)**	
Mental workload[h]	–	–		
Physical overload[i]	0.70 (0.59–0.83)**	–	–	
Interpersonal conflict[h]	–	1.42 (1.21–1.65)**	–	–
Job control[h]	–	0.80 (0.70–0.92)**	–	–
Skill utilization[i]	–	–	–	–
Job suitability[k]	–		–	

Appendix D: Japanese SBS Questionnaire, Azuma et al 2017

Table 8 Significant risk factors associated with weekly building-related symptoms in final model in winter ($N = 3335$) and summer ($N = 3024$)

Symptoms and seasons	Significant risk factors		
	Job stressor	Work environment	Indoor air quality
Eye irritation			
Winter	• Excessive work • Adequate skill utilization	• Carpeting • Poor lighting • Uncomfortable seating • Often use of odorous chemicals[a]	• Too cold • Too dry • Strong static electricity • Airflow from air conditioner • Dust and dirt
Summer	• Excessive work • Low physical overload	• Crowded workplace • Carpeting • Often reflection or glare in vision • Uncomfortable seating • Computer work • Often use of odorous chemicals[a]	• Varying room temperature • Too dry • Noise • Tobacco smoke odor • Unpleasant other odor[b]
General symptoms			
Winter	• Excessive work • High mental workload • Strong interpersonal conflict • Low job suitability • Low work satisfaction	• Crowded workplace	• Too little air movement • Varying room temperature • Too cold • Too dry • Noise • Dust and dirt • Unpleasant other odor[b]
Summer	• Excessive work • Strong interpersonal conflict • Low job control • Low work satisfaction	• Carpeting • Reflection or glare in vision • Uncomfortable seating	• Too little air movement • Too cold • Too humid • Noise • Unpleasant other odor[b]
Upper respiratory			
Winter	• Strong interpersonal conflict	• Crowded workplace • Installation of bubble jet printer	• Too dry • Dust and dirt • Unpleasant other odor[b]
Summer	• Excessive work	• Carpeting • Uncomfortable seating • Recent painted wall	• Too little air movement • Too dry • Noise • Dust and dirt • Unpleasant chemical odor
Skin symptoms			
Winter	• Low work satisfaction		• Varying room temperature • Too dry • Noise • Airflow from air conditioner • Dust and dirt
Summer			• Too dry • Unpleasant chemical odor

Appendix E: Technical Attributes of Buildings Systems (TABS) Thermal/IAQ and Visual

Recording the technical attributes of the building systems is critical to addressing concerns with measured IAQ and occupant satisfaction in the near and long term.

Thermal & Air Quality TABS: Baseline Physical Attributes/ Quality Differences

by floor or by zone, circle the existing physical attributes affecting user satisfaction and field measurements; if multiple conditions exist, add % of workstations affected by each; add real specifications if available at end of each row

Size of Zone in core (#people/thermostat)	>75 people	25-75	15-25	10-15	5-10	2-5	Individual control
Core System Type Yr major maintenance_____	Package unit	VAV	CV	VAV w/terminal reheat	mult. mixing boxes	Local a.c.	Separate thermal and ventilation/ UFA
Core: Level of Control for open workstations	Hidden thermostat	Locked but visible thermostat with setpoint	Locked but visible with setpoint & status		Accessible thermostat with setpoint	Accessible thermostat with setpoint & status	Individual or Group temp/volume control Air: direction/ speed control
Core: Level of Control for closed offices/meeting	Hidden thermostat	Locked but visible thermostat with setpoint	Locked but visible with setpoint & status		Accessible thermostat with setpoint	Accessible thermostat with setpoint & status	Individual or Group temp/volume control Air: direction/ speed control
Diffuser density	>5 occupants per diffuser	3-5 occupants per diffuser	2 occupant per diffuser	1 occupant per diffuser	2 diffusers per occupant	>2 diffusers per occupant or 2 relocatable	
Diffuser alignment	Poor alignment,high panels, cluttered	Poor alignment, med panels, cluttered	Poor alignment, low panels	Good alignment,high panels, cluttered	Good alignment, med panels,	Good alignment, low panels	Occupant relocatable, UFA
Perimeter System Type: Yr major maintenance_____	Central control, entire facade	Central control, multiple facades	Central control, multiple units	Central control, indiv. units	Local control, 2-3 shared	Local control, indiv.	Separate thermal & vent. & indiv. control
Seasonal switchover	Set days fall and spring	As needed, <4 per year		Whole bldg, as often as needed	Each zone, as often as needed	Each zone continuous control	Each occ. continuous control
IAQ/OA mgmt Dehumidification Y/N Floor by Floor AHU: Y/N Age of AHU: Economizer: Y/N	No OA		10 cfm/person		20cfm per person		30cfm per person
	No filter	<80% filter	80% filter	85% filter	90% filter	95% filter	>95% HEPA filter
		Spray humidification	Steam humidification	Electrostatic humidification		CO_2 sensors/+ central OA control	CO_2 sensors/ local OA control
Return air density	<1/100	1 per 25-100		1 per 10-25		1 per 5	1 per person
Dedicated exhausts	No dedicated spaces or Exhausts for copy/kitchen		Some dedicated spaces no Exhausts for copy/kitchen		All dedicated spaces, some with exhausts for copy/kitchen		All dedicated spaces with exhausts for copy/kitchen
Level of maintenance HVAC system	rare maint.	maintenance as needed	2-3 years	annual maint.	annual maint w/ EMCS monitoring	Annual Cx Commiss.	Continous Cx
Pollution source mgmt	Circle all that apply: No pesticides, low VOC paints, low VOC fabrics/carpets, benign adhesives, remote outgassing, no occupancy w/ dedicated ventilation during renovation, green cleaning products						
	1	2	3	4	5	6	7
Window quality Cold,/heat, air and sun	1 pane			2 panes		3 panes	superwindows
	Leaky/ drafts			mod tight			tight
	No shading, typ E/W	No shading, typ N/S	Low solar t, low views		Low solar t, good views	Group internal shades	Indiv. Internal shades
Window controls % of workstations <20 ft. from window _____%	**% of wall glazed _____%** Circle all that apply: low solar transmission glass, high visible transmission glass, User controls: roller/mesh shades, blackout shades, vertical blinds, horizontal venetian blinds, dominant north & south facing windows, external overhang/awning/trellis, light shelf, operable windows.						

attach peak/ annual energy use y (by fuel type, by end use if submetered), attach complaint data, describe HVAC system

Lighting TABS: Baseline Physical Attributes /Quality Differences

by floor or by zone, circle the existing physical attributes affecting user satisfaction and field measurement s; if multiple conditions exist, add % of workstations affected by each; add real specifications if available a t end of each row

Circle answers for **both** open and closed offices, with annotations if different

Ceiling Fixture Type & Shape ceiling height_____			2 by 2	2x4 or or I / I-D w/ hot spots	1 x 4	I-D w/out hotspots	I-D ambient & task
Ceiling Light Lens Type	Flush/ K-12 prismatic lens	Flush/ K-16 prismatic lens	Large cell parabolic	Small cell parabolic	Medium cell parabolic	I-D in 2x2 or 2x4 inset	
			Specular	Matte	Semi- specular		
Ceiling Light Lamps #/fixture _____, (CRI _______)	Incandescent	T-12		T-8		T-5, CFL	
Ceiling Light Ballast Type	magnetic	hybrid	High-output electronic	Electronic Instant start	Electronic rapid start	Auto-Dimming electronic	User-Dimming electronic
Alignment w/workstations sq.ft./fixture______	<50%	60%	70%	80%	90%	100%	Relocatable ceiling fixtures
Level of ceiling light control	**Select level of control:** Floor by floor only, >10 workstations only, 2-10 workstations only, Individual **Select all types of control available**: on-off, step dimming, continuous dimming, timers, daylight sensors, occupancysensors						
	Identify panel heights: ___% at ___ft., ___% at ___ft. **Identify panel color:** light, medium, dark **Identify level of clutter for ceiling light distribution** (bins, cabinets, high density and misalignment: low clutter, medium, high						
Type of computer screens	Old CRT	Old CRT with polarizing screen	VDT w/polarizing	VDT	Flat screen laptop	Flat screen desktop	Plasma Screen
Task Lights	**Identify number per workstation**: 0, 1, 2, 3, 4 and percent with those numbers **Identify mobility**: fixed underbin, fixed desktop, relocatable desktop, articulated arm desktop, articulated arm and relocatable desktop **Identify ballast/lamp type**: magnetic ballast T-12, incandescent, halogen, electronic ballast T-8, T-5, compact florescent.						
Daylight effectiveness	**percent with seated view of window** _______% **average maximum distance to window** _________ft. **window dimensions**: punched windows, band of windows, curtain wall, curtain wall with clerestory **glass light transmission**: mirror glass, <25%, 25-50%, >50% visible transmission						
Window controls ___# of occupants share?	No controls	Roll-down opaque shades,	Roll-down mesh shades	Vertical Blinds	Horizontal, Venetian blinds,	External shading and internal blinds	light shelf and internal blinds

Watts/sq.ft with tasks lights off ___________ and on _____________

% of workstations with physical indicators of visual concern: taped over light fixtures, light shields, polarizing screens, personal task lights, taped over windows

attach *watts/sq.ft with tasks lights off and on; complaint data, describe lighting system/ specifications*
Measurements to include: Light levels with tasks off and on; brightness contrast; glare; color temperature.

Appendix E: Technical Attributes of Buildings Systems (TABS)
Acoustic and Spatial

Acoustic TABS: Baseline Physical Attributes/ Quality Differences

by floor or by zone, circle the existing physical attributes affecting user satisfaction and field measurements; if multiple conditions exist, add % of workstations affected by each; add real specifications if available at end of each row

#______ open workstations, #_____ closed workstations; #______ open meeting spaces, #______ closed meeting:
#_____open copy _____ kitchen, #_____ closed copy _____ kitchen

Ceiling Height ____ ft & Ceiling quality	Hard surface or open w/out acoustic material	floating acoustic elements	painted acoustic tile	acoustic plaster	metal or wood slats with fiberglass	mineral acoustic tile,	fiberglass acoustic tile
Floor quality	Hard Surface throughout	Carpet in circulation areas		Thin Carpet throughout			Thick carpet w/ padding
Open plan partition thickness & quality		1 inch	1.5 inch	2 inch	2.5 inch	3 inch	4 inch
		Empty inside		Insulation inside			Insulation and foil/board inside
		Hard surface		Perforated surface		Fabric surface	
Partition height inches & number of sides/workstation (note % of each)	No partitions	1 side (heights?____)	2 sides (heights?____)	3 sides (heights?____)	3.5 sides (heights?____)		4 sides w/door (heights?____)
Overhead bins # of sides		0	1	2	3		
closed office/rooms wall quality		Relocatable wall not tight with floor or ceiling	Demountable partition wall, tight with floor & ceiling	Gyp on wood stud, tight w/ floor & ceiling	Gyp on metal stud,tight w/ floor & ceiling	Gyp on insulated stud, tight w/floor & thru ceiling	Fixed, tight with floor and slab above
Size/density of open workstations Gross sqft/wkst ______	< or = to 36 sqft workstation size	<48 sqft	<64 sqft	<80 sqft	<100sqft	<150sqft	>150 sqft
Distributed Noise: % of workstations <20 ft.from open meeting, coffee, copy, main circulation...	>40% of worksta. W/in 20ft.	20-40% of worksta	10-20% of worksta	2-10% of worksta			<2% of worksta
HVAC noise	Low frequency rumble	Noticeable hiss/ squeak/clang/tone	cycling	Even/quiet sound			
Masking Sound Y/N?	Too loud >50dB(A)/	Too quiet <30dB(A)	Noticeably unbalanced				
Office Protocols?	Identify those in practice: no using speaker phones, quiet phone ringers, no using headphones, use of headphones, no conversations adjacent to individual workstation, no interruptions if _______________, other: ____________________						

Spatial/Ergonomic TABS: Baseline Physical Attributes/ Quality Differences

by floor or by zone, circle the existing physical attributes affecting user satisfaction and field measurements; if multiple conditions exist, add % of workstations affected by each; add real specifications if available at end of each row

 # ________open workstations ______vs. #___________closed # __________ open meeting spaces vs. # ________closed / density gross sqft/person _____

Typical open workst. sizes give actual size and % of each	<36sqft eg 6 by 6	<50sqft eg 7 by 7	<64 sqft eg 8 by 8	<80 sqft eg 8 by 10	<100 sqft eg 10 by 10	<120sqft eg 10 by 12	>120sqft
Typical closed workst. sizes give actual size and % of each	<64 sqft eg 8 by 8	<80 sqft eg 8 by 10	<100 sqft eg 10 by 10	<120sqft eg 10 by 12	<150sqft	<200sqft	>200sqft
Partition height (inches) **& number of sides** (note % of each)	No panels	1 sides (heights?____)	2 sides (heights?____)	3 sides (heights?____)	3.5 sides (heights?____)		4 sides w/door (heights?____)
Worksurface and Reconfigurability give % of workstations	<5 feet surface		5-10 ft	10-15 ft		15-20 ft	>20 feet
	______ total # of worksurfaces per average workstation: _____# panel hung, ______# on wheels, ______# freestanding/occupant relocatable, other:						
Storage per workstation (linear feet of shelf, drawer)	<10 ft	10-15	15-20 ft	20-25 ft	25-30 ft	30-35 ft	>35 ft
ergonomic support (>90% of workstations)	Circle # of adjustments: adjustable seat pan height; adjustable lumbar support; adjustable keyboard tray with mouse; articulated keyboard support with mouse pad; adjustable chair arms; adjustable seat pan depth; adjustable monitor ht/direction, ergonomic training/breaks.						
	1	2	3	4	5	6	7
Connectivity/ mobility	Average workstation connectivity available: ______# data, ______# voice, _______# power; wireless throughout building Y/N; wireless on campus Y/N.						
Seated Views	<20%	>20%	>40%	>50%	>60%	>80%	100%
Disruption from Circulation/ Wayfinding	. **Receptionist?** Y/N **Clear Signage for Visitors wayfinding?** Y/N **% of desks visually open to circulation aisles?** (visitors in workers line of sight)						
Group Meeting space	**Floor area** dedicated to shared open and closed meeting spaces ___________sq.ft. __________% of floor For given ___________ # of closed meeting spaces: identify **distribution of sizes**/ # chairs:						
Individual Meeting space	For _________ # of all **workstations**: identify: ________ # with 1 guest chair, _______# with 2 guest chairs, _______# with guest table and chairs.						
Local Kitchen/break areas	identify **# of coffee/refrigerator/break areas** in the following locations: ______# at individual's desk; ______# at empty workstation; ______# in circulation areas; ______# in dedicated open spaces; ______# in dedicated rooms. Of dedicated kitchen/break spaces and/or rooms, identify if break areas include adequate sitting space Y/N; dedicated exhaust Y/N; include windows Y/N;						
Local Copy/printing areas	identify **# of copy/printing areas** in the following locations: ______# at individual's desk; ______# at empty workstation; ______# in circulation areas; ______# in dedicated open spaces; ______# in dedicated rooms. Of dedicated copy/printing spaces and/or rooms, identify if break areas include adequate material layout space Y/N; dedicated exhaust Y/N; windows Y/N;						
Quality of Finishes and Furnishings	Very ragged, dirty, and moldy	Very ragged, dirty,	Old, worn, not especially clean	Old, worn, but clean	Relatively new, clean	New, cheap quality, flimsy	New, high end quality
Building amenities	**Circle amenities** within building or 3 blocks walk: cafeteria, gift store, gym, daycare, café, travel office, dry cleaning, bank, free parking, eldercare, outdoor break/work areas, other:						
	none	Cafeteria only	3	4	5	6,	>7 includ daycare

Chapter 5

Research for Improving Room OA and Equivalent Clear Air (ECA)

Background

Even if a central AHU is ideally controlled for outside air (OA) intake, filtration and delivery, the actual delivery of ventilation air in each zone can be a mystery. The open questions are:

1. How much OA breathing air has reached the zone and each diffuser?
2. Is zone cfm (l/s) or air change rate (ACH) an indication of OA delivery?
3. Is the quantity of OA still matched to occupant density in the zone or room?
4. Is the OA still adequately filtered?
5. Do the supply and return air diffuser design and location affect the delivery of filtered breathing air to each occupant without room contamination?
6. Is the room and furniture configuration compromising the delivery of the filtered breathing air to each occupant?

If the HVAC system combines thermal and ventilation into a single supply air duct that is then controlled by thermostats at the zone level, the quantity of ventilation air may depend on thermal demands for cooling or heating – which are highly variable. The combined thermal and ventilation systems are typically sized to meet the cooling demands of spaces, often ten times the ventilation demand, with outside air percentages set to meet expected occupant density in each zone. For ventilation guarantees, most HVAC systems have a requirement for minimum damper positions at the zone level to ensure OA breathing air delivery, using air volume control or electric resistance or water-based terminal reheat to avoid overcooling spaces - often necessary given the cooling-centric supply air temperatures from the air handling unit.

The combination of several damper positions – outside air damper, return air damper, mixing damper, and zone damper – should provide an indication of outside air delivery to each zone relative to the 'design' area served and occupant density. However, standard and affordable techniques for measuring the effectiveness of room or even workstation air delivery are critically needed. Today's field research standard is using tracer gas to follow the supply air, techniques that cannot be readily applied for a widespread ventilation effectiveness measure. CO2 sensors in the room or in the zone return air have often been used as a marker for OA ventilation effectiveness at the room or zone level, with thresholds of 600, 800, or 1000 ppm deemed critical for human health and productivity (see chapter 4). CO2 sensors do not assess outdoor or room generated contaminants beyond CO2, leaving undetected levels of PM2.5, viruses, VOCs, mold, and more – that might demand higher ventilation rates.

Researching Zone or Room OA Solution Sets

With the challenge of rapid SARS-Covid transmission in occupied spaces, a number of critical solution sets have emerged for improving IAQ at the zone, room, and workstation level. With a large portfolio of buildings that have diverse HVAC configurations and controls, GSA has the potential to demonstrate and quantify the effectiveness of these solution sets:

1. Smaller zone sizes with managed occupant densities.
2. Rapid repair of zone or terminal unit faults (FDD) related to ventilation delivery.
3. CO2 driven ventilation supply rates in each zone or rooms that have supply air dampers (updating thermostats to thermal+CO2 sensors).
4. CO2 + PM2.5 + other contaminant driven ventilation supply rates in each zone or room that has supply air dampers (updating thermostats to thermal+IAQ sensors).
5. In room HEPA filters to address PM2.5 and other contaminants to achieve equivalent clean air change rates (ECA) rather than increasing OA – at various locations and densities.
6. Ceiling based UVGI to address contaminants to achieve ECA air change rates rather than increasing OA – at various locations and densities.
7. Separating ventilation delivery from controls for thermal conditioning - through terminal heating/cooling systems and dedicated outside air (DOAS).

Selecting a set of GSA buildings for Zone OA Studies

The following sections outline baseline measurements and three different interventions that can be evaluated through field studies in federal facilities - next generation thermostats, in-room HEPA and UVGI filters, and separate DOAS plus heat pump retrofits integral with building electrification. The selection of GSA buildings for these interventions may need to represent:

- Variations in HVAC zone delivery configurations
  (terminal reheat/recool, DOAS, large vs small zones etc)
- variations in climate zones
- variations in central AHU OA rates, known High and Low OA buildings
- AHU with economizer, as well as energy recovery, offering increased OA
- variations in terminal unit design and FDD concerns

5.1 Measure the State of the Room: Baseline IAQ measurements of zone/room/workstations with comparisons to calculated OA delivery

NIH differentiates air exchange efficiency - how efficiently the fresh air is being distributed in the room - from ventilation effectiveness - how efficiently the airborne pollutant is being removed from the room. The question is whether existing HVAC configurations and operations are ensuring adequate OA quantities given the distribution paths, diffuser locations, and furniture configurations in conditioned zones and effectively removing contaminants of concern.

The hypothesis that '*existing OA sensors, fan speeds, and damper controls in both the central AHU and in the zone are adequately ensuring OA delivery for each occupant and removing contaminants of concern'* needs to be confirmed in multiple zones across different configurations in a number of buildings. The impact of OA damper positions, ducted distances, zone size, damper, and diffuser locations and types, and workstation layout should be assessed as possible across existing building configurations, comparing actual to calculated OA supply.

Research #5. Field research in federal buildings should explore the use of existing distributed continuous CO_2 sensor data to estimate the ventilation OA and equivalent air change rate per zone and per person, adding additional sensors or engaging occupant centric sensors where data is too sparse to establish the baseline ventilation OA rate and contaminant removal to establish the 'State of the Room'.

There are only a few methods for testing air exchange and/or ventilation effectiveness, most notably through 'cfm' or ACH calculations or through tracer gas testing, both to be discussed further.

Calculated Ventilation Effectiveness

In the past year, the CDC has recommended 5 or more air changes per hour (ACH) of 'clean' air to help reduce contaminants such as SARS-Covid in the air. This can be achieved through any combination of outdoor air, 'clean' recirculated air from central ventilation systems, natural ventilation, or additional devices that provide equivalent ACH (eACH†) to the existing ventilation (https://www.cdc.gov/coronavirus/2019). To calculate the ACH (or eACH):

1. Determine (or measure) the airflow through the system in cfm.
2. Determine the area of the room = length (ft) x width (ft)
3. Determine the height of the room (ft).
4. Calculate ACH = cfm × 60 min/hr divided by Area×Height
5. When multiple strategies are used, repeat the ACH calculation for each system, then add them together for a total ACH value (which could be compared to the minimum 5 ACH recommendation)

While these calculations quantify the overall flow of air in the room, they do not calculate the percent of that flow that is outside air, which may still be set to minimums. While ‘clean air’ exchanges might be invaluable to the dilution of indoor pollutants, they do not guarantee the delivery of outside air that is needed for oxygen to breathe. The assumption is that the cfm (l/s) of air arriving in a room or zone has the necessary minimum component of outside breathing air for the occupant densities, based on the position of the OA/SA dampers and the zone damper relative to the overall flow.

These calculated OA quantities could be compared to existing AHU configurations and operational setpoints, building zone sizes, and diffuser configurations, alongside metrics of satisfaction, health, and IAQ (see Chapter 4).

Tracer gas decay testing of ventilation effectiveness

An alternative method for testing air exchange efficiency and/or ventilation effectiveness is the Tracer Gas method, injecting an amount of tracer gas into the indoor environment and after a mixing period, measuring the tracer gas concentration *decay* due to ventilation and air exchange. The decay rate of the tracer gas can be used to estimate the air change rate of the space.

The tracer gas decay method is based on the mass balance equation of the tracer gas in the air written as

$$V\frac{dC_t}{dt} + Q\left(C_t - C_{outdoor}\right) = 0$$

$$\lambda = \frac{Q}{V}$$

V is the room volume, C_t is the tracer gas concentration minus the outdoor concentration of that tracer gas, Q is the airflow rate of the outdoor air, and λ is the resultant Air change rate. The air change rate can be estimated using the concentration of the tracer gas at the start time, and the concentration of the tracer gas at the end time, given the decay duration (Persily, 1988, Laussmann, 2011, Cui, 2015, Allen, 2020).

CO_2 versus SF_6 as Tracer Gas

Sulfur hexafluoride (SF_6) has been the most commonly used tracer gas, but it has serious environmental constraints since it stays in the atmosphere for 3,200 years (EPA, 2023). As a result, CO_2 is now the preferred choice for estimating air change rates in indoor spaces due to its natural presence, ease of measurement, and lower cost. In a 2016 experimental study, Edouard et al. compared the estimated ventilation rates based on CO_2- and SF_6-based tracer gas methods in naturally ventilated dairy barns. Both methods for estimating ventilation rates gave similar results, only 10-12% lower with the CO_2 mass balance method than SF_6-based measurements (Edouard et al 2016).

After the selection of the tracer gas to be injected into the room supply air stream, the location of the sensors measuring decay must be established. In a 2009 lab experimental study, Van et al. placed 37 CO_2 sensors in different positions in the test room, revealing that the measurement errors can be as large as 86% of the actual ventilation rate (fig. 5.1). This study identified that the best position for tracer gas sampling may need to include both supply and return air diffusers, although return air locations gave measurement errors within 10% of the reference value (Van Buggenhout et al 2009).

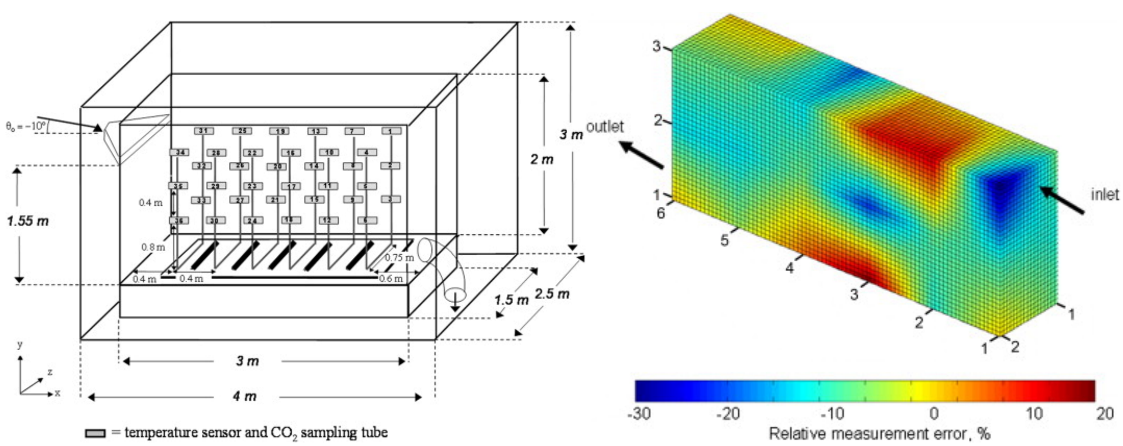


fig. 5.1 The 3D configuration of 37 temperature and CO_2 sampling tubes in the test chamber (left) and 3D representation of the distribution of the relative error on the actual ventilation rate for a ventilation rate of 18 air changes h^{-1} (right) (Van Buggenhout et al 2009).

Using Occupant-Generated CO_2 as the Tracer Gas

Instead of injecting tracer gas into an occupied space, the actual increase of the concentration of the CO_2 generated by people in the room can be treated as the injection of tracer gas. After the occupants leave the study zone, the decay period of the CO_2 concentration can be used to calculate the air change rate from continuously recorded CO_2 sensor data.

In a 2002 experimental study, Claude-Alain et al. used the continuous zone CO_2 records to calculate the air change rate and compared the results with the tracer-gas decay method using SF_6, with a difference of less than 2% (fig. 5.2). This experiment was confirmed in 2018 by Nowak (Claude-Alain 2002, Nowak 2018).

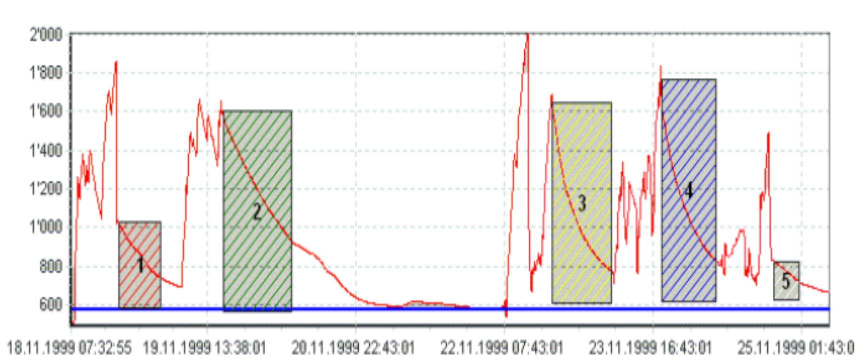


Figure 3. Records of carbon dioxide concentration in another office room in the LESO building

fig. 5.2. In 2002, Claude-Alain demonstrated that the Air Change rate (ACH) can be calculated by assessing the decay of CO_2 during periods of no occupancy (1-4).

In a uniformly ventilated area with consistent CO_2 levels, ventilation rate and CO_2 concentration maintain steady-state conditions, assuming a constant CO_2 generation rate (from people), HVAC ventilation rate, and outdoor CO_2 concentration throughout the analysis period of mass balance.

The steady-state equation can be written as:

$$Q_0 = \frac{10^6 \times G}{C_{in,eq} - C_{out}}$$

Q_0 = outdoor airflow rate into the zone, L/s
G = CO_2 generation rate in the zone, L/s
$C_{in,eq}$ = equilibrium CO_2 concentration in the zone, ppm
C_{out} = outdoor CO_2 concentration, ppm

The equation can also be written in terms of the outdoor airflow rate per person by dividing the number of people on both sides of the equation. In this case, the outdoor airflow rate per person can be calculated by the equation below:

$$Q_p = \frac{10^6 \times G_p}{C_{in,eq} - C_{out}}$$

Q_p = outdoor air flow rate per person into the zone, L/s per person
G_p = CO_2 generation rate in the zone per person, L/s per person
with adult at 1.2 met CO_2 generation estimated at 0.0052 L/s (ASTM 2012)

This occupant-generated CO_2 steady-state method has been used in a number of studies to ascertain CO2 rate of change post occupancy.

*In a 2013 two-year study of 28 schools in three school districts, Mendell et al. identified that **each additional 1 L/s per person of ventilation rate,** calculated with the CO_2 steady state method in 162 3rd-5th-grade classrooms, resulted in a **1.6% reduction in illness absenc**e ($p<0.05$). They also identified that all school districts had median ventilation rates below the 7.1L/s per person mandated in the California standard. They estimated that increasing classroom ventilation from the average of 4 l/s-person to the State standard would decrease illness absenteeism by 3.4% and increase attendance-linked funding to schools by $33 million annually, at a first cost of $4 million and small annual operations cost.*

In a 2020 study of 94 classrooms in 11 schools, Chan et al. identified that the mean and median ventilation rate per person was only 5.2L/s per person and 4.8L/s per person, respectively, using the ~~post-occupancy CO_2 decay method~~ occupant-generated CO2 steady state method. Only 15% of the classrooms met the 7L/s per person code requirement. They also identified that classrooms with economizer operation had 22.5% lower mean CO_2 concentrations than classrooms with fixed-position ventilators ($p<0.05$), and classrooms with dirty filters had 33.6% lower ventilation rates per person and higher mean CO_2 concentrations on average than classrooms with relatively clean air filters ($p<0.05$).

Using DNA-tagged Tracer Aerosols to Simulate Airborne Transmission

DNA-tagged liquid aerosols is a novel tracer that can be used to simulate pathogens embedded in respiratory particles to indicate airborne transmission rates and paths. The test approach involves a liquid solution with composition similar to respiratory fluid and containing a known concentration of synthetic DNA. After the aerosol is released into the environment, the tracer will be spread and circulated by the ventilation system. The aerosol collected by the air sampling equipment will be measured with polymerase chain reaction (PCR) technology to count the reduction of the DNA-tagged tracers in the air and evaluate the effectiveness of airborne infection isolation. In a 2022 experimental study, Mousavi et al. used DNA-tagged tracer to evaluate the impact of ventilation rate, negative pressure, airflow barriers, and other retrofit measures on bioaerosol concentration and paths in long-term care (LTC) environments. They found that increasing outdoor air change rates from 1 to 6 ACH reduced the time required to remove 99% of infectious contaminants from 3 hour to less than 40 minutes once the infectious source was removed.

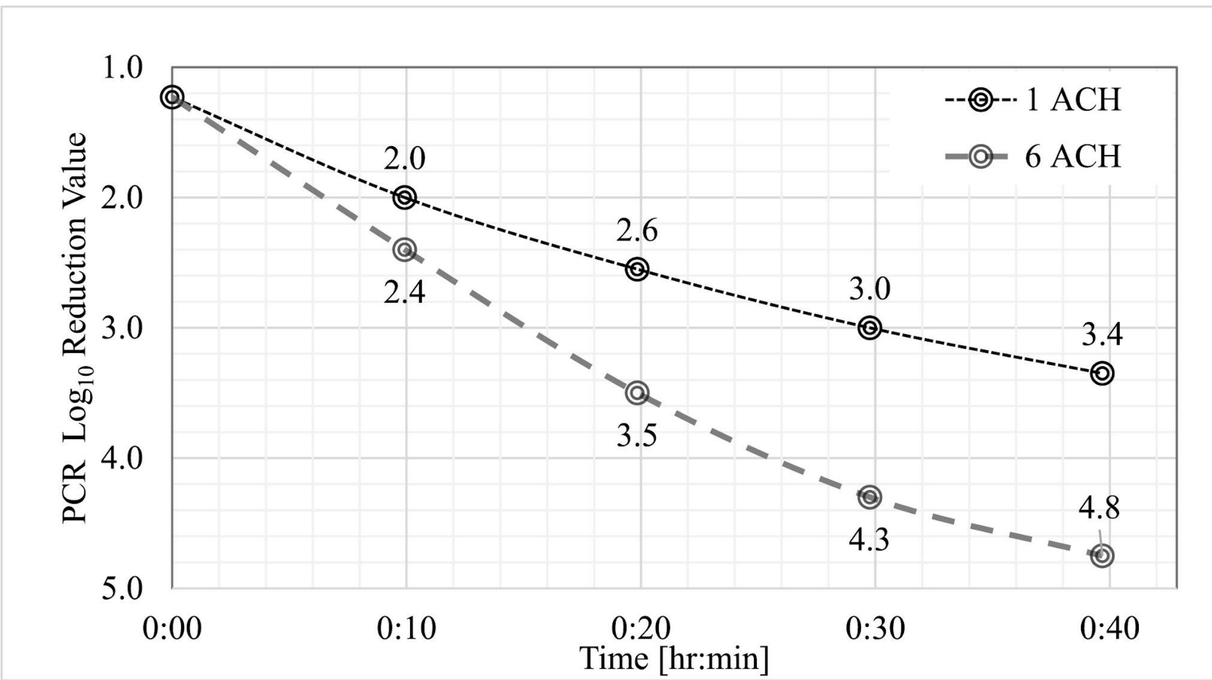


fig. 5.3 Increasing Outdoor Air ACH speeds the 'decay' in Contaminate load (p/L) (Mousavi et al 2022)

Relative to identifying room air change rates in contrast to viral decay, Arvelo et al identified that DNA-tagged liquid aerosol tracers do not match the accuracy of traditional tracer gasses such as SF6 and CO2 A 2022 experimental compared the DNA-tagged liquid aerosol tracer with traditional air change rate measurements across varying air change rates and filter types, concluding that SF6 and CO2 are the most accurate methods for measuring outdoor air ventilation rates.

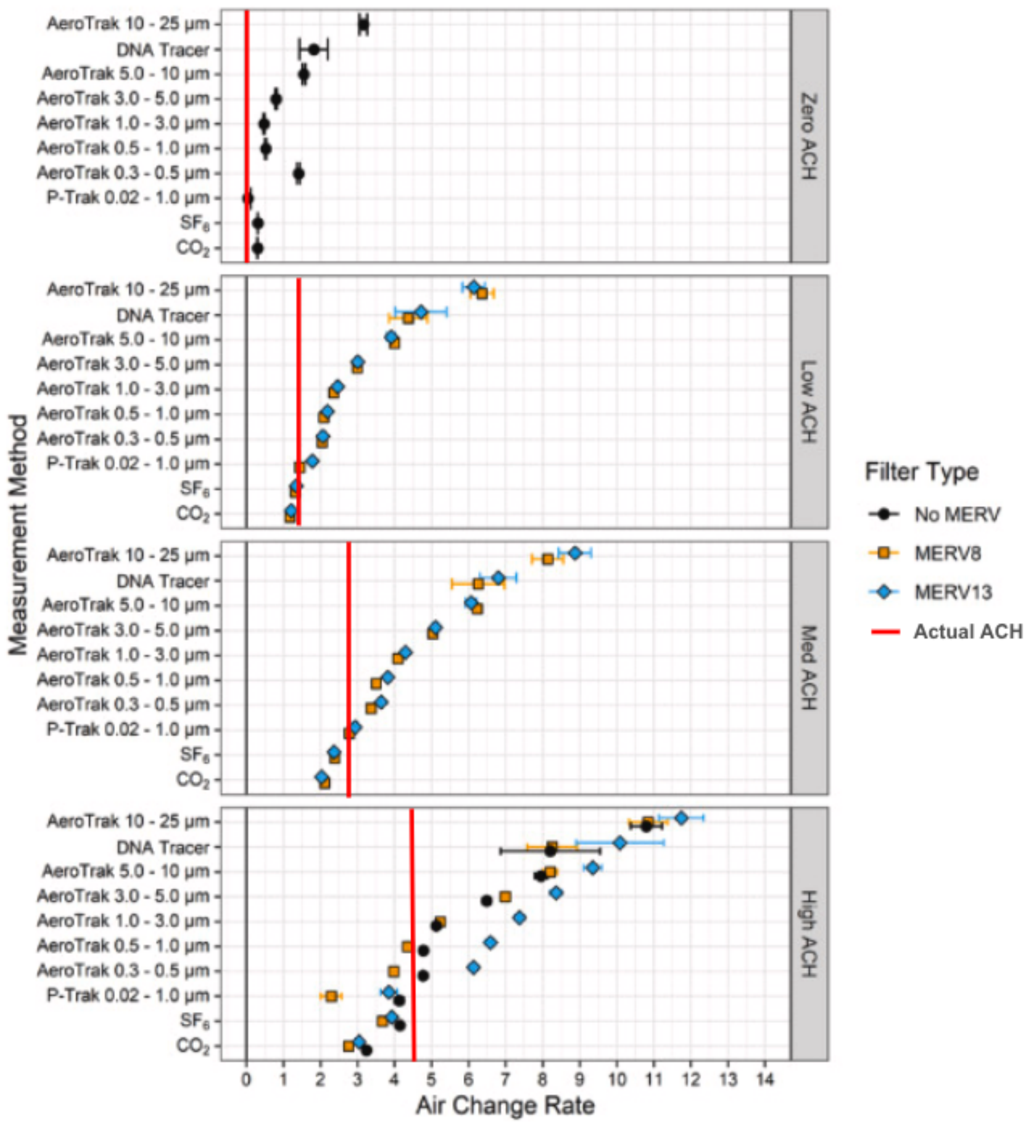


fig. 5.4 The accuracy of average (±95% CI) decay rates measured with tracer gasses (SF6 and CO2), particle distributions (AeroTrak), and DNA tracer concentrations given a range of ventilation rates (Zero, Low, Med, High) and filtration conditions (No MERV, MERV8, MERV13). (Arvelo et al 2022)

These studies reveal a range of approaches to establishing the State of the Room IAQ that should be developed and implemented in large commercial buildings. Baseline research on the State of the Room IAQ is critical to establishing both outside air delivery rates and equivalent air change rates in the diversity of mechanical zones and rooms served in existing buildings. A sampling of different central HVAC configurations, zone sizes, diffuser densities, and controls would yield invaluable insights into the performance of existing HVAC system configurations and operations for delivering ventilation.

5.2 Test the next generation of 'thermostats' in conditioned zones and/or rooms to improve IAQ for health and to save energy.

Temperature-only sensors for establishing ventilation rates (cfm) have driven building controls and are most likely inadequate for ensuring the level of outside air (OA) or air change rate (cfm) needed to deliver breathing air and dilute or extract higher indoor contaminants in each building zone. The thermostat has no measure of air quality and a single variable measure for thermal comfort (dry bulb temperature), yet it continues to dominate the control of HVAC delivery of ventilation and thermal conditioning.

While innumerable research efforts have explored the innovative use of thermostatic data for achieving thermal comfort at the lowest energy demand, very little research has been undertaken as to the use of the thermostat for effective ventilation control. This led to the introduction of CO2 and occupancy sensors in conference rooms and other high occupancy spaces to ensure increases in ventilation rates when needed, and to reduce ventilation when not needed to save energy. These demand controlled ventilation (DCV) sensors may have been overused for energy savings, leaving spaces unventilated for periods of time, leading to ASHRAE, CDC, and GSA recommendations that they be disconnected in times of high health concerns.

Research #6. Field research in federal buildings should initiate a next-gen thermostat research intervention that would compare conventional temperature-centric thermostats with temperature+IAQ sensors (wireless or wired sensor suite) with commensurate improvements to the BAS control of dampers and fans, in side-by-side analyses of IAQ, health and energy outcomes.

Integrating IAQ sensor into the control logic of HVAC system has been experimentally tested in a number of buildings:

> *In an 2020 office study in India, Vadamalraj et al demonstrated that the multi-objective optimization of CO2, occupancy and TVOC to control hybrid ventilation between increased outside air ventilation (DOAS using Renson Healthbox 3.0) and air conditioning, resulted in superior IAQ (CO2 < 850 ppm, TVOC < 1000 ppb, RH 40~60%) with 20% energy savings while keeping temperature within the thermal comfort zone over a 10 day period (fig. 5.6). Soft sensors were also trained by historic sensor data to predict the future IAQ and cooling loads to further the model predictive control.*

fig. 5.5 Device used for Hybrid Ventilation - Renson Healthbox.

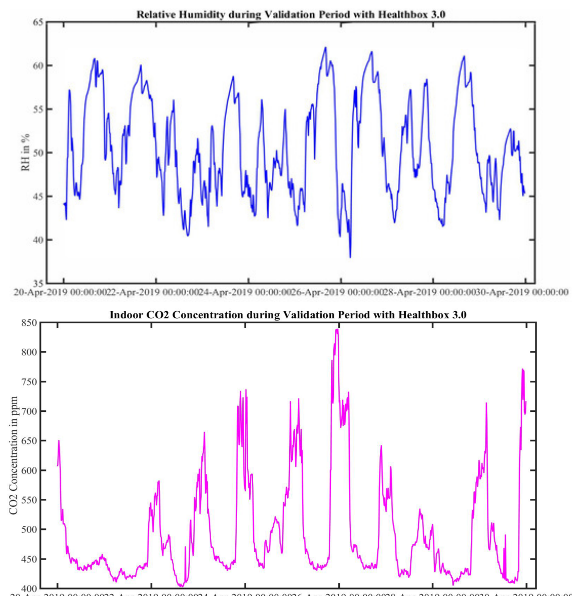


fig. 5.6. Indoor Relative Humidity and CO2 concentration under the Hybrid Ventilation Control.

Moreover, since CO2 can serve as an indicator of occupant density when spaces are underventilated, monitoring CO2 concentration can support the control of contagion risk, adding to the value of integrating IAQ sensors into conventional thermostats.

> *In a 2022 field and simulation study for dynamic occupancies in commercial building spaces, Li and Cai demonstrated a novel CO2-based ventilation strategy to simultaneously adjust zone dampers to maintain CO2 concentration below 600 ppm to reduce the risk of viral infection below an R of 1, while achieving an energy saving of 30%-50% compared to the fixed ventilation approach for three different building types (fig. 5.7).*

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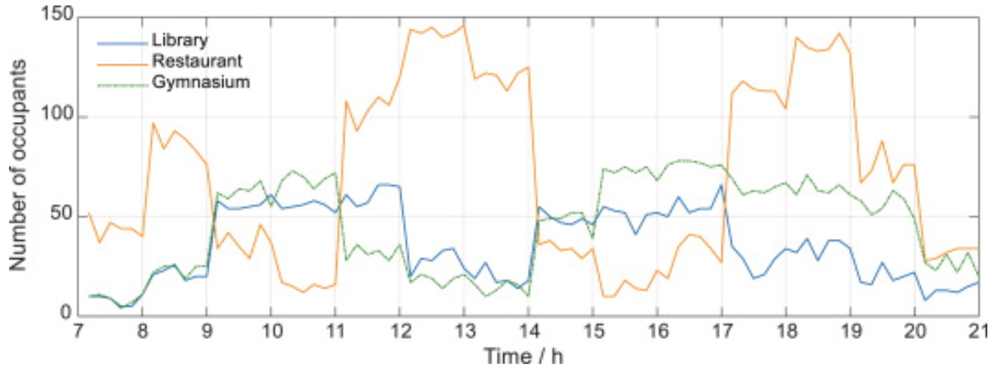


fig. 5.7 Occupancy profiles for the testing scenarios (Li and Cai, 2022).

In this and many other studies, the quantitative relationship between CO2 concentration and air flow rate is evaluated in the Wells-Riley model to calculate a virus risk index R, describing the possibility of virus propagation, where R<1 means the virus is unlikely to spread (fig. 5.8).

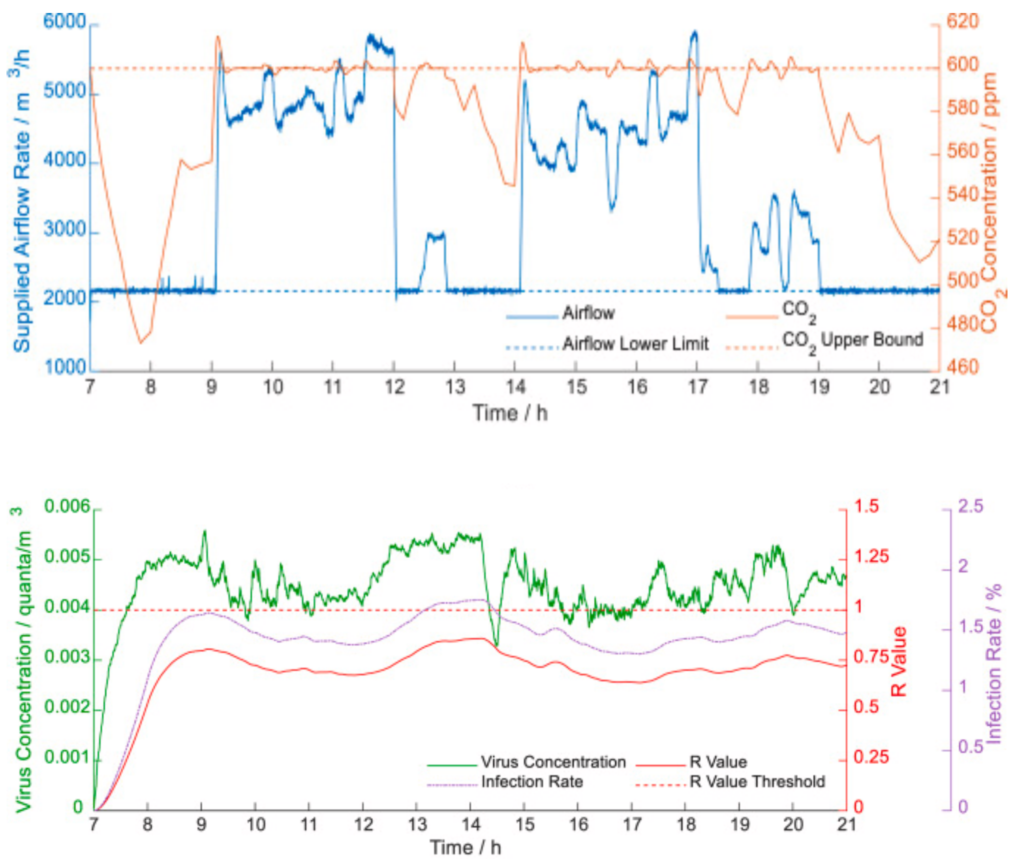
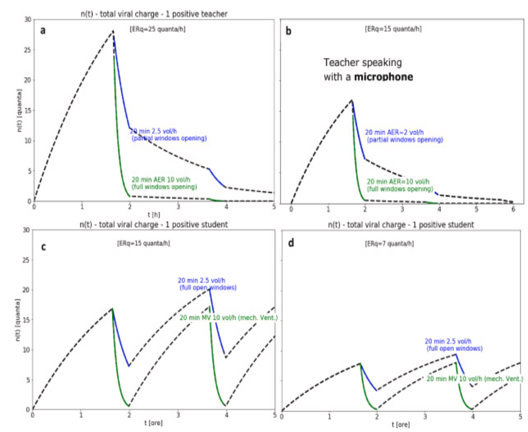


fig. 5.8 CO2 sensor driven control of indoor CO2 reduces infection rates (Li and Cai 2022).

An extension of the Wells-Riley model called Gammaitoni-Nucci Model considers the decay of the viral charge over time and on risk of infection, and has been used to evaluate a number of building design and operational choices, including the value of natural ventilation for risk remediation.

In a 2021 field and simulation study in Italy, Zivelonghi and Lai identified that increasing the natural ventilation rate from 2 air changes per hour to 10 air changes per hour corresponds to reducing airborne risk of Covid-19 from 6.6% to 3.3%, given one infected teacher, or from 5.6% to 3.25% given one infected student in a 170m^3 classroom. If teachers' used microphones, airborne risk was further reduced to 1.6%, and if students spoke softly airborne risk was further reduced to 1.8%. (fig. 5.9).



Source	Ventilation during breaks [Vol/h]	Source emission timespan [h]	Face-mask effectiveness	$\overline{ERq}_j$ range[quanta h-1]	$\overline{\overline{ERq}}$ [quanta h-1]	R_c (5h)
Teacher	2	2h	75%	1–80	32	6.6%
	10	2h	75%			3.3%
Teacher with microphone	2	2h	75%	0.5–30	16	3.3%
	10	2h	75%			1.6%
Student	2	5h	75%	0.7–60	13	5.6%
	10	5h	75%			3.25%
Student speaking quietly	2	5h	75%	0.2–20	6	3.1%
	10	5h	75%			1.8%

*fig. 5.9 Natural ventilation reduced airborne risk by 13.3% in winter and 3.3% in summer compared to mechanical ventilation,
further reduced by the use of microphones or quieter speaking.*

While the next-gen IAQ-thermostat could inform the operation of the central AHU and zone dampers, these sensors could also control devices in the occupied space, such as air purifiers to maintain good indoor air quality.

In a weeklong field study in China in 2017, Yang et al identified that a WiFi-enabled zone PM2.5 monitor could control the fan speed of a local HEPA filter unit to maintain PM2.5 concentrations below a setpoint of 40~50 μg/m3 as compared to 175 μg/m3 in the same zone before the PM2.5 sensor or local HEPA unit was operated (fig. 5.10).

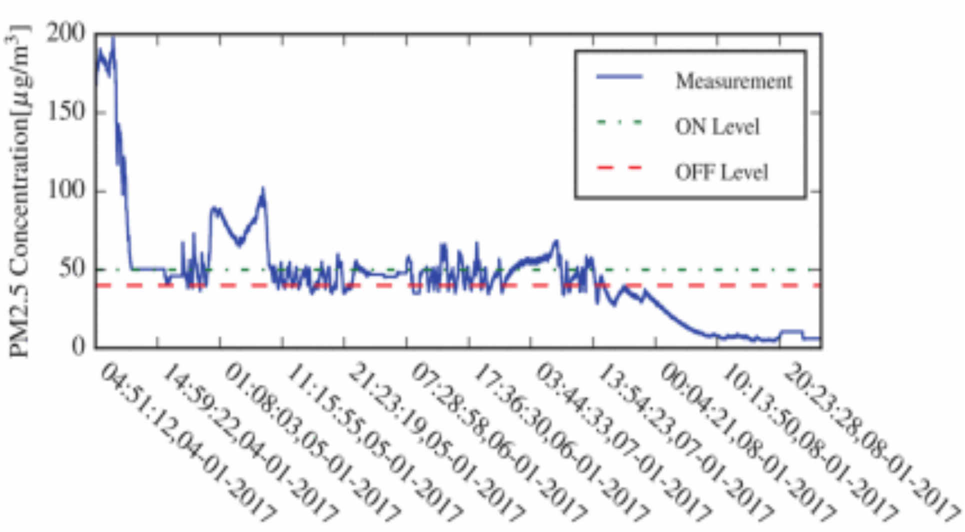


fig. 5.10 Indoor PM 2.5 Sensors used to control room HEPA filters.

What to incorporate into the Next Gen Thermostat

There is an emerging body of literature demonstrating that IAQ measurements, including CO2, PM2.5, and TVOC can advance HVAC control for improving indoor air quality, health, comfort, and energy efficiency. Deciding on the exact suite of sensors to include in the next gen thermostat requires further evaluation relative to cost, robustness, and prioritization of human health outcomes.

In a 2023 Master of Science in Building Performance and Diagnostics thesis, Yunhao Hu evaluated the range of manufacturers that have developed IAQ sensor suites to capture sensor types, range and error of measurement (fig. 5.11, Hu 2023). In almost all cases, these sensor suites have not been integrated into the building automation system although they often have wifi or cellular capability to communicate with BacNet.

Company	Product	Temp	RH	TVOCs	CO2	PM2.5	PM10	CO	Ozone	HCHO	Occup.
ecobee	Smart Thermostat Premium	■	■	■	■ (blue)						■
Kaiterra	Sensedge Mini	■	■	■	■	■	■		■		
	Sensedge	■	■	■	■	■	■				
Awair	Omni	■	■	■	■	■					
Airthings	Space Pro	■	■	■	■	■					
	Space CO2 Mini	■	■		■	■					■ (blue)
Honeywell	C7355A	■	■	■	■	■	■				
	C7355B	■	■	■	■	■	■				
	TR50	■	■	■	■	■	■				
Aircuity	various	■	■	■	■	■		■			
PurpleAir	Classic	■	■			■	■				
	Touch	■	■			■	■				
	Flex	■	■			■	■				
	Zen	■	■			■	■				
uHoo	Aura	■	■	■	■	■	■	■	■	■	
Breathforce	NANO	■	■	■	■	■		■	■	■	
	OPC	■	■	■	■	■					
	ORI	■	■	■	■	■			■		

fig. 5.11 Range of pollutants/contaminants captured by Integrated IAQ Sensors Currently on the Market (Blue cells refer to virtual sensors, which calculates the item from other measured metrics using estimation algorithms).

Research on the IAQ value of next-gen thermostats could be undertaken in partnership with several leaders in remote sensing, comparing next-gen thermostatic control of HVAC with temperature-only control in multiple zones of fully occupied federal buildings (fig. 5.12). The diversity, sensitivity and reliability of sensors to be incorporated into the next-gen thermostat is a critical research question, weighed against known health risks of those contaminants or conditions, known actions to reduce those contaminants or conditions, as well as the cost and maintenance involved. The short list might include temperature, CO2, PM2.5, TVOC, RH and occupancy, but must be based on long term field testing of the sensor suite, matched with the thresholds of concern, and the success of facility management actions that can be successfully undertaken.

fig. 5.12 Examples of Integrated IAQ Sensors on the Market (clockwise from top left: Ecobee Thermostat Premium; Awair Omni; Airthings Space Pro; Kaiterra Sensedge).

In addition to next-gen thermostat+IAQ sensors, there is potential for in-duct sensors for monitoring IAQ at the AHU level. Building occupants may also begin to acquire their own IAQ sensor suites - wearable sensors or smart phone and laptop connected sensors. The potential to engage these sensor readings as well as occupancy locations and densities should be embraced.

In a 2023 field study of 18 workstations in an office building, Nojedehi et al. identified that improving the FDD algorithm for airflow and air temperature faults with wearable devices monitoring CO2 concentrations to adjust the K-factor of the VAV box (+/-30%) reduced CO2 concentration by 10% and reduced thermal discomfort 29%.

5.3 Invest in Zone Equivalent Clean Air (ECA or eqOA) with Local Filtration to improve IAQ and Health - HEPA and UVGI (and coordinate with ASHRAE 241)

Filtered outside air has been the gold standard for providing safe indoor air. However, increasing outside air rates as the critical path to addressing airborne contaminants may have significant energy and carbon costs and may not adequately address person to person infection transfers. As a result, ASHRAE has released an updated Building Readiness Guide to amend ventilation requirements to include increased room air delivery and room filtration in the critical path for addressing breathing needs and airborne contaminants.

- Provide and maintain at least the required minimum outdoor airflow rates for ventilation as specified by applicable codes and standards.
- Use combinations of filters and air cleaners that achieve MERV 13 or better levels of performance for air recirculated by HVAC systems.
- Only use air cleaners for which evidence of effectiveness and safety are clear.
- Select control options, including standalone filters and air cleaners, that provide desired exposure reduction while minimizing associated energy penalties.

These new standards often amend the terms OA, ventilation rate, and air change per hour (ACH) to introduce equivalent clean air (ECA, CADR or eqOA), or equivalent ACH (eACH), to reflect the benefits of filtered recirculated air and in room filtration. At the same time, increasing filtered outside air quantities (OA) to each zone in order to reduce health concerns from indoor contaminants can have energy benefits during the many days when outdoor conditions are favorable. For either outdoor air increases or larger volumes of clean recirculated air, the healthiness of the increased ventilation rates will be dependent on the quality and condition of the central filters, ideally monitored. To augment the increased air delivery rates from the AHU to each zone during periods of high occupancy or high health concern, emerging standards include the addition of zone or in-room HEPA or UVGI filters to reduce indoor contaminants, also measured in the ECA, equivalent clean air, standards.

Research #7: Field research in federal buildings should comparatively assess the IAQ, energy and operational benefits of eqOA delivery with in-room HEPA and UVGI as compared to increased outside air from the central air handler (and possibly operable windows).

In-room HEPA for ECH (eqOA) or eACH

There is a growing body of evidence to support the value of in-room HEPA filters for particulate reduction associated with occupant health. HEPA filters are primarily mechanical filters that physically capture particles rather than killing or inactivating microorganisms so they are less effective at removing bacteria and viruses (microbials) which are much smaller than 0.3 microns. However, reducing particulates is critical to reducing bio-aerosol transmission of these microbials. HEPA filters are also less effective at removing gas pollutants including TVOC and formaldehyde, although HEPA units can include activated carbon filters to capture additional pollutants.

> *In a 2020 field intervention study in South Korea, Park et al. identified that introducing a HEPA air cleaner resulted in 14.9% reduction in PM10 and 18.4% reduction in PM 2.5 concentrations, at the expense of a 15$ per student in first cost increase.*
>
> *In a 2021 field study of a university lab in India, Dubey et al. identified that in-room HEPA AP2 filter (150 m3/h, 30 watts, 20-40 dBA) resulted in 37%, 47% and 54% decreases in PM2.5, PM5, and PM10 respectively ($p<=0.1$, $t=6h$), as well as a 53.7% decrease in estimated human health risk under general indoor air conditions.*
>
> *When in the presence of an introduced pollutant source (candles and incense smoke), the HEPA AP2 also resulted in 52% and 60% decrease in ultrafine PM 0.25 and PM 0.5 ($p < 0.05$, $t = 6h$) as well as 66% decrease in estimated human health risk. Non-carcinogenic risk (posed by PM10) was estimated by Hazard Quotient (HQ) similarly to Morakinyo et al. (2017) and carcinogenic risk (posed by PM2.5) was estimated with Excess Lifetime Cancer Risk (ELCR) similarly to Kim et al. (2018).*
>
> *In a 2021 meta-analysis study of a hospital building, Dai et al identified that HEPA filter reduced indoor bioaerosol concentrations of bacteria by 113.13 (95% CI: -197.89, -28.38) CFU/m3 and fungi by 6.53 (95% CI: -10.50, -2.55) CFU/m3. Meanwhile, the indoor bacterial concentration of LAF systems decreased by 40.05 (95% CI: -55.52, -24.58) CFU/m3 compared to that of conventional HVAC systems.*
>
> *In a 2021 tracer gas (sodium chloride) study in classrooms without natural ventilation at the University of Southern California, Aldekheel et al. identified that in addition to the MERV 13 filter already installed in the AHU (achieving a 55%*

PM2.5 reduction), installing a H13 HEPA in-room purifier further improved the PM2.5 filtration efficiency by 7.38% when the flow rate of the in-room purifier is 267m3/h and by 41.35% when the purifier was operated at 748 m3/h. (this suggests the benefits of using variable fan speeds for HEPA units in periods of high occupancy).

In a 2023 intervention study in an office in Beijing, Zhou et al. identified that introducing an in-room HEPA filter at each desk resulted in a 79.4% decrease in PM2.5 concentration (from 18 to 3.7 µg/m3, $p<0.05$), a 7.3% increase in employees' cognitive performance at memory tasks, and a 8.2% increase in employee's perception of cognitive performance ($n=55$, $p<0.05$). This was achieved with a $400 Atem Desk Air purifier from Switzerland, delivering customizable clean air delivery rates (from 4 to 66 m3/h), at 35dB and 1.5-3.4 watts of energy use per hour.

This body of research on the success of HEPA filters has also revealed the importance: of well-located units (eg. on the desk surface, at distributed points in the room); of acceptable wattages at different fan speeds (1.5, 1.9, 3.4 Watt corresponding to 8, 15, 30, 66 m3/h fan speed, with standby: < 0.5 Watt); of acceptable purchase and maintenance costs per unit; and of minimized noise disruption with 35 dbA limits.

In-Room UVGI for ECA (eqOA) or eACH

In-room HEPA filters offer substantial reductions in particulate contaminants but are not effective as removing gas pollutants (such as TVOC, formaldehyde) unless activated carbon filters are also included, or microbials, unless UVGI is included in the unit. In-room UVGI units may have a critical contribution to make for reducing microorganism concentrations, including mold, viruses and bacteria, both in bio-aerosols or surface contamination, albeit at higher first costs and operational energy costs.

In a 2017 field study of two classrooms with mechanical ventilation in the U.S Midwest, Su et al. identified that installing four upper-room UVGI units on the four walls of each classroom (2.4 meters high for safety) resulted in a 9.1% decrease in fine fluorescent bioaerosol counts (FBCs <3 µm)) and a 2.7% decrease in coarse FBC (>10µm) ($p<0.05$, t=20 days), with 36 watt demand for each UVGI unit (published in Kowalski 2010).

In a 2022 controlled study in 10 commercial buildings, Lee et al. identified that installing ceiling-mounted UVGI units for each 32 m3 (370 sqft) of space achieves an average of 73% reduction of total airborne bacteria (with a range of 71-88%) and an average 55% reduction of non-high tough surface bacteria (with a range of 28-88%) (both $p<0.0001$).

In a 2023 field study of an Iowa State teaching classroom with poultry and mechanical ventilation (at 2.09 m3/h), Li et al. identified that introducing an in-room air cleaner with UV lamps resulted in a 55% reduction of total suspended particulate (58% for PM1, 58% for PM2.5, 57% for PM4, and 56% for PM10) and a 46.8% reduction of daily airborne viable bacteria concentrations ($p<0.05$, t=25 days), with the penalty of an estimated $446 annual electricity cost and an estimated $760 annual part replacement (UV-C bulbs, filters, etc.).

In a 2023 intervention study in 3 oncology clinic rooms, Knobling et al. identified that introducing UV-C units resulted in a 54.8% - 75.7% decrease in the mean pathogen concentrations of different parts of the patient examination chair. The authors also identified that manual disinfection with alcoholic wipes resulted in a 71% - 100% decrease in pathogen concentrations on the examination chairs.

However, introducing UVGI alone can sometimes lead to unwanted IAQ effects relative to particulates and VOC's.

In a 2023 experimental study of an aerosol physics laboratory with mechanical ventilation in Finland, Graeffe et al. identified that introducing a 2 kW UVC disinfection device resulted in a more than 45 times increase (from 1000 cm3 to between 45,000/cm3 and 160,000/cm3) in PM concentration and 80% increase in VOC concentration.

In a 2023 experimental study of a 150 L experimental chamber in United States, Barber et al. identified that introducing a 11 W 222 nm UVGI unit resulted in a 27.3% and a 50% decrease in hexanal concentration and cyclohexene concentration, respectively. However, ozone concentration increased from almost 0 to 103 ppb at 3.1 ACH, 119 ppb at 2.6 ACH, and 206 ppb 1.3 ACH, during 100 min of operation after which the ozone concentration eventually leveled off to a steady state, which all exceed the healthy standard of 70 ppb.

To avoid the drawbacks of UVGI and maximize indoor air quality, it may be critical to combine the benefits of in-room HEPA air cleaners and UVGI. There are a number of different configurations for in-room UVGI - above ceiling with fan; floor, wall or ceiling mounted with convective air flow; and UVGI integrated with HEPA filters (fig. 5.11).

fig. 5.11 Examples of room UVGI configurations: in-ceiling with fan, wall or floor mounted, and integrated into the HEPA filter unit (Iris, rZero, Puraclenz).

The effectiveness of air cleaning devices is also highly dependent on the clean air delivery rate, cycling, and placement of the UV filters. Newly developed UV sensitive aerosols, that might be mapped to pathogens, and dilution tests would be needed to evaluate the impact of the combined eqOA with room HEPA and UVGI filters.

This ‘OA versus ECA’ intervention research effort would compare increasing the outside air quantities in room air change rates versus keeping OA at code minimum but adding local HEPA filters for every 2 occupants in side by side analyses, then in-room HEPA plus UVGI, with measurements of IAQ, health and energy outcomes. UVGI to date is best suited for filtration at the AHU as a tool for microbiologically healthy indoor air but deployed along with good ventilation, not in substitution for ventilation. Further study of room UVGI alone (or in combination with HEPA air filters) is needed to understand safe exposures and measured effectiveness for addressing contaminants of concern such as respiratory droplets. This research should be coordinated with ASHRAE 241 to quantify the health benefits of ECA or eACH.

Operable Windows: Evaluating Biophilic Approaches to Improving Room IAQ

In addition to expanding economizer operations to increase actual outside air contributions to zone IAQ and occupant health, there is also research linking natural ventilation with employee health in commercial buildings. Operable windows offer the potential for significant increases in outdoor air exchange especially when outdoor temperatures are lower than indoor setpoints. Since outside air may contain contaminants of concern during various periods of the year, the addition of natural ventilation for commercial buildings should be integrated with the mechanical ventilation and thermal conditioning systems - into mixed mode systems (https://cbe.berkeley.edu/research/mixed-mode-building-research/).

In a 2003 cross sectional study of 2 office buildings in downtown Rio De Janeiro, Brazil, Rios et al identified that naturally ventilated office buildings resulted in an 18.6% reduction in eye dryness, a 16.1% reduction in runny nose, a 14.3% reduction in dry throat, and a 13.7% reduction in lethargy, as compared to sealed office buildings. ($p<0.05$, $n=3686$)

In a 2004 multiple building study in France, Preziosi et al identified that natural ventilation in the workplace resulted in a 57.1% reduction in absenteeism, as compared to workplaces with mechanical air conditioning. ($p<0.001$, $n=920$)

In a 2023 intervention study of an office building in Beijing, Zhou et al. identified that mixed-mode ventilation resulted in a 79.4% reduction in PM2.5 concentration level (from 18.0 to 3.7 with air purifiers), a 14.6% increase in perceived productivity, and a 25% increase in air quality satisfaction ($p<0.01$, $n=55$).

Since GSA has a large building portfolio, it should be possible to undertake field measurements of zone IAQ and human health indices in both sealed and naturally ventilated workspaces in the same cities as well as sunny and non-sunny spaces in the same building. Additionally, it may also be possible to study the effects of sounds of nature in naturally ventilated workspaces with operable windows as compared to those without. It may also be possible to study spaces with substantial greenery added and those without - to begin the quantification of the benefits of biophilia to human health and performance in the workplace.

In a 2018 lab experiment of 11 built microcosms at the University of Oregon, Fahimipour et al identified that the presence of daylight and sunlight in a microcosm (through windows) resulted in a 5.9% reduction of viable bacteria over a 90-day experiment as compared to a windowless microcosm. ($p<0.001$).

In a 2011 field study of 12 office buildings in Seoul, South Korea, Kim et al identified that the addition of indoor plants (1 large + 12 small per room) in newly built buildings resulted in a 33.1% reduction in formaldehyde ($p=0.01$), a 79.5% reduction in toluene ($p=0.01$), and a 79.6% reduction in xylene ($p=0.05$) over a 6-month period as compared to an office with no indoor plants.

In a 2021 lab experiment simulating an open-plan office environment, Zhang et al identified that introducing a spring water masking sound condition at medium SNR (4.4dB) by loud speaker to an office with noise levels of 31.8 dB resulted in a 10.3% increase in cognitive task accuracy rates ($p<0.05$) as compared to an unmasked 'speech only' condition. (n=30, t=7 days x 2 measurements)

Chapter 5 Zone OA and ECA References

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Chapter 6

Research for Improving Central AHU Outdoor Air Quantity, Filtration and Delivery

After KPI's for O&M and improving room eqOA, the third area of critical research is to improve the quantity and quality of outdoor air (OA) delivered from each air handling unit to the occupied zones served. This research could help to address a number of concerns:

- The method of measuring the quantity of OA intake and delivery from the AHU, and to the zone is not adequate.
- Outside air sensors, actuators, dampers and software are not robust, data quality is suspect and there are too many damper failures.
- The FM team does not have adequate training in outside air hardware and software; OA during the very cold or hot seasons may be below ASHRAE 36 minimums.
- Unbalanced systems may not deliver OA equally across zones, especially with density changes.
- Economizers have mixed success, mixed standards of operation, and incomplete metrics of performance that focus on energy rather than air quality.

Given limitations in budgets, manpower and even access, central air handlers can introduce a number of air quality concerns, ranging from inadequate fresh air intake given damper operations, to fouled filters, drip pans and duct lining. Most of these concerns can be met by improvements in operation and maintenance, hopefully spurred by the development of KPI's outlined in Chapter 4. However, three research efforts could definitely demonstrate the value of increasing outside air quantities, improving filter quality, and introducing dedicated outside air for improving IAQ for occupant health and performance.

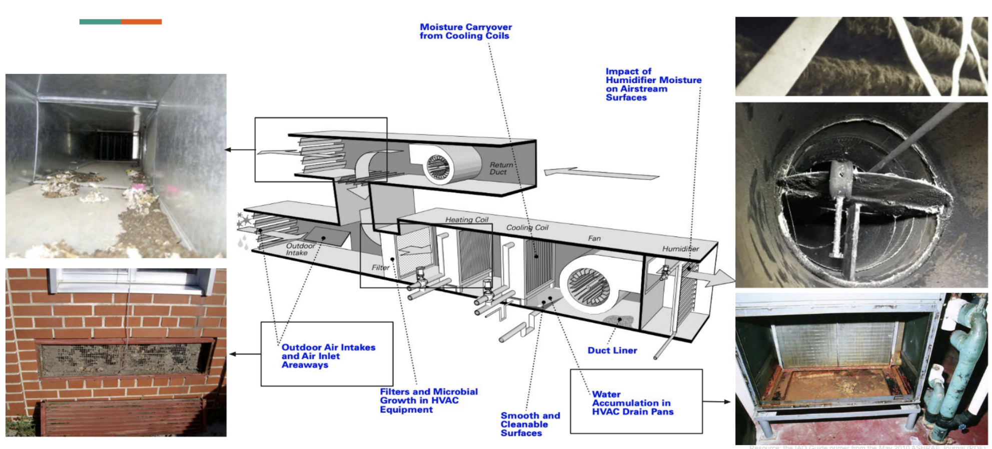


fig. 6.1 Examples of faulty operation of AHU components.

Several hypotheses could be answered by GSA field research efforts for impacts on user satisfaction, health outcomes and indoor air quality measurements:

a. The quantity of filtered outside air can be measurably increased at the central air handler without energy penalty (updating iteratively damper/sensor/actuator, VFD fans and BAS assemblies, airside economizers with updated ranges, economizers with energy recovery).

b. The quality of filtered outside air can be measurably improved at the central air handler through filter material quality, replacement schedule, and location.

c. The introduction of dedicated outside air (DOAS to the zone or room) with separate thermal conditioning (VRF, radiant, dual duct in either new or retrofit buildings) will improve IAQ for occupants, save energy, ensure thermal comfort, and support mixed mode with natural ventilation (as appropriate).

6.1 Increasing OA quantities for improving IAQ in occupied spaces

The NOVA 62 building AHU study undertaken by GSA revealed disparity in outside air ventilation rates relative to ASHRAE minimums or Design standards across over 1200 air handling units (see fig. 6.2).

NOVA Summary: **Outside Air Delivery Rates**

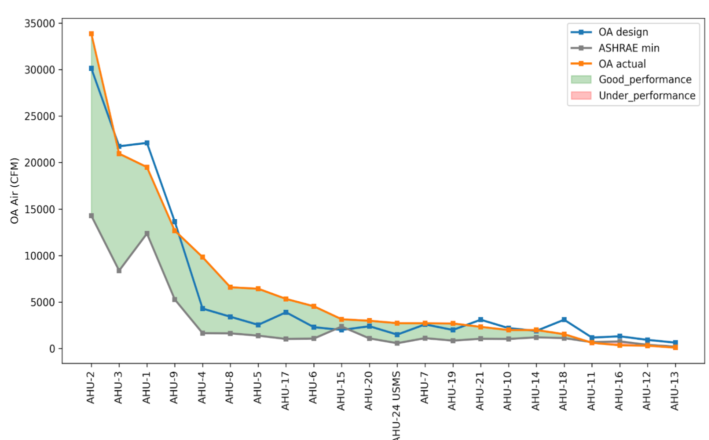


fig. 6.2. 63% of 1263 AHUs studied in 62 buildings had measured OA (orange line) exceeding the calculated ASHRAE minimum (grey), with recorded design OA in blue.

While over 63% of air handlers are delivering more than ASHRAE minimums (dark green of which 47% are delivering over 160% of minimums in pale green), there are still 37% of AHU providing inadequate OA ventilation given the assumed size and occupant density of the zone they serve (red bars in fig. 6.3).

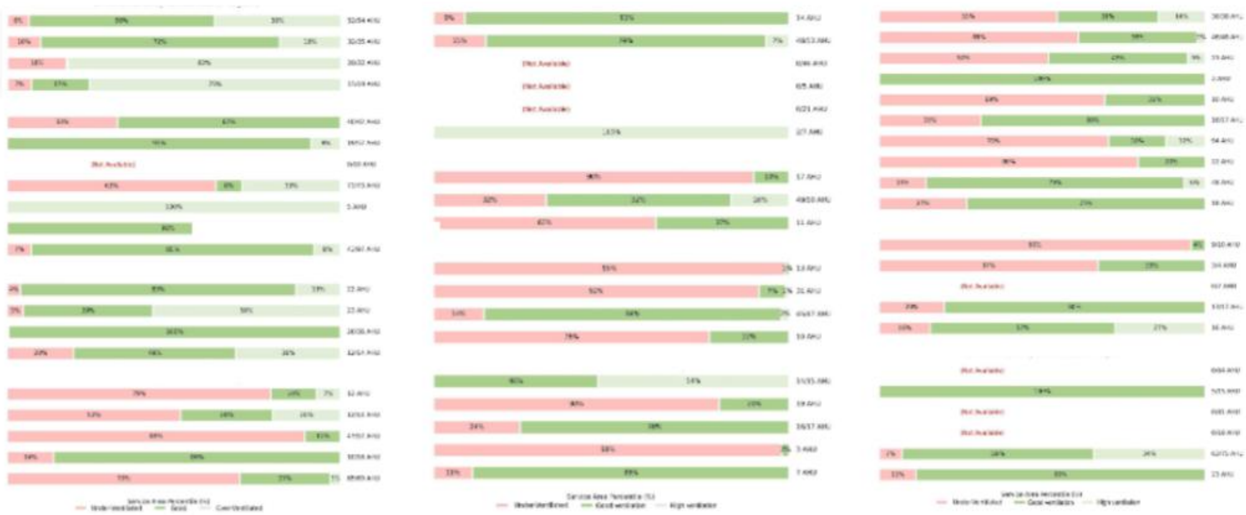


fig. 6.3 Aggregating the 24-60 AHU's in each building studied reveals the 37% that do not meet ASHRAE minimums for the assumed area and occupant density served.

The NOVA field teams identified a number of conditions that may contribute to these disparities in delivering outside air:

NOVA Concerns
OA damper flaws in 48% of AHUs across 62 buildings
OA damper manually closed in 9% of AHUs
OA sensor/actuator flaws in 13% of AHUs
OA damper BAS control flaws in 17% of AHUs
No Economizer operation in 38% of AHUs
DCV not disabled (as recommended) in 26% of AHUs

At the same time, the portfolio wide NOVA field assessments did not extend to evaluations of ventilation delivery in building zones or at terminal units. Actual zone or diffuser delivery of outside air may be compromised by duct and damper conditions, temperature-only controllers, or variations in occupancy density - resulting in unequal delivery of OA between building zones. For the assurance of adequate delivery of OA from the central AHU to each building zone or terminal unit, a number of field interventions for ensuring and even increasing OA delivery from the AHU could be evaluated with GSA leadership.

Research Linking Outside Air Rates (ACH, cfm, l/s) to Health and Productivity

The ongoing research linking outside air rates to health and productivity has prompted ASHRAE, the CDC, and numerous international organizations to recommend measurable increases in ventilation rates through more outside air and/or through more locally filtered air (captured in new units called eqOA or equivalent clean air described in chapter 2 and 5).

> *In a 1997 meta-analysis study, Fisk and Rosenfeld identify a **10 to 30% reduction in the incidence of respiratory disease, asthma, and allergies** and a corresponding reduction in associated health and productivity costs as a result of **improved delivery of outside air through an increased ventilation rate, reduced air recirculation, and improved filtration** ($p < 0.05$)**.***

> *In a seminal 2000 controlled experiment in a normally furnished office space, Wargocki et al. identified that each incremental increase in ventilation rate from 3 to 10 to 30 L/s per person (corresponding to an air change rate of 0.6, 2, or 6 ACH) resulted in a **1.7% increase in performance at task for each two-fold increase in ventilation rate** ($p < 0.03$).*

> *In a 2000 multiple building case study throughout the U.S., Apte et al. identify that a **reduction in indoor CO2 concentrations from 800 ppm to 400 ppm** (achieved through increases in OA) result in a percentage risk reduction of up to 70-85% in certain **SBS symptoms (sore throat, nose/sinus, chest tight, and wheeze)** ($p < 0.05$, BASE study).*

> *In a 2003 controlled field experiment, Wargocki et al identified a **6.7% improvement in call center employee performance when outdoor air is supplied at 25 L/s/person** (80% of total air supply) as compared to when outdoor air is supplied at 2.5 L/s/person (8% of total air supply), with new filters in the ventilation system ($p < 0.05$).*

> *In a 2004 multiple-building study of three office buildings in Boston, Myatt et al. identify a **6.8% reduction in risk of exposure to airborne-transmitted rhinovirus (colds)** for workers in offices with higher outdoor air ventilation rates as indicated by indoor CO2 **differential (indoor minus outdoor CO2) less than 100 ppm**, as compared to those in offices with indoor CO2 differential higher than 100 ppm ($p = 0.039$).*

*In a 2005 lab experiment carried out at the International Center for Indoor Environment and Energy, DTU, Denmark, Seduikyte et al. identified a significant increase in perceived IAQ (general perception of air quality 65%, odor intensity 15%), **reduction of self-reported SBS symptoms** (eyes irritation 11%, difficulty to think 12%) and a measured average of **11.5% work productivity increase** when increasing **ventilation rates from 3 L/s/p** with a pollution source in the room **to 20 L/s/p** with no pollution source ($p < 0.05$).*

*In a 2012 study of 635 children attending 20-day care centers in Denmark, Kolarik et al. identified a **12% decrease in the number of sick days for each air change per hour increase (ACH)**, supporting the need for improved air quality in daycare centers ($p < 0.05$).*

*In a 2016 building case study of randomly chosen houses in Cook County, IL and Indiana, P. W. Francisco et al. identified a **31% reduction in children headaches due to an increase in ventilation** as per ASHRAE 62.2-2010 (mean 79 cfm / 37.3 l/sec) compared to ASHRAE 62-1989 (mean 39 cfm / 18.4 l/sec) ($n = 107$, $p = 0.001$, $t = 7.7$ months)*

*In a 2017 study of the human bio effluent CO_2 in a climate chamber in Denmark, Zhang et al. identified that increasing in the outside air supply rate from 38 m3/h to 720 m3/hr **lowered CO_2 from 3000 ppm to 500 ppm, and improved cognitive performance** by 12.5% for addition speed and 11% for the number of correct links identified ($p<0.05$), as well as a 46% reduction in headache reports from 25 subjects ($p=0.05$).*

*In a 2020 field study of student performance in a school located in in the city of Valby close to Copenhagen, Denmark, Hviid et al. identified a **6.0% increase in t-test performance by increasing the ventilation rate from 3.9 l/s to 10.6 l/s per person** ($p < 0.001$, $n = 81$).*

Baseline Research on Actual OA Delivery Rates

Baseline conditions relative to the quantities of OA delivered to each building zone in large commercial buildings can be tested through **analysis of existing data from the GSA portfolio**. A database of existing OA delivery conditions can be built based on BAS sensors and actuator positions at the central and zone level for comparison with site measured CO_2 or other indoor contaminants.. Using 2018 & 2019 data from 14 NOVA buildings that also have TECI analysis and GSALink BAS data, a number of possible correlations between condition assessments, control algorithms and delivered ventilation can be tested:

- NOVA AHU OA flow records vs. OA actual (AHU and zone)
- correlations of cfm, damper position, central and zone CO2 or other contaminant measurements
- BAS CO2 performance at AHU RA and at zone RA vs. OA actual
- OA minimums and maximum setting impacts on CO2 sensors (AHU & zone)
- RA temperature, humidity, static pressure, smoke, enthalpy readings impact on BAS actions.
- OA hourly damper position versus outdoor conditions, with zone calculated cfm delivery and energy use.

These baselines will help to establish the value of improving outside air quantities by building or even by AHU, with a range of possible solutions outlined for staged research in the following sections.

Field Studies on the Impacts of Increased OA quantities at the AHU for IAQ

Research #8. The quantity of filtered outside air can be measurably increased at the central air handler without energy penalty - updating iteratively damper/sensor/actuator, VFD fans, correlated BAS algorithms, airside economizers with updated ranges at high and low temperatures, and economizers with energy recovery.

Code required outside air minimums and economizer increases to outside air delivery relies on a series of temperature, humidity and airflow sensors to modulate outside air delivery during hot, moderate and cold periods. Economizer controls increase the outside air quantities when the temperature of outdoor air is suitable for cooling (lower than the indoor air temperature) for energy savings and for increased ventilation benefits. Economizer operation is often limited in low temperature periods for fear of freezing coils and in high, humid periods for fear of condensation on cooling coils (fig. 6.4, Kim 2022). In the NOVA study of 62 buildings and 1287 AHUs, 38.2% of the economizer operations had been disabled.

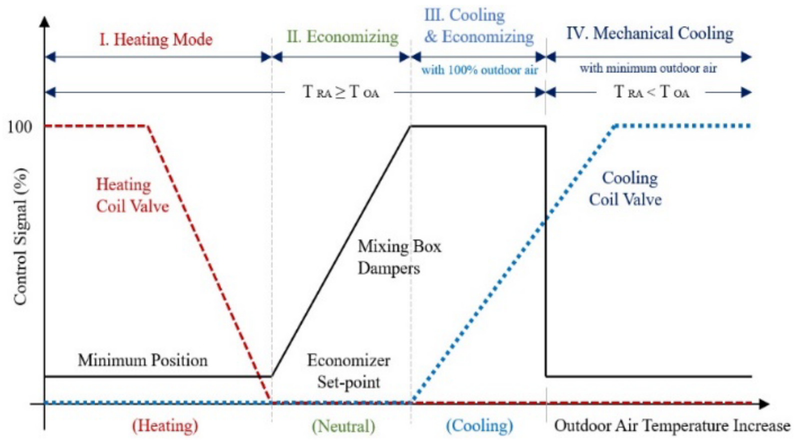


fig. 6.4 Setting threshold temperatures for economizer operations.

The hardware and software for introducing outside air, and mixing with return air or directly exhausting, may critically need updating to achieve improved OA delivery for a full suite of IAQ variables measured at OA, RA and SA locations. Investing in updates sequentially, while recognizing climate variations, can support a staged research project to evaluate the quantity of OA delivered, the filtered air quality (CO2, PM2.5, VOC, bacteria, fungi) leaving the AHU, and the energy cost-savings of upgrades to AHU in large commercial buildings:

1. New damper/sensor/actuator suite (hardware investment)
2. BAS update for baseline air-side economizer effectiveness
3. Warmer indoor temperature setpoints for extended air-side economizer hours in warm weather
4. New mixing box damper for extended air-side economizer hours in cold weather (hardware investment)
5. Energy/Enthalpy recovery for maximum extended economizer operation (comparatives across existing AHU with ERV or adding new hardware)

This suite of upgrades was selected because over 48% of the AHU's evaluated by the NOVA field teams had damper/sensor/actuator and BAS linkage challenges, and because economizer has proven to be invaluable for energy savings in many US climates, but rarely tested for ventilation gains. When updating damper/sensor/actuator hardware and the corresponding BAS software, it is possible to update the minimum and maximum outdoor temperature and humidity assumptions for controlling the hardware.

If summer indoor temperatures were raised above the annual norm of 72F or 22C, which should increase thermal comfort and save energy, the economizer operation can be extended in both humid climates and dry climates. This is significant for both energy efficiency and for human health, as revealed in a 2022 study by Risbeck:

> *In a multi-climate simulation study, Risbeck et al identified that* ***increasing summer supply air temperature from 55F (to 60F in humid climates and 65 in dry climates)*** *that supports longer economizer operation, in combination with MERV 13 filters, would* ***provide 1 ACH increase in effective outdoor air (EOA) at the lowest energy cost*** *compared to doubling ventilation rates or installing in-room filtration given ASHRAE baselines between 2-2.5 ACH.*

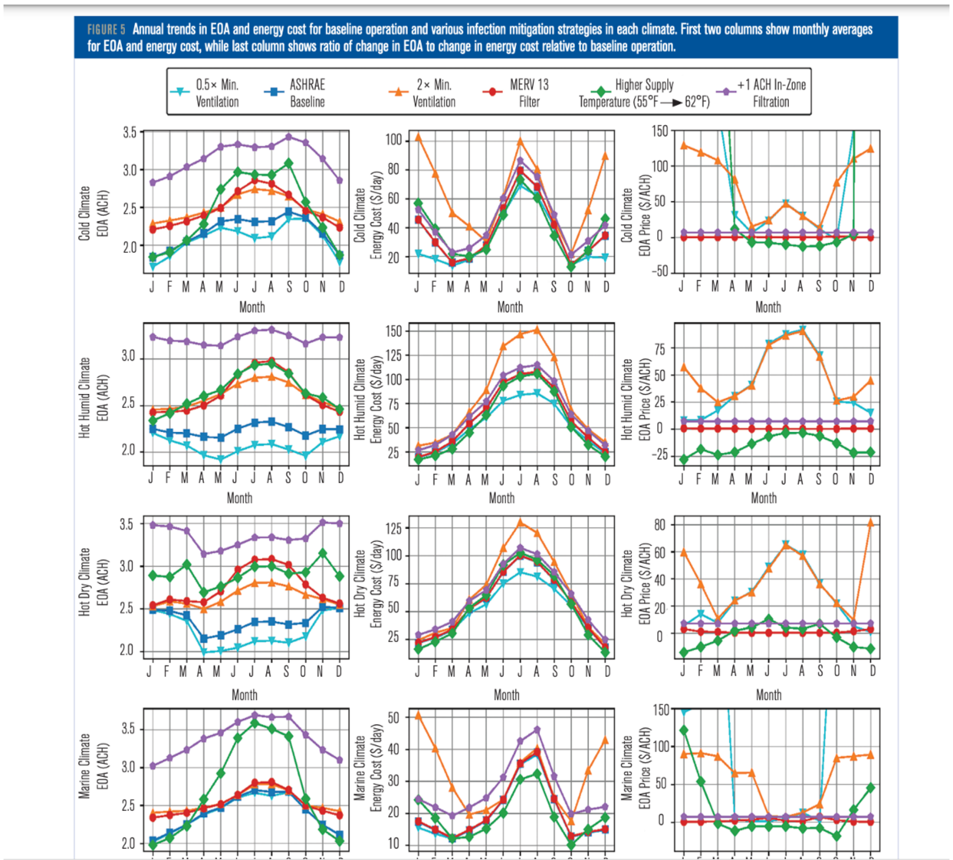
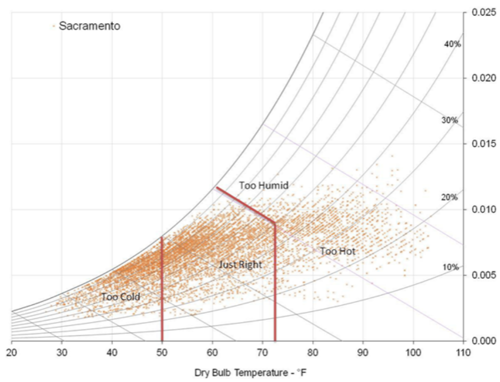


FIGURE 5 Annual trends in EOA and energy cost for baseline operation and various infection mitigation strategies in each climate. First two columns show monthly averages for EOA and energy cost, while last column shows ratio of change in EOA to change in energy cost relative to baseline operation.

fig. 6.5 Airborne Disease Transmission Risk and Energy Impact of HVAC Mitigation Strategies (OA, MERV 13, zone ACH), Risbeck et al ASHRAE Journal May 2022.

> *In a 2014 study of failures in economizers, Heinemeier identified that the magnitude of savings from an economizer depends directly on the high limit setpoint, given a Jacobs 2004 field study of California climate zones that increasing upper limit setpoints from 65 F to 70 F would save 50% of conditioning energy across most California climates, 70% in CZ5 and over 220% in CZ9 (fig. 6.6).*



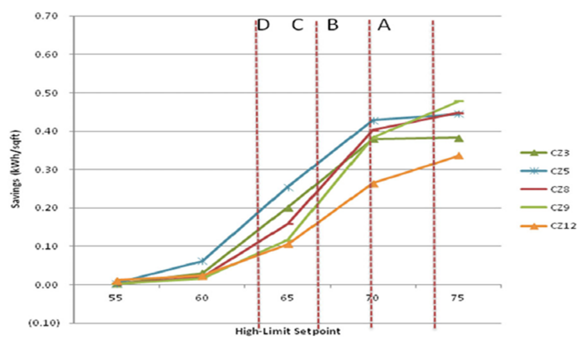


fig. 6.6 expanding the outdoor T setpoints from 65-70oF
can increase the hours of higher OA ACH by 50% in California.

In a simulation study of California offices in multiple climates, Dutton and Fisk identified that economizers provided free cooling and improved IAQ during 79% of the estimated occupancy hours, lowering HVAC EUI by 20% and reducing the predicted average indoor formaldehyde exposure by 38% compared to reference models without economizers.

Recognizing the energy savings of economizer operation at higher temperatures, ASHRAE 90.1 identifies four types of economizer operation - fixed OA drybulb operation, differential OA/RA drybulb operation, fixed enthalpy (T/RH) operation and differential enthalpy (T/RH) operation - as appropriate in different US climates, each with their own upper limits (fig. 6.7). However, to date the increased outside air ventilation rates that would accompany these expanded hours of operation have not been quantified.

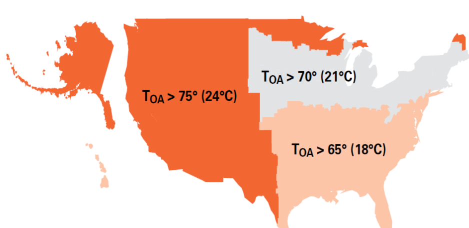


Table 1. Permissible economizer control types and high-limit shutoff setpoint conditions

Control type	Allowed in climate zone	Required high-limit shutoff setpoint
Fixed dry-bulb temperature	1B, 2B, 3B, 3C, 4B, 4C, 5B, 5C, 6B, 7, 8	T_{OA} > 75°F (24°C)
	5A, 6A	T_{OA} > 70°F (21°C)
	1A, 2A, 3A, 4A	T_{OA} > 65°F (18°C)
Differential dry-bulb temperature	1B, 2B, 3B, 3C, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 7, 8	T_{OA} > T_{RA}
Fixed enthalpy with fixed dry-bulb temperature	All	h_{OA} > 28 Btu/lb (47 kJ/kg) or T_{OA} > 75°F (24°C)
Differential enthalpy with fixed dry-bulb temperature	All	h_{OA} > h_{RA} or T_{OA} > 75°F (24°C)

fig. 6.7 increasing OA 'economizer' operation with warmer thresholds
based on sensor type and climate.

Investments in new outside air dampers with integrated sensor-actuator suites and correlated BAS algorithms should most likely focus on differential dry bulb or enthalpy sensors, correlating OA sensors with RA sensors and possibly even zone CO2 and other IAQ sensors for actuation.

In a 2015 simulation simulation study of an office building, Choi et al. identified that the Differential Enthalpy control of the economizer resulted in the lowest CO2 concentration (ppm) among different control types, while reducing energy consumption by 12 kWh/m2 compared to the Fixed Dry Bulb control which consumed the most energy.

	Control type	Input
CASE1	Fixed Dry Bulb	Economizer maximum limit dry bulb T: 28℃
CASE2	Fixed Dry Bulb	Economizer maximum limit dry bulb T: 24℃
CASE3	Fixed Enthalpy	Economizer maximum limit enthalpy : 61.45kJ/kg
CASE4	Fixed Enthalpy	Economizer maximum limit enthalpy : 50.22kJ/kg
CASE5	Differential Dry Bulb	-
CASE6	Differential Enthalpy	-

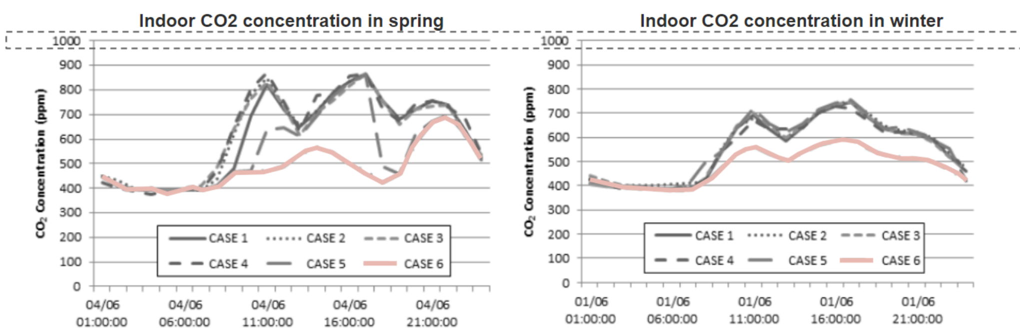


fig. 6.8 Indoor CO2 concentration in spring in Spring and Winter (Study based on South Korea; similar to the ASHRAE CZ 4A).

At the other end of the 'acceptable temperature band' that controls the outside air damper, there is emerging evidence that updated mixing boxes using 'channel blender' technology can enable increased settings for outside air minimums (from 20% to 30%) and extend hours of operation from 55F down to 15F without freezing concerns.

*In a field intervention at St. Peter's Hospital in Albany NY, Starns et al identified that the introduction of c**hannel air blenders in the AHU mixing box would eliminate freeze stat trips, reduce air stratification, and maintain 30% minimum OA air flow** (above the 20% typical minimum) even during cold weather, by **extending economizer operations to OA temperatures range to 15°F-30°F** with a 1.9 year payback.*

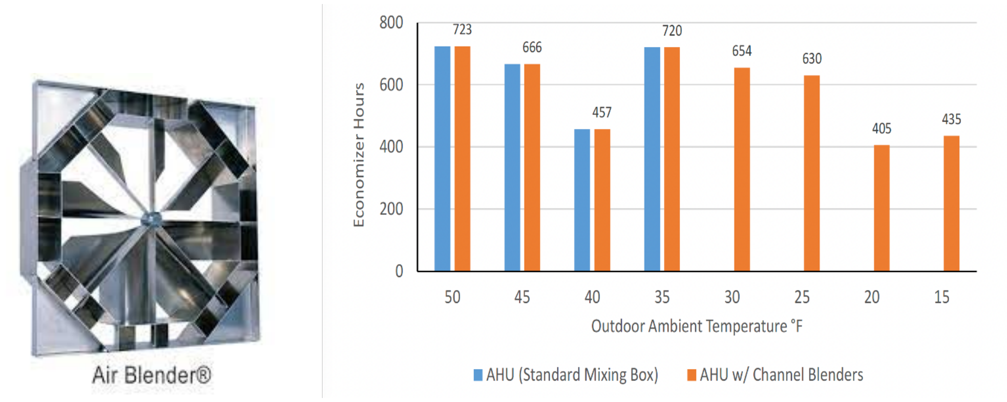


fig. 6.9 Extend Economizer Operations for AHUs and Improve Ventilation with Effective Mixing (Starns, Dorste, Pavol, Blender Products, 2021).

In a GSA staged research project on the quantities of outside air (OA) that can be delivered from the central AHU without energy penalty, the following steps could be considered:

- baseline comparison of cfm and CO2 sensor data for AHU with baseline economizer operation compared to AHU without economizer.
- comparison of cfm and CO2 sensor data for AHU after updating the OA damper/sensor/actuator suite.
- comparison of cfm and CO2 sensor data for AHU after introducing warmer summer indoor temperature setpoints, alongside zone records of IAQ and thermal comfort.
- comparison of cfm and CO2 sensor data for AHU after introducing channel blenders to extend economizer operation to significantly colder setpoints, also with zone thermal comfort assessment.

Maximizing Economizer Outside Air Delivery with Energy Recovery Ventilation

The potential for increased use of economizer cycles to iteratively improve zone and room delivery of outside air and ventilation air change rates is critically needed for improving the performance of existing air handlers in commercial buildings for IAQ and human health.

In a comprehensive simulation study in 13 US cities, Pistochini et al identified that the 10-50% increased ventilation from Economizer Operation (by climate) reduced disease transmission by .1-.5% and provided energy savings up to 12%, strongly promoting the importance of economizer research in federal buildings (fig. 6.10).

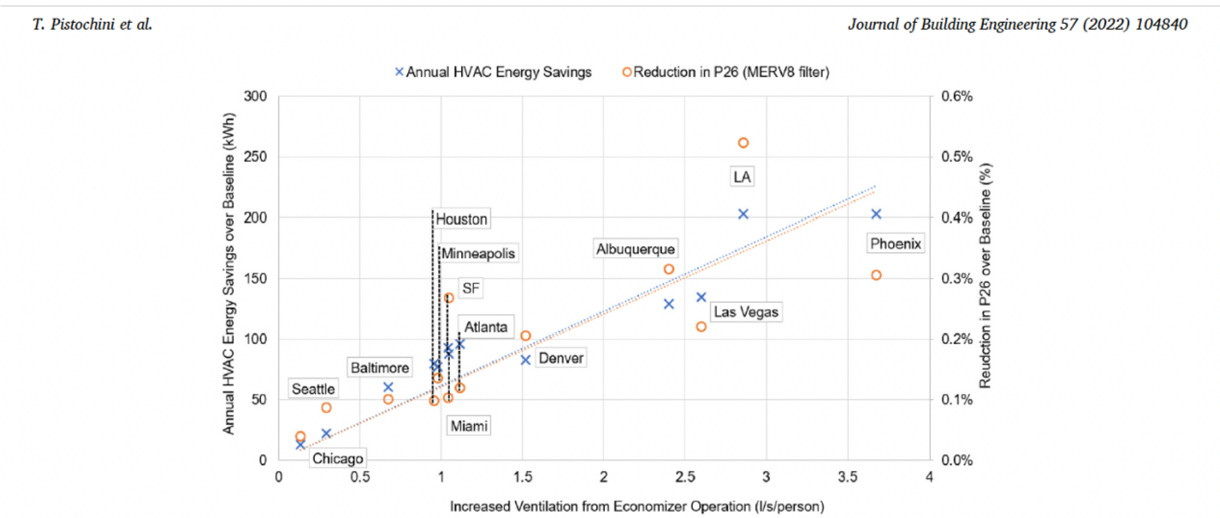


fig. 6.10 Impact of economizer controls on increase in ventilation rate over baseline of 7 l/(s.person), annual HVAC energy savings, and absolute reduction in infection probability (Pistochini et al, 2022).

While this study was based on conventional economizer temperature limits, raising summer indoor setpoints and introducing Channel Mixers for the mixing box can substantially increase economizer operations beyond this study, with energy recovery wheels expanding the hours of operation even further. .

The introduction of heat recovery or enthalpy recovery wheels to the air handling units can significantly expand economizer cycles for both improving ventilation and increasing energy savings. Since the GSA building portfolio has air handlers operating with energy recovery wheels, the quantities and duration of outside air delivery should be compared to AHU without energy recovery wheels, at both the supply air and zone air level.

Comparative IAQ conditions should also be undertaken wherever ERV's are to be added to existing AHU. Enthalpy recovery may be the better retrofit for IAQ and health because it not only enables thermal energy transfer but supports moisture transfer to reduce humidity in summer and raise humidity in winter. Research revealing the importance of controlling humidity to improve health and reduce infection is emerging (CBPD, 2022).

> *In a comprehensive analysis of commercial ventilation systems, Red Car Analytics identified that the introduction of enthalpy recovery wheels with VFD fans and bypass controls can turn conventional AHU into dedicated outside air systems (DOAS) for 80-99% of the time in the North West, without the need for auxiliary heating, given 82-88% sensible energy recovery inclusive of defrost control.*

[TABLE 2: APPLICABILITY ACROSS NORTHWEST CLIMATE ZONES]

Climate Zone	Representative City	ASHRAE 99.6% heating dry-bulb temperature	Percent of occupied hours supply air is delivered within 7°F of room temperature without supplemental heating	Hours outside of 7°F	Sensible Recovery Required to meet 99% of hours within 7°F
4C	Portland, OR	25.9°F	99.2%	18	82%
5B	Boise, ID	11.4°F	91.5%	199	86%
6B	Missoula, MT	-1.7°F	81.3%	438	88%

figure 6.10 Applicability across Northwest climate zones (VHE_DOAS, 2022).

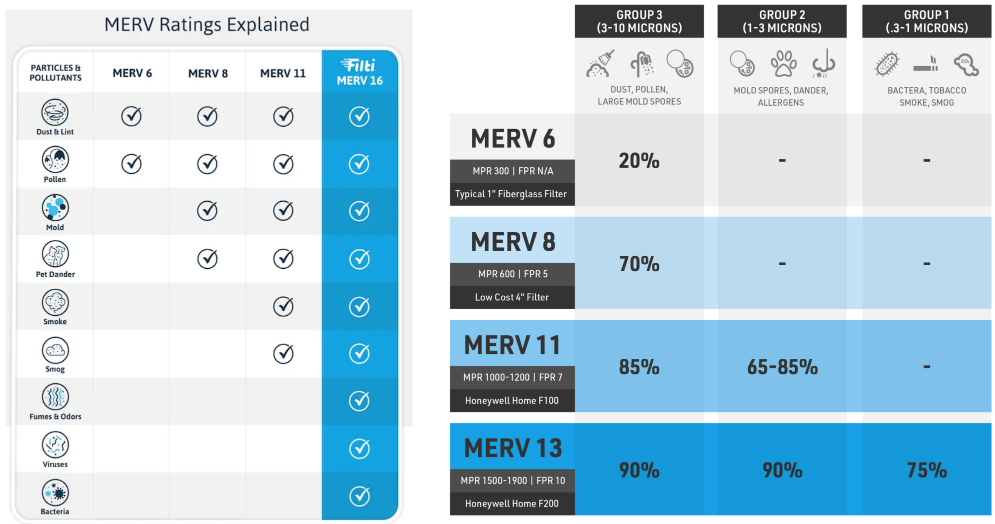
Upgrading OA quantities delivered from the AHU to terminal units may be a more viable solution to achieving eqOA or clean air rates than the introduction of thousands of room filtration units. GSA research on the use of baseline, extended and maximum economizer with enthalpy recovery at the AHU is critically needed alongside measurements of objective and subjective IAQ improvement for building occupants, and energy savings.

6.2 Field Studies on the Impacts of AHU Filters for IAQ

A sweep of field and laboratory research reveals the importance of improving filters in air handling units to minimize a range of pollutants from entering the supply air that then ventilates each building zone. ASHRAE has identified the importance of effective filtration to reduce infectious disease transfer, with Minimum Efficiency Reporting Value (MERV) ratings recommended at 13 or higher as key to a healthier future, captured in multiple vendor materials (figures 6.11, captured from filter industries).

MERV Rating	Air filter will trap particles sized .3 to 1.0 microns	Air filter will trap particles sized 1.0 to 3.0 microns	Air filter will trap particles sized 3.0 to 10 microns	Filter Type & Particles Removed
MERV 1	<20%	<20%	<20%	Fiberglass and Aluminum Mesh pollen, dust mites, spray paint, carpet fibers, pet dander
MERV 2	<20%	<20%	<20%	
MERV 3	<20%	<20%	<20%	
MERV 4	<20%	<20%	<20%	
MERV 5	<20%	<20%	20% - 34%	Disposable Filters mold spores, kitchen aerosols, hair spray, furniture polish, household cleaning sprays
MERV 6	<20%	<20%	35% - 49%	
MERV 7	<20%	<20%	50% - 69%	
MERV 8	<20%	<20%	70% - 85%	
MERV 9	<20%	>50%	85% or better	Home Box Filters lead dust, flour, auto fumes, welding fumes
MERV 10	<20%	50% - 64%	85% or better	
MERV 11	<20%	65% - 79%	85% or better	
MERV 12	<20%	80% - 90%	90% or better	Commercial Filters bacteria, wildfire smoke, respiratory droplets
MERV 13	>75%	90% or better	90% or better	
MERV 14	75% - 84%	90% or better	90% or better	
MERV 15	85% - 94%	95% or better	90% or better	
MERV 16	95% or better	95% or better	90% or better	
MERV 17	99.97%	99% or better	99% or better	HEPA and ULPA viruses, carbon dust
MERV 18	99.997%	99% or better	99% or better	
MERV 19	99.9997%	99% or better	99% or better	
MERV 20	99.99997%	99% or better	99% or better	

ISO-Aire



Figures. 6.11 Filter Manufacturers explain Minimum Efficiency Reporting Value (MERV) ratings

The research relating MERV ratings for filters and health outcomes in buildings is emerging and emphasizes the importance of installing MERV13 or better in every air handling unit, with mandated replacement cycles.

> *In a 2013 study, Azimi and Stephens simulated the impact of HVAC filters on influenza risk (Wells-Riley) and the related annual cost for office buildings, revealing that higher MERV ratings reduced the risk of infection dramatically, with acceptable increased annual costs for filter replacement, labor, and fan energy usage. The author suggested that using MERV 13 or 14 can achieve a high-risk reduction at the most affordable investment.*

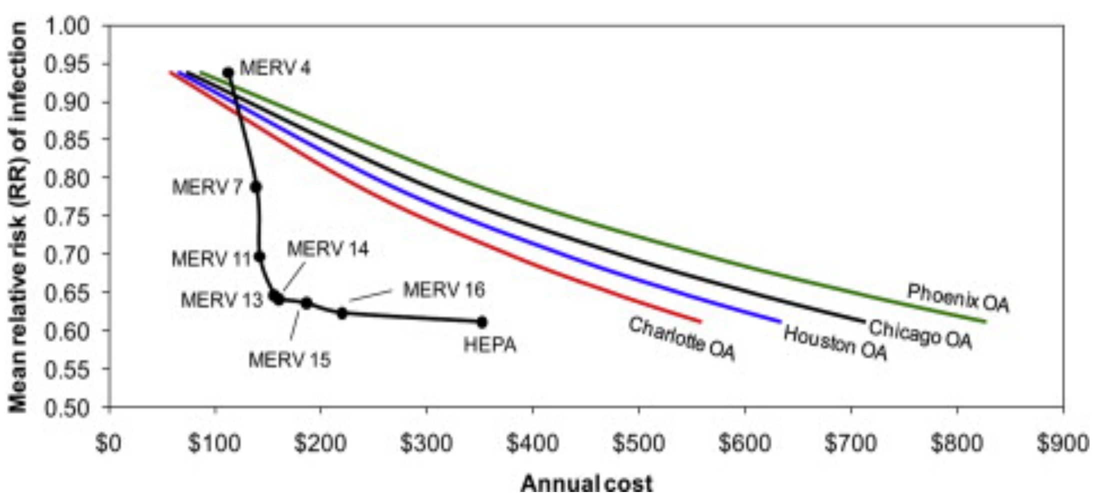


fig. 6.12 Relative risk (RR) of influenza transmission in the hypothetical office environment with both HVAC filtration and equivalent outdoor air ventilation rates.

In a 2018 66-day controlled experiment in a Drexel University office building, Ben-David et. al. evaluated low and high efficiency filtration over a range of ventilation Air Exchange Rates and identified that improving filter efficiency from MERV 8 to MERV 14 would increase the PM2.5 removal efficiency from 20% (R2= 0.98) to 70% at three air exchange rates (100% OA).

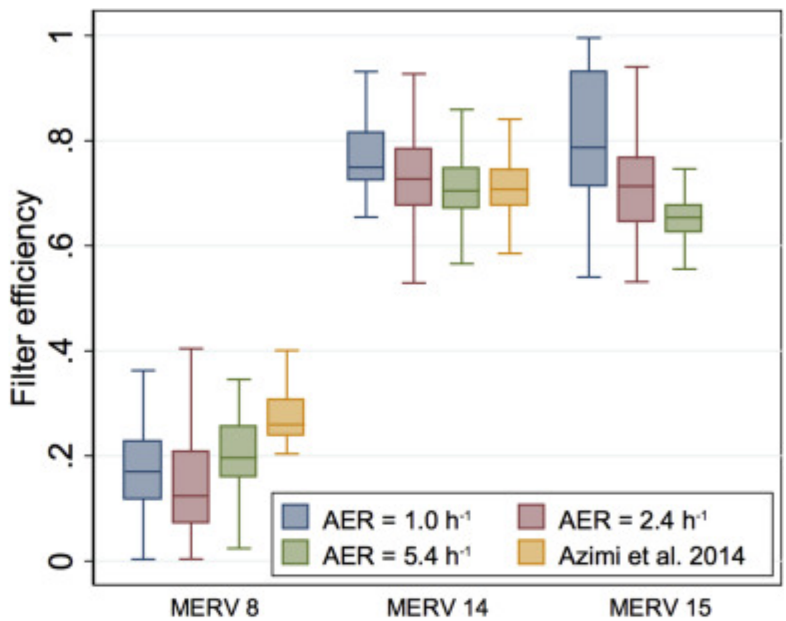


fig. 6.13 Calculated PM2.5 filter removal by filter efficiency for 3 air exchange rates. Azimi 2014

Research #9. The quality of filtered outside air can be measurably improved at the central air handler through filter material quality, replacement schedule, and location.

While achieving MERV 13 (or higher if appropriate for the fan power) is a critical action for IAQ, three other filter related actions could be evaluated in field research:

1. filter maintenance and replacement schedules for IAQ
2. the value of combining pre and final filters for IAQ
3. the type of filter (pocket and dynamic filters) for IAQ

ASHRAE recommends bi-annual filter replacements for both pre-filters and final filters, or according to the filter manufacturer, to ensure there is no performance reduction over time and no re-emission of pollutants that may have built up over time. They also recommend that filters be installed appropriately, with excellent fit to reduce leakage or ‘bypass’ of the air stream around the filter. The standards state “Install the filter correctly, such as the filter direction, size to the duct, and make sure the filter is fixed on spot and sealed firmly. Tapes and gaskets can be used to prevent leaking or bypass. HEPA filters need much better sealing as even a tiny 0.3% leak will give 10x as much penetration.”

The research supports the increased attention to MERV rating, replacement cycle, and tightness of fit.

> *In a 2009 experimental study about the implication of air bypass around the filter, VerShaw et al. identified that gaps between the filters and the AHU could detrimentally impact the efficiency of the filters and make the degradation more obvious for high MERV filters.*
>
> *In a 2019 field study in 91 classrooms in 11 California schools, Chan et. al. identified that the ventilation rates of classrooms could be improved 94%, 3.4 L/s-person to 6.6 L/s-person, just by proper HVAC filter replacement. The schools included a diverse mix of urban, rural, wealthy, poor that were located in various regions from north to south, coastal to inland.*

Given that MERV13 filters may now be the federal standard, replaced annually or bi-annually, there is a question of whether a pre-filter is actually needed to protect the final filter.

> *In 2012 simulation and field study, Montgomery et al. identified that the addition of pre-filters increased the life of final filters by 50% (from 1 to 2 years to 1.5 to 3 years), but increased the total annual operating costs by 10% compared to the systems without pre-filters.*
>
> *In 2019 lab experiment, Tian et. al. found that a two-stage filtration system can decrease the pressure drop growth rate and manage higher total particulate loads when coarse particulates dominate.*
>
> *In a 2019 field study in a commercial office building in Hong Kong, Che et al. identified that upgrading the central AHU from a coarse particle filter of aluminum mesh (aluminum filter) to a two-stage filtration system that has both the aluminum mesh filter and a pleated MERV 13 filter resulted in increased reductions of indoor PM10 (from an average 55% to 85%) ($R2 = 0.61\sim0.80$), PM2.5 (from 35% to 70%) ($R2 = 0.84\sim0.91$), and PM1 (from 15% to 60%) ($R2 = 0.84 \sim 0.93$).*

In a 2022 lab experiment study, Wu et al. evaluated the performance of two-stage filtration systems in a pandemic setting. The results showed that for a two-stage filtration system, MERV 8 combined with MERV 11 filters can achieve the highest particle removal efficiency of 51% for 0.1-1 um at 1 m/s air velocity, as compared to MERV 6 combined with MERV 11, respectively.

The potential value of increasing 'final' filter maintenance cycles to 6 months and eliminating pre-filters to improve ventilation rates and energy efficiency has not been adequately investigated. This might best be accomplished in a laboratory setting alongside a study of how different types of filters perform relative to the suite of outdoor and indoor pollutants of concern, given its position after the mixing chamber. The six types of filters in dominant use across the federal portfolio are shown in fig. 6.14 There is some evidence that the pleated, pocket and dynamic filters may be most effective for ensuring IAQ.

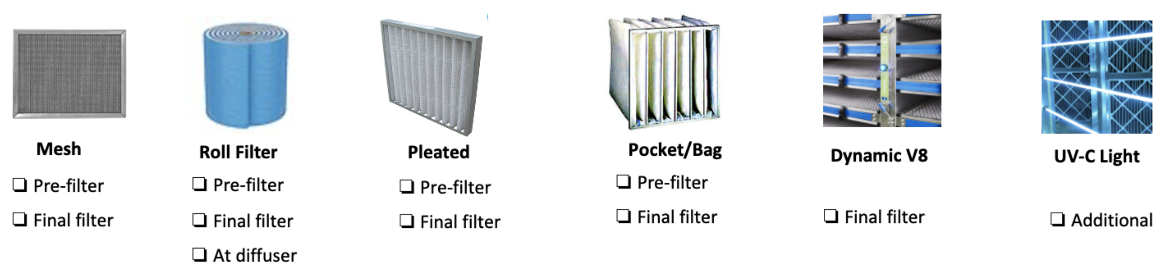


fig. 6.14 Identified filtration types in federal buildings.

Dynamic V8 filtration units may have a number of advantages relative to pollutant filtration at the lowest energy cost and longest period of service without maintenance or replacement.

Although a proprietary technology, tests comparing filtration effectiveness of the Dynamic V8 compared to bag filters reveal superior filtration of particulates at all air change rates, and significantly lower pressure drop over time (fig. 6.15) prolonging replacement requirements.

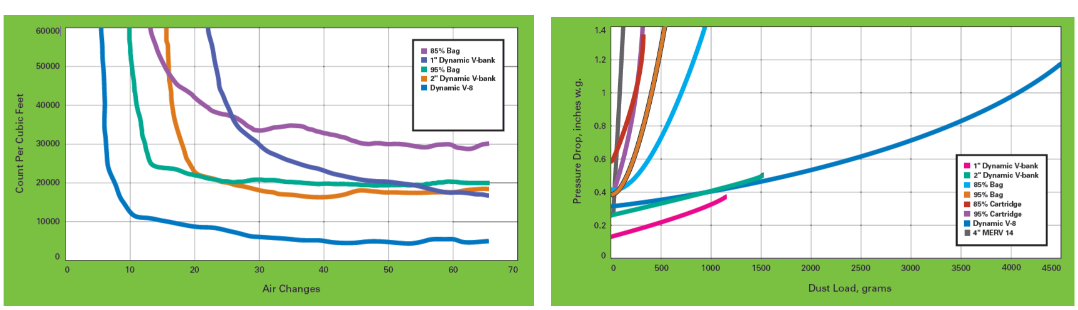


fig. 6.15 The particle counts at 0.3 microns in 2,000 cfm airflow were reduced to the least using the Dynamic V8 system, and pressure drops were the lowest over time.

In a Canadian hospital field study in 2014, the Dynamic V8's filtration efficiency was higher than a rated MERV15 bag filter in all particulate ranges. While the bag filter was effectively a MERV 12 in the field, the Dynamic V8 remained over MERV 14+. (Kaeppner, 2014).

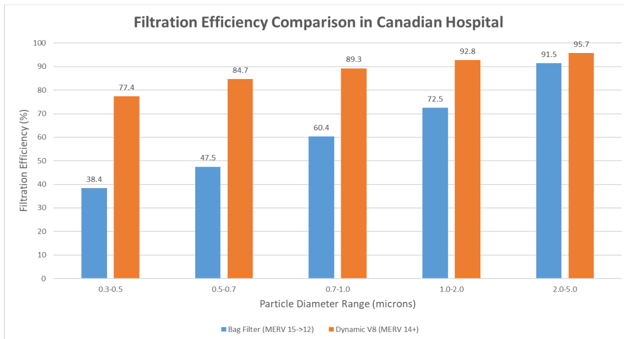


fig. 6.16 Filtration efficiency of bag filter and Dynamic V8 across particle sizes in a Canadian hospital.

The dynamic filters also seemed to perform well during recent wildfire events. In an office building in Princeton, New Jersey, the indoor PM 2.5 was 97% lower than the outdoor levels given a dynamic filter system, even when the outside PM 2.5 peaked.

Research relative to updating filters and filter maintenance in federal facilities

Given GSA's commitment to MERV13 or better filters across federal facilities, there is not a critical research effort needed at this time. Only 18% of the final filters in the AHU's captured in the NOVA report are below MERV13 and still require updating. There is some emerging evidence that the presence of filtered air in offices may provide healthier work settings than the home office, especially in periods of elevated pollutant concerns.

> *In a 2021 field test study in McAkken, Texas, Roh et al. identified that the workplace indoor air quality had 49.82% lower PM2.5 compared with the home office (office: 8.18 µg/m3, home: 16.3 µg/m3) and 19.19% lower TVOCs (office:175.75 µg/m3, Home: 217.49 µg/m3). They also observed a lower frequency of SBS symptoms at the office due to the better IAQ. ($n = 8$, $p < 0.05$).*

NOVA reporting suggests that federal filter maintenance or replacement seems to be effective, with less than 18% out of 1756 AHUs that were identified with dirty filters. However, based on BAS screen captures in the NOVA report, 64% out of 1019 AHUs have pressure drop alerts for the facility management team regarding the filter performance. There is incomplete or no records regarding the time between filter changes, and this would be an invaluable KPI for each of the multiple AHUs in different federal buildings. Side-by-side air quality assessment at various AHU supply air diffusers over time could also support the comparative performance of different filter types and maintenance schedules, from pleated to shallow bag to deep bag to dynamic filters - relative to the full set of pollutants/contaminants of concern.

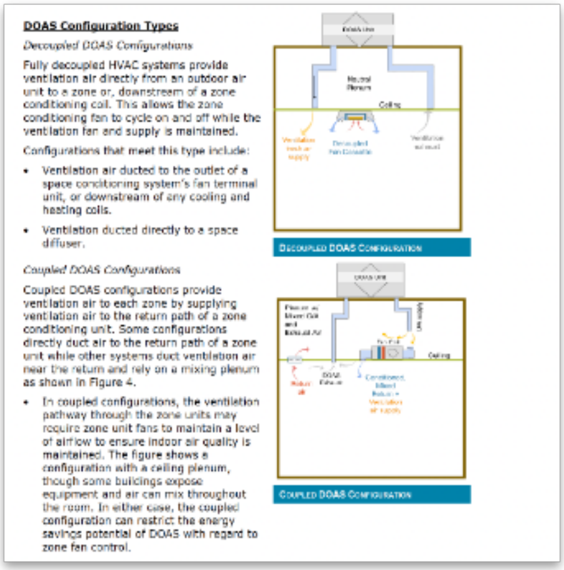
GSA should consider adopting the RESET Core & Shell standard, or a customized variation of this, to monitor and benchmark the air quality index (AQI) being delivered from all central AHUs. This would at a minimum monitor IAQ (TVOC, PM2.5, CO2, temp, RH) at both high and low OA intakes and record that a minimum of 30% of all supply SA from the AHU is outside air OA (up to 100% whenever practical). A typical building could be covered with significantly fewer monitors as compared to zone level monitoring.

6.3 Retrofit Dedicated Outside Air Systems (DOAS) with Electrified Thermal

Research #10. The introduction of dedicated outside air (DOAS to the zone or room) with separate thermal conditioning (VRF, radiant, dual duct in either new or retrofit buildings) will improve IAQ for occupants, save energy, ensure thermal comfort, and support mixed mode with natural ventilation (as appropriate).

There is growing evidence that dedicated outside air systems (DOAS) with separated thermal conditioning save substantial energy while supporting adaptable ventilation delivery based on occupancy and health alerts. These systems are designed to bring in 100% outside air to meet all ventilation loads in each zone/ terminal unit. These dedicated outside air systems assume appropriately conditioned air, dehumidified as needed, with superior filtration, and exhausting an equivalent amount of return air to ensure that spaces are not pressurized or depressurized. DOAS is not designed to meet the cooling loads of spaces when temperatures or internal loads are high. They can meet the heating loads of spaces through appropriate supply air temperatures and excellent enclosure design. The remaining thermal loads are met by separate water or air systems dedicated to each zone or space, with piped water/refrigerant to split heat pump units or radiant units, or by ducted cool air. The DOAS and thermal conditioning may be kept independent (decoupled) or merged at the terminal unit (coupled) in the occupied space, in the form of cooling/reheating of ventilation air or active chilled beams or combinations of these.

In a 2022 report on DOAS for new construction and retrofits in the State of California, PGE defined coupled and decoupled DOAS systems as distinct from DOAS units serving existing mixed-air systems (fig. 6.17).



DOAS Configuration Types

Decoupled DOAS Configurations

Fully decoupled HVAC systems provide ventilation air directly from an outdoor air unit to a zone or, downstream of a zone conditioning coil. This allows the zone conditioning fan to cycle on and off while the ventilation fan and supply is maintained.

Configurations that meet this type include:

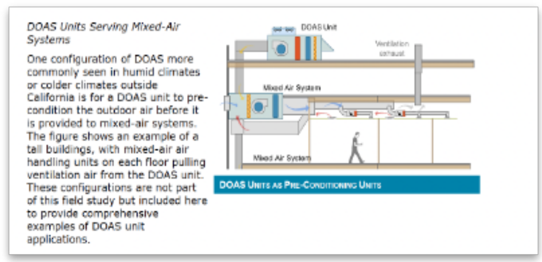
- Ventilation air ducted to the outlet of a space conditioning system's fan terminal unit, or downstream of any cooling and heating coils.
- Ventilation ducted directly to a space diffuser.

Coupled DOAS Configurations

Coupled DOAS configurations provide ventilation air to each zone by supplying ventilation air to the return path of a zone conditioning unit. Some configurations directly duct air to the return path of a zone unit while other systems duct ventilation air near the return and rely on a mixing plenum as shown in Figure 4.

- In coupled configurations, the ventilation pathway through the zone units may require zone unit fans to maintain a level of airflow to ensure indoor air quality is maintained. The figure shows a configuration with a ceiling plenum, though some buildings expose equipment and air can mix throughout the room. In either case, the coupled configuration can restrict the energy savings potential of DOAS with regard to zone fan control.

versus



DOAS Units Serving Mixed-Air Systems

One configuration of DOAS more commonly seen in humid climates or colder climates outside California is for a DOAS unit to pre-condition the outdoor air before it is provided to mixed-air systems. The figure shows an example of a tall buildings, with mixed-air air handling units on each floor pulling ventilation air from the DOAS unit. These configurations are not part of this field study but included here to provide comprehensive examples of DOAS unit applications.

fig. 6.17 Coupled and decoupled DOAS ventilation and HP thermal configurations compared to conventional DOAS feeding central AHU for mixed air/thermal delivery.

In depth thermal operations and power consumption data was collected in five California buildings ranging from 20,000-65,000 sqft with different types of DOAS units installed, including sensible heat recovery ventilators (HRV-DOAS), energy recovery ventilators (ERV-DOAS), direct expansion DOAS units (DX-DOAS), and slightly different thermal conditioning solutions - VRF with heat recovery and boilers with radiant panels.

The study identified 41-66% HVAC energy compared to the California benchmark for building energy end uses for HVAC in CEUS 2006 when the DOAS was designed for ventilation rates 100-140% of Title 24 (Dedicated Outside Air System Field Assessment Results at https://www.etcc-ca.com/reports/code-readiness-dedicated-outdoor-air-system-field-assessment-results). The PG&E DOAS study revealed that DOAS systems should have partial economizer capability for maximum energy savings, with OA sized for 40% above minimum and controlled between 100% and 140% using economizer logic.

DOAS with separate thermal conditioning now represents 20% of California new construction and 5% of retrofits of commercial buildings (one configuration in fig. 6.18).

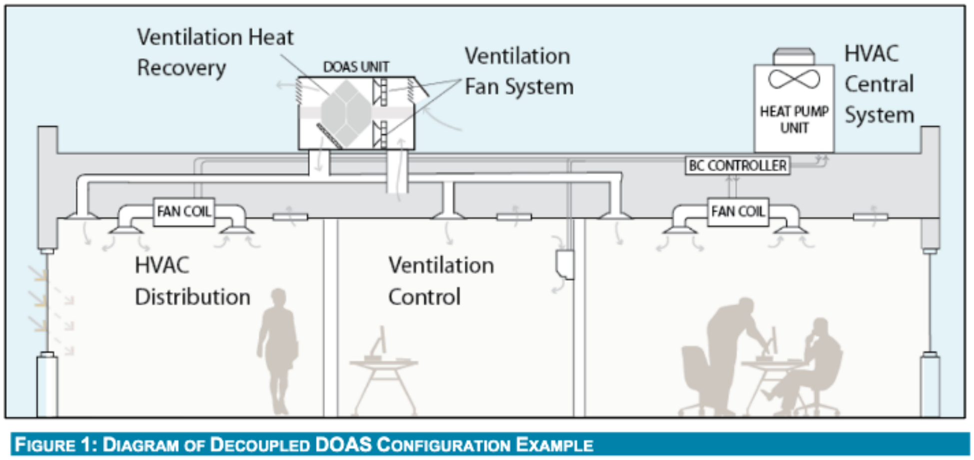


fig. 6.18 Decoupled DOAS and HP thermal retrofit configurations.

Oversized DOAS with separate thermal conditioning can be very effectively bundled with the **electrification of existing and new commercial buildings**. Thermal conditioning is delivered through much more energy efficient all-electric heat pumps and variable refrigerant flow piping (VRF) to terminal units. The dedicated outside air units are now designed to meet the maximum load of occupancy and health alerts with variable speed drives, and incorporate energy recovery ventilators to achieve the greater than 40% HVAC annual energy savings. The full suite of findings are transformative:

1. *Field monitoring of the four DOAS field sites with VRF revealed HVAC annual energy cost reductions of 41% to 66% compared to the California benchmark for building energy end uses for HVAC (CEUS 2006).*
2. *The use of heat recovery ventilation or energy recovery ventilation in a DOAS unit reduced HVAC annual energy costs by 4% to 14%.*
3. *The use of ventilation heat recovery reduced building electrical peak demand in summer months by 0.1 W/sf and 0.3 W/sf in winter months in mild climates (CZ03, CZ04). In the more extreme climate zone, CZ12, ventilation heat recovery was estimated to have reduced the summer peak by 0.5 W/sf and winter peak by 0.7 W/sf.*
4. *DOAS supply and relief fans in office and classroom sites used between 0.16 W/cfm and 0.57 W/cfm. Since most of the fans were smaller than the smallest fans regulated by the energy standard, the power per unit airflow was compared with*

the smallest fan power allowances the energy standard does regulate. On average, the ventilation fan system used 67% less power than the T24 2019 Part 6 requirements and 47% less power than fan power assumptions used in the 2022 Codes and Standards Enhancement (CASE) proposal for non-residential HVAC Controls (California IOUs, 2021).

5. *Across the four sites using a VRF heat pump system, the average operational power of all terminal unit fans (fan coils or fan cassettes) per site was 12%, 17%, 29%, and 69% of the installed maximum fan power at full airflow for each respective site. These findings suggest a significant potential for demand and energy savings from turn down of distributed fan terminal units with multi-speed controls.*
6. *DOAS configurations carry a first-cost premium compared with single zone RTUs and mixed-air VAV systems. Market research suggests that as VRF and other systems are adopted more widely, the overall cost of a DOAS configuration will become competitive.*
7. *Analysis of VRF heat pump energy use data indicates that sites used between 16% and 34% more cooling energy during airside economizing weather conditions than a comparable building with DOAS full economizing capabilities* would have (table 19). These findings suggest that variable speed heat pump systems such as VRF are more efficient than the energy standard recognizes today, which may provide opportunities for further code enhancements.*

   For the purposes of this comparison, the authors assumed that the economizer on a system with full economizing capabilities would provide 85% of the cooling load when outdoor temperatures are between 56F and 65F and 15% of the cooling load when outdoor temperatures are between 66F and 75F.

This study gathered explanations for the benefits of decoupled DOAS and thermal conditioning from a host of past studies (DOE, 2017), (Heller, Baylon, & Oram, 2014), (A10, NBI, Pathfinder E&A, 2021) (NEEA Pilot sites for Very High Efficiency (VHE) DOAS, 2016-2018) (NEEA) Very High Efficiency DOAS System Requirements (NEEA_VHE-DOAS, 2021). The benefits of decoupled DOAS configurations include:

1. *Small ventilation-only systems can be designed at very low pressure given the small volume of air they move, reducing fan energy.*
2. *Separation of ventilation from heating and cooling allows for zone (thermal) conditioning fans to be fully shut off when there is no call for heating and cooling.*
3. *Multi-speed zone fans, in the case of fan coils, or variable speed pumps in the case of hydronic systems such as chilled beams or radiant panels and slabs,*

can cycle to lower speeds to match thermal loads and thereby reduce distribution energy.

4. *Space conditioning systems can utilize very high efficiency cooling and heating since the need to control moisture is managed by the ventilation air and in systems with ventilation heat recovery, extremely cold air is pre-conditioned reducing the heating intensity required.*
5. *Using ventilation heat recovery or energy recovery to supply tempered air and eliminating the need for additional, active heating or cooling of the ventilation air in California's dry climate can be a cost-effective solution to reduce both annual heating and cooling energy, as well as peak demand.*
6. *Dehumidification and temperature control can be separated, with a DOAS unit managing moisture control and space conditioning units maintaining thermal control. Decoupled DOAS can reduce unnecessary dehumidification that occurs in mixed air systems that provide cooling with cold dry air.*
7. *Decoupled DOAS configurations can be used to reduce the overall size of a building HVAC system's physical size, using smaller ducts for ventilation and, when utilizing VRF systems, running refrigerant piping for space conditioning. Through a holistic building design, this approach can reduce overall project cost and maximize usable space by reducing floor to floor heights in tall buildings and dedicating less space to mechanical equipment while saving energy.*

2020 NEAA Study of Retrofit Decoupled DOAS and Thermal in Low-rise Commercial Buildings

In a parallel report on pilot low-rise commercial projects, published in 2020 by NEAA in collaboration with NYSERDA, IMT and Better Bricks, the benefits were summarized:

"DOAS separates the functions of building ventilation and building heating and cooling so that each of these critical building functions can be optimally controlled." In eight small commercial building demonstration sites, the HVAC rooftop retrofit research captured 43-85% HVAC energy savings, 8-63% total energy savings, significant improvements in self-reported indoor air quality and thermal comfort, and reduced equipment sizing and complexity.

"The eight projects used the separate control systems that come with the Ventacity HRVs (including those enabling scheduling, economizing, and demand control ventilation), combined with the controls that came with the respective VRF/VRV or DHP systems. In most projects, this HRV/VRF (or DHP) combination replaces one or more packaged or split systems of 10 tons or less in capacity—systems that inefficiently combine space conditioning and ventilation air. Ceiling radiant hydronic heating and cooling systems, now standard practice in Europe, would also be an ideal heating and cooling system type for such conversions." Office project EUI's were reduced by 10-60%. 5 of these projects also replaced the existing gas heating with electric systems and resulted in 13-59% reductions in peak demands in summer with much less variable seasonal demand for electricity. In the cases where winter electric demand increased, the increase was modest, and was the result of relatively low fan power in the existing HVAC and the addition of heat pump heating (load profile changes for 1 of 8 pilot buildings fig. 6.19).

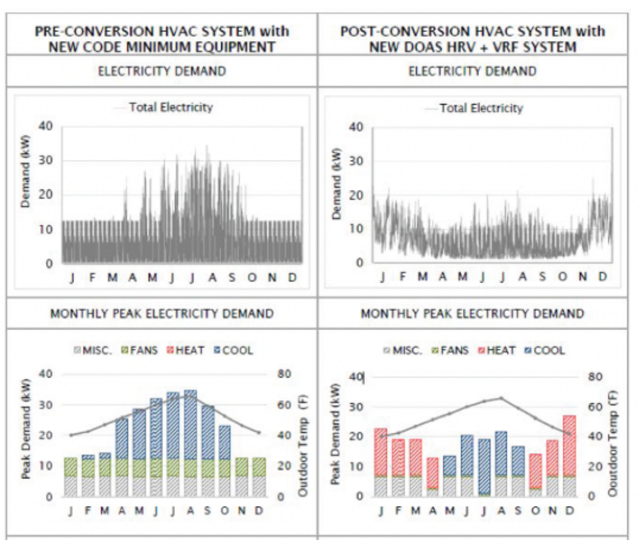


fig. 6.19 Before and after performance of 12,000 sqft law office in Portland, OR.

Electrification of Buildings through DOAS with separate thermal conditioning

As GSA begins to electrify buildings presently using natural gas, the overwhelming advantage of dedicated outside air systems with separate heat pump thermal conditioning systems should define the investments for four key outcomes: carbon and energy efficiency, improved ventilation rates without energy penalty, and improved thermal controls for the occupants.

In the PGE case studies, the resulting total energy use at the site (site EUI) ranged from 19 to 52 kBtu/sqft/yr, in competition with the net zero energy buildings (NZEB). By comparison, the energy demand of similarly sized commercial office projects, designed to meet the range of state and federal standards in place at the date of construction, are shown on the right in fig. 6.20.

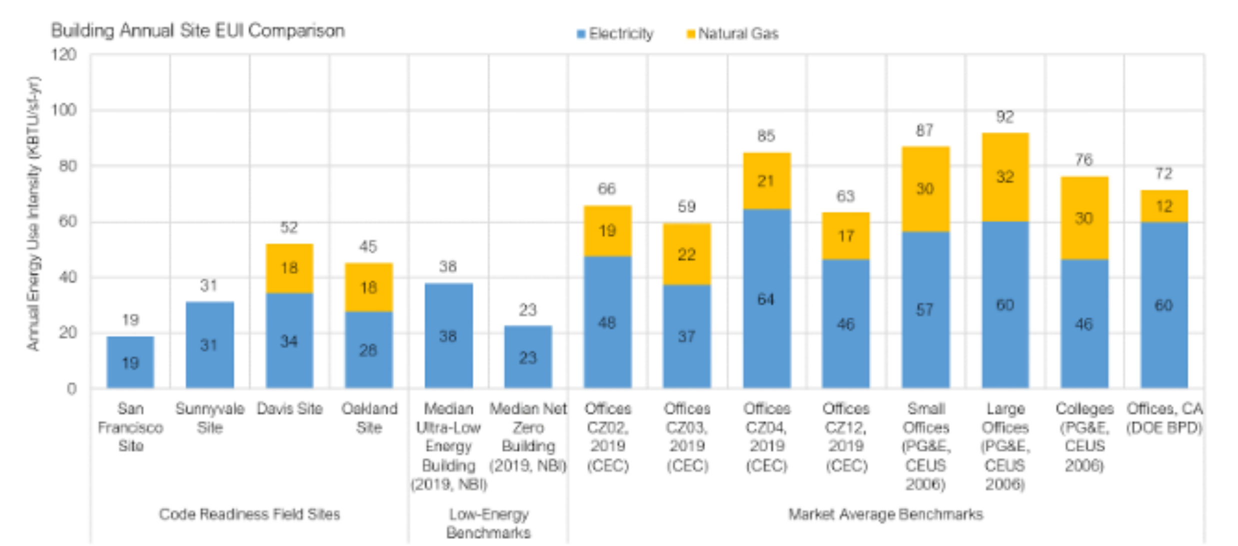


fig. 6.20 Building annual site EUI comparison (PGE 2022) .

Until central system upgrades are made, however, it may be possible to compare the zone delivery of outside air (cfm, ACH or CO2) in existing buildings that have dedicated ventilation systems (CV or VAV based on ventilation demand) operated independently of thermal conditioning. If the HVAC system already has terminal re-heat and re-cool with occupancy-centric constant volume air delivery, or has separate ventilation and thermal conditioning systems, then zone delivery of OA breathing air can be independent of thermal demands and optimized for health, in most cases with energy savings. Field assessment of zone IAQ in existing DOAS buildings can be compared to zone IAQ in existing buildings with mixing ventilation through VAV diffusers (driven by thermostats), with parallel assessment of health and energy performance.

The electrification of federal buildings provide an opportunity to introduce heat pumps and zone VRF units for thermal conditioning separated from the delivery of filtered outside air for before and after assessment of IAQ, health and energy - a critical Green Proving Ground innovation.

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