WELL V2:

EVIDENCE BEHIND THE AIR CONCEPT

FEATURE A01: FUNDAMENTAL AIR QUALITY

OVERVIEW

Part 1: Meet thresholds for permissible concentrations of $PM_{2.5}$ and PM_{10}.
Part 2: Meet thresholds for permissible concentrations of select volatile organic compounds.
Part 3: Meet thresholds for maximum allowable concentrations of carbon monoxide and ozone.
Part 4: Meet the threshold for the maximum allowable concentration of radon or meet mechanical ventilation requirements.
Part 5: Monitor pollutant levels at least once a year following sampling guidance provided in the WELL Performance Verification Guidebook and submit results annually to the WELL digital platform.

SCIENTIFIC BACKGROUND

- Ventilation systems bring outdoor air indoors, and without proper treatment, pollutants can enter the space. Approximately 65% of exposure to outdoor air pollution occurs indoors, thus managing both indoor and outdoor pollutants is necessary to achieve holistic building air quality.[1]

KEY HEALTH AND WELL-BEING EFFECTS

- Poor environmental conditions in the workplace are associated with employee productivity losses of up to 10%.[2-5]
- Particulate matter (PM) air pollution is a complex mixture of small, solid particles and liquid droplets. Inhaling elevated levels of PM has been shown to lead to various adverse health effects primarily associated with the cardiopulmonary system.[6] Exposure to high levels of PM is the leading source of mortality among all outdoor air pollutants.[1]
- Exposure to volatile organic compounds (VOCs), such as benzene, formaldehyde or toluene, is associated with irritation of the eye, nose and throat, as well as liver and kidney damage.[7]
    - Effects on the central nervous system (CNS), including dizziness or loss of coordination, may be an early indication of VOC exposure. VOCs are known to permeate lipid membranes making the brain an easy target due to its high lipid content.[8]
    - There are documented hematological effects, such as aplastic anemia, thrombocytopenia and leukemia, which have been seen among workers who have experienced long-term occupational exposure to airborne benzene concentrations greater than 3.25 mg/m^3.[9]
    - Exposure to formaldehyde (0.36 mg/m^3 for four hours) has been shown to cause eye irritation in humans. The International Agency for Research on Cancer (IARC) recognizes sufficient evidence that formaldehyde can cause both nasopharyngeal cancer and myeloid leukemia.[9]
    - Acute exposure to elevated airborne levels of toluene can cause nervous system dysfunction and narcosis. Chronic occupational exposure has also been related to adverse neurobehavioral effects, in addition to eye, nose and throat irritation.[10]
- Carbon monoxide (CO) is associated with fatigue, headaches, nausea and other health effects, including death.[9,11,12]
- Ozone (O_3) can trap air in parts of the lungs, adversely affecting lung function and triggering respiratory symptoms like wheezing, coughing, chest pain and shortness of breath, and making the lungs more susceptible to damage and disease.[13-15]
    - Short-term exposure to ozone is associated with several adverse health effects, including increases in mortality.[16]
- Among nonsmokers, indoor exposure to radon is the leading cause of lung cancer in many countries.[17,18]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Monitoring exposure levels of different population groups, especially sensitive individuals, is key to running successful health impact assessments and mitigating health risks associated with poor air quality.[19]
- A study in the United States spanning seven years has shown that for every 10 $\mu g/m^3$ decrease of $PM_{2.5}$, there is a corresponding increase in life expectancy of 0.35 years.[20]
- The U.S. National Ambient Air Quality Standards (NAAQS) enforce an annual mean (averaged over three years) threshold value of 15 $\mu g/m^3$ as a secondary standard for $PM_{2.5}$.[21]

    - NAAQS secondary standards are designed to protect public welfare, including the protection of animals, crops and buildings. NAAQS primary standards are focused on public health protection, including the protection of sensitive individuals (such as people with asthma, children or older adults), and are typically more stringent than secondary standards.[21]
- The World Health Organization (WHO) recommends that PM_{10} levels do not exceed 50 $\mu g/m^3$ (24-hour concentration).[22] The WHO also provides higher interim targets if the recommended level is not achievable but notes health risks increase as PM_{10} levels rise. Data from developed and developing countries indicate that for every 10 $\mu g/m^3$ increment in daily concentration of PM_{10}, there is a 0.5% increase in mortality.[22]
- The WHO does not endorse a specific threshold of benzene – a genotoxic carcinogen – that is deemed to be "safe." The WHO recommends reducing indoor exposure levels as much as possible by avoiding smoking tobacco, specific cleaning solvents and materials that off-gas benzene, to lower the risk of adverse health effects related to exposure.[9]
- While symptoms such as skin or eye irritation may be prevented by keeping formaldehyde below 100 ppb, many regulatory bodies recommend lower limits of formaldehyde, primarily to protect against cancer, including 44 ppb, 9 ppb, and below the limits of detection.[23-26]
- The California Office of Environmental Health Hazard Assessment (OEHHA) in the United States provides Chronic Reference Exposure Levels (CRELs) for the maximum allowable concentration of individual component VOCs. These thresholds are based on research indicating a reduced likelihood of severe adverse health effects (excluding cancer) in the general population, including sensitive individuals under conditions of chronic exposure (defined as 10 years or longer).[23]
    - Reduced likelihood of nervous system, respiratory system and developmental impacts have been associated with concentrations at or below 300 ug/m^3.[27]
- The WHO recommends a guideline value of 9 ppm of CO for eight-hour weighted averages to prevent carboxyhemoglobin (COHb) levels in humans from rising above 2.5% based on studies with non-smokers.[28]
    - Increased levels of COHb impairs the oxygen-carrying capacity of blood and is the primary reason for adverse health effects associated with CO exposure.[28]
- O_3 levels below 100 $\mu g/m^3$ provide adequate protection against adverse health effects.[9]
- Radon is odorless, colorless and tasteless, and enters working and living spaces through cracks in building foundations.[29] The WHO has established that there are no safe levels of radon exposure as even very low levels of exposure pose health risks, particularly for lung cancer, so the aim should be to eliminate radon exposure whenever possible[18].
    - The U.S. Environmental Protection Agency notes that while radon levels less than 4 pCi/L may still pose a risk, this can serve as a threshold value for intervention.[29]

FEATURE A02: SMOKE-FREE ENVIRONMENT

OVERVIEW

Part 1: Prohibit smoking and the use of electronic cigarettes (e-cigarettes) in indoor spaces.
Part 2: Prohibit smoking as noted by signage in immediately adjacent outdoor areas and require educational signage on the harmful effects of smoking in more distal areas within the project boundary that allow smoking (if any).

SCIENTIFIC BACKGROUND

- There are many types of tobacco products, but the most popular form of nicotine use globally is through smoking cigarettes.[30]
    - Cigarettes contain and produce though combustion (i.e., burning) several thousand harmful chemicals. Nicotine is of particular interest because of its psychoactive properties (i.e., affecting the brain) – it is powerfully addictive and induces behavioral changes such as increased attention, anxiety reduction and appetite suppression.[30-33] This psychoactive affect also explains some of the withdrawal symptoms associated with quitting tobacco, which include irritability, depressed mood, decreased heart rate and increased appetite.[30-33]
- Globally, tobacco use is responsible for killing half of its 1.1 billion users, including more than seven million people a year.[34] If trends continue, by 2030 tobacco use will cause an estimated 10 million deaths every year — a preventable death every three seconds that would eclipse deaths by any other cause.[35]
- Smoking tobacco directly can affect the smoker and also have negative impacts on the people in the surrounding environment through secondhand and thirdhand smoke exposure.[36]
    - Secondhand smoke exposure occurs when smoke is inhaled by people in the environment near the smoker.
    - Thirdhand smoke exposure occurs when people, through direct contact or off-gassing, are exposed to residual chemicals from smoking that stay in the air, in dust or on surfaces, such as clothing, hair, carpets and walls.
- E-cigarettes are relatively new products that evaporate liquids containing humectants, flavorings, and usually some amount of nicotine. Oftentimes, they are used in tobacco smoking cessation efforts and meant to replace the use of traditional cigarettes. But more long-term data is needed to further understand health effects associated with use.[37]

KEY HEALTH AND WELL-BEING EFFECTS

- There is no safe level of exposure to tobacco smoke, but an estimated 1.1 billion people smoke tobacco worldwide. Smoking kills more than seven million people annually.[38,39]
- Smoking harms nearly every organ in the body and causes several cancers (lung, liver, colorectal, prostate, breast), respiratory diseases (chronic obstructive pulmonary disease, tuberculosis, bronchitis), cardiovascular problems (stroke, angina, heart attacks) and other adverse health outcomes such as diabetes, rheumatoid arthritis, and a compromised immune system.[40-42]
- Eliminating the presence of secondhand smoke can prevent “involuntary smoking” and the onset of several adverse health effects accounting for more than 890,000 premature deaths per year.[39]
- Removing opportunities for thirdhand smoke to persist in the environment protects people from further exposure to nicotine and a number of other harmful contaminants, including potential carcinogens that form as a function of chemical interactions between thirdhand smoke and other air contaminants.[43-45]
- Most secondhand smoke exposure occurs in homes and offices, making these environments particularly important for intervention for children and nonsmokers. Children are an important group to consider in tobacco prevention campaigns overall. In particular, they are uniquely susceptible to both secondhand and thirdhand smoke exposure as data in homes demonstrate particularly well.[46-49]
    - A 2011 study demonstrated that thirdhand smoke persists in homes months after smokers vacate the residence, even if the homes are cleaned, re-carpeted and painted.[50]
- Health risks specific to the use of e-cigarettes are unclear, as is the actual effectiveness of e-cigarettes in aiding tobacco cessation efforts. Some studies suggest that e-cigarettes are indeed useful tobacco replacement products, while others note that growing data on the liquids used (especially flavorings) may be associated with adverse health outcomes, and e-cigarettes in general may re-normalize smoking and represent a new avenue for engaging people who would otherwise remain nonsmokers.[51-56]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- The best way to protect people against the harmful effects of direct, secondhand and thirdhand smoke is to create completely smoke-free environments.[40,49,57]
- Studies conducted in Ireland, Italy, the United States and Brazil have demonstrated that contaminant levels in indoor environments are significantly reduced following smoking bans.[58-61]
- Eliminating the positive promotion and advertising of tobacco products can decrease tobacco consumption by up to 7% on a country level and prevent up to a third of all cases of children experimenting with cigarettes and other tobacco products.[39,62]

ADDITIONAL NOTES

- Around the world, smoking is more common in males than in females, and in low- and middle-income countries than in higher-income countries. Smoking rates also vary across racial, ethnic and socioeconomic groups, as well as by age and educational attainment level.[38]
- The World Health Organization (WHO) notes that smoking is generally on the decline around the world, but the prevalence of smoking may actually be rising in the WHO Eastern Mediterranean and African Regions.[38]

FEATURE A03: VENTILATION DESIGN

OVERVIEW

Part 1: Meet mechanical ventilation supply and exhaust rates as prescribed in specified design guidelines or meet natural ventilation design requirements and ensure outdoor ambient air is acceptable.

SCIENTIFIC BACKGROUND

- Both humans and buildings need to engage in a process of ventilation to exchange the gases needed by their "occupants" (people or cells).
- Ventilation is another word for breathing. When humans breathe, oxygen-rich air is drawn into the lungs and gas is exchanged with the circulatory system, delivering oxygen to tissues all over the body via the bloodstream.[63] CO_2-rich air then is expelled out of the lungs.[63]
- Building ventilation mirrors this process of inhalation and exhalation. Air is supplied to and removed from spaces at specific speeds, volumes and rates of exchange, by mechanical and/or natural systems.[64]
- In the United States, ASHRAE Standard 62.1 and 62.2 are widely referenced voluntary indoor air quality standards that set minimum ventilation rates acceptable to building occupants. ASHRAE describes air exchange rate, HVAC (i.e., heating, ventilation, air conditioning) design and the use of outdoor air quality data when creating a building ventilation system.
- In Europe, indoor air quality standards and associated ventilation rates are set by the European Committee for Standardisation (CEN) or the Chartered Institution of Building Services Engineers (CIBSE). CEN and CIBSE generally set higher minimum ventilation rates compared to ASHRAE.

KEY HEALTH AND WELL-BEING EFFECTS

- Low ventilation rates are associated with increased illness, absence, sick building syndrome (SBS) symptoms, negative odor perceptions and reduced task performance.[65-67]
    - Sick building syndrome refers to a condition in which building occupants experience acute health effects with no known cause, which appear to be connected to the length of time spent within the building. The associated symptoms, ranging from headaches and dizziness to nausea, are often relieved upon leaving.[68] SBS is most frequently attributed to poor ventilation and has also been associated with off-gassing by some newly installed building materials and furnishings.[69]
- Children are particularly vulnerable to the health effects of poor indoor air quality. Student attention and performance has been shown to be diminished in classrooms where ventilation rates are low.[70]
- Typical indoor air pollutants which need to be addressed by the building's ventilation system are PM, CO, O_3, CO_2 and VOCs.
    - Inhaling elevated levels of PM have been shown to lead to various adverse health effects primarily associated with the cardiopulmonary system.[6] Exposure to elevated levels of PM is the leading source of mortality among outdoor air pollutants.[1] However, a reported 65% of exposure to outdoor air pollutants occur when an individual is indoors; thus managing pollutants of both indoor and outdoor origin is necessary to achieve comprehensive building air quality.[1]
    - Carbon monoxide (CO) exposure is associated with fatigue, headaches, nausea and other symptoms, including death, as a result of CO poisoning.[11,12,71]
    - Ozone (O_3) can trap air in parts of the lungs, adversely affecting lung function and triggering respiratory symptoms like wheezing, coughing, chest pain and shortness of breath, making the lungs more susceptible to damage and disease.[13-15]
    - Current literature has supported that levels at 1,000 ppm can have health effects on humans.[72] CO_2 levels of 1,000 ppm have been observed in spaces such as poorly ventilated bedrooms, offices, classrooms, trains and planes.[72]
    - Exposure to volatile organic compounds (VOCs) is associated with irritation of the eye, nose and throat, as well as liver and kidney damage.[7] Effects on the central nervous system, including dizziness or loss of coordination, may be an early indication of VOC exposure, as VOCs are known to be able to permeate lipid membranes, making the brain an easy target due to its high lipid content.[8]

- A growing body of evidence over the last two decades has shown that ventilation rates exceeding rates set by air quality standards like ASHRAE Standard 62.1 and 62.2 can improve productivity and reduce sick building syndrome symptoms in occupants.[73] There may also be significant cognitive and task performance increases, as well as sick leave reductions.[74-76]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- When removing or reducing indoor pollution sources is not possible, ventilation (mechanical or natural) can reduce their effect by replacing polluted indoor air with clean outdoor air.[77]
    - If properly designed, natural ventilation can reduce operating costs and reliance on fossil fuels compared to mechanical ventilation systems while still providing sufficient air change rates for acceptable occupant comfort and indoor air quality.[78-80]
- Ventilation rates established in building standards represent the most widely used guidelines for building design but are often not based on public health research and rather focus on data based on sensory perceptions of air quality (e.g., odors).[64,81,82] Ventilation rates in these standards are intended to ensure that a certain threshold percentage of people as defined in the respective standard do not express dissatisfaction with indoor air quality, meaning that while health requirements are considered to some extent, rates are established more as a function of minimizing risks of sensory discomfort[64].
- Research that does focus strictly on health effects finds that increased ventilation is associated with reduced rates of SBS and potential improvements in cognitive abilities and other respiratory health effects.[83-85]
- Studies indicate that ventilation rates below five to 10 L/s-person (liters of outdoor air delivered to the space per second for each occupant) corresponds to a 23% increase in SBS symptoms in occupants, and as ventilation rates increase from 10 to 25 L/s-person there is also a corresponding 29% decrease in the prevalence of SBS systems.[83]
    - Other reviews indicate that the lowest ventilation rates where no negative health effects were observed in occupants were approximately 6-7 L/s-person, though some older studies have proposed higher minimum acceptable ventilation rates, ranging from 10-25 L/s-person to eliminate all health risks.[86-89]
    - Higher ventilation rates, when utilizing non-energy efficient technologies, can also mean higher rates of energy consumption and subsequent increases in greenhouse gas emissions.[64] In these instances the immediate benefits to indoor air quality must be weighed against contributions to climate change and poorer environmental health conditions at large.[64] Many of the design guidelines set by organizations like ASHRAE and CEN accordingly consider energy-related factors in setting ventilation rates.

FEATURE A04: CONSTRUCTION POLLUTION MANAGEMENT

OVERVIEW

Part 1: Requires projects to maintain indoor air quality during building construction and renovation through a combination of strategies such as envelope protection, moisture and dust management, filter replacement, air flush and proper construction equipment selection.

SCIENTIFIC BACKGROUND

- The construction industry is one of the primary sources of air pollution in many countries.[90]
- Increasing urbanization is expected to increase air pollution and greenhouse gas (GHG) emissions from construction sources.[91,92]
- Standards on levels of particulate matter released from construction activities vary internationally, but protections for workers are often inadequate.[90,93]
- Indoor air quality levels can be compromised during building construction and renovation.
- Indoor air quality is affected by both sources of pollution generated indoors as well as from pollutants that enter buildings from outdoors.[94]
- Building construction and renovations are mostly a source of coarse particulate matter, but they may also be source of airborne ultrafine particles.[95,96]

KEY HEALTH AND WELL-BEING EFFECTS

- Air pollution originating from construction and demolition work is associated with increased mortality owing to chronic obstructive pulmonary disease (COPD) among people working and residing nearby.[90,97]
    - A systematic review found that 15-20% of COPD rates among construction workers could be attributed to occupational exposures.[98]
- Urban spaces and residents surrounding construction sites experience PM_{10} exposure increases as well.
    - In Chicago, the demolition of three separate high-rise public housing sites between January 2003 and February 2004 was linked to a 74% increase in PM_{10} levels (24-hr averaging time) 100m downwind of the sites.[99]
    - The London Atmospheric Emissions Inventory (LAEI) estimates that construction related activities accounted for 1.4% of total PM_{10} levels citywide from 2010.[100]
    - Another study, focusing on measurements taken between January 2002 and December 2013, observed that PM_{10} carried downwind from London-based construction sites in significant concentrations, when assessing concentrations between working hours and non-working hours.[101]
- Long-term exposure to PM has been linked with numerous chronic health conditions, such as cardiovascular disease, inflammatory lung injury, subclinical atherosclerosis, increased onset of COPD, as well as premature death due to cardiovascular mortality.[102]
    - Sources of on-site irritants include blowing dust, exhaust from construction vehicles and exhaust from daily surrounding traffic.[103]
- Increased emissions of PM_{10} in the vicinity of construction sites are associated with an increased risk of respiratory disease.[103]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Proper mitigation of risks during construction and renovation can help maintain indoor air quality and reduce negative implications on health and well-being.
- The 2007 SMACNA IAQ Guidelines for Occupied Buildings Under Construction suggest sealing ducts during construction to prevent contaminants from entering the HVAC system during construction.[104]
- Proper installation of media filters and replacing them after construction and before occupancy can help to limit the introduction of contaminants in the occupied space, as well as limit outdoor air pollution and $PM_{2.5}$.[96,105,106]
    - Improper installation and maintenance can reduce a filter's Minimum Efficiency Reporting Value (MERV) rating and its capacity to filter the particle size for which it is graded.[107]
- Industry standards suggest storing absorbent materials such as carpeting, fabric and other materials away from construction zones to reduce contamination before installation.[105]
    - Carpets hold and release more dust than hardwood due to the suspension of particles containing microbes

after physical disturbance, such as walking, and are an important source of exposure to indoor particulates.[108]

- Industry standards suggest a best practice of sealing active work areas from other areas to reduce contamination across spaces.[104]
- Walk-off mats may be used to reduce transfer of contaminants from outdoors to indoors.[105]
    - Foot traffic transfers dirt and other contaminants from outdoors to indoors. During dry weather conditions, 1,000 people entering a building can carry roughly a quarter pound of dirt into the building.[109]
    - Installing walk-off mats at entryways connected to outdoor spaces can help mitigate airborne particles and dust, which supports reduction of the incidence of respiratory disorders such as asthma.[109]

ADDITIONAL NOTES

- Demographic information on construction workers suggests that the population is aging and therefore, more susceptible to cardiopulmonary problems.[90,110]
- Children also are particularly vulnerable to air pollution. Exposure to NO_2 early in life can lead to allergenic diseases such as asthma and long-term negative effects on lung function.[111,112]
- Seasonal fluctuations in temperature and the effects of climate change, including increases in annual mean temperatures and extended periods of warm days, can impact levels of air pollutants, such as O_3 and NO_2.[113]

FEATURE A05: ENHANCED AIR QUALITY

OVERVIEW

Part 1: Further reduce contaminant levels for both $PM_{2.5}$ and PM_{10} beyond thresholds set in the precondition.
Part 2: Further reduce volatile organic compound (VOC) levels beyond thresholds set in the precondition and focuses on minimizing benzene exposure.
Part 3: Further reduce carbon monoxide levels beyond thresholds set in the precondition and introduces limits for nitrogen dioxide.

SCIENTIFIC BACKGROUND

- Airborne contaminants in outdoor air originate most often from traffic or industry sources, tobacco smoke, biomass fuels, and certain building materials and furniture.[114-116]
- These contaminants not only come into contact with our eyes, nose and skin but also enter our bodies when we breathe, primarily affecting lung function and respiratory health and sometimes triggering downstream effects in other body systems.[117-121]
- For many contaminants, such as the ones addressed by this feature, health effects vary depending on the dose or the length of time exposed and whether it accumulates in our bodies over time.
- The best way to minimize our chances of getting sick is to limit or completely restrict exposure to such airborne contaminants in the first place.

KEY HEALTH AND WELL-BEING EFFECTS

- Inhaling elevated levels of particulate matter (PM) has been shown to lead to various adverse health effects primarily associated with the cardiopulmonary system.[6] Exposure to high levels of PM is the leading source of mortality among outdoor air pollutants.[1]
- There is evidence that acute acetaldehyde exposure can cause eye, nose and throat irritation. At high concentrations (350–1,000 mg/m^3) bronchoconstriction in people with asthma was also reported.[122]
- Acrylonitrile is classified as a probable human carcinogen by the Environmental Protection Agency (EPA). Short-term occupational exposure is associated with mucous membrane irritation, headaches, dizziness, and nausea.[123]
- Restricting exposure to benzene can further help to reduce the risk of various blood disorders, including anemia and acute myeloid leukemia.[124-126]
    - A study in Chinese offices, homes, schools and restaurants found that in each environment, benzene alone accounted for 40% or more of the lifetime cancer risk to occupants.[127]
- Both acute and chronic occupational inhalation of caprolactam has been associated with headaches, malaise, confusion, and nervous irritation. There is evidence that acute exposure can also cause a burning sensation in the eyes.[128]
- Restricting exposure to formaldehyde can help prevent nasopharyngeal cancer and leukemia, and potentially sinonasal cancer as well.[117]
    - A small subset of the working group for formaldehyde at the International Agency for Research on Cancer considered the evidence limited in showing that formaldehyde causes leukemia.[129]
    - Some studies suggest formaldehyde may also have adverse reproductive and developmental effects, but the evidence is inconclusive, and more research is needed to determine if such associations exist.[130]
- Protecting people from exposure to contaminants in the air such as formaldehyde and benzene can help prevent eye, nose and throat irritation.[120,121,131]
- Restricting exposure to naphthalene can help prevent respiratory tract lesions, including upper respiratory tract tumors and hemolytic anemia.[9]
- Acute exposure to elevated airborne levels of toluene can cause nervous system dysfunction and narcosis. Chronic occupational exposure has also been related to adverse neurobehavioral effects, in addition to eye, nose and throat irritation.[10]
- Monitoring and limiting carbon monoxide in the air can help prevent fatigue, headaches, nausea, and other symptoms, including even death as a result of carbon monoxide poisoning.[132-134]
- Restricting nitrogen dioxide protects against an increased risk of respiratory infection, and some studies suggest it may also protect against the development of diseases such as emphysema and bronchitis.[22,135-137]

- Nitrogen dioxide often serves as a proxy for a cocktail of other contaminants in the air created through combustion sources (e.g., fireplaces, gas stoves, space heaters).[138]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- $PM_{2.5}$ levels below 12 μg/m^3 help ensure the protection of sensitive populations, including people with asthma, children and the elderly.[139]
  - These levels and associated health effects refer to long-term particulate matter exposure, meaning thresholds are determined based on annual mean concentration levels, typically averaged over three or four years.
- $PM_{2.5}$ levels below 10 μg/m^3 can prevent increases in risk for cardiopulmonary and lung cancer deaths as well as total deaths.[134,140]
  - Studies in several cities in the United States report that increases in the risk of adverse health effects are observed even between 11 - 15 μg/m^3 annual mean concentrations of $PM_{2.5}$.[141]
  - The World Health Organization converts 10 μg/m^3 $PM_{2.5}$ to a corresponding 20 μg/m^3 PM_{10} value for long-term exposures using a $PM_{2.5}$/ PM_{10} ratio of 0.5 based on typical concentrations found in urban areas.[134]
- PM_{10} levels below 30 μg/m^3 are associated with an approximate 12% reduction in risk of disease and early death compared to when PM_{10} levels are at 70 μg/m^3.[134]
- Acetaldehyde levels are anticipated to have no respiratory health effects at concentrations at or below 140 μg/m^3.[27]
- The impacts of acrylonitrile on respiratory symptoms can be minimized if concentrations remain at or below 5 μg/m^3.[27]
- Benzene levels below 3 μg/m^3 may protect against noncancerous health effects while restricting benzene entirely can help protect against the destruction of red blood cells.[121,142,143]
- Respiratory symptoms and sensory irritation of the eyes related to occupational exposure of caprolactam can be reduced if concentrations fall at or below 2.2 μg/m^3.[27]
- While symptoms such as skin or eye irritation may be prevented by keeping formaldehyde below 100 parts per billion (ppb), many regulatory bodies recommend lower limits of formaldehyde, primarily to protect against cancer, ranging from 44 ppb to 9 ppb to below the limits of detection.[117,121,144-146]
- The risk of adverse naphthalene-related health effects on the respiratory tract can be minimized if naphthalene levels are at or below 9 μg/m^3.[27]
- Reduced likelihood of nervous system, respiratory system and developmental impacts have been established when toluene concentrations are at or below 300 μg /m^3.[27]
- Carbon monoxide levels below 6 parts per million (ppm) facilitates maximal exercise ability and helps reduce the risk of cardiovascular disease.[147]
- Nitrogen dioxide below 21 ppb (40 ug/m^3) has been a long-standing international guideline for chronic exposure, and some studies suggest that improvements at increments of about 30 μg/m^3 can prevent a 20% increased risk of respiratory illness in children between 5 to 12 years old.[22,148]

ADDITIONAL NOTES

- Certain populations are more sensitive to the potential adverse health effects triggered by contaminants in the air compared to the average person. These include children, the elderly, and people with asthma or other pre-existing conditions that may be exacerbated.[121,148-150] Ensuring the enhanced air quality conditions may, therefore, be particularly effective in environments that cater to such vulnerable populations.
- Furthermore, these contaminants are particularly important to consider in developing countries where a higher proportion of the population may use biomass fuels indoors. This often means women and children are especially vulnerable to the adverse health effects posed by poor indoor air.[151,152]

FEATURE A06: ENHANCED VENTILATION DESIGN

OVERVIEW

Part 1: Increase outdoor air supply rates or implement demand-controlled ventilation for mechanically ventilated spaces or implement an engineered system for naturally ventilated spaces.
Part 2: Implement displacement ventilation for heating and/or cooling of regularly occupied spaces, and advanced air distribution in workstations through personalized ventilation strategies.

SCIENTIFIC BACKGROUND

- When removing or reducing indoor pollution sources is not possible, ventilation (mechanical or natural) can replace polluted indoor air with outdoor air.[77]
    - In the United States, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.1 is a widely referenced voluntary indoor air quality standard that sets minimum ventilation rates acceptable to building occupants, but this standard is not based on public health research.[81,82]
    - In Europe, indoor air quality standards and associated ventilation rates are set by the European Committee for Standardisation (CEN) or Chartered Institution of Building Services Engineers (CIBSE). CEN and CIBSE set higher minimum ventilation rates compared to ASHRAE.
- Carbon dioxide (CO_2) concentration is a proxy measure for ventilation effectiveness and indoor air quality, which can be readily measured using relatively low-cost sensors. In addition to simply increasing the amount of outdoor air supplied to the space, there are several mechanical ventilation methods for maintaining low CO_2 indoors.
    - Natural ventilation can reduce indoor pollutant levels and promote air flow through opening windows and doors.[153]
    - A sensor-controlled strategy, demand-controlled ventilation, saves energy in buildings by measuring CO_2 levels and adjusting the rate of air supply to prevent exceeding pre-determined CO_2 thresholds.[75,154]
    - Displacement ventilation introduces air through floor diffusers at low velocity and exhausts it through the ceiling. In doing so, more fresh air arrives in the breathing zone compared to a ceiling supply system. It has been used and studied in a variety of indoor spaces, including offices, schools, hospitals and airplanes.[155-158]

KEY HEALTH AND WELL-BEING EFFECTS

- Low ventilation rates are associated with increased illness, missed work days, sick building syndrome (SBS) symptoms, negative odor perceptions and reduced task performance.[65-67]
    - Sick building syndrome refers to a condition in which building occupants experience acute health effects with no known cause, which appear to be connected to the length of time spent within the building. The associated symptoms, ranging from headaches and dizziness to nausea, are often relieved upon leaving.[68]
- A growing body of evidence during the last two decades has shown that ventilation rates exceeding rates set by air quality standards such as ASHRAE 62.1 can improve productivity and task performance and reduce sick building syndrome and sick leave among occupants.[73-76]
    - In an environmentally-controlled study of office workers who were blinded to ventilation rates, researchers found that there were significant cognitive benefits to increasing ventilation rates beyond the ASHRAE minimum requirement and using low-VOC emitting products.[74]
    - In an all-female, experimental workplace study, researchers found benefits in health and performance when ventilation rates were well above the prescribed minimum levels. For example, study participants reported significant improvements in satisfaction with air quality, reduced sensation of dryness in the mouth and throat, and eased difficulty in thinking while performing standard office tasks.[73]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- In 2017, an extensive study modeling eight ventilation strategies found that using a demand-controlled ventilation system with a low CO_2 setpoint, in conjunction with airside economizing and supply air temperature reset (SR, used when applicable), was associated with increased work productivity due to improved IAQ. Median benefits for small-to-medium-large offices in the United States were estimated to be $55 billion annually, when ventilation strategies prioritized indoor air quality and worker performance over energy savings.[75]

- Displacement ventilation, combined with chilled ceilings, has increased cooling capacity and may provide an environment with high air quality and acceptable thermal comfort conditions.[159,160]
    - Chilled ceilings refer to systems where pipes with cold water are bonded to ceiling tiles, resulting in a ceiling tile surface temperature between 16-19°C [61-66°F].
    - Downward displacement ventilation provides cool, dense air that drops to the floor and avoids mixing. When operated and maintained properly, this is an ideal strategy for removing large droplets in healthcare facilities such as isolation wards.[161]
- Use of a CO_2-controlled ventilation system was associated with reductions of elevated levels of CO_2 and slight reductions in headache and tiredness, as well as improvements in perceived air quality, in a blinded study of university students.[162]
- Another strategy for improving indoor air quality is providing ventilation close to the breathing zone of the occupants.[73] Personalized ventilation delivers clean air directly to occupant's breathing zone at workstations and facilitates individual control that may be associated with improved thermal comfort and perceived air quality.[163] In a simulation study, personalized ventilation strategies greatly influenced the temperature and VOCs distributed around the occupant, but had little impact on other parts of the office.[164]
    - In hot, humid climates, personalized ventilation with ambient air-conditioning systems has been shown to reduce energy consumption by 15-30% and improve ventilation effectiveness in the breathing zone by up to 50% more compared to typical mixing ventilation.[165]
    - When used in conjunction with under floor air distribution systems, personalized ventilation was shown to be associated with improvements in perceived air quality and thermal sensation compared to just using under floor air distribution systems and mixing ventilation systems.[166]
    - Personalized ventilation delivering clean (i.e., outdoor, highly filtered, or disinfected) air to the occupant breathing zone may protect against infectious aerosols.[167]

ADDITIONAL NOTES

- Children, who have higher breathing rates than adults, are particularly vulnerable to the health effects of poor indoor air quality while their bodies are still developing.[168] Student attention and performance has been shown to be diminished in classrooms where CO_2 levels are high and ventilation rates are low.[70] Studies in various parts of the world have shown peak indoor concentrations of CO_2 exceeding 2,000 ppm (compared to target levels typically between 600-1,000 ppm).[77,169]
- When school building ventilation systems are not properly maintained or operated, they can have adverse health impacts compared to naturally ventilated classrooms. Fewer complaints have been reported in classrooms with natural or displacement ventilation, compared to mixing flow or mechanical exhaust ventilation.[170] Additionally, after the installation of displacement ventilation, there were fewer reported cases of asthma and other respiratory symptoms in students compared to the number of cases when the building used other ventilation strategies.[171]

FEATURE A07: OPERABLE WINDOWS

OVERVIEW

Part 1: Provide adequate coverage of operable windows (i.e., that can be opened and closed).
Part 2: Monitor common air quality metrics, making data available to occupants, and implement a system that notifies occupants when outdoor air quality is acceptable for open windows.

SCIENTIFIC BACKGROUND

- Building ventilation supplies and removes air from spaces at specific speeds, volumes and rates of exchange, by mechanical and/or natural systems, the latter of which refers to the use of windows, doors and other types of fenestration.
- Many buildings favor sealed windows to better control the conditions of the indoor environment. But aside from facilitating ventilation, people generally prefer to have access to windows and report feelings of relaxation, comfort and even improved motivation at workplaces when provided window access.[172-174]

KEY HEALTH AND WELL-BEING EFFECTS

- Concentrations of air pollutants in indoor spaces can build up if air is not adequately expelled from the space.
    - For example, formaldehyde, a common indoor air pollutant, off-gasses from wood-based products or paints, as well as from varnishes or finishes.[175] It is associated with an increased risk of upper respiratory tract cancers under certain exposure conditions (e.g., a concentration of 100 ppb for 30 minutes in non-occupational settings).[120]
    - CO_2 can easily accumulate in indoor spaces and burgeoning evidence suggests that exposure to high concentrations of CO_2 (e.g., 2,500 ppm compared to 600 ppm) may impair cognitive function, such as those related to decision-making processes.[176]
- Outdoor pollutants can infiltrate indoor environments and degrade indoor air quality, potentially leading to negative acute and long-term health impacts.
    - Particulate matter (PM) air pollution is a complex mixture of small, solid particles and liquid droplets. Inhaling elevated levels of PM has been shown to lead to various adverse health effects, primarily associated with the cardiopulmonary system.[6] Exposure to elevated levels of PM is the leading source of mortality among outdoor air pollutants.[1]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Natural ventilation (i.e., buildings that use operable windows, doors or other fenestration) can reduce operating costs and reliance on fossil fuels compared to mechanical ventilation systems, while still providing sufficient air change rates for acceptable occupant comfort and indoor air quality.[78-80]
- However, it is critical to monitor outdoor conditions to ensure that if and when ambient pollutant levels exceed advisable thresholds, or when outdoor conditions such as temperature and humidity differ dramatically from desired indoor levels, windows remain closed to limit infiltration of pollutants and support occupant comfort.
- Occupant satisfaction in terms of thermal comfort, sense of personal control and connection to nature are all improved in spaces with operable windows.[177-182]
- Studies have demonstrated that people in naturally ventilated buildings experience fewer symptoms of sick building syndrome (SBS) compared to people in mechanically ventilated spaces.[181,183-185]
    - Sick building syndrome refers to a condition in which building occupants experience acute health effects with no known cause, which appear to be connected to the length of time spent within the building. The associated symptoms, ranging from headaches and dizziness to nausea, are often relieved upon leaving.[68] SBS may be linked to sealed or tightly-enclosed buildings, non-operable windows, increased temperatures and levels of dust or cigarette smoke.[186]
    - A study set in residences across Slovakia found that households that opened windows during cleaning activities had significantly lower total volatile organic compound concentration levels indoors compared to when windows were not opened during cleaning.[187]

- Studies in healthcare settings indicate that naturally ventilated spaces, through the use of operable windows, may be more effective than mechanically ventilated spaces with sealed windows at preventing airborne transmission of diseases, even if the room is ventilated at recommended rates, particularly for tuberculosis.[188-191]
- Opening windows for longer periods of time (e.g., 20 minutes versus 5 minutes) can reduce the concentrations of indoor-generated pollutants but also can increase the levels of particles and contaminants that enter the building from the outdoors, such as pollutants from combustion-based sources like traffic.[192,193]
- An optimal strategy for operable window usage may be to aim for a relatively short window opening time and a relatively high window opening frequency, particularly given that window airing seems more effective in terms of ventilation rates and air flow at the beginning, when the window first is opened.[194]
- A number of factors should be considered in window usage, such as the total area of the windows, the area of doors and the number of hours either are open — all of which were found in one study to be inversely associated with the number of hours levels of $PM_{2.5}$ exceeded 100 µg/m^3 (e.g., as window area increased, particulate matter levels decreased).[195]

ADDITIONAL NOTES

- Much of the data on mortality associated with specific air pollutants is derived from studies evaluating outdoor, ambient conditions. More research is needed to understand if health effects to the same degree could be expected based on common indoor pollutant levels. But outdoor levels of pollutants and associated health effects nevertheless can inform whether windows should be opened and if how doing so can affect indoor air quality and associated effects on occupants.

FEATURE A08: AIR QUALITY MONITORING AND AWARENESS

OVERVIEW

Part 1: Install air quality monitors for pollutants as specified and submit data annually to the WELL digital platform.
Part 2: Facilitate real-time display of data on pollutant concentrations and educate occupants on air quality.

SCIENTIFIC BACKGROUND

- The air we breathe is mostly a composition of nitrogen and oxygen, along with small amounts of inert gasses and water vapor.
- Quality indoor and outdoor air are essential for public health.[134] Municipal-level outdoor air quality monitoring is common.[196] As we spend increasing amounts of time in indoor environments, it's important to measure and monitor indoor air quality (IAQ), especially given that exposure levels to several air pollutants can range from two to five times higher indoors than outdoors.[196]
- Indoor and outdoor air quality are interrelated, as a reported 65% of inhalation of outdoor air occurs when an individual is in indoors.[1]
- Indoor air quality typically is assessed by measuring a handful of basic parameters, such as temperature, humidity, air speed and a selection of pollutants or indicators such as carbon dioxide (CO_2) or particulates.[134,197]
- While it is helpful to have such data, monitoring only those basic parameters is often inadequate to accurately characterize air quality to understand impacts across all of the dimensions of human health and well-being that can be affected by certain concentration levels of airborne pollutants.[198]

KEY HEALTH AND WELL-BEING EFFECTS

- Particulate matter (PM) air pollution is a complex mixture of small, solid particles and liquid droplets. Inhaling elevated levels of PM has been shown to lead to various adverse health effects, primarily associated with the cardiopulmonary system.[6] Exposure to elevated levels of PM is the leading source of mortality among outdoor air pollutants.[1]
- Most living organisms, including humans, exhale CO_2 through respiration. Without sufficient ventilation, CO_2 would accumulate continuously in occupied buildings.[199] CO_2 is not harmful at commonly observed indoor levels, but emerging evidence suggests that CO_2 exposure may lead to impaired decision-making.[176,199]
    - In a seminal study, participants were exposed to three different CO_2 levels in an otherwise unchanged room for two and a half hours and asked to complete nine decision-making tests and questionnaires.[176] Relative to the lowest level of CO_2 (600 ppm), moderate but statistically significant reductions in performance were seen at 1,000 ppm, and large, statistically significant reductions at 2,500 ppm.[176]
- Carbon monoxide (CO) is associated with fatigue, headaches, nausea and other symptoms, including death as a result of CO poisoning.[11,12,134]
- Ozone (O_3) can trap air in parts of the lungs, adversely affecting lung function and triggering respiratory symptoms such as wheezing, coughing, chest pain and shortness of breath, making the lungs more susceptible to damage and disease.[13-15]
- Nitrogen dioxide (NO_2) exposure can lead to respiratory effects, including airway inflammation and increased symptoms in people with asthma.[200] It is also associated with increased risks of respiratory infection and potentially emphysema and bronchitis as well.[201-203]
- Exposure to volatile organic compounds (VOCs) is associated with irritation of the eye, nose and throat, as well as liver and kidney damage.[7] Effects on the central nervous system, including dizziness or loss of coordination, may be an early indication of VOC exposure, as VOCs are known to permeate lipid membranes, making the brain an easy target due to its high lipid content.[8]
    - Materials used for ongoing maintenance, such as cleaning products, air fresheners, pest control chemicals and furniture polish, can increase VOC levels for a period of time, and their presence indoors is commonly two to five times higher than outdoor levels.[7]
- Formaldehyde exposure can cause eye, skin and throat irritation, and is further associated with risks of nasopharyngeal cancer and leukemia, and potentially sinonasal cancer.[25,204]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Educating occupants about air quality conditions and other environmental health concerns equips individuals with critical health knowledge and skills, allowing them to participate in social agency and better engage in their own health and well-being.[205]
- Commercially available, real-time air quality monitoring devices are growing in popularity and represent more widely-accessible and cost-effective ways to track environmental parameters, even to individual-specific exposure levels through personal sensing devices.[206-208]
    - While these devices can provide useful data and convey broad changes in environmental quality to raise awareness of conditions, studies indicate that there are challenges related to the robustness of sensors and repeatability of measurements, indicating that lower-cost tools may not be appropriate for applications requiring greater accuracy.[209-211] Thus, it is important to select a monitor with sufficient documented accuracy and the ability for recalibration.
- Providing occupants with information on building-related parameters that are not immediately obvious (e.g., energy usage or environmental conditions) can affect occupant behavior and promote positive changes in how people interact with the spaces they occupy.[212,213]
    - Most of the data on this topic are derived from sustainability-related literature, and more research is needed to identify specific strategies related to air quality monitoring and related occupant behaviors.
- Studies indicate that the use of a system that visualizes whether or not indoor environmental conditions are poor, or one that proactively warns occupants when conditions are poor, may be beneficial in motivating occupants to take actions to improve conditions or otherwise take action to protect themselves.[214]
- CO_2 concentration levels often serve as a proxy measure for ventilation effectiveness and indoor air quality, which can be measured using sensors that are readily available in the market.[200] Similarly, NO_2 levels often serve as a proxy for a cocktail of other contaminants in the air created through combustion sources (e.g., fireplaces, gas stoves and space heaters).[201]
    - A sensor-controlled strategy, demand-controlled ventilation, saves energy in buildings by measuring CO_2 levels and adjusting the rate of air supply to prevent exceeding pre-determined CO_2 thresholds.[75,154]
- Anthropometrical data indicates that eye-level height typically ranges between 1.2-1.3 m [3.8-4.4 ft] for seated persons and between 1.4-1.8 m [4.6-5.7 ft] for standing persons.[215] Accordingly, monitor displays should be positioned to accommodate ease of view by users of all heights and abilities.[215]
    - These height ranges also approximate the breathing zone of a seated or standing individual (e.g., nose and mouth height), making it an ideal range for the position of environmental parameter-monitoring devices to capture air quality conditions at the height at which people are most likely to breathe.

FEATURE A09: POLLUTION INFILTRATION MANAGEMENT

OVERVIEW

Part 1: Minimize the transfer of contaminants from outdoor to indoor spaces at building entryways.
Part 2: Define building envelope performance metrics at the concept stage of design and conduct building commissioning.

SCIENTIFIC BACKGROUND

- Indoor and outdoor air quality are interrelated, as a reported 65% of inhalation of outdoor air occurs when an individual is indoors.[1]
- Infiltration refers to the process whereby outdoor air enters indoor spaces. Common pathways include fenestration (doors and windows), cracks and joints.[153]
- Air contaminants from the outdoors can enter buildings through infiltration as well as through ventilation systems, doors and windows, and human activity (e.g., tracking dust and particles indoors on clothes or shoes).[216]

KEY HEALTH AND WELL-BEING EFFECTS

- Indoor particulate matter (PM) levels (especially finer particles) appear to track closely to outdoor levels, demonstrating that outdoor levels are correlated with the levels of pollutants that enter indoor spaces, mediated by the extent of infiltration that occurs through building envelopes and entryways.[217-222]
    - One study modeling mortality per 10 $\mu g/m^3$ rise in PM_{10} predicted a 0.81%, 1.2% and 0.7% increase in all-cause mortality in the United States, Europe and China, respectively.[223]
    - In the same study, researchers estimated that indoor PM pollution from outdoor sources accounted for 81-89% of the mortality increases associated with rising outdoor PM levels.[223]
    - Several studies demonstrate that ambient PM, both fine and coarse, is associated with increased risk of cardiovascular disease, including death caused by cardiovascular disease.[224-231]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Building commissioning is a way to check and confirm that a building is performing as designed. Envelope commissioning in particular – the testing of the building's outer shell for resistance to air, water, heat, light, and noise transfer – alongside an evaluation of the HVAC system, has the highest potential to maintain good indoor air quality.[232]
- Outdoor soil that is tracked indoors is a common source of indoor dust. One study estimates that up to 50% of indoor dust is made up of soil brought in from outside.[233] Walk-off mats can be effective solutions for collecting dust at entryways.[234] One study suggests that the presence of lead, which often contaminates outdoor soil, may be reduced by up to 90% in carpets in homes by either removing shoes indoors or using walk-off mats at entryways.[235]
- Entryway systems that incorporate the use of walk-off mats should consider environmental conditions when choosing the appropriate mat material, texture and length. Climates with a lot of snow may require longer systems; rainy environments may need a more adsorptive mat; muddy locations may require the use of multiple mats.[236]
- Automatic entrance doors are estimated to account for up to 80% of the total air infiltration of a building.[237] The installation of door vestibules (e.g., a small entry room that connects an outer door to the interior space) can decrease the rate of airflow infiltration into a building from the outdoors by up to 33% compared to automatic entrance doors.[237,238] Studies suggest that vestibules may thereby reduce the concentration of air pollutants in indoor spaces by up to 24%.[238-241]
- Conventional open-door systems can result in up to five times more air infiltration than revolving entrance doors, which are often also the most energy-efficient entryway solution.[242-244]

ADDITIONAL NOTES

- Children, older adults and people with cardiovascular or respiratory disease tend to spend more time indoors compared to others.[245] These individuals are often particularly susceptible to the adverse effects of pollution; therefore, taking measures to limit the introduction of contaminants into indoor spaces at entryways may help protect particularly vulnerable populations.[245]

FEATURE A10: COMBUSTION MINIMIZATION

OVERVIEW

Part 1: Manage combustion-based appliances, equipment and practices, including vehicle engine idling.

SCIENTIFIC BACKGROUND

- Combustion, or burning, refers to when a substance reacts with oxygen and produces energy in the form of light and heat.
- Indoor combustion sources (e.g., tobacco smoke, stoves, furnaces, fireplaces) can release several pollutants into the air, one of the most troubling of which is particulate matter (PM).
    - Particles with a diameter less than 2.5 µm are known as $PM_{2.5}$ and are referred to as "fine" particles. These particles are able to penetrate deeper into the lungs (compared to PM_{10}) and are believed to pose a greater health risk compared to larger particles, as do ultrafine particulate matter (UFP).[246] Coarse particulate matter, known as PM_{10}, refers to particles between 2.5 µm and 10 µm in diameter.[247]
- As a consequence of incomplete combustion processes, the exhaust of diesel engines contains various gases, liquids and solid particles composed of elemental carbon with sulfates, metals and other potentially toxic substances.[248]
- Nitrogen dioxide (NO_2) is a product of combustion, mainly found near burning sources such as wood smoke and traffic. Nitrogen dioxide and nitrogen oxide (NO), often formed simultaneously during combustion processes, are collectively classified as NO_X.[249] Indoor areas with gas stoves, fireplaces and cigarette smoke often have a high concentration of NO_2.
- Polycyclic aromatic hydrocarbons (PAHs) are widespread organic pollutants that originate from combustion processes/sources such as vehicle exhaust, cigarette smoke, home heating and the application of asphalt. Benzo[a]pyrene (BaP) is one of the most potent carcinogenic PAHs.[250]

KEY HEALTH AND WELL-BEING EFFECTS

- Increased $PM_{2.5}$ levels from combustion related to traffic and coal have been associated with increased daily mortality rates.[251,252] Another study found that a 10 $\mu g/m^3$ reduction in the concentration of $PM_{2.5}$ was associated with an average 0.35-year increase in life expectancy.[20]
- Diesel exhaust particulate matter (DEP) created by trucks, boats, farm equipment and generators can cause adverse health effects, such as coughing and nausea (especially in children) and short-term irritation of the eyes and throat.[248]
- The International Agency for Research on Cancer (IARC) of the World Health Organization (WHO) classifies diesel exhaust as a known (group 1) human carcinogen.[253]
    - This classification is based on animal studies investigating the development of lung cancer following exposure to high concentrations of diesel emissions.[254] More research is needed regarding the mechanisms and the particle concentrations and duration of exposure that lead to lung cancer in humans.[254]
- Exposure to nitrogen dioxide (NO_2) can lead to respiratory problems, including airway inflammation and increased symptoms in people with asthma.[249,255]
- The WHO states that chronic exposure across a lifetime to PAH concentrations common in European or North American cities is associated with up to 50 excess cases of lung cancer per 1,000,000 people.[250] As a subset of PAHs, BaP is associated with chromosomal replication errors, leading to multiple types of cancer.[256-258]
- Household air pollution (HAP) is strongly associated with respiratory and cardiovascular disease related to the release of fine particulate matter from household combustion emissions and can negatively affect overall mortality risk and life expectancy.[224,259-269]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- The use of improved or low-emitting fuels, cookstoves, heaters, furnaces and ventilation all have been demonstrated to reduce the concentration of various pollutants in indoor spaces, especially in residences, where HAP is a significant concern and driver of adverse health outcomes.[270-274]
    - Combustion heaters significantly contribute to ambient PM levels and in countries such as China, concentrations of $PM_{2.5}$ can be up to three times higher in the winter compared to the summer.[275,276] Heaters are implicated as the main source of this increase in pollution.[277,278]

    - A series of studies in Montana, USA found that 80% of ambient $PM_{2.5}$ levels were attributable to residential wood stoves. Upon replacing 95% of stoves in the community with lower emission stoves, the average $PM_{2.5}$ levels in the winter dropped by 27%.[279-282]
- Cars use more fuel and emit more carbon dioxide when they idle for more than 10 seconds compared with turning off and restarting the engine.[283] Cars and trucks that use gas generate approximately 60,000 µg of NO_x per minute of idling, as well as anywhere between 3-15 times more formaldehyde when idle compared to higher engine load conditions, particulate matter and total volatile organic compounds.[284-286] Therefore, pollution can be reduced by avoiding or limiting vehicle idling.[284,287]
    - Minimizing idling is even more important in the case of heavy-duty diesel vehicles, which can generate approximately 18,000 µg of $PM_{2.5}$ per minute of idling.[286]

ADDITIONAL NOTES

- Globally, more than 3 billion people and 41% of households rely on solid fuel combustion for cooking and heating.[270,288-290] The exposure to the resultant air pollution is responsible for an estimated 4 million premature deaths every year among children and adults around the world.[272] The burden of illness falls primarily to developing countries, where the use of solid fuels is more common, and by women and children, who are more often responsible for cooking and related domestic tasks.[270]

FEATURE A11: SOURCE SEPARATION

OVERVIEW

Part 1: Separate rooms that may be the source of indoor air pollution and ensure adequate ventilation in commercial kitchens and dwelling unites through kitchen space and appliance design.

SCIENTIFIC BACKGROUND

- Certain appliances used in indoor spaces can also contribute to poor indoor air quality. Photocopiers and printers are known to contribute to the emission of several pollutants, most significantly ozone, which also can react with other pollutants to produce UFPs.[291-293]
- Overall, cooking can significantly increase the concentration of several contaminants in the air, including particulate matter (PM), formaldehyde, carbon monoxide (CO), nitrogen dioxide (NO_2), benzene and polycyclic aromatic hydrocarbons (PAHs).[294-296]
    - Particles with a diameter of less than 2.5 µm are known as $PM_{2.5}$ and are referred to as "fine" particles. These particles are able to penetrate deeper into the lungs (compared to PM_{10}) and are believed to pose a greater health risk compared to larger particles, as do ultrafine particulate matter (UFP).[246] Coarse particulate matter, known as PM_{10}, refers to particles between 2.5 µm and 10 µm in diameter.[247]
    - Some cooking processes contribute more to toxic compounds than others. In particular, deep-frying appears to be associated with the greatest emissions of particulate matter, followed by frying, stir-frying, boiling and then steaming.[297]
- Cooking processes typically involve heating oils, fats and other food ingredients. These combustion-based processes can pollute indoor air quality.[298] Gas, wood and electric ovens used for cooking can all contribute to poor indoor air quality as well by releasing appliance-related pollutants into the air or through wood smoke.[298]
- The WHO recognizes that some viruses, such as SARS-CoV-2, can be spread through fecal-oral transmission routes. Aerosol plumes can be created when flushing toilets with open lids and virus-containing droplets can be dispersed.[299]

KEY HEALTH AND WELL-BEING EFFECTS

- Photocopiers and printers are a significant source of ozone and, along with paper dust, are associated with upper respiratory and skin symptoms, headache, fatigue, breathlessness, tonsillitis and middle ear infections.[300] Ozone from these kinds of appliances can exacerbate asthma symptoms.[301]
- In restaurants, employees with asthma can also experience adverse symptoms via exposure to compounds such as NO_2, CO and PM produced by the fuel and fumes of cooking.[294]
- Exposure to UFPs from cooking can lead to DNA damage, inflammation of the cells in the lungs and, among people who are susceptible to respiratory problems, increased risk of respiratory and cardiovascular-related mortality.[302-305]
- Cooking fumes are associated with an increased risk of lung cancer, with the extent of the risk mediated by factors such as the type of cooking oil used and cooking methods (e.g., deep frying).[306,307]
    - One study based in China estimates that up to 30% of indoor particulates derive from emissions related to cooking processes.[308]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- The most straightforward way to reduce concentrations of air contaminants is to eliminate or constrain the source of the pollutant.[309] Other strategies, when these avenues are not possible, include localized ventilation as well as strategic design planning to position sources of indoor pollution away from occupied areas.[310]
- In places such as office environments, studies recommend locating printers and photocopiers away from working areas and improving ventilation in spaces where handling is required.[300]
- Kitchen ventilation removes moisture and pollutants from the source area in a residence, restaurant or any other space with an area for cooking.[311,312] Range hoods, effectively placed exhaust fans and the use of side panels can help reduce the quantity of toxic contaminants released beyond the cooking area into the surrounding air.[311,313] Back burner use (in combination with a range hood) and strategically placed walls can further decrease indoor levels of ultrafine particles when cooking.[311,314]

- Gas stovetops and ovens, as well as common cooking practices such as frying or sautéing, are major sources of PM, formaldehyde, NO_2 and PAHs. Venting hoods can significantly reduce the level of pollution produced by these indoor sources.[315,316]
- Exhaust ventilation systems and negative pressurization in bathrooms may prevent plume-related fecal-oral transmission of viruses like SARS-CoV-2.[299]
- Damp or moldy indoor spaces can be associated with adverse health effects, making it critical to control moisture. This can be done by preventing water intrusion and condensation in areas that should remain dry, separating such spaces or limiting areas of the building that routinely are wet (e.g., bathrooms, janitorial closets).[317]

FEATURE A12: AIR FILTRATION

OVERVIEW

Part 1: Meet specific air filtration levels for particulate matter in mechanically and mixed-mode ventilation spaces depending on outdoor pollution concentration.

SCIENTIFIC BACKGROUND

- Sources of outdoor air pollution include traffic-related combustion, power generation, industrial activities and wastes sites.[318]
    - Indoor $PM_{2.5}$ levels can be higher than outdoor levels because, in indoor settings, $PM_{2.5}$ can become concentrated due to inadequate ventilation, particle intrusion, high temperatures, indoor sources and humidity levels.[319-321]
- The Minimum Efficiency Reporting Value, commonly known as a MERV rating, is a measurement defined in ASHRAE Standard 52.2 of the effectiveness of air filtration on a 16-point scale (1-lowest efficiency, 16-highest).[322] For example, a filter with a MERV rating of 13 or higher will remove at least 90% of all particles one micron or larger.
- A high efficiency particulate air filter (HEPA filter), as defined by the U.S. Department of Energy, is designed to remove at least 99.97% of particles of 0.3 microns or larger.[323]
- Regular filter maintenance is critical for maintaining proper air filtration and the efficiency of the air conditioning system.[324,325] Once loaded with particles, filters will begin to reduce airflow and the pressure may drop. In an analysis of the cost-benefit of filtration versus energy efficiency, replacing filters more often than recommended by manufacturers could save energy and may decrease filtration costs.[325]
    - More efficient filters tend to have increased pleating and depth to reduce pressure drops. Larger filters will often have an increased lifetime between replacements because of their increased surface area.[325]

KEY HEALTH AND WELL-BEING EFFECTS

- The World Health Organization (WHO) estimates that 4.2 million deaths every year are attributed to ambient, outdoor air pollution.[318]
- In children and adults, both short- and long-term exposure to air pollution can lead to reduced lung function, respiratory infections and aggravated asthma.[326]
- Of the air pollutants, fine particles, defined as those less than 2.5 microns ($PM_{2.5}$) in diameter, pose the most considerable risks to health, as they are capable of penetrating deep into the lungs, evading the body's natural defenses and entering the bloodstream. PM_{10} can block and inflame airways but cannot be inhaled deeply into the lungs and are deposited in the primary bronchi causing a range of respiratory-related conditions that can lead to illness and/or death.[326]
    - A landmark air pollution study, the Harvard Six Cities Study, found that as ambient air pollution increased, there was an increase in both all-cause mortality (i.e., deaths from any cause in a given population or subset of a population across a certain length of time) and cardiopulmonary mortality.[141] Studies in China have confirmed similar associations between respiratory and cardiovascular health and $PM_{2.5}$ exposure.[327]
- More broadly, exposure to $PM_{2.5}$ is associated with cellular damage, the formation of DNA adducts (a section of DNA bound to a chemical, indicating exposure to carcinogens) and result in asthma exacerbation, allergic conjunctivitis, sleep disorders and increased mortality.[269,328-330]
- There is significant scientific evidence that both short and long term exposure to $PM_{2.5}$ is associated with cardiovascular and respiratory health outcomes, including cardiovascular and pediatric asthma hospitalizations, heart failure, ischemic stroke, altered heart rate variability, lost workdays, inflammation and premature mortality.[224,331]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- The most substantial benefits of particle filtration may be reductions in morbidity and mortality associated with reducing indoor exposures to particles from outdoor air. In a study examining the impact of indoor $PM_{2.5}$ levels of outdoor origin on long-term health, researchers found that the use of high efficiency HVAC filters in residential homes was likely to reduce premature morbidity and increase life expectancy. The greatest benefits were anticipated to be seen in older homes using filters classified as MERV 12 or above.

- Use of air filters has been shown to reduce particulate matter concentrations in various settings including schools, offices and residential spaces, which may result in more extensive health benefits and savings.[332-336]
- Particle filtration can be modestly effective in reducing adverse allergy and asthma outcomes, particularly in homes with pets.[337]
    - In a modeling study of filter-based interventions, the use of a MERV 12 or higher filter in home ventilation systems effectively reduced indoor levels of these common asthma and allergy triggers. These reductions in airborne allergens may subsequently reduce allergy and asthma symptoms, especially if employed in conjunction with other environmental management measures recommended for allergy and asthma patients.[338]
- In a study of residential and occupational buildings using MERV 13 rated filters, researchers estimated a 27% reduction in total exposure to $PM_{2.5}$ from outdoor air and a 20% reduction in total exposure to $PM_{2.5}$ from both indoor and outdoor air. They suggested if this intervention were applied across Europe, it would be associated with a decrease of 27,000-100,000 particulate matter-related deaths per year.[339]
- In a study replacing conventional filters in a mixed-mode building, the use of high-efficiency filters (efficiency rating of 95% at 0.3 micrometers with higher efficiencies for both smaller and larger particles) was associated with improvements in performance and self-reports of environmental satisfaction and fatigue.[340]
- In a study using a model of an office building, researchers estimated that the use of a MERV 13 equivalent filter was associated with reductions in PM_{10}-related health effects and significant annual economic benefits, and required a low annual operating costs per person.[334]

ADDITIONAL NOTES

- Maternal exposure to ambient air pollution is associated with adverse birth outcomes, such as low birth weight, pre-term birth and small gestational age births.[341] The short-term decrease in ambient air pollution during the 2008 Beijing Olympics was associated with higher birth weight compared to babies born during conditions of increased pollution in 2007 and 2009 .[342] Higher maternal exposure to $PM_{2.5}$ during pregnancy, particularly the third trimester, is associated with increased odds of having a child with Autism Spectrum Disorder.[343]
- When building new or retrofitting a pre-existing building with mechanical ventilation is not feasible, portable room air cleaners (PRACs), devices containing a fan for circulation and air cleaning filters, provide a potential alternative.[344] From healthy adults to asthmatic children, a positive association between portable room air cleaner use and respiratory and cardiovascular health benefits has been observed.[345-347] PRAC use in residential settings has been associated with a reduction of eye and nose irritation, asthma and other respiratory symptoms.[344] In wood-smoke affected communities, the use of air purifiers resulted in improved endothelial function and reduced inflammation markers.[345]
- Other methods for reducing particulate air pollution indoors can occur at the city, regional and national level. Strategies include encouraging energy efficient modes of transportation (e.g., bus rapid transit, biking, walking), using cleaner cooking fuels, transitioning away from fossil fuel combustion and reducing nearby waste and agricultural burning practices.[348]

FEATURE A13: ENHANCED AIR SUPPLY

OVERVIEW

Part 1: Use supply air that is not recirculated or that is treated with carbon filters, media filters or ultraviolet germicidal irradiation (UVGI).

SCIENTIFIC BACKGROUND

- While some pollutants such as particulate matter (PM) enter buildings mainly through outdoor air, others, such as Volatile Organic Compounds (VOCs), have indoor origins.[349-351] Similarly, occupants themselves can generate particles of concern indoors, such as those harboring infectious diseases.[352]
- Building materials, furnishings (e.g., carpets and furniture finishes), fabrics, cleaning compounds, office equipment, adhesives, solvents and air fresheners can all emit VOCs into the indoor environment.[351]
- For thirty years, scientists have documented the presence and distribution of more than 320 types of VOCs.[353] Recent studies reveal that 150 VOCs are commonly found in indoor environments globally, such as in the home or in school buildings.[354]
    - VOCs are omnipresent in indoor and outdoor environments. They are generated from both natural (e.g., wood and plant-based materials, fragrances) and anthropogenic sources (e.g., traffic emissions, landfills, cooking, artificial fragrances).
- In mechanical ventilation with in-duct systems, activated carbon and media filters can be installed at different locations, including outdoor air intake, occupied spaces, main return air ducts and main supply air ducts. In each of these locations, activated carbon filters can cause changes in air flow and energy consumption.[355]
    - Activated carbon filters in mechanical or standalone air cleaners use the process of adsorption to remove gaseous pollutants. Carbon that is "activated" has been treated (often by heating) to enhance its adsorptive ability.[356]
    - The advantage of activated carbon filtration is that it is a proven and efficient method of removing VOCs, but it can saturate quickly resulting in pollutant reemission if filters are not changed in a timely manner.[356]
- The structure and concentration of target VOCs in the environment, as well as the humidity and temperature, can influence the efficiency and cleaning capacity of an activated carbon filter. Different compounds adhere to activated carbon differently. Thus the properties of the material used, the mesh size of the filter and the interaction of different VOCs may change absorption rates.[355]
    - The efficiency of VOC adsorption-based filters decrease over time and require regular maintenance and replacement.[357]

KEY HEALTH AND WELL-BEING EFFECTS

- Recirculation of air that contains particles which harbor infectious diseases has the potential of increasing transmission.[299,352]
- In the short term, high levels of VOCs can result in symptoms associated with sick building syndrome (SBS) in new or renovated buildings, including eye irritation and headache or sore throat.[295,358]
    - SBS refers to a condition where building occupants experience acute health effects with no known cause, which appear to be connected to the length of time spent within the building. The associated symptoms, ranging from headaches and dizziness to nausea, are often relieved upon leaving.[68]
- Even low concentrations of benzene, ethylbenzene and toluene can increase the risk of asthma in young children. For every 10 $\mu g/m^3$ increase in the concentration of toluene and benzene, the risk of developing asthma increased by 2-3 times.[359,360]
    - Other health effects associated with these compounds include irritation of the eyes and nose, headaches, dizziness, liver and kidney damage, a decrease in red blood cells, anemia and health complications.[360-363]
- Other carcinogenic VOCs include formaldehyde, acetaldehyde and benzene.[361,364] Toluene concentrations tend to be greater in places with high ink use, such as copy centers and newspaper stands.[361,363]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Operating ventilation systems without the use of recirculated air will help minimize any VOCs or disease-containing particles from being distributed between rooms in a building. Heat exchangers can help offset any increase in energy

use, but they must be commissioned and operated correctly to avoid air leakage that would contribute to recirculation.[299,357]

- Use of activated carbon filters have removal efficiencies of 70-80% for most VOCs, though only 25-30% for formaldehyde.[365]
- Studies have shown that activated carbon filters may be more effective at removing VOCs when they are combined with other filtration approaches and coated with different compounds.[366]
    - Experimental tests showed that activated charcoal filters with a manganese dioxide (MnO_2) filter and a photocatalyst filter had the most significant impact on air concentrations of benzene and formaldehyde.[367]
    - The use of activated carbon filters with titanium dioxide (TiO_2) filters increased the removal efficiency of toluene, nitrogen oxide and chlorinated by-products (e.g., chloroform, TCBA, TCE).[366,368,369]
- HEPA or high-MERV filters can help remove virus particles since the virus often travels as part of a larger particle.[167,370] UVGI systems can also be effective, both when irradiating the upper portion of the room or in the air ducts, so long as they are powerful and/or the air speed is slow enough to provide sufficient UV dose.[167,371]

ADDITIONAL NOTES

- Other vulnerable populations include restaurant and other food service workers who are at risk of high exposures due to heating grease, which can emit aromatic hydrocarbons like toluene and benzene, as well as ethylene and acetylene.[372-375] Certain occupational settings have high VOC levels, such as nail salons, car repair shops, printing facilities and hospitals.[376-378]
- Beyond activated carbon, there are other filtration methods for reducing VOCs including photocatalytic oxidation, biofiltration and thermal catalysis.[356,379] Studies show that portable air cleaners that use air ionization and ozone oxidation for VOC control have limited efficacy to remove VOCs and generate ozone and may not represent the best technologies for use in office or residential settings.[380]

FEATURE A14: MICROBE AND MOLD CONTROL

OVERVIEW

Part 1: Manage microbe and mold on cooling coils through regular cleaning or ultraviolet germicidal irradiation (UVGI) in cooling coils and drain pans that are regularly monitored and maintained.

SCIENTIFIC BACKGROUND

- Air conditioning systems use cooling coils to reduce the air temperature. During this cooling process, the air typically drops below the dew point temperature, which means that condensate will form. Due to the condensation, the coil and drain pan can be a source of mold, and subsequent air purification may be difficult or ineffective in this setting.[381]
- If mold growth does occur, HVAC air distribution systems can enable spreading of mold spores throughout buildings.[382]

KEY HEALTH AND WELL-BEING EFFECTS

- In 2009, the World Health Organization (WHO) concluded that there is sufficient epidemiological evidence of a relationship between mold, dampness and adverse health outcomes, including asthma development and exacerbation, dyspnea, wheezing, bronchitis and cough.[383-387] Neurocognitive impacts such as depression, anxiety, fatigue, dizziness and movement disorders have also been documented.[388]
- Toxicological evidence suggests that mold and dampness cause an inflammatory and toxic response in humans.[386,389]
- Mold developed on cooling coils may shed particles into the building's indoor air and trigger asthma, headaches, allergies and other respiratory system disorders.[384,390-392]
    - Although it's challenging to establish a causal relationship between health effects and mold on coiling coils specifically, the impacts of mold are well documented, and studies have shown that adverse health outcomes are associated with the type of microbiological contaminants that can grow on poorly maintained cooling systems.[383]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Ultraviolet (UV) lamps have been shown to kill mold and other living organisms once the infestation has occurred, but they do not address the root cause of mold growth.[393] Therefore, condensation management plans and mold inspection provide a timely, proactive approach to helping prevent mold and moisture damage. Performing visual inspections of cooling coils quarterly and implementing appropriate cleaning procedures, if necessary, can help to prevent system failure early on and decrease the risk of mold proliferation.[382]
    - In one study, treating microbial contamination of heating, ventilation and air-conditioning systems with ultraviolet germicidal lights resulted in a 99% reduction of microbial and endotoxin concentrations on irradiated surfaces within the ventilation system. The analysis estimated that if North American offices used UVGI, 4 million employee-reported respiratory and mucosal building-related illnesses would be resolved.[394]
    - A second study found that UVGI sanitizers significantly lowered fungi growth on insulation within an air-handling unit as well as airborne fungi levels in an office building after four months of use.[381]
- In healthcare settings, UV irradiation can be a method for controlling common pathogens including methicillin-resistant Staphylococcus aureus (MRSA), vancomycin-resistant Enterococcus (VRE), Acinetobacter, norovirus and Clostridium difficile. This approach can quickly decontaminate room surfaces and equipment without leaving harmful residues for patients and while removing resistant pathogen strains.[395,396]

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