WELL V2:

EVIDENCE BEHIND THE THERMAL COMFORT CONCEPT

FEATURE T01: THERMAL PERFORMANCE

OVERVIEW

Part 1: Ensure that indoor conditions are established in such a way to facilitate thermal comfort for occupants in both cold and hot weather.
Part 2: Monitor dry-bulb temperature, relative humidity, mean radiant temperature and air speed and submit results annually to the WELL digital platform.

SCIENTIFIC BACKGROUND

- Human thermal comfort is a function of six factors: air temperature, mean radiant temperature, air speed, humidity, metabolic rate and clothing insulation.[1] The first four factors are physical parameters of the environment, while the last two are personal.[1]
    - Air temperature is a measure of the hotness or coldness of the air (i.e., the kinetic energy of the gases that make up the air).
    - Mean radiant temperature is a measure of the impact of surface temperatures of all objects in a room on an occupant.
    - Air speed refers to the movement of air.
    - Humidity is a function of the amount of water vapor in the air.
    - Metabolic rate refers to the energy expended by an organism in a given unit of time and varies by activity.
    - Clothing insulation quantifies the degree to which clothing slows heat loss from the body.
- Operative temperature is calculated by combining mean radiant temperature and dry bulb temperature (i.e., the true temperature of the air, protected from radiation and moisture).
    - Mean radiant temperature may be a better predictor of weather- and heat-related mortalities than air temperature, and studies further suggest that indoor heat stress and discomfort could be better understood by measuring mean radiant temperature.[2-4]

KEY HEALTH AND WELL-BEING EFFECTS

- Thermal comfort is ranked by building occupants as one of the most important factors of a building, often rated as more important than visual or acoustic comfort or good air quality.[5]
- A growing body of indoor-based studies indicate that cold indoor temperatures are associated with increased blood pressure, asthma symptoms and poor mental health.[6,7] Cold residences are implicated in excess morbidity and mortality in winter seasons amounting to an estimated 38,200 more deaths per year across 11 European countries.[8]
- Available research on high indoor temperatures show that it is associated with thermal discomfort and higher rates of emergency hospitalizations and cardiovascular and all-cause mortality (i.e., deaths from any cause in a given population or subset of a population across a certain length of time).[9-15] Further, higher temperatures and humidity are associated with poorer scores in various tests of academic achievement in students.[16-18]
- High humidity conditions are conducive to the accumulation of dust mites and fungal growth.[19] Subsequently, mold growth can lead to the agitation of the respiratory system, resulting in allergic reactions, asthma and other respiratory conditions.[20]
- Increased air speed means water on the body evaporates more quickly and cools the body, which can be beneficial in warm climates or uncomfortable in cold climates.[21] Air speeds also affect particle deposition (i.e., particles attaching to surfaces) and thereby can affect the concentration of airborne particles in indoor spaces.[22] The impact on particles by various air speeds varies by particle.[22]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- A primary goal of heating or cooling an indoor environment is to achieve thermal comfort, meaning that all the component factors that influence thermal comfort (e.g., air temperature, mean radiant temperature, air speed, humidity) must be considered and evaluated.[23,24]
- The predicted mean vote (PMV) and predicted percent dissatisfied (PPD) are metrics that take into consideration all of the factors relevant to human thermal comfort beyond ambient temperature, including estimations of metabolic rate and clothing insulation.[25] Despite their names, PMV and PPD do not involve survey results but instead are

representations of the physical environment based on the six thermal comfort factors. PMV ranges from -3 to +3, and many standards and codes prescribe acceptable ranges, such as within -0.5 to +0.5.[26] However, these estimations are often difficult to calculate accurately.[27] Typically used in offices, studies suggest that this method can be applied in environments such as fitness facilities and potentially in healthcare spaces.[28-30]

  - There almost always will be a percentage of people dissatisfied with the thermal environment in a given space, considering the subjective nature and complex interactions of all of the component factors of thermal comfort. Nevertheless, the PMV-PPD model remains the most widely accepted approach in the industry for measuring indoor thermal comfort.
  - Healthcare facilities represent a unique challenge in balancing several types of occupant groups with varying thermal needs (including both patients and healthcare professionals), alongside infection and disease transmission prevention efforts tied to heating, ventilation and air conditioning systems.[31-33] Further studies and reviews of available studies are needed to identify the most appropriate design parameters across facilities in tropical and other climates.
- Another approach also adopted by ASHRAE and other standards worldwide as an alternative to the PMV-PPD model is the adaptive model, which was developed based on studies in naturally ventilated spaces.[15,26,34-37] The adaptive comfort model further takes into consideration how humans react psychologically, behaviorally and physiologically to the thermal environment and establishes varying acceptability ranges for indoor operative temperatures based on outdoor climate.[34,38-42]
- In environments with elevated air speeds (i.e., air speed greater than 0.2 m/s [39.4 fpm]), PMV calculations can use an additional calculation method that takes into consideration how moving air can contribute to a potential cooling effect.[43] Available empirical research indicates that occupants may prefer higher air speeds over less air movement.[43]
  - Ambient air flow rate is associated with thermal comfort. Increased air speed evaporates water more quickly and cools the body, which can be either beneficial in warm climates or uncomfortable in cold climates.[21] Air speeds also affect particle deposition (i.e., particles attaching to surfaces) and thereby can impact the concentration of airborne particles in indoor spaces.[22] The impact on particles by various air speeds varies by the particle in question.[22]
- Kitchen spaces represent a unique space type in thermal comfort, as temperatures can vary widely and often may exceed comfortable ranges due to cooking activities. Studies suggest that the PMV-PPD method is not appropriate for kitchen spaces, indicating that other strategies, such as setting operative temperature limits, may be a better approach.[44,45]
- A Cochrane Review found that investing in physical changes to support thermal comfort in housing (e.g., heating installation, insulation) is associated with improved health (e.g., general, mental health, susceptibility to illness), pointing specifically to efforts that improve thermal comfort in a cost-effective manner.[46] The review also reported that improving thermal conditions in the home and thereby increasing usable living space may improve privacy and familial or other in-home social relationships.[46]

ADDITIONAL NOTES

- Children have under-developed thermoregulatory systems, making them more vulnerable to adverse effects from exposure to temperature outside of the World Health Organization comfort range.[47] Similarly, people with psychiatric, cardiovascular or pulmonary conditions are more vulnerable, as are older adults (typically defined as those over the age of 65).[48,49] Older adults may also have poorer temperature discrimination abilities, meaning they may feel comfortable even in unhealthy temperatures.[50,51]

FEATURE T02: VERIFIED THERMAL COMFORT

OVERVIEW

Part 1: Conduct a post-occupancy thermal survey of regular building occupants to assess thermal comfort satisfaction at least six months after occupancy to evaluate overall satisfaction.

SCIENTIFIC BACKGROUND

- Human thermal comfort is a function of six factors: air temperature, mean radiant temperature, airspeed, humidity, metabolic rate and clothing insulation.[1]
    - Air temperature is a measure of the hotness or coldness of the air (i.e., the kinetic energy of the gases that make up the air).
    - Mean radiant temperature is a measure of the impact of surface temperatures of all objects in a room on an occupant.
    - Airspeed refers to the movement of air.
    - Humidity is a function of the amount of water vapor in the air.
    - Metabolic rate refers to the energy expended by an organism in a given unit of time and varies by activity.
    - Clothing insulation quantifies the degree to which clothing slows heat loss from the body.
- Survey research is the collection of data from a sample of individuals based on their answers to questions.[52] Surveys are often interpreted generally to mean questionnaires, but survey research in fact refers to a variety of research aims, sampling and recruitment strategies, data collection instruments, and methods of survey administration and analysis.[52]
- Surveys also capture what cannot be captured from objective research, including respondents' thoughts, feelings, attitudes and self-reported behaviors.[53]
    - Monitoring building environmental parameters alone (e.g., indoor air quality) is called objective research and is typically not sufficient to accurately or deeply understand occupant experiences and related health effects.[54-56]
    - This is particularly true as human perceptions of concepts like "comfort" are a highly subjective phenomenon that can vary as a function of individual physiological differences and behavioral and psychological factors.[5,39,40,57]

KEY HEALTH AND WELL-BEING EFFECTS

- Thermal comfort is ranked by building occupants as one of the most critical factors of building performance, often rated more important than visual or acoustic comfort or good air quality.[5]
    - One survey study found that the level of satisfaction with either temperature or noise can overpower satisfaction with the environment on the whole.[58]
- Indoor thermal comfort is associated with overall satisfaction with the indoor environment and also may be related to productivity in office workers.[59-62]
- The most widely used thermal comfort models consider only some personal factors that are known to influence comfort, such as metabolic rate and clothing insulation.[5,27,63]
- Other personal parameters are also relevant, including skin temperature, skin wetness and core body temperature.[64,65] These factors are a function of the body's net heat exchange with the environment through the body's thermoregulation system.[66] Other factors, such as age, gender and body composition (e.g., percentage of body fat), also may affect a given person's perception of thermal comfort.[67-71]
- Studies indicate that women are more likely to be dissatisfied with the thermal environment compared to men and are more sensitive to deviations from an optimal temperature range.[69,70] Therefore, assessing building-occupant-specific comfort experiences beyond reliance on generic comfort models is critical to creating a comfortable environment for the most individuals.
    - On average, women tend to have smaller total and lean body mass, a larger ratio of body surface to body mass and lower resting metabolic rates, which may contribute to different thermal comfort experiences among women compared to men. Physiological changes that occur during menstruation and post-menopause, including to thermoregulatory processes and core body temperature, may also contribute.[71,72]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- An optimal thermal environment is one that creates conditions found to be thermally comfortable for the highest possible percentage of people in the space.[1]
- Surveys are a well-established research method that can provide information on a population of interest through the use of data collected from a subset (sample) of that population.[73]
- Post-occupancy surveys are a way for building designers, building owners and facility managers to assess building conditions and receive feedback to identify areas that require improvement or could otherwise promote greater comfort or satisfaction for occupants.[74]
- Using third-party surveys and third-party expert analysis enhances the likelihood that an administered survey is measuring its intended subject.[75] Third-party providers can also help improve credibility of the results, enable benchmarking (or comparison) across similar projects, and help participants feel that their responses are confidential, encouraging a higher response rate.[76]
- There are several key implementation and analysis considerations when conducting survey research.
    - (1) Sampling. Sampling is a critical part of conducting surveys and can have a significant impact on the usefulness and accuracy of findings. Ideally, sample groups should be large and selected in a randomized methodology so that the data collected appropriately reflects the conditions and experiences of the entire population of interest, as opposed to those of the individuals who are most likely to provide feedback or are most convenient to poll (i.e., a convenience sample).[52,77]

      This is not always possible in a building-level study, so attempts should be made to get a sample that is as representative (i.e., the sample responding to the survey resembles the population of the building) as possible.[78]
    - (2) Response Rate. Strategies to achieve higher response rates include designing questions to be concise and easily understood and sending reminders to respondents to complete surveys.[79] Offering respondents insights on results after survey completion is another way to improve response rates to questionnaires.[80]
    - (3) Consent and privacy. Informed consent and issues of privacy and confidentiality are basic principles of ethical research conduct.[81] Best practice includes informing participants of the main research goals, providing contact information for the principal investigator and a strict assurance and outlining of the procedures to protect confidentiality and data storage protocols.[81,82]

FEATURE T03: THERMAL ZONING

OVERVIEW

Part 1: Provide thermal control through use of monitored temperature sensors that allow all regular building occupants to control thermostats, as well as creation of thermal zones and encouragement of multiple zones when appropriate.

SCIENTIFIC BACKGROUND

- The Predicted Mean Vote (PMV) model, which is one of the most widely referenced thermal comfort models in building standards, assumes that the ideal thermal sensation is neutral (i.e., thermoneutrality).[83] However, studies indicate that thermoneutrality does not necessarily align with a person's preferred thermal sensations. For example, in warm outdoor climates, people often prefer cooler conditions indoors, and in cold outdoor climates, people often prefer warmer conditions indoors.[84-86]
- Stable, static thermal environments do not necessarily ensure individual thermal comfort.[87,88]
- Personal factors like size, weight, age, fitness level, clothing insulation and work rate have been known to impact thermal comfort. These factors can interact with commonly used environmental thermal comfort indicators, such as air temperature and air velocity, causing variations in thermal satisfaction.[89]
    - One study found that during warm weather seasons the number of indoor hot and cold complaints among office workers were roughly equal, demonstrating the varying nature of experienced thermal comfort and the need for thermal zoning. When provided with individual thermostat control, occupant satisfaction increased by 20%.[90]

KEY HEALTH AND WELL-BEING EFFECTS

- Thermal comfort is ranked by building occupants as one of the most important factors of a building, often rated more important than visual or acoustic comfort or good air quality.[5]
    - One survey study found that the level of satisfaction with either temperature or noise can overpower satisfaction with the environment on the whole.[58]
- Indoor thermal comfort is associated with overall satisfaction with the indoor environment and also may be associated with productivity in office workers.[59-62]
- High air temperature, lack of air movement and relative humidity levels above 70% can cause unpleasant or uncomfortable working conditions. This has been associated with increases in worker absenteeism, poorer performance and lower employee morale.[91,92]
    - In a 12-subject study, participants performing office tasks in a 30°C environment reported an increase in sick building symptoms, negative mood and decreased willingness to exert effort.[93]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- The differences between temperatures that are considered either neutral or preferred by occupants can vary by 3 °C [5 °F] or more.[67,94,95]
- Studies show that occupants are more tolerant of potentially uncomfortable departures from thermoneutrality when allowed control over the temperature or other aspects of the thermal environment.[83,96,97]
    - One study spanning 215 buildings and over 34,000 occupants in America, Canada and Finland found that 76% of individuals with thermostat control were satisfied with the environment compared to 56% satisfied in a control group who did not have access to a thermostat.[90]
    - In a workplace study conducted in Shenzhen, China, building occupants who had the ability to adjust their environment (e.g., thermostat control) reported significantly fewer adverse environmental and perceptions of lack of control than those who did not have the ability to adjust, contributing to overall workplace satisfaction.[98]
- In addition to control over thermal conditions, it is also important that the temperature controls are easy for occupants to use. A study across 13 offices in Finland found that even when occupants experience discomfort, available temperature controls were not used because of the perceived difficulty in operating user interfaces for the system.[99]

FEATURE T04: INDIVIDUAL THERMAL CONTROL

OVERVIEW

Part 1: Provide access to personal cooling devices or occupant control over localized thermal conditions.
Part 2: Provide access to personal heating devices or occupant control over localized thermal conditions.
Part 3: Allow a flexible dress code for personal thermal comfort.

SCIENTIFIC BACKGROUND

- Even within environmental parameters that reasonably could be expected to create thermally acceptable conditions, people often experience dissatisfaction or discomfort due to the highly subjective nature of thermal comfort.[5,27,63]
- Further complexity is introduced when considering potential adaptive changes made by humans in response to the thermal environment that also can influence perceptions of comfort, including physiological acclimatization to new climates as well as behavioral modifications (e.g., adding or removing layers of clothing, opening a window).[39,61,95,100]
- Geographical considerations are key when assessing preferences in thermal comfort. Outdoor climate and temperature directly correlate to indoor climates, both in human perception and in physicality.[101] Outdoor temperatures are factored in to personal clothing decisions, natural ventilation options, and level of HVAC usage.[101]

KEY HEALTH AND WELL-BEING EFFECTS

- Thermal comfort is ranked by building occupants as one of the most important factors of a building, often rated more important than visual or acoustic comfort or good air quality.[5]
  - One survey study found that the level of satisfaction with either temperature or noise can overpower satisfaction with the environment on the whole.[58]
- Indoor thermal comfort is associated with overall satisfaction with the indoor environment and also may be associated with productivity in office workers.[59-62]
- Thermal comfort models typically include a consideration of some personal factors that influence comfort, such as metabolic rate and clothing insulation, in the most widely used models. But other personal parameters are also relevant, including skin temperature, skin wetness and core body temperature.[64,65] These factors are a function of the body's net heat exchange with the environment through the body's thermoregulation system.[66] Other factors, such as age, gender and body composition (e.g., percentage of body fat), also may affect a given person's perception of thermal comfort.[67-71]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Providing a measure of occupant control over indoor climate can help to improve satisfaction. Studies indicate that providing occupants with the possibility of controlling environmental parameters can improve satisfaction with thermal comfort, as well as with air quality and overall satisfaction with the indoor environment.[5] Occupants have expressed frustration when systems are controlled centrally and cannot be modified by building residents, as needed.[102]
- Survey data from Danish residential buildings showed that occupants prefer to have manual control over indoor environments. For temperature, automatic controls that facilitate minimum acceptable conditions were received more positively, but the study indicates that coupling this with the possibility for manual adjustment may be the best approach, highlighting occupant desire for control of their indoor conditions.[103]
- Personalized conditioning systems, such as cooling or heating chairs, have been shown in studies to be effective in improving thermal sensations and overall comfort.[104-106] Between approximately 25.5 °C to 30.0 °C [77.9 °F to 86 °F], personally controlled fans may be sufficient to facilitate thermal comfort, even without background cooling.[107-109] Similarly, below 19.5 °C [67.1 °F], personally controlled heaters may be a way to provide sufficient thermal comfort that can reduce energy use building-wide.[107]
  - One review of studies estimates that energy savings up to 60% can be achieved using personalized conditioning strategies for thermal comfort that alleviate reliance on background systems for building-wide heating, cooling and ventilation.[106]
  - One study that evaluated the use of heated and cooled seats across 11 laboratory-based climate environments ranging from air temperatures of 15 °C to 45 °C [59 °F to 113 °F] found that modifications to

seat temperature could expand the range of ambient air temperature considered acceptable by 80% of occupants.[110]

- Devices that offer localized, radiant heating/cooling (e.g., controllable, radiant panels such as cooled slabs or heated floors) can affect mean radiant temperature and also have been shown to be effective in improving thermal comfort.[111,112]
    - One study comparing under-desk or floor radiant heating panels and heated chairs showed that heated chairs may be a more effective option for thermal comfort.[108]
- Studies across several countries and cultural contexts demonstrate that a key adaptive behavior in response to thermal environments is related to changing clothing by either adding or removing layers, depending on additional heating or cooling needs, respectively.[113-115] Therefore, environments should allow individuals to be free to adjust clothing as necessary in response to the thermal environment, particularly as this is a no-cost strategy for increasing occupant comfort that does not require the provision of personalized devices or adjustments to background systems.[42,116]
    - Clothing represents layers of insulation that reduce heat loss from the body. In cooler environments, items such as blankets similarly could act as a layer of insulation. But more studies are needed to evaluate the potential use of such provisions by occupants across building types.

FEATURE T05: RADIANT THERMAL COMFORT

OVERVIEW

Part 1: At least 50% of the floor area is serviced by radiant heating systems.
Part 2: At least 50% of the floor area is serviced by radiant cooling systems.

SCIENTIFIC BACKGROUND

- The human body exchanges heat with the environment through four mechanisms: conduction, convection, radiation and evaporation.[117] For most indoor environments, convection (e.g., forced air) and radiation (e.g., heated/cooled surfaces) are the dominant types that support heat exchange in humans.[117]
- Indoors, radiative heat gain is most common from either warm radiation via direct solar heat gain (i.e., passing through windows onto receiving surfaces) or from radiant heating systems that supply direct heat to intentionally create warm surfaces (e.g., floors, walls, ceilings).
- Radiant heating and/or cooling systems provide more than 50% of the total heat flux by thermal radiation.[118]
    - The most commonly used radiant heating systems integrate under-floor hydronic distribution using water heated by a boiler and pumped through tubing.[119]
    - Radiant cooling can be accomplished by installing similar under-floor systems using chilled water, although in some places, like North America, a popular strategy for residential applications circulates chilled water through aluminum panels suspended from the ceiling. Radiant cooling is most effective in arid regions, where condensation is less likely to occur.[120]
- Radiant systems are designed to affect mean radiant temperature (MRT), which is a measure of the impact of surface temperatures as an area-weighted mean of all objects in a room on an occupant.[121]
- Radiant systems have been increasingly popular in residential, commercial and industrial buildings due to energy saving opportunities, quiet operation and interoperability with easy integration into other building elements and systems.[122-130]

KEY HEALTH AND WELL-BEING EFFECTS

- There is a relationship between indoor thermal factors and symptoms such as dry throat, coughing, itchy skin and fatigue.[131,132] Studies show that these are more common when the environment is considered too hot or too cold, suggesting that symptoms reflect perceived thermal dissatisfaction.[133-136]
- Indoor thermal comfort is associated with overall satisfaction with the indoor environment and may be associated with productivity in office workers.[59-62]
- Linkages have been established between dissatisfaction with thermal environment (most commonly air temperature and humidity levels) and learning performance and fatigue levels in schools.[137]
- Correlations have been seen in hospitals between thermal satisfaction and healing processes in patients, although unique thermal comfort requirements in hospitals, including air movement restrictions and variations between patient and hospital personnel activity levels, make it difficult to establish ideal threshold recommendations.[137-139]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Radiant heating systems result in reduced air movement and decreased dust distribution compared to forced air systems, making them preferable, particularly in environments where people are more susceptible to allergies.[119,140-143]
- Radiant floors provide more uniform thermal conditions within a space, resulting in fewer temperature asymmetries (e.g., smaller differences in vertical air temperature), which can reduce occupant thermal discomfort.[144-147]
- A review comparing radiant systems with convective, all-air systems found that radiant systems generally provided thermal comfort at least as well as all-air systems. Studies in this review relied on building simulations, physical measurements and human subjects testing with occupant surveys.[148]
    - Five studies included in the review could not establish a thermal comfort preference between all-air and radiant systems, while the remaining three studies demonstrated preferences for radiant systems.[70,149-155]
- The use of dedicated outdoor air systems with radiant cooling systems represents an energy-efficient alternative to conventional, all-air systems by providing cooling in ways that preserve high quality indoor air and thermal comfort.[156-159] Coupling systems in this way can help to alleviate latent load burdens (e.g., energy needed for

dehumidification) while mitigating condensation-related issues that could otherwise pose challenges with a radiant cooling system.[160]

- Radiant cooling can be used in tropical climates, but temperature and humidity concerns in such environments require a more sophisticated system.[161] The use of dedicated outdoor air systems alongside radiant cooling systems is particularly effective in such climates.[157]

FEATURE T06: THERMAL COMFORT MONITORING

OVERVIEW

Part 1: Regularly measure thermal environment in occupiable areas with real-time display to occupants, as well as report measured data annually through the WELL digital platform.

SCIENTIFIC BACKGROUND

- There is a growing trend in multi-system communication in building operations (e.g., integrated sensors and controls); this has led to better building performance across productivity, efficiency and convenience, as well as increased environmental control and responsiveness to human needs.[162-165]
- It has also provided the infrastructure foundation for studies which further our understanding of thermal comfort.
    - For example, European studies which involved continuously monitoring thermal environments of office spaces found that that occupants' indoor clothing choices are determined by mean outdoor temperatures, suggesting that indoor environments could be more adaptive to daily outdoor conditions.[61,166]
- Restricting analysis of the thermal environment during occupied hours may be more accurate for human exposure considerations because daily averages incorporate long hours of no or limited occupancy that can under- or over-estimate temperature and humidity conditions.[167,168]
- Calibration is necessary to ensure monitors are systematically responding to changes in concentrations, have not drifted over the time used and are providing accurate and consistent readings.[169] Beyond the cost of the sensor, calibration, repair, upkeep and replacement should be considered during sensor selection.[170]
    - Sensor drift refers to the low-frequency change of a sensor, linked to electronic wear and tear and aging of the tool over time.[171]
- Recent technological advancements have led to an increased availability of real-time direct reading instruments that can continuously capture thermal parameters tied to human comfort.[172,173] To guide operations, building professionals may consider low-cost, easy to deploy and non-invasive sensors that can measure several of these parameters, such as indoor dry-bulb temperature, relative humidity, air speed and mean radiant temperature with temporal and spatial granularity.[174,175]

KEY HEALTH AND WELL-BEING EFFECTS

- Variations in air speed and air temperature can be seen over short distances in indoor environments, due to factors such as fluid dynamics produced by air supply vents, sun position, solar shading and weather outside.[173] When the temperature is too high or there is limited air movement, building occupants frequently report unpleasant and uncomfortable conditions. This has been shown to be associated with increases in worker absenteeism, poorer performance and lower employee morale.[91,92,176]
- High-temperature indoor environments can have adverse reactions on cognitive function in healthy adults, school-aged children and the elderly.[177-179] Real-time monitoring of indoor spaces may improve the adaptive capacity of indoor environments by activating ventilation and cooling systems during extreme heat events.[179]
- Cold temperature indoor environments are also associated with adverse reactions, including increased blood pressure, worsening of asthma symptoms and poor mental health.[180] Use of real-time monitoring in occupied areas could help to quickly identify poor thermal conditions.
- Available, exercised and perceived control play a role in thermal perception.[63] IEQ monitoring systems can provide tenants and/or building occupants with applicable data and give them agency to compare their indoor environment with expected conditions.[173]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Temperature and humidity monitors in epidemiological studies have assisted understandings of the impact of these variables on health and productivity, including fatigue, student test performance and effects on pre-existing health conditions.[16,181-183] Use of such monitoring devices has also informed understandings of environmental conditions that can lead to high indoor temperatures, including building size, floor level, indoor-outdoor relationship and types of air conditioning.[184,185]
- Continuous temperature and humidity monitoring throughout the day and year can identify when and where poor thermal conditions exist. Measurements can identify factors affecting indoor climate including indoor sources of heat,

areas of heat gain from windows, heat exchange through the thermal envelope, temperature fluctuations between and within offices and other outdoor conditions influencing indoor space.[91,176]

ADDITIONAL NOTES

- Increasing innovations in wearable sensors can track individuals' sweat rate in real-time, and other individualized thermal comfort monitoring metrics may become more mainstream looking forward, such as mean skin temperature and peripheral blood flow tracking.[186]

FEATURE T07: HUMIDITY CONTROL

OVERVIEW

Part 1: Demonstrate the project can achieve relative humidity levels between 30-60% either through mechanical control, humidity modeling or long-term data collection, in all areas except intentional high-humidity areas (e.g., pool or shower areas).

SCIENTIFIC BACKGROUND

- Thermal comfort is determined by multiple personal and environmental factors, including metabolic rate, clothing, air temperature, humidity, air movement, mean radiant temperature of surrounding surfaces and other contextual factors.[1]
- Relative humidity (RH) is the ratio of the amount of water vapor present in the air to the maximum amount of water vapor that the air can hold at a given temperature.
- Humidity is more noticeable to the skin in warmer environments, primarily because it reduces the rate of evaporation and thereby decreases the efficiency of sweating, one of the body's natural cooling mechanisms.[187]
- When the human body sweats, moisture and salts are released from sweat glands in the skin. This moisture covers the skin and transfers heat from the body to the atmosphere as the sweat evaporates. As humidity increases, the process of evaporation slows and the body retains heat for a longer period, resulting in reduced physical comfort.

KEY HEALTH AND WELL-BEING EFFECTS

- The perception of air quality is affected by both temperature and humidity.[188,189] Studies indicate that people perceive the air as less acceptable with increasing temperature and humidity, and at particularly high levels this was true regardless of whether or not the air was free of pollutants.[190]
- Extremely low RH (below 20%) may cause eye irritation and contribute to dryness of the nose and throat.[191-195] RH at about 40% appears to be more beneficial for the eyes, airways and mucous membranes of the body.[196]
- Insufficient evaporative and convective cooling of the mucous membranes in the upper respiratory tract may cause local discomfort and a sense of stuffiness and staleness, which can occur when temperature and humidity are high.[64]
- The humidity and temperature of an environment can affect lung function, particularly among more sensitive people such as those with asthma.[197-200]
- The airborne viral transmission in indoor environments is a function of six factors:
    - (1) Number of people who are infected and produce contaminated aerosols in the environment.
    - (2) Number of susceptible, non-infected persons.
    - (3) Duration of the exposure.
    - (4) Ventilation rate in the space.
    - (5) Settling rate of contaminated aerosols.
    - (6) Survival and other related characteristics of the pathogens that are attached to the aerosols.[201]
- Low RH (between 20-35%) appears to create conditions that are favorable for the survival and transmission of certain viruses such as influenza and human rotavirus.[202-204] RH below 50% may allow for prolonged survival of some other viruses such as the measles, herpes and rubella viruses.[19]
    - Whether the survivability of viruses on inanimate surfaces is aided by low or high RH may depend on the type of virus. Humidity affects both the settling rate of aerosols and the survivability of pathogens.[19] Enveloped viruses thrive when RH is below 50%, while nonenveloped viruses thrive when RH is above 80%.[205] Other studies show that lower humidity levels (below 40%) further increase the survivability of enveloped viruses (such as coronaviruses).[206]
    - Low humidity also may increase the susceptibility of viral infections.[207] One study compared the effect of 20% RH to 50% RH (at a constant temperature of 20 °C [68 °F] to find whether the difference in environmental conditions had an impact on influenza infection rates. An association was found between host exposure to the drier air and impaired mucociliary clearance, innate antiviral defense and tissue repair function.[207]
- On the other hand, some viruses appear better able to survive in conditions of high RH (above 70%). These include the adenovirus and coxsackie viruses.[208,209]

- Long-term exposure of either high or low humidity is conducive to the accumulation of dust mites and fungal growth.[19] This increased likelihood of mold growth can lead to the agitation of the respiratory system, resulting in allergic reactions, asthma and other respiratory conditions.[20]
  - Dust mites, in particular, seem to track closely with indoor RH levels. Field studies show that mite populations are almost eliminated in winter when RH levels are below 50%.[210-212]
  - Most fungal growth occurs when RH is at 75% or higher.[19]

HEALTH PROMOTION BENEFITS AND STRATEGIES

- Indoor humidity at levels between 30-50% RH are considered ideal.[213,214]
- Many adverse health effects associated with RH can be minimized by maintaining levels between 40-60%.[19] Chemical interactions in the environment appear to increase when RH is above 30% consistently (e.g., higher concentration of formaldehyde in the air at a RH of 70% compared to 30%).[215]
- Ideal humidity levels can be maintained by using humidifiers (in the case of dry air) or either dehumidifiers or air conditioners (when humidity levels are too high).[213]
  - Several types of devices can increase RH, including central humidifiers, ultrasonic humidifiers, impeller humidifiers, evaporators and steam vaporizers. If the air is too damp, air conditioning units (either central or window-mounted) or dehumidifiers can be used to bring the humidity back to a recommended level.[213]

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