ASHRAE Position Document on Indoor Carbon Dioxide

Approved by ASHRAE Board of Directors
February 2, 2022

Expires
February 2, 2025

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HISTORY OF REVISION/REAFFIRMATION/WITHDRAWAL DATES

The following summarizes this document's revision, reaffirmation, and withdrawal dates:

2/2/2022—BOD approves Position Document titled *ASHRAE Position Document on Indoor Carbon Dioxide*

Note: ASHRAE's Technology Council and the cognizant committee recommend revision, reaffirmation, or withdrawal every 30 months.

Note: ASHRAE position documents are approved by the Board of Directors and express the views of the Society on a specific issue. The purpose of these documents is to provide objective, authoritative background information to persons interested in issues within ASHRAE's expertise, particularly in areas where such information will be helpful in drafting sound public policy. A related purpose is also to serve as an educational tool clarifying ASHRAE's position for its members and professionals, in general, advancing the arts and sciences of HVAC&R.

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ABSTRACT

Indoor carbon dioxide (CO_2) has played a key role in discussions of ventilation and indoor air quality (IAQ) for centuries. Those discussions have evolved to focus on the use of indoor CO_2 as an IAQ metric, estimation of ventilation rates using CO_2 as a tracer gas, control of outdoor air ventilation based on CO_2 concentrations, and impacts of CO_2 on building occupants. More recently, the measurement of indoor CO_2 has been discussed in the context of airborne infectious disease transmission. However, many applications of indoor CO_2 do not reflect a sound technical understanding of the relationship between indoor CO_2 concentrations, ventilation, and IAQ. Some applications have been technically flawed, leading to misinterpretations of the significance of indoor CO_2. This position document discusses the role of indoor CO_2 in the context of building ventilation and IAQ based on ASHRAE's long involvement with those topics as well as the interests of its members and stakeholders. The positions stated within address the use of CO_2 as a metric of IAQ and ventilation, the impacts of CO_2 on building occupants, the measurement of CO_2 concentrations, the use of CO_2 to evaluate and control outdoor air ventilation, and the relationship of indoor CO_2 to airborne infectious disease transmission. This document recommends research into the impacts of CO_2 on occupant health, comfort, and performance and on the application of indoor CO_2 concentrations in building operation, as well as the development of guidance on the measurement and practical application of CO_2 concentrations.

EXECUTIVE SUMMARY

While indoor CO_2 concentrations have long been considered in the context of building ventilation and IAQ, the meaning of indoor CO_2 as an indicator of IAQ and ventilation is commonly misinterpreted within the HVAC industry and the research community and among the public. Despite many efforts to address this confusion in standards and guidance documents, technical publications, conference presentations, and workshops, significant misunderstandings remain. Given ASHRAE's involvement in ventilation and IAQ research and standards, this position document has been developed to clarify the role of indoor CO_2 and how it can be used to understand and manage building performance. It addresses the history of CO_2 in relation to ventilation and IAQ, what is known about health and cognitive impacts of CO_2 exposure on building occupants, existing standards and guidelines on indoor CO_2 concentrations, limitations in the use of CO_2 as an indicator of ventilation and IAQ, how CO_2 can be used to evaluate and control outdoor air ventilation, increases and variations in outdoor CO_2 concentrations, indoor air cleaning to remove CO_2, and the use of CO_2 as an indicator of the risk of airborne disease transmission indoors. It focuses on non-industrial indoor environments intended for human occupancy, including residences, offices, schools, and transportation environments.

ASHRAE takes the following positions:

- Indoor CO_2 concentrations do not provide an overall indication of IAQ, but they can be a useful tool in IAQ assessments if users understand the limitations in these applications.
- Existing evidence for direct impacts of CO_2 on health, well-being, learning outcomes, and work performance at commonly observed indoor concentrations is inconsistent, and therefore does not currently justify changes to ventilation and IAQ standards, regulations, or guidelines.
- The use of indoor CO_2 measurements to assess and control the risk of airborne disease transmission must account for the definition of acceptable risk, the type of space and its occupancy, and differences in CO_2 and infectious aerosol emissions and their subsequent fate and transport.
- Differences between indoor and outdoor CO_2 concentrations can be used to evaluate ventilation rates and air distribution using established tracer gas measurement methods, but accurate results require the validity of several assumptions and accurate input values.
- Sensor accuracy, location, and calibration are all critical for drawing meaningful inferences from measured indoor CO_2 concentrations.
- Air-cleaning technologies that remove only CO_2 will not necessarily improve overall IAQ and can interfere with systems using CO_2 for ventilation control or IAQ monitoring.

ASHRAE recommends research on the following topics:

- Indoor CO_2 exposure as a modifier of human responses to other environmental factors such as thermal comfort and other airborne contaminants
- The development of IAQ metrics that cover the wide range of indoor contaminants and sources
- Health and performance impacts of indoor CO_2 in concentration ranges typical of non-industrial indoor environments in both laboratory and field settings covering a diverse range of subjects, including variations in age, gender, and health status

- Physiological impacts of elevated CO_2 concentrations, such as changes in blood chemistry and respiration, including those associated with increasing outdoor CO_2 concentrations
- The relationship between indoor CO_2 concentrations and the risks of airborne infectious disease transmission
- Indoor CO_2 concentration measurement, including sensor performance and sensor locations for different applications and the performance and application of low-cost CO_2 sensors
- The use of occupant-generated CO_2 as a tracer gas to estimate building ventilation rates, including approaches that capture transient effects and account for multiple-space ventilation systems and different air distribution approaches
- Strategies for demand-controlled ventilation (DCV) using CO_2 and other indicators of occupancy that overcome limitations of current approaches and control contaminants that are not linked to occupancy
- Indoor CO_2 concentrations, ventilation rates, and occupancy in different building types in different countries to establish benchmark data and better understand the impacts of new building and system designs, tighter construction, advanced operation and control strategies, and other changes in the building stock

ASHRAE also recommends the following activities:

- Development of guidance and standards on indoor CO_2 concentration measurement and sensor selection, especially for DCV applications
- Development of educational programs, conference sessions and workshops, and guidance documents to help practitioners and researchers understand the application of indoor CO_2 concentrations as an indicator of ventilation and IAQ
- Development of guidance on HVAC equipment and controls using CO_2 monitoring
- Development of guidance on the use of CO_2 as a tracer gas for measuring building ventilation rates and air distribution

1. THE ISSUE

Indoor CO_2 has been considered in the context of ventilation and IAQ for centuries. These discussions have focused on two areas: how CO_2 concentrations relate to occupant perception of human bioeffluents and other aspects of IAQ, and the use of CO_2 to evaluate outdoor air ventilation rates. While these topics have been studied for decades, misinterpretation of CO_2 concentration as an indicator of IAQ and ventilation still occurs in the HVAC industry, IAQ research community, and the public. Despite many efforts to address this confusion in standards and guidance documents, technical publications, conference presentations and workshops, significant misunderstanding remains.

In addition to the need to clarify the relationship of indoor CO_2 concentration to IAQ and ventilation, another motivation for this position document is the need to address recent research results on the impacts of CO_2 on human performance at commonly observed indoor concentrations. Given trends of increasing outdoor CO_2 concentrations, additional concerns have been expressed regarding these potential health and performance impacts. Moreover, a variety of organizations and government bodies have issued standards and regulations for indoor CO_2 concentrations in non-industrial workplaces. Also, concerns have long existed regarding the accuracy of indoor CO_2 concentration measurements, which are increasingly common due to the availability and more widespread application of less expensive sensors. Indoor CO_2 monitoring has also been promoted as a ventilation indicator in the context of managing the risks of airborne disease transmission. Finally, most of these applications of indoor CO_2 measurements require values for the rate at which building occupants generate CO_2 and other inputs, and the uncertainty of these values has not been well characterized.

2. BACKGROUND

This section expands on the topics in the The Issue section in support of the positions and recommendations in this document. Specifically, this section covers the history of the role of indoor CO_2 concentrations in the context of ventilation and IAQ, health and cognitive impacts of exposure to CO_2, existing standards and regulations for indoor CO_2 concentrations, CO_2 as an indicator of IAQ and ventilation, use of CO_2 as a tracer gas for estimating ventilation rates, increases in outdoor CO_2 concentrations, air cleaning directed at CO_2 removal, and CO_2 as an indicator of the risk of airborne disease transmission. More detail on these topics, including extensive references for the statements herein, is contained in the appendix to this position document.

2.1 History of CO_2 in Relation to Building Ventilation and IAQ

Carbon dioxide has been discussed in the context of building ventilation since the seventeenth and eighteenth centuries, when CO_2 rather than a lack of oxygen was considered to be a cause of physiological effects attributed to bad air. In the nineteenth century, Pettenkofer stated that it was not CO_2 but the presence of organic material from human skin and lungs that caused the negative effects attributed to poor ventilation, proposing that CO_2 not be considered as a cause of discomfort but rather as a surrogate for vitiated air. In the early twentieth century, studies by Billings, Hermans, Flugge, Hill, and others showed that warmth combined with smells in a crowded room were a source of discomfort in poorly ventilated rooms. The work of Lemberg and later Yaglou showed that occupant perception of body odor produced by humans could be used as a criterion for ventilation. Perceived odor intensity was used as a criterion for ventilation rate requirements of about 7.5 to 10 L/s (15 to 20 cfm) per person, and again CO_2 was not considered to be a pollutant but rather an indicator of body odor. Studies in the latter part of the twentieth century by Fanger, Cain, and Iwashita confirmed the results of Yaglou and Lemberg. This research on body odor perception was used to develop the ventilation requirements in ASHRAE and European Committee for Standardization (CEN) standards. The 1989 edition of ASHRAE's ventilation standard, Standard 62 (subsequently Standard 62.1), had a CO_2 limit of 1000 ppm_v, but this was removed from subsequent editions due to its common misinterpretation.

2.2 Health and Cognitive Effects of CO_2 Exposure

Indoor concentrations of CO_2 greater than 1000 ppm_v have been associated with increases in self-reported, nonspecific symptoms commonly referred to as *sick building syndrome (SBS) symptoms*. However, these observations were not controlled for other contaminants or environmental parameters; therefore, elevated CO_2 concentrations likely served as indicators of inadequate ventilation that increased the concentrations of all contaminants with indoor sources. More recently, several groups have explored the cognitive effects of short-term exposure (2 to 8 h) to pure CO_2 at concentrations between 600 and 5000 ppm_v. Some of these studies demonstrated concentration-dependent impairment, an indicator of a causal effect, but other studies did not show any effects on cognition. These inconsistencies require further investigation, including study of the mechanisms involved. This research is a priority due to the ubiquity of indoor concentrations of CO_2 in excess of 1000 ppm_v.

2.3 Existing Standards and Regulations for Indoor CO_2 Concentrations

Many countries have proposed mandatory or suggested guideline values for indoor CO_2 in non-industrial spaces. It should be noted that the rationales supporting these guideline values are not generally provided along with these guideline values. These indoor CO_2 limits tend to be on the order of 1000 ppm_v but range as high as about 1500 ppm_v. They are generally intended for the management of generic IAQ concerns and SBS symptoms. CO_2 guideline values in the context of airborne infectious disease transmission are discussed in the later section on CO_2 as an indicator of airborne infection risk transmission.

For workplaces, the United States Occupational Safety and Health Administration (OSHA) and National Institute for Occupational Safety and Health (NIOSH) have established a time-weighted average limit value of 5000 ppm_v for airborne exposure in any 8-hour work shift during a 40-hour workweek and 30,000 ppm_v as a short-term exposure limit, i.e., a 15-minute time-weighted average that should not be exceeded at any time during a workday. ASHRAE Standard 62.1 has not contained a limit value for indoor CO_2 since the 1989 edition of the standard. Misunderstanding of previous editions of the standard continue to lead many to incorrectly attribute a 1000 ppm_v limit to ASHRAE.

2.4 CO_2 as an Indicator of IAQ and Ventilation

As noted previously, indoor CO_2 has been prominent in discussions of ventilation and IAQ for centuries. While CO_2 concentrations are related to the perception of human bioeffluents and the level of acceptance of their odors, they are not a good overall metric of IAQ, as many important contaminant sources do not depend on the number of occupants in a space. For example, contaminants emitted by building materials and those that enter from outdoors are not correlated with CO_2 concentrations. Nevertheless, if outdoor air ventilation rates are reduced in an occupied building, concentrations of CO_2 will increase along with the concentrations of other contaminants generated indoors.

An indoor CO_2 concentration below 1000 ppm_v has long been considered an indicator of acceptable IAQ, but this concentration is at best an indicator of outdoor air ventilation rate per person. This value of 1000 ppm_v has been used for decades without an understanding of its basis, which is its link to the perception of human body odor by building occupants. This misunderstanding of the significance of 1000 ppm_v has resulted in many confusing and erroneous conclusions about IAQ and ventilation in buildings. The use of CO_2 as an indicator of outdoor air ventilation must reflect the fact that outdoor air ventilation requirements depend on space type, occupant density, and occupant characteristics (e.g., age, body mass, and activity levels). Therefore, a single CO_2 concentration does not apply to all space types and occupancies for the purposes of assessing the ventilation rate. Also, CO_2 concentrations can vary significantly within a building or space based on the details of how ventilation and air distribution are implemented.

Indoor CO_2 concentrations have long been used to control outdoor air intake rates, using demand-controlled ventilation (DCV). This control strategy reduces the energy use associated with overventilation during periods of low occupancy and helps to ensure that spaces are adequately ventilated based on their actual occupancy. DCV is in fact required by some energy efficiency standards such as ASHRAE/IES Standard 90.1, and CO_2 monitoring is one means of implementing DCV. Note that this control strategy can be more complex to implement in multiple-space ventilation systems when complying with the ventilation requirements in ASHRAE Standard 62.1 and the designer still must address contaminants not associated with occupancy levels.

2.5 Use of Occupant-Generated CO_2 as a Tracer Gas

The use of indoor CO_2 concentration as an indicator of the adequacy of outdoor air ventilation rates is based on the application of CO_2 as a tracer gas. Tracer gas dilution methods for measuring outdoor air change rates have been used for decades and are well documented in existing ASTM and ISO standards. Application of CO_2 with these methods simply takes advantage of a convenient tracer gas source, the building occupants. Tracer gas methods also exist to quantify air distribution and ventilation efficiency in spaces, and CO_2 can be used for these measurements as well.

There are two common tracer gas methods for estimating outdoor air ventilation rates using CO_2: decay and steady state, both of which are best suited to single zones. Both methods are based on the following assumptions: the tracer gas concentration is uniform in the space being monitored, the outdoor CO_2 concentration is constant during the test (or monitored in real time), and the rate at which occupants generate CO_2 is known and constant for the steady-state method. People emit CO_2 at a rate based on their sex, age, body mass, and level of activity, and therefore information on the occupants is required to estimate these rates. Because these are single-zone methods, they do not account for airflow or CO_2 transport between the zone of interest and other building zones. The measurement errors associated with using a single-zone approach in a space or building that is not a single zone at a uniform concentration are difficult to quantify, and these errors are often neglected in the application of these methods.

2.6 Increases in Outdoor CO_2 Concentrations

Outdoor CO_2 concentrations are relevant to consideration of indoor CO_2 for two reasons. First, when using DCV based on the absolute indoor CO_2 concentration, and not the indoor-outdoor difference, the outdoor air intake rate varies not only with occupancy but also with the outdoor CO_2 concentration. Second, if exposure to CO_2 is established to have health and cognitive impacts, then increases in outdoor concentrations will increase the prevalence of these impacts.

Global average CO_2 concentrations are determined by a complex interaction of sources, sinks, and driving forces. On a geological timescale, they have varied widely, but for hundreds of thousands of years, up until the early twentieth century, they were below 300 ppm_v, first exceeding 300 ppm_v in 1912. Since that time, the average outdoor CO_2 concentration has increased, reaching 420 ppm_v in 2021. Superimposed on the trend of increasing outdoor CO_2 concentration are daily and seasonal variations, as well as larger variations in urban areas. These variations in outdoor CO_2 make it important to measure outdoor concentrations when monitoring indoor CO_2.

2.7 Air Cleaning Directed at CO_2 Removal Alone

While CO_2 may be a useful indicator of ventilation and IAQ under limited circumstances, indoor CO_2 concentrations are not necessarily well correlated with other important indoor air pollutants such as viruses, mold, formaldehyde, carbon monoxide, asbestos, and airborne particles. Using air-cleaning technologies to reduce CO_2 for commonly observed indoor concentrations can result in an unjustified expectation that other indoor pollutants are not a concern. It is critical not to presume that air cleaning directed at CO_2 removal or conversion alone will remove other important indoor air contaminants. Also, when using CO_2-based DCV, the ventilation system will not operate as intended if using CO_2 removal.

2.8 CO_2 as an Indicator of Airborne Infection Risk Transmission

During the COVID-19 pandemic, recommendations have been made to use indoor CO_2 measurement as an indicator of the risk of airborne infection transmission. ASHRAE does not recommend a specific CO_2 concentration as a metric of infection risk, but other organizations have issued recommended or mandated CO_2 concentration limits. Many of these are based on CO_2 as an indicator of the outdoor ventilation rate per person. The ventilation rates on which many of these CO_2 concentrations are based can be derived from ventilation standards that are intended to provide acceptable IAQ but do not target the control of airborne disease transmission, except in healthcare settings. Recommendations or requirements for ventilation rates and CO_2 concentrations to limit infectious disease transmission have been suggested but are highly uncertain given the many factors that impact infection risk, including differences between pathogens.

All else being equal, higher CO_2 concentrations correspond to lower outdoor air ventilation rates and the potential for an increased risk of airborne transmission. While CO_2 concentrations can be a useful qualitative indicator, they do not capture the impacts of the reduced occupancy that is common in many buildings or the impacts of particle filtration and air cleaning on infection risk. Other factors impact exposure and transmission risk, such as the amount of virus in the air (which does not necessarily scale with CO_2), respiratory activity, and type of pathogen. Note also that if CO_2-based DCV is being used, lower occupancy will reduce the outdoor air ventilation rate and presumably increase the risk of transmission, which is why several organizations have recommended disabling DCV systems.

Rather than using indoor CO_2 concentration as an indicator of desired ventilation rates, several analyses of airborne infection risk have used CO_2 as an indicator of the “rebreathed fraction” of indoor air (the fraction of inhaled air that was exhaled by someone else in the space). If the incidence of an airborne disease in the population and the infectious dose of the pathogen are known, these methods can be used to estimate the percentage of new infections for a particular scenario. These methods rely on multiple assumptions about the distribution of indoor CO_2 and infectious aerosol, the relative significance of different infection modes, and dose response relationships that are subject to large uncertainties. Consequently, they may not be highly accurate predictors of risk.

APPENDIX

This appendix contains a detailed and thoroughly referenced expansion of the discussion in the Background section of this position document for readers who desire an in-depth understanding of that material. As does the Background section, this appendix expands on the topics identified in the The Issue section in support of the positions and recommendations in this document: the history of the role of indoor CO_2 concentrations in the context of building ventilation and IAQ, health and cognitive impacts of exposure to CO_2, existing standards and regulations for indoor CO_2 concentrations, CO_2 as an indicator of IAQ and ventilation, use of CO_2 as a tracer gas for estimating ventilation rates, increases in outdoor CO_2 concentrations, air cleaning directed at CO_2 removal alone, and CO_2 as an indicator of the risk of airborne disease transmission.

A.1 History of CO_2 in Relation to Building Ventilation and IAQ

The overview of early CO_2 research discussed in this paragraph is provided by Wargocki (2021). Carbon dioxide has been discussed in the context of building ventilation since the seventeenth century when Mayow proposed igneo-aerial particles produced by candles to cause the demise of animals. In the eighteenth century, Lavoisier attributed the effects of these particles to CO_2. At that time, CO_2 rather than a lack of oxygen was considered to be a cause of physiological effects attributed to bad air and an indicator of whether the air was stale or fresh. In the nineteenth century, Max Josef von Pettenkofer stated that it was not CO_2 but the presence of organic material from human skin and lungs that caused the negative effects attributed to poor ventilation. He and Saeltzer proposed that CO_2 not be considered as a cause of discomfort but rather as a surrogate for vitiated air and an indicator of deleterious airborne substances of unknown origin. Pettenkofer proposed 1000 ppm_v of CO_2 as a marker of inadequate ventilation indoors and 700 ppm_v for bedrooms. In the early twentieth century, studies by Billings, Hermans, Flugge, Hill and others showed that warmth combined with smells in a crowded room were a source of discomfort in poorly ventilated rooms. Experiments with CO_2 increasing to 3% or 4% and oxygen falling to 17% did not show negative effects except for deepened breath and the need for cooling. The work of Lemberg and later Yaglou showed that response to body odor produced by humans could be used as a criterion for ventilation. Perceived odor intensity was used as a criterion for ventilation rate requirements of about 7.5 to 10 L/s (15 to 20 cfm) per person (Persily 2015). CO_2 was, again, not considered a pollutant but rather a marker of body odor perception, since humans emit both CO_2 and bioeffluents at rates related to their metabolism. Studies in the latter part of the twentieth century by Fanger, Cain, and Iwashita, in which acceptability of perceived air quality was used as the criterion for ventilation requirements, confirmed the results of Yaglou and Lemberg. This research on body odor perception was used to develop the ventilation requirements in ASHRAE and European Committee for Standardization (CEN) standards. The 1989 edition of ASHRAE's ventilation standard, Standard 62 (subsequently Standard 62.1), had a CO_2 limit of 1000 ppm_v, but this was removed from subsequent editions due to its common misinterpretation.

A.2 Health and Cognitive Effects of CO_2 Exposure

Carbon dioxide is considered nontoxic at concentrations up to 5000 ppm_v, which is the U.S. federal standard (Permissible Exposure Level) for workplaces set by the Occupational Safety and Health Administration (OSHA) as noted in the later section on existing standards and regulations. Guidelines for the International Space Station and U.S. submarines currently suggest that CO_2 concentrations be maintained at 4000 to 5000 ppm_v to reduce the incidence of headaches (James and Zalesak 2013; Scully et al. 2019). Indoor concentrations greater than 1000 ppm_v have been associated with increases in self-reported, nonspecific symptoms commonly referred to as *sick building syndrome (SBS) symptoms*, as well as decreased performance of office work and schoolwork, as discussed in the following paragraph. These observations were not controlled for other contaminants or environmental parameters; therefore, elevated CO_2 concentrations likely served as indicators of inadequate ventilation that increases the concentration of all contaminants with indoor sources (Persily 2015; Lowther et al. 2021).

Several groups have explored the effects of acute exposure (duration from 2 to 8 h) to pure CO_2 at concentrations between 600 and 5000 ppm_v, as summarized by Fisk et al. (2019), Du et al. (2020), and Lowther et al. (2021). Five studies reported an association between CO_2 and decreased cognitive performance at concentrations in the range of 1000 ppm_v (Satish et al. 2012; Allen et al. 2016, 2018; Kajtar and Herczeg 2012; Lee et al. 2022), and one was equivocal (Scully et al. 2019). While three of these studies demonstrated concentration-dependent impairment, an indicator of a causal effect, other studies did not show any cognitive effects (Zhang et al. 2016a, 2016b). These inconsistencies require further investigation, including study of the mechanisms involved. Further human subject research is a priority due to the ubiquity of indoor concentrations in excess of 1000 ppm_v as well as recent animal work that provides direction for investigation of mechanisms for declines in cognitive function.

Although CO_2 lacks direct chemical reactivity, recent studies with mice show inflammatory changes in the blood at 2000 to 4000 ppm_v and leakage of fluid from blood vessels into brain tissue at 2000 ppm_v (Thom et al. 2017a). Further confirmation of these results was found in in-vitro experiments with human neutrophils (a type of white blood cell) at the same concentrations (Thom et al., 2017b). These findings support the phenomenon of brain toxicity from pure CO_2 and are mechanistically consistent with reports of cognitive changes observed in the human experiments at commonly observed indoor concentrations. Further research to resolve questions regarding the neurotoxicity of CO_2 should be a priority (Jacobson et al. 2019).

A.3 Existing Standards and Regulations for Indoor CO_2 Concentrations

Many countries have proposed mandatory or suggested guideline values for indoor CO_2 in non-industrial spaces. It should be noted that the rationales supporting these guideline values are not necessarily provided in the reference documents and that CO_2 guideline values proposed in the context of the COVID-19 pandemic are not included in this discussion. Pandemic-motivated values are discussed in the later section on airborne infection risk transmission.

Several countries have published indoor CO_2 limits, in some cases for all occupied buildings and in other cases making a distinction between residential and nonresidential buildings. These limits tend to be on the order of 1000 ppm_v but range as high as about 1500 ppm_v. They are generally intended for the management of generic IAQ concerns and SBS symptoms, with CO_2 being used as an indicator of ventilation. Of particular note is the 1000 ppm_v limit in Japan that was issued in 1970; thousands of buildings are tested every year to determine if they comply with the Building Sanitation Maintenance Law.

For workplaces, the United States Occupational Safety and Health Administration (OSHA) and National Institute for Occupational Safety and Health (NIOSH) have established a time-weighted average limit value of 5000 ppm_v for airborne exposure in any 8-hour work shift during a 40-hour workweek and 30,000 ppm_v as a short-term exposure limit, i.e., a 15-minutes time-weighted average that should not be exceeded at any time during a workday (NIOSH 1976; OSHA 2017).

Despite many statements to the contrary, ANSI/ASHRAE Standard 62.1 (ASHRAE 2019b) does not provide a limit value for indoor CO_2. Misunderstanding of information in previous editions of the standard continue to lead many to incorrectly attribute a 1000 ppm_v limit to ASHRAE. CEN 16798-1 (2019) provides four categories of indoor environmental quality that include CO_2 concentrations above outdoors, noting that these values serve as indicators of outdoor air ventilation rates per person: Category I, 550 ppm_v; Category II, 800 ppm_v; and Category III and IV, 1350 ppm_v. These categories correspond to the expectations of occupants, with normal expectations corresponding to Category II.

Carbon dioxide is also addressed in green building certification programs. Two recent reviews of the major green building certifications developed worldwide and the indicators they use to assess indoor environment quality showed that CO_2 is one of the top IAQ metrics in these certifications (Wei et al. 2015, 2020). However, the reference values used to assess CO_2 concentrations are not uniform, varying from 530 to 1500 ppm_v (Wei et al. 2015).

A.4 CO_2 as an Indicator of IAQ and Ventilation

As previously noted in the history section, indoor CO_2 has been prominent in discussions of ventilation and IAQ for centuries. While CO_2 concentrations are related to the perception of human bioeffluents and the level of acceptance of their odors, they are not a good overall metric of IAQ, as many important contaminant sources do not depend on the number of occupants in a space. For example, contaminants emitted by building materials and those that enter from outdoors are not correlated with CO_2 concentrations. Nevertheless, all else being equal, if outdoor air ventilation rates are reduced in an occupied building, concentrations of CO_2 will increase along with the concentrations of other contaminants generated indoors. This fact likely explains observed associations of increased CO_2 concentrations with higher SBS symptom rates, absenteeism, and other effects (Apte et al. 2000; Shendell et al. 2004; Gaihre et al. 2014; Fisk 2017).

An indoor CO_2 concentration below 1000 ppm_v has long been considered an indicator of acceptable IAQ, but this concentration is at best an indicator of outdoor air ventilation rate per person. That relationship is based on the use of CO_2 as a tracer gas as described in the next section and is associated with an outdoor air ventilation rate of about 8 L/s (16 cfm) per person. This value of 1000 ppm_v has been used for decades without an understanding of its basis, which is its link to the perception of human body odor by building occupants. This misunderstanding of the significance of 1000 ppm_v has resulted in many confusing and erroneous conclusions about IAQ and ventilation in buildings. Use of CO_2 as an indicator of outdoor air ventilation must reflect the fact that outdoor air ventilation requirements are a function of space type and occupant characteristics (e.g., age and body mass), activity levels, and density. Therefore, a single CO_2 concentration does not apply to all space types and occupancies for the purposes of assessing the ventilation rate. Also, CO_2 concentrations can vary significantly within a building or space based on the details of how ventilation and air distribution are implemented.

Indoor CO_2 concentrations have long been used to control outdoor air intake rates, using a process referred to as *demand-controlled ventilation* (DCV) (Emmerich and Persily 1997). This control strategy reduces the energy use associated with overventilation during periods of low occupancy and helps to ensure that spaces are adequately ventilated based on their actual occupancy. DCV is in fact required by some energy efficiency standards such as ASHRAE/IES Standard 90.1 (ASHRAE 2019a), and CO_2 monitoring is one means of implementing DCV. Note that this control strategy can be more complex to implement in multiple-space ventilation systems when complying with the ventilation requirements in ASHRAE Standard 62.1 (ASHRAE 2019b) and the designer still must address contaminants not associated with occupancy levels. Recent research on DCV has led to control sequences for multiple-space systems (Lin and Lau 2015), which must also address the number and locations of sensors in different building zones and variations in CO_2 generation among zones and over time.

A.5 Use of Occupant-Generated CO_2 as a Tracer Gas

The use of indoor CO_2 concentration as an indicator of the adequacy of outdoor air ventilation rates is based on the application of CO_2 as a tracer gas. Tracer gas dilution methods for measuring outdoor air change rates have been used for decades and are well documented in existing standards (ASTM 2011; ISO 2017). Application of CO_2 to these methods simply takes advantage of a convenient tracer gas source, i.e., the building occupants. Tracer gas methods also exist to quantify air distribution and ventilation efficiency in spaces, and CO_2 can be used for these measurements as well. However, most applications of CO_2 as a tracer gas assume the space in question is a single zone at a uniform tracer gas concentration.

As noted in ASTM D6245 (2018), there are two tracer gas methods for estimating outdoor air ventilation rates using CO_2: decay and steady state, both of which are best suited to single zones. Both methods are based on the following assumptions: the tracer gas concentration is uniform in the space being monitored, the outdoor CO_2 concentration is constant during the test (or monitored in real time), and the rate at which occupants generate CO_2 is known and constant for the steady-state method. People emit CO_2 at a rate based on their sex, age, body mass, and level of activity as described in ASTM D6245, and therefore information on the occupants is required to estimate these rates. When reporting the results of these tracer gas measurements, it is essential also to report the uncertainty of the results. ASTM D6245 discusses how to estimate these uncertainties. Because these are single-zone methods, they do not account for airflow and CO_2 transport between the zone of interest and other building zones. The measurement errors associated with using a single-zone approach in a space or building that is not a single zone at a uniform concentration is difficult to quantify, and these errors are often neglected in the application of these methods.

Peak CO_2 concentrations are commonly used to estimate ventilation rates per person using the constant injection tracer gas dilution method. For this approach to yield a valid result, the indoor concentration must be at steady state and the ventilation rate must be constant. Using a CO_2 concentration measured before achieving steady state will overestimate the ventilation rate. In a study of the uncertainty associated with CO_2 tracer gas measurements in an occupied space (Kabirikopaei and Lau 2020), the steady-state approach resulted in the lowest uncertainty and CO_2 sensor accuracy was the dominant factor in determining the overall uncertainty.

A.6 Increases in Outdoor CO_2 Concentrations

Outdoor CO_2 concentrations are relevant to consideration of indoor CO_2 for two reasons. First, when using DCV based on the absolute indoor CO_2 concentration, and not the indoor-outdoor difference, the outdoor air intake rate varies not only with occupancy but also with the outdoor air concentration. Second, if exposure to CO_2 is established to have health and cognitive impacts, then increases in outdoor concentrations will increase the prevalence of these impacts.

Global average CO_2 concentrations are determined by a complex interaction of sources, sinks, and driving forces. On a geological timescale, they have varied widely, but for hundreds of thousands of years, up until the early twentieth century, they were below 300 ppm_v, first exceeding 300 ppm_v in 1912 (EPA 2021). Over the ensuing half century, the average outdoor CO_2 concentration grew slowly, reaching 317 ppm_v in 1960 as measured at the Mauna Loa observatory in Hawaii. Since that time, atmospheric CO_2 concentrations have risen more rapidly, passing 400 ppm_v in 2013 and reaching 420 ppm_v in 2021. The annual growth rate has increased from less than 1 ppm_v per year in 1959 to roughly 2.5 ppm_v per year (NOAA 2021).

Superimposed on the trend of increasing outdoor CO_2 concentration are daily, seasonal, and annual variations. Daily variations are generally small, but a study of concentration over terrestrial ecosystems found an average seasonal peak-to-trough amplitude of 14.8 ppm_v, roughly three times the variation observed at the Mauna Loa observatory (Liu et al. 2015). Seasonal variations are attributable to cycles of biomass and photosynthetic activity of plants, with CO_2 being higher when plants are less active (Cleveland et al. 1983). Urban areas may experience much larger excursions of CO_2 above the global average due to lack of vegetation and the effects of internal combustion engine vehicles, as well as large vertical variations (Lietzke and Vogt 2013). Transient local concentrations may be hundreds of ppm_v above average in some locations, approaching or exceeding 600 ppm_v (Balling et al. 2001). Local concentrations can also be below the average depending on season, time of day, and local vegetation (Liu et al. 2015). These variations in outdoor CO_2 make it important to measure outdoor concentrations when monitoring indoor CO_2.

A.7 Air Cleaning Directed at CO_2 Removal Alone

While CO_2 can be useful as an indicator of ventilation and IAQ under limited circumstances, indoor CO_2 concentrations are not necessarily well correlated with other important indoor air pollutants such as viruses, mold, formaldehyde, carbon monoxide, asbestos, and airborne particles. Using air-cleaning technologies to reduce CO_2 for commonly observed indoor concentrations can result in an unjustified expectation that other indoor pollutants are not a concern.

It is important to distinguish between different air-cleaning technologies and how they impact different types of pollutants. The removal or conversion of CO_2 in the air can be achieved only by chemical reaction processes using sorption-type air cleaners (Hu et al. 2017). The removal of other important indoor contaminants requires other approaches, for example, airborne particle removal by mechanical filters. It is critical not to presume that air cleaning directed at CO_2 removal or conversion alone will remove other indoor air contaminants that might be of more concern. Also, when using CO_2-based DCV, the ventilation system will not operate as intended if using CO_2 removal devices, since these ventilation controls assume that the measured indoor CO_2 concentration is proportional to human occupancy.

A.8 CO_2 as an Indicator of Airborne Infection Risk Transmission

During the COVID-19 pandemic, recommendations have been made to use indoor CO_2 measurements as an indicator of the risk of airborne infection transmission. ASHRAE does not recommend a specific CO_2 concentration as a metric of infection risk, but other organizations have recommended (Centers for Disease Control and Prevention [CDC 2021] in the United

States; Federation of European Heating, Ventilation and Air Conditioning Associations [REHVA 2021] in Europe; and Environmental Modelling Group and Scientific Pandemic Insights Group on Behaviours [EMG/SPI-B 2021] in the United Kingdom) or mandated (Belgian Federal Government [BFG 2021]) CO_2 concentration limits. Many of these are based on CO_2 as an indicator of the outdoor ventilation rate per person, which implicitly involves the use of CO_2 as a tracer gas along with a target ventilation rate. The ventilation rates on which these CO_2 concentrations are based can be derived from ventilation standards, which are not based on the control of airborne disease transmission except in healthcare settings, or from a ventilation rate specifically intended to control transmission. Note that the ventilation requirements in ASHRAE Standard 62.1 (2019b) are a function of space use and occupancy and therefore the corresponding indoor CO_2 concentration varies by space type. For example, the steady-state CO_2 concentrations corresponding to the ventilation requirements in Standard 62.1 range from about 1000 ppm_v in office spaces and classrooms with younger students to between 1500 and 2000 ppm_v in restaurants, lecture classrooms, and retail spaces to above 2500 ppm_v in conference rooms and auditoriums. Recommendations or requirements for ventilation rates and CO_2 concentrations to limit infectious disease transmission have been suggested but are highly uncertain given the many factors that impact infection risk, including differences between pathogens. It is important to bear in mind that ventilation is only one control strategy that should be implemented as part of a layered approach to risk management.

All else being equal, higher CO_2 concentrations correspond to lower outdoor air ventilation rates and potentially an increased risk of airborne transmission. While CO_2 concentrations can be a useful qualitative indicator, they do not capture the impacts of the reduced occupancy that is common in many buildings or the impacts of particle filtration and air cleaning on infection risk. Other factors impact exposure and transmission risk, such as the amount of virus in the air (which does not necessarily scale with CO_2), respiratory activity, and type of pathogen. Note also that if CO_2-based DCV is being used, lower occupancy will reduce the outdoor air ventilation rate and presumably increase the risk of transmission, which is why several organizations have recommended disabling DCV systems or lowering their set points. These two strategies will have different impacts on outdoor air ventilation rates, with the former maintaining design minimum outdoor air intake and the latter potentially increasing outdoor air ventilation.

Rather than using indoor CO_2 concentration as an indicator of desired ventilation rates, several analyses of airborne infection risk have used CO_2 as an indicator of the “rebreathed fraction” of indoor air (the fraction of inhaled air that was exhaled by someone else in the space). If the incidence of an airborne disease in the population and the infectious dose of the pathogen are known, these methods can be used to estimate the percentage of new infections for a particular scenario (Rudnick and Milton 2003; Peng and Jimenez 2021). These methods rely on multiple assumptions about the distribution of indoor CO_2 and infectious aerosol, the relative significance of different infection modes, and dose response relationships that are subject to large uncertainties. Consequently, they may not be highly accurate predictors of absolute risk.

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