

# Indoor Carbon Dioxide Concentrations in Ventilation and Indoor Air Quality Standards

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## SUMMARY

Indoor carbon dioxide (CO<sub>2</sub>) concentrations have played a role in discussions of ventilation and indoor air quality (IAQ) since the 18<sup>th</sup> century. Those discussions have evolved over the years to focus on the impacts of CO<sub>2</sub> on building occupants, how CO<sub>2</sub> concentrations relate to occupant perception of bioeffluents, the use of indoor CO<sub>2</sub> to estimate ventilation rates, and CO<sub>2</sub>-based demand control ventilation. The relevance of CO<sub>2</sub> concentrations to ventilation and IAQ standards is based primarily on two considerations: their relation to indoor levels of bioeffluents, and their relation to ventilation rates per person. This paper reviews these concepts and discusses the role of indoor CO<sub>2</sub> in various ventilation and IAQ standards. CO<sub>2</sub>

## PRACTICAL IMPLICATIONS

While indoor CO<sub>2</sub> concentrations are relevant to building ventilation and IAQ, much confusion remains regarding their significance. While some of the issues are complex, the roles of CO<sub>2</sub> in ventilation and IAQ standards are clear and this paper summarizes what these standards do and don't say about CO<sub>2</sub>.

## KEYWORDS

*carbon dioxide, guidelines, indoor air quality, standards, ventilation*

## 1 INTRODUCTION

Indoor CO<sub>2</sub> concentrations have been prominent in discussions of ventilation and IAQ since the 18<sup>th</sup> century when Lavoisier suggested that CO<sub>2</sub> build-up rather than oxygen depletion was responsible for “bad air” indoors. About one hundred years later, von Pettenkofer suggested that biological contaminants from human occupants were causing indoor air problems, not CO<sub>2</sub> (Klauss, et al. 1970). Discussions of CO<sub>2</sub> in relation to IAQ and ventilation have evolved since that time, focusing on the following issues: impacts of CO<sub>2</sub> concentrations on building occupants, how these concentrations relate to occupant perception of bioeffluents, the use of indoor CO<sub>2</sub> concentrations to estimate ventilation rates, and the use of CO<sub>2</sub> to control outdoor air ventilation rates. This paper reviews how CO<sub>2</sub> is dealt with in ventilation and IAQ standards and guidance documents.

### 1.1 Carbon dioxide concentrations in standards and guidelines

While indoor CO<sub>2</sub> concentrations are rarely close to health-based limits, much confusion has resulted regarding CO<sub>2</sub> levels in ventilation and IAQ standards. ASHRAE Standard 62.1-2016 contains a list of CO<sub>2</sub> limits in other documents, four of which are equal to 9000 mg/m<sup>3</sup> and one at 6300 mg/m<sup>3</sup> (ASHRAE 2016). The short-term exposure limits in this list tend to be higher, ranging from 18 000 mg/m<sup>3</sup> to 54 000 mg/m<sup>3</sup>. These higher limits are drawn from values developed for industrial environments, which are not applicable to general populations as discussed below. However, the CO<sub>2</sub> limits in Standard 62.1 are in an informative appendix;

the standard contains no requirements limiting indoor CO<sub>2</sub> concentrations. The basis for the commonly-considered, lower value of 1800 mg/m<sup>3</sup> (1000 ppm<sub>v</sub>) is described later.

ASHRAE Standard 62-1981 contained an indoor CO<sub>2</sub> limit of 4500 mg/m<sup>3</sup> for use when applying the performance approach to complying with the standard, i.e., the IAQ Procedure. That limit was changed without explanation to 1800 mg/m<sup>3</sup> in 1989 and then dropped from the standard entirely in 1999. CEN standards 13779 and 15251 also do not contain indoor CO<sub>2</sub> limits, but have informative annexes that provide default CO<sub>2</sub> concentrations for four classes of IAQ (CEN 2007a, CEN 2007b). The highest IAQ class is associated with concentrations about 700 mg/m<sup>3</sup> above outdoors, with the lowest class 1800 mg/m<sup>3</sup> above outdoors.

Other standards and guidance documents also address indoor CO<sub>2</sub> concentrations. ASTM Standard D6245 does not contain limits on indoor CO<sub>2</sub> concentrations (ASTM 2012), but notes that adverse health effects from elevated CO<sub>2</sub> have not been observed until concentrations are in the range of 12 600 mg/m<sup>3</sup> to 36 000 mg/m<sup>3</sup> based on exposures of at least 30 days (EPA 1991, ECA 1992). LEED v4 includes requirements for naturally ventilated spaces in which one of three different options for monitoring system performance must be employed (USGBC 2014). One of those options is to monitor CO<sub>2</sub> concentrations in each thermal zone and to issue an audible or visual alert if the concentration exceeds the setpoint by more than 10 %. LEED v4 refers to Standard 62.1 for the determination of these setpoints, but no setpoint values are provided in either document. LEED also awards extra points for monitoring CO<sub>2</sub> concentrations in densely occupied spaces, but again no concentration limits are provided. Other building design standards and guidelines allow for the use of CO<sub>2</sub> in demand control ventilation systems as described below.

CO<sub>2</sub> values in existing standards and guidelines range from about 1000 mg/m<sup>3</sup> (as a general IAQ indicator) to 20 000 mg/m<sup>3</sup> or more (based on industrial limits). However, considering a number of studies in different countries and different building types, measured indoor values tend to be typically less than 2000 mg/m<sup>3</sup>, with a small fraction above 5000 mg/m<sup>3</sup>, but none in the range of industrial exposure limits (Persily 2015b).

## **1.2 Questions and issues related to carbon dioxide**

In considering indoor CO<sub>2</sub> in the context of ventilation and IAQ standards, a number of issues have been raised and some level of confusion exists. This section presents the issues that have been raised, providing context for the discussion that follows:

- Impacts of CO<sub>2</sub> on building occupants
- Relationship of indoor CO<sub>2</sub> and perception of odors from human bioeffluents
- Relationship of indoor CO<sub>2</sub> levels to ventilation rates
- Application of indoor CO<sub>2</sub> levels to controlling outdoor air ventilation

ASTM Standard D6245-12, Standard Guide for Using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation, first issued in 1998, discusses all of these issues (ASTM 2012). However, per the ASTM definition of a Guide, this document serves as a "... compendium of information or series of options that does not recommend a specific course of action" in order to increase "... awareness of information and approaches in a given subject area" This is the only standard specific to the interpretation of indoor CO<sub>2</sub> concentrations and addresses all of the issues outlined above, plus some others including the measurement of indoor CO<sub>2</sub> concentrations. However, being a guide, this standard does not contain detailed calculation approaches or specific instructions.

## 2 IMPACTS OF CO<sub>2</sub> ON BUILDING OCCUPANTS

While indoor CO<sub>2</sub> concentrations in non-industrial buildings are rarely close to any health-based guidelines for industrial environments, much confusion has resulted regarding the health impacts of exposure to CO<sub>2</sub> in buildings. As noted earlier, concentration limits in standards and guidelines for industrial environments are not typically relevant to commercial, institutional and residential buildings (ASHRAE 2009). Part of the reason is that industrial workers are typically exposed to high concentrations of specific contaminants, while occupants of non-industrial buildings are exposed to a varied mixture of contaminants for long periods of time. Also, the occupants of nonindustrial environments cover a broad range of age, sex, physical condition and pre-existing health conditions. ASHRAE Standard 62.1-2016 discusses the application of industrial guideline concentrations, noting that they are intended to limit exposure in order to not interfere with work processes, but not to eliminate effects such as odors or mild irritation (ASHRAE 2016). In addition, the standard notes that healthy industrial workers will change jobs if the exposure is intolerable, while occupants of non-industrial building occupants have less choice about where they spend their time and include individuals "...who may be more sensitive, such as children, asthmatics, allergic individuals, and the elderly."

While occupational CO<sub>2</sub> exposure limits are not relevant to non-industrial environments and indoor concentrations almost never reach those levels, an indoor concentration of 1800 mg/m<sup>3</sup> has become a de facto standard in many applications without a sound understanding of its basis (Persily 1997). This reference notes the existence of anecdotal discussions associating CO<sub>2</sub> concentrations in this range with occupant symptoms such as stuffiness and discomfort, but notes that peer-reviewed studies do not support these associations with CO<sub>2</sub> itself. While studies have shown associations of elevated CO<sub>2</sub> levels with symptoms, absenteeism and other effects (Apte, et al. 2000, Shendell, et al. 2004, Gaihre, et al. 2014), these associations are likely due to lower ventilation rates elevating the concentrations of other contaminants with health and comfort impacts at the same time they are elevating CO<sub>2</sub>.

The 1800 mg/m<sup>3</sup> CO<sub>2</sub> "guideline value" is commonly attributed to ASHRAE Standard 62. As noted earlier, the 1981 version of that standard contained an indoor CO<sub>2</sub> limit of 4500 mg/m<sup>3</sup> for use when applying the IAQ Procedure, which was changed to 1800 mg/m<sup>3</sup> in 1989 and removed in 1999. That and subsequent versions of the standard contained an informative appendix explaining that if a space is ventilated at a rate of 7.5 L/s per person, then the steady-state CO<sub>2</sub> concentration will equal 1800 mg/m<sup>3</sup> for assumed values of the CO<sub>2</sub> generation rate per person and the outdoor CO<sub>2</sub> concentration. There is nothing in the standard declaring 1800 mg/m<sup>3</sup> or any other CO<sub>2</sub> concentration to be a health or comfort based limit. The 1800 mg/m<sup>3</sup> "limit" is simply based on its association with a ventilation requirement of 7.5 L/s per person for control of body odor perception as discussed below.

While indoor CO<sub>2</sub> concentrations are typically well below values of interest based on health concerns, some recent studies have shown evidence of impacts on human performance. These chamber studies of individuals completing computer-based tests showed statistically significant decreases in decision-making performance at CO<sub>2</sub> concentrations as low as 1800 mg/m<sup>3</sup> (Satish, et al. 2012, Allen, et al. 2015). These experiments were designed to expose the subjects to elevated CO<sub>2</sub> but not to other contaminants. Another recent study exposed individuals to pure CO<sub>2</sub> as well as to CO<sub>2</sub> mixed with bioeffluents and did not see the same impacts of pure CO<sub>2</sub> at concentrations at or below 5400 mg/m<sup>3</sup> on occupant subjective perceptions of the environment or on performance (Zhang, et al. 2016). However, when mixed with bioeffluents, CO<sub>2</sub> at these same concentrations did impact perceived air quality and

performance. This work has not yet impacted ventilation and IAQ standards, but if the findings showing impacts of such low levels are repeated, they may support future changes.

### **3 CO<sub>2</sub> AND THE PERCEPTION OF BODY ODOR**

There have been many decades of research into outdoor air requirements, which, starting in the second half of the nineteenth century, focused on the control of human body odor associated with the byproducts of human metabolism, often referred to as bioeffluents (Klauss, et al. 1970). Building on the seminal work of von Pettenkofer and others, Yaglou et al. (1936) used environmental chambers to investigate ventilation rates required to control the odor from bioeffluents. In these studies, human test subjects rated odor intensity as a function of the ventilation airflow per person. This research found that about 7.5 L/s to 9 L/s per person of ventilation air was needed to dilute body odor to levels judged to be acceptable by individuals entering the room from relatively clean air. Since the time of Yaglou's research, a number of researchers have reported similar results in both laboratory chambers and actual buildings (Cain, et al. 1983, Fanger and Berg-Munch 1983, Iwashita, et al. 1990).

Some of these experiments also studied the relationship between CO<sub>2</sub> concentrations and body odor acceptability. The finding that about 7 L/s per person of ventilation controlled human body odor such that about 80 % of unadapted individuals found the odor to be acceptable was accompanied by the result that the same level of acceptability occurred at CO<sub>2</sub> concentrations about 1250 mg/m<sup>3</sup> above outdoors. For an outdoor CO<sub>2</sub> level of 630 mg/m<sup>3</sup>, this indoor concentration roughly corresponds to the commonly cited value of 1800 mg/m<sup>3</sup>. The relationship between the percentage of subjects dissatisfied with body odor and CO<sub>2</sub> concentrations has been seen experimentally in several studies, with the results largely independent of the level of physical activity (Fanger and Berg-Munch 1983, Rasmussen, et al. 1985, Berg-Munch, et al. 1986). In addition, the relationship did not require that the indoor CO<sub>2</sub> concentration be at steady-state. The lack of a strong dependency on physical activity arises from the fact that humans produce CO<sub>2</sub> and bioeffluents at rates that are roughly proportional to one another. The fact that these relationships do not require the existence of steady-state conditions arises because both CO<sub>2</sub> and odor levels increase at a rate that is primarily dependent on the air change rate of the space in question. This research supports 1800 mg/m<sup>3</sup> of CO<sub>2</sub> as a reflection of body odor acceptability perceived by unadapted visitors to a building. Of course, there are many other indoor air contaminants that are not associated with the number of occupants, and CO<sub>2</sub> concentration is not a good indicator of those.

### **4 CO<sub>2</sub> AND VENTILATION RATES**

As discussed previously (Persily 1997, ASTM 2012), per person ventilation rates and indoor CO<sub>2</sub> levels are related based on a single-zone mass balance of CO<sub>2</sub>. This relationship has been discussed in Standard 62 since 1981, with the steady-state equation presented as follows:

$$Q = G/\Delta C \tag{1}$$

where Q is the outdoor air ventilation rate per person, G is the CO<sub>2</sub> generation rate per person and  $\Delta C$  is the difference between the indoor and outdoor CO<sub>2</sub> concentrations. For a ventilation rate of 7.5 L/s per person and a CO<sub>2</sub> generation rate of 0.3 L/min per person, the indoor CO<sub>2</sub> concentration will be about 1200 mg/m<sup>3</sup> above outdoors. Using slightly different values of the generation rate, one arrives at an indoor CO<sub>2</sub> concentration value of 1800 mg/m<sup>3</sup>. This value is often referred to as a CO<sub>2</sub> "limit" erroneously attributed to ventilation standards, but as discussed earlier, is actually related to recommended ventilation rates for body odor control under idealized, steady state conditions, not to the health or comfort impacts of the CO<sub>2</sub>.

This relationship between CO<sub>2</sub> concentrations and ventilation rates is essentially an application of the constant injection tracer gas method, which has been well-understood for decades (Hunt, 1980), and is too often used to estimate ventilation rates without an adequate understanding of its basis. The constant injection method, described in ASTM E741 (ASTM 2011), involves injecting tracer gas at a constant rate into the space being tested and monitoring the concentration response. Since the so-called peak CO<sub>2</sub> approach is a single-zone steady-state tracer technique, it must abide by the following assumptions to yield a valid air change rate: the CO<sub>2</sub> generation rate is known, constant, and uniform throughout the building being tested; the CO<sub>2</sub> concentration is uniform throughout the building and has achieved steady state; the outdoor CO<sub>2</sub> concentration is known and constant; and, the outdoor air ventilation rate is constant. Given that the method is based on a single-zone mass balance, it can only be used to determine the air change rate of an entire building with a uniform concentration. If the CO<sub>2</sub> concentration varies among rooms, the single-zone approach is not valid and one must employ a multizone mass balance of CO<sub>2</sub> that accounts for the airflows between zones and is far more complicated to apply. Similarly, the steady-state CO<sub>2</sub> value in a single room cannot be used to calculate the ventilation rate of that room if adjoining spaces are at different CO<sub>2</sub> concentrations.

In order for the CO<sub>2</sub> generation rate to be known, constant, and uniform throughout the building, the occupancy level must also be known, constant, and uniform. Assuming it is, the CO<sub>2</sub> generation rate can be estimated based on the number and characteristics of the building occupants, that is, their age, size and level of physical activity (ASTM 2012). However, as noted in that standard, CO<sub>2</sub> generation rates can vary significantly among individuals. Also, the requirement for the CO<sub>2</sub> concentration being at steady state translates to conditions being constant for long enough that a steady-state concentration is achieved. As described in Persily (1997) and ASTM (2012), the time required to achieve steady state depends on the air change rate of the building. For a given air change rate, the concentration will be within 95 % of steady state after three time constants, where the time constant is the inverse of the air change rate. For an air change rate of 1 h<sup>-1</sup>, it will take 3 h to reach 95 % of the steady-state. For an air change rate of 0.25 h<sup>-1</sup>, it will take 12 h. During this time, the ventilation rate, occupancy, and outdoor concentration must all be constant. Using a CO<sub>2</sub> concentration before steady state has been achieved will overestimate the air change rate, in some cases by significant amounts.

While indoor CO<sub>2</sub> concentrations are related to ventilation rates, that relationship is complicated by the multizone, transient nature of building airflow systems as well as temporal and spatial variations in occupancy (i.e., CO<sub>2</sub> generation). The relationship is simple under only very specific circumstances, making CO<sub>2</sub> a questionable indicator of ventilation rates.

## **5 DEMAND CONTROL VENTILATION (DCV) USING CO<sub>2</sub>**

Ventilation and IAQ standards allow the use of DCV to control outdoor air ventilation rates; in fact it is required under some circumstances by energy efficiency standards (ASHRAE 2013). Under ASHRAE Standard 62.1-2016, the ventilation requirement of a space is the sum of a per-person rate multiplied by the number of occupants plus an area rate multiplied by the floor area of the space. The use of DCV is relevant only to control of the ventilation requirement based on the number of occupants, i.e., the rate based on the floor area must always be maintained. In practice, the standard allows the use of CO<sub>2</sub> as means to implement DCV, with the outdoor air intake rate controlled such that the intake rate increases as the CO<sub>2</sub> levels rises and decreases as it drops, similar to temperature control using a thermostat. The CO<sub>2</sub> setpoint depends on the ventilation rate requirement of the space of interest, which is a function of the space type, the number of occupants and the floor area. However, Standard

62.1 does not contain requirements specific to the application of CO<sub>2</sub> DCV; it simply allows DCV to be used to dynamically reset outdoor air intake flows and mentions CO<sub>2</sub> as an acceptable means of doing so. The application of CO<sub>2</sub> DCV per the standard is described in detail in the Users Manual for the standard (ASHRAE 2010). Additional information on the application of CO<sub>2</sub>-based DCV, specifically setpoint values for different space types, is available in Lawrence (2008). More specific requirements for the use of CO<sub>2</sub> DCV are contained in California Title 24 and ANSI/ASHRAE/IES/USGBC Standard 189.1 (CEC 2013, ASHRAE 2014). Title 24 contains requirements regarding the number of CO<sub>2</sub> sensors, their location and their accuracy. It specifies a setpoint of 1080 mg/m<sup>3</sup> above the outdoor concentration, which can be measured or assumed to equal 720 mg/m<sup>3</sup>. Standard 189.1 also contains requirements for sensor location and accuracy, but requires that the outdoor concentration be measured.

## 6 CONCLUSIONS

This paper summarizes how CO<sub>2</sub> is dealt with in ventilation and IAQ standards, focusing on the impacts CO<sub>2</sub> on building occupants, how CO<sub>2</sub> concentrations relate to occupant perception of bioeffluents, the use of indoor CO<sub>2</sub> to estimate ventilation rates, and the use of CO<sub>2</sub> to control outdoor air ventilation rates. Regarding the impacts of CO<sub>2</sub> on occupants, indoor concentrations are rarely close to limits in health-based guidelines, but much confusion still exists regarding CO<sub>2</sub> levels in ventilation and IAQ standards. Based on studies in different countries and different building types, most measured indoor CO<sub>2</sub> concentrations are less than 2000 mg/m<sup>3</sup>, with a small fraction above 5000 mg/m<sup>3</sup>, but none are in the range of industrial exposure limits. Nevertheless, discussions of indoor CO<sub>2</sub> have long referred to the health impacts of exposure to CO<sub>2</sub>. Similarly, many have referred to 1800 mg/m<sup>3</sup> as a “guideline value” for indoor CO<sub>2</sub> or even a requirement, most commonly attributing it to ASHRAE Standard 62. However, there is nothing in the standard declaring 1800 mg/m<sup>3</sup> or any other CO<sub>2</sub> concentration as a health or comfort based requirement. The notion of an 1800 mg/m<sup>3</sup> “limit” is based on its association with a nominal ventilation requirement of 7.5 L/s per person under very specific circumstances as discussed in this paper. Research does exist that associates CO<sub>2</sub> concentrations of 1800 mg/m<sup>3</sup> with body odor acceptability of unadapted visitors to a building. However, there are many other indoor air contaminants that are not associated with occupancy, and CO<sub>2</sub> is not a good indicator of those contaminants.

As discussed here, indoor CO<sub>2</sub> concentrations are related to ventilation rates but that relationship is complicated by the multizone, transient nature of building airflow systems as well as variations in building occupancy (i.e., CO<sub>2</sub> generation rates) both temporally and spatially. The relationship can be used to estimate ventilation rates from CO<sub>2</sub> concentrations under only very specific and somewhat unusual circumstances, making CO<sub>2</sub> a questionable indicator of ventilation rates. Finally, ventilation and energy efficiency standards allow, in some cases require, the use of CO<sub>2</sub> concentrations to control ventilation rates.

In conclusion, we understand most of the issues related to indoor CO<sub>2</sub> in buildings, with this paper focusing on those issues covered by ventilation and IAQ standards. Nevertheless, many practitioners and other users of these standards are still confused regarding these issues. Standards, guidelines and technical papers are available to reduce this confusion, but they only have an impact when read and understood. Other mechanisms, such as training, need to be employed to get this information where it is needed. It is also important that technical papers that refer to the use of CO<sub>2</sub> concentrations for measuring ventilation rates or which discuss the place of CO<sub>2</sub> in ventilation and IAQ standards be very carefully reviewed by knowledgeable individuals.

## 7 ACKNOWLEDGEMENT

The author gratefully acknowledges Stuart Dols, Steven Emmerich and Al Hodgson for their helpful reviews of this paper.

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